

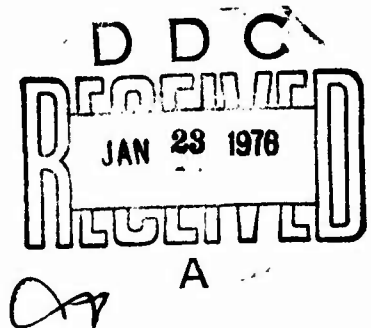
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REPORT NO. U-75-27

STEADY-STATE COMBUSTION OF NONMETALLIZED COMPOSITE SOLID
PROPELLANT

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JULY 1975

INTERIM REPORT FOR PERIOD 1 MAY 1974 - 30 JUNE 1975

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PREPARED FOR

DEPARTMENT OF THE AIR FORCE
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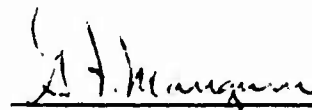
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FOREWORD

This is an interim report covering the work completed under Contract F44620-74-C-0080 for the period 1 May 1974 through 30 June 1975. Publication of this report does not constitute Air Force approval of the findings or conclusions contained herein. It is published only for the exchange of data and stimulation of ideas.

The program is monitored by Capt. L. R. Lawrence, Jr., of the Air Force. Mr. G. F. Mangum is the Project Director and Dr. M. Miller is the Program Manager.



G. F. Mangum
Project Director

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ABSTRACT

Monodisperse BDP combustion model was extended to nonmetallized propellants with mixed, polydisperse oxidizers by embedding monodisperse model in statistical framework including mixture ratio effects. Basically, polydisperse propellant is "disassembled and rearranged" to form sequence of monodisperse pseudo-propellants whose rates are computed via monodisperse model. Re-assembly provides real propellant's burning rate. Approach provides information pertaining to distribution of regression rates and surface structure among different size ox. particles. Preliminary results suggest that significant factor in rate increases wrought by introduction of small oxidizer modes is mixture ratio alterations in larger modes.

Hydraulic T-burner analog was constructed and employed to visualize vent flow phenomena. Studies showed that flow enters vent with axial momentum and that that momentum is partially transformed to vent into Karman vortex sheet. Fact that flow enters vent with axial momentum invalidates boundary condition of Culick analysis for flow turning gain; "correct" boundary condition leads to null vent gain. Experimental facts consistent with proof that in formal one-dimensional flow vent gain violates second law of thermodynamics.

Logical and consistent way to reduce solid rocket data when pressure-time history is not neutral was derived. Since current techniques are not self-consistent in this situation, these results open door to reclamation of performance data heretofore rejected.

INTRODUCTION

Since 1972 when Culick⁽¹⁾ first found that formal analysis of the linearized, one-dimensional equations of change led to acoustic/mean flow interactions (A/MFI), the rather surprising flow turning gain associated with a T-burner's vent has been regarded skeptically. The situation was not improved by the appearance of another "theory" predicting different A/MFI⁽²⁾ and indecisive results obtained from T-burner tests aimed at evaluating A/MFI. The situation in 1973* is described in some detail by Shoner⁽³⁾.

It is not surprising that Culick's one-dimensional results conflict with results stemming from the theory developed by McClure, Hart, and Cantrell⁽⁵⁾ in an area where mixing and viscous effects are important. Culick's theory implicitly includes mixing while MHC's theory explicitly (through the inviscid media assumption) disallows mixing. Clearly, what is required is qualitative knowledge of the flow phenomena so that "intelligent" modeling of A/MFI can be accomplished. A cost effective approach to obtaining qualitative information about multi-dimensional nonsteady flows is to employ the hydraulic analogy. Accordingly, a proposal was prepared and submitted to AFOSR with the expressed purpose of examining the vent region flow in a T-burner with the hydraulic analogy.

Since 1970 steady-state composite propellant combustion modeling has been dominated by the Beckstead, Derr, Price (BDP) model⁽⁶⁾. Although the basic model applied solely to additive-free propellant with spherical, monodisperse oxidizer, Cohen, Derr, and Price⁽⁷⁾ extended the model to propellants with aluminum and bimodal oxidizer. Sammons⁽⁸⁾ subsequently extended the model to propellants with polydisperse oxidizer.

Since composite solid propellant is a random packing of solid particles filled with binder and the deflagration wave traverses the solid, the burning surface must also possess random structure. Because of the discrete particulate nature and random structure of the burning surface, a classical steady state where state variables are invariant in time cannot exist; at any fixed time spatial variations of state variables are random to some length scale; at any fixed position relative to the burning surface the state variables are random in time to some time scale. Consequently, steady-state combustion can only mean that statistical means are stationary in time.

In the monodisperse BDP model the random, nonsteady phenomena at the burning surface is "averaged" into a mean state in a particle's life. Treating this state as quasi-steady and applying mass and energy conservation, kinetics principles, etc., an implicit "relation" for burning rate is obtained. No derivation has been given for the averaging procedure. Cohen, Derr, and Price⁽⁷⁾ extended the model to bi-modal distributions by assuming all particle sizes burn at the

*The situation in 1974 was not greatly changed; see discussion in Reference 4.

same rate. This seems highly improbable. On the other hand, Sammons⁽⁸⁾ extended the model to polydispersions by apparently assuming that the polydispersion could be averaged into a single particle. No derivation was given for this averaging procedure.

In 1973 Glick⁽⁹⁾⁽¹⁰⁾ advanced a statistical combustion modeling formalism that applied to polydisperse situations and eliminated the aforementioned approximations. Consequently, a proposal was prepared and submitted to AFOSR with the expressed purpose of embedding the basic BDP combustion model in this statistical formalism.

These separate proposals were ultimately combined into a single program with the following objectives:

- Construct a hydraulic analogue of a T-burner utilizing a water table.
- Investigate the flow pattern in the vent region of the T-burner analogue to determine whether or not acoustic energy is convected out the vent.
- Compare the experimental results in qualitative fashion with the predictions of present T-burner theories.
- Adapt the Beckstead, Derr, Price combustion model as modified by Sammons to the contractor's statistical combustion model. Investigate the properties of the resulting model as it pertains to propellants with polydispersions of spherical, mixed oxidizers.

This program was monitored, in the best sense of the word, by Capt. L. R. Lawrence, Jr. This report describes in detail the work that was accomplished under this program.

STEADY-STATE COMBUSTION OF NONMETALLIZED COMPOSITE SOLID PROPELLANT

Development of Theory

The most obvious feature of composite solid propellants is their heterogeneous structure. Since high specific impulse is desirable for propulsion systems, total solids content is generally as large as possible. Since composite propellant is essentially a packing of solid particles filled with binder, high total solids content demands a dense packing. To achieve a dense packing, the particles must be polydisperse with a broad range of particle sizes so that the smaller particles can fill the voids in the packing of the larger particles. Therefore, virtually all practical propellants are polydisperse. In the past ammonium perchlorate (AP) was the preferred oxidizer specie. Consequently, propellants with mixed oxidizers were rare. However, recent emphasis on reduced visual

signature has aroused interest in oxidizers other than AP and propellants with non-AP oxidizer, mixtures of non-AP oxidizers, and AP and non-AP mixtures are being explored. Therefore, realistic combustion modeling must consider, in the least, propellants with mixed, polydisperse oxidizers.

Composite propellants are created by mixing their several ingredients together. Therefore, a randomly packed, particulate structure is expected above some length scale. Since the deflagrating surface transverses the solid, the arrangement/structure of oxidizer particles on the burning surface must also be random above some length scale. Because of this randomness and the discontinuous chemistry wrought by heterogeneity, composite propellant combustion is never steady-state in the sense that state variables are invariant in time; at any time state variables are spatially random above some length scale; at any fixed position relative to the mean burning surface state variables vary randomly in time above some time scale. Consequently, analysis of "steady-state" combustion must be directed toward the determination of state variable means and distributions.

Consider now a large, quasi-planar deflagrating surface of composite solid propellant (see Figure 1). Application of mass conservation to the control surface yields

$$\frac{dm_{cv}}{dt} = \oint_{S_b} m'' dS - \oint_{S_p} m'' dS \quad (1)$$

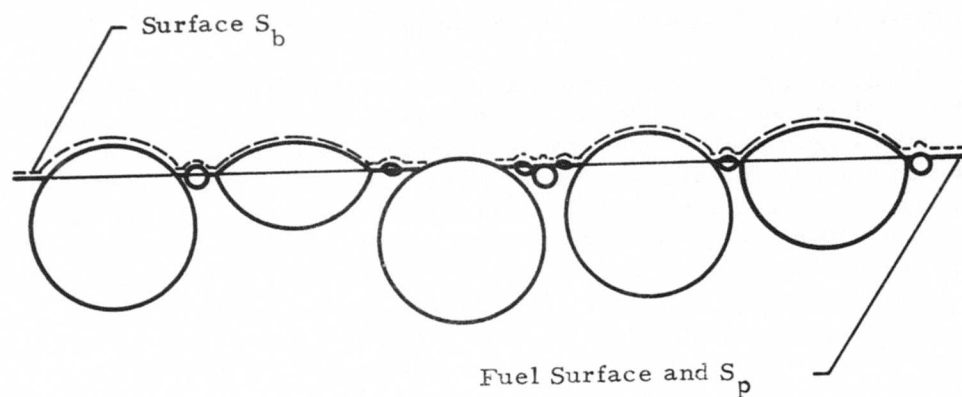
Experience shows that when $dp = dT_i = 0$ $\lim_{S_p \rightarrow \infty} \frac{dm_{cv}}{dt} = 0$. Consequently, for steady-state combustion

$$\oint_{S_p} m'' dS = \oint_{S_b} m'' dS \quad (2)$$

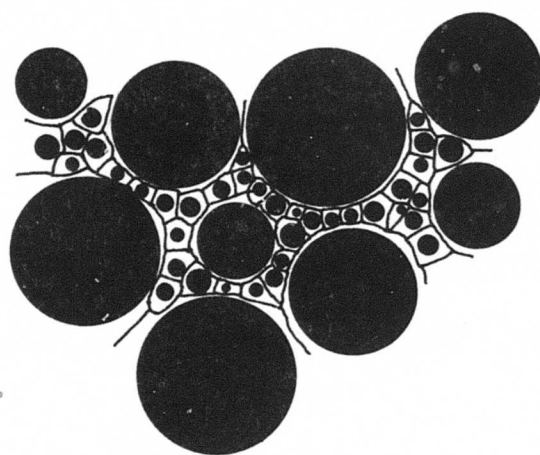
Applying the mean value theorem for integrals to the LHS of Eq. (1) yields

$$\bar{m}_t = \oint_{S_b} m'' dS / S_p = \bar{r} \rho_t \quad (3)$$

The surface S_b may be visualized as a jigsaw puzzle-like arrangement of oxidizer particle/fuel surface pairs. For composite propellant with polydisperse, mixed oxidizers, some of these oxidizer particle/fuel surface pairs will have the same particle diameter and specie. Therefore, rearrange the oxidizer particle/fuel surface pairs so that those with common particle diameters and species are neighbors. This rearrangement creates a sequence of monodisperse propellant subsurfaces. If it is assumed that combustion of all oxidizer particle/fuel surface pairs are independent, the deflagration rate of any monodisperse subsurface can be computed by application of any monodisperse combustion (BDP for example) model. Consequently, proper summation of these subsurface rates should yield the burning rate of composite propellant with mixed, polydisperse oxidizer.



ELEVATION



PLAN

Figure 1. Schematic of Propellant Surface

To accomplish this approach rearrange the burning surface's oxidizer particle/fuel surface pairs into Q monodisperse subsurfaces. Then Eq. (3) becomes

$$\bar{m}_t'' = \sum_{i=1}^Q \left(\sum_{k=1}^s \oint_{\Delta S_{b,d,k}} m_{d,k}'' dS \right) / S_p \quad (4)$$

where $\Delta S_{b,d,k}$ is the portion of S_b occupied by and $m_{d,k}''$ is the mass flux from oxidizer particle/fuel surface pairs possessing oxidizer particles with $D \leq D \leq D + \Delta D$ and specie k . Application of the mean value theorem for integrals to the RHS of Eq. (4) yields

$$\bar{m}_t'' = \sum_{i=1}^Q \left(\sum_{k=1}^s \bar{m}_{d,k}'' \Delta S_{b,d,k} \right) / S_p \quad (5)$$

The term $\bar{m}_{d,k}'' \Delta S_{b,d,k}$ is the mass flow of products from the monodisperse subsurface $\Delta S_{b,d,k}$. Therefore,

$$\bar{m}_{d,k}'' \Delta S_{b,d,k} = \bar{m}_{p,d,k}'' \Delta S_{p,d,k} \quad (6)$$

where $\bar{m}_{p,d,k}''$ is the mean mass flux (based on planar area) from the monodisperse subsurface $\Delta S_{b,d,k}$ and $\Delta S_{p,d,k}$ is the projection of $\Delta S_{b,d,k}$ on S_p .

If $\Delta N_{p,d,k}$ is the number of oxidizer particles on S_p with $D \leq D \leq D + \Delta D$ and specie k per unit area of S_p ,

$$\Delta S_{p,d,k} / S_p = \bar{\Delta S}_{p,d,k} \Delta N_{p,d,k} \quad (7)$$

where $\bar{\Delta S}_{p,d,k}$ is the average planar surface for an oxidizer particle/fuel surface pair possessing oxidizer particles with $D_i \leq D_i \leq D_i + \Delta D$ and specie k .

Define a distribution function $F_{p,d,k}$ such that

$$\Delta N_{p,d,k} = N F_{p,d,k} \Delta D \quad (8)$$

Then combining Eqs. (5) - (8) yields

$$\bar{m}_t = N \sum_{k=1}^s \left(\sum_{i=1}^Q \bar{m}_{p,d,k}'' \Delta \bar{S}_{p,d,k} F_{p,d,k} \Delta D \right) \quad (9)$$

Passing to the limit of the sum on i as $Q \rightarrow \infty$ yields

$$\bar{m}_t'' = N \sum_{k=1}^s \oint_D \bar{m}_{p,d,k}'' \Delta \bar{S}_{p,d,k} F_{p,d,k} dD = \bar{r} \rho_t \quad (10)$$

Equation (10) is a statistical formalism that enables the mean burning rate of propellant with mixed, polydisperse oxidizers to be computed from the mean burning rates ($\bar{m}_{p,d,k} = \bar{r}_{d,k} \rho_{t,d,k}$) of the sequence of monodisperse psuedo-propellants that "compose" it IF THE COMBUSTION OF EACH OXIDIZER PARTICLE/FUEL SURFACE PAIR IS INDEPENDENT. This approach permits consideration of mixed oxidizers and avoids the requirement that a single particle be selected to represent a polydispersion. Since a polydispersion is represented as a polydispersion, information concerning the variation of surface geometry, temperature, regression rate, etc. can also be computed.

The next step is to investigate the statistical characteristics of the burning surface and thereby relate $\Delta \bar{S}_{p,d,k}$, $F_{p,d,k}$, and the properties of the monodisperse psuedo-propellants to propellant formulation variables. Assuming that the statistical characteristics of the random packing are homogeneous and isotropic, the statistical characteristics of surface S_p can be explored within the propellant. Figure 2 illustrates a random polydisperse packing schematically. Clearly, particles with $D \leq D \leq D + dD$ must lie within $z = \pm D/2$ to intersect plane S . Therefore, if $dN_{v,d}$ is the number of particles per unit volume with $D \leq D \leq D + dD$, the number of these particles that intersect S per unit area of S is

$$dN_{p,d} = dN_{v,d} D \quad (11)$$

The volume fraction of spherical particles with diameter D is

$$d\zeta_d = (\pi D^3 / 6) dN_{v,d} \quad (12)$$

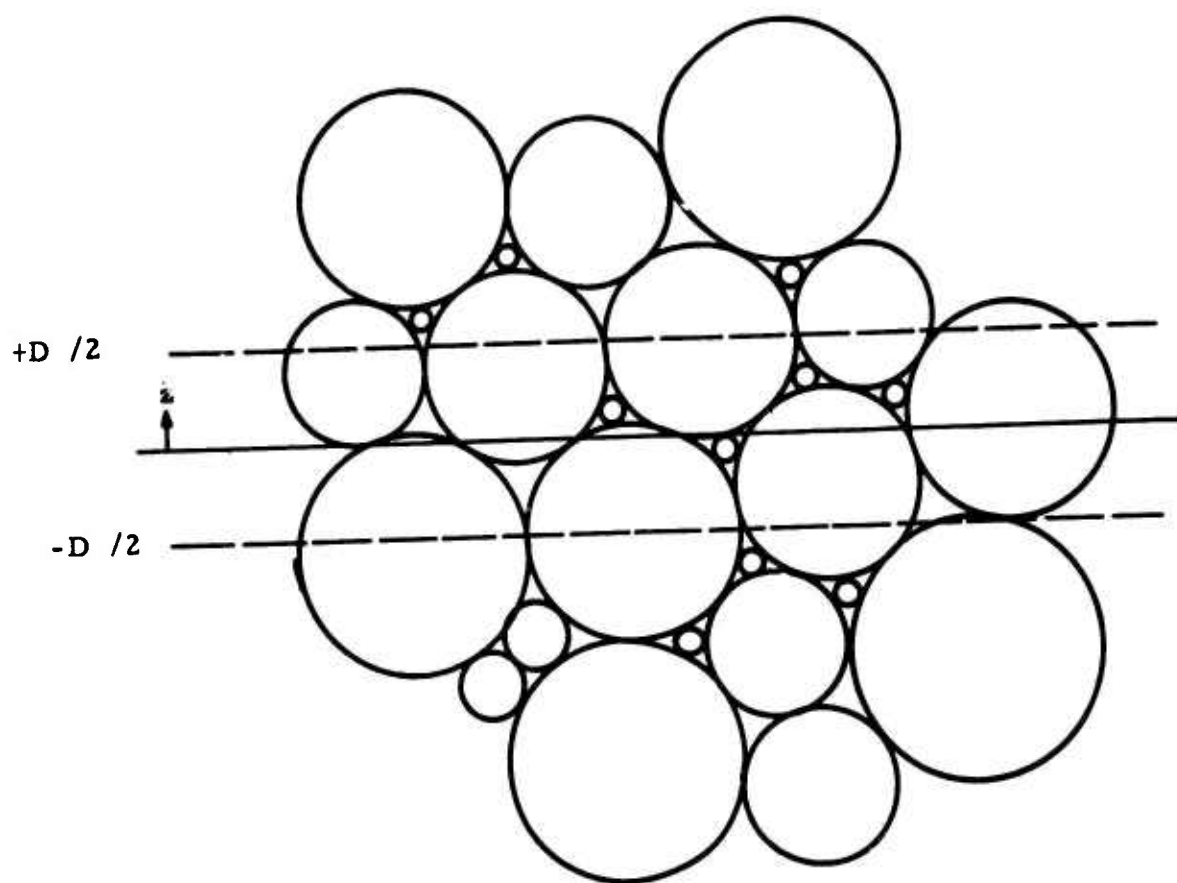


Figure 2 Schematic of Particle Packing

Therefore,

$$dN_{p,d} = (6/\pi D^2) d\zeta_d \quad (13)$$

If the number fraction of particles with $D \leq D \leq D + dD$ and species k in the propellant is $\eta_{d,k}^*$, the number of these particles per unit area of S is

$$dN_{p,d,k} = (6/\pi D^2) \eta_{d,k} d\zeta_d = (6/\pi D^2) d\zeta_{d,k} \quad (14)$$

Now move the plane a distance Δz . The volume of oxidizer particles with $D \leq D \leq D + dD$ in the swept volume is

$$dV_d = d\zeta_d S \Delta z \quad (15)$$

However, the statistical characteristics are homogeneous and isotropic. Therefore, this volume is also swept out by intersections of S with oxidizer particles having $D \leq D \leq D + dD$. Since $dS_{p,d} = (\pi \bar{D}_d^2/4) dN_{p,d}$,

$$dV_d = (\pi \bar{D}_d^2/4) dN_{p,d} \Delta z \quad (16)$$

Combining Eqs. (13), (15), and (16) yields the mean particle intersection diameter

$$\bar{D}_d = \sqrt{2/3} D \quad (17)$$

Therefore, the average oxidizer particle intersection area is

$$\Delta \bar{S}_{o,d,k} = \pi D_{d,k}^2/6 \quad (18)$$

* Note that $\sum \eta_{d,k} = 1$. Since all these particles have same diameter, $\eta_{d,k}$ is $k = 1$ also a volume fraction.

It is important to note that $\bar{D}_d$, $dN_{v,d}$ and $dN_{p,d}$ are functions of D alone. This means that statistical characteristics of the monodisperse cuts in a polydisperse propellant are the same as those in a monodisperse propellant. In short, each monodisperse cut behaves as if it alone occupied the propellant. Notice the similarity to mixtures of perfect gases.

The mean statistical characteristics of the fuel surface in each monodisperse cut of oxidizer fuel surface pairs cannot be determined exactly because it requires a statistical determination of how the smaller particles pack inside the packing of larger particles. This information is unavailable. Therefore, approximations must be introduced. Examination of the characteristics of regular geometric packings⁽¹¹⁾ suggests that the mean volume of fuel associated with a particle should be roughly proportional to its surface or $\bar{\Delta V}_{f,d} \propto D^2$. However, to allow for some variation assume

$$\bar{\Delta V}_{f,d} = C D^n \quad (19)$$

where n is a parameter to be determined experimentally. Since oxidizer volume is proportional to D^3 , $d(O/F)/dD \geq 0$ when $n \geq 3$. Particle diameter alone is important in a packing. Therefore, $\bar{\Delta V}_{f,d,k} = \bar{\Delta V}_{f,d}$.

The volume fraction of fuel associated with particles having $D \leq D \leq D + dD$ and species k is

$$dV_{f,d} = \bar{\Delta V}_{f,d} dN_{v,d} \quad (20)$$

The volume fraction of fuel in the real propellant is $1 - \zeta_o$; it is also the integral of Eq. (20) over all particle diameters. Employing this fact and Eqs. (12) and (20) yields after integrating over all diameters

$$C = [\pi (1 - \zeta_o)/6] / \int_D^\infty D^{n-3} d\zeta_d \quad (21)$$

With both particle diameter and mean volume of fuel associated with that particle diameter "known" the volume and mass fractions and the density of a pseudo-propellant formed from mono-diameter and specie oxidizer particle/fuel surface pairs can be computed. The volume fraction is $\bar{\Delta V}_{o,d,k} / (\bar{\Delta V}_{o,d,k} + \bar{\Delta V}_{f,d,k})$ so

$$\zeta_{d,k}^* = (1 + 6CD^{n-3}/\pi)^{-1} \quad (22)$$

The mass fraction is $\overline{\Delta m}_{o,d,k} / (\overline{\Delta m}_{o,d,k} + \overline{\Delta m}_{f,d,k})$ so

$$\alpha_{d,k}^* = [1 + 6C\rho_f D^{n-3} / (\pi \rho_{o,k})]^{-1} \quad (23)$$

The pseudo-propellant's density is

$$\rho_{d,k}^* = \rho_{o,k} \zeta_{d,k}^* / \alpha_{d,k}^* \quad (24)$$

Since $\zeta_{d,k}^* = S_{o,d,k}^* / S_{p,d,k}^* = \Delta \bar{S}_{o,d,k} / \Delta \bar{S}_{d,k}$, Eq. (18) becomes

$$\Delta \bar{S}_{d,k} = \pi D^2 / (6 \zeta_{d,k}^*) \quad (25)$$

The mass flux in Eq. (10) corresponds to the mean mass flux stemming from combustion of pseudo-propellant. Therefore,

$$\overline{m}_{p,d,k}'' = \overline{m}_{d,k}'' = \overline{r}_{d,k}^* \rho_{d,k}^* \quad (26)$$

The only tasks remaining are to relate $F_{p,d,k}$ and $d\zeta_{d,k}$ to the independent propellant formulation variables $\alpha_{k,j}$, $F_{k,j}$, M_k , and s . The volume fraction of oxidizer specie k with diameter D is defined as

$$d\zeta_{d,k} = dV_{o,d,k} / V_t \quad (27)$$

Since $dV_{o,d,k} = dm_{o,d,k} / \rho_{o,k}$ and $V_t = m_T / \rho_t$

$$d\zeta_{d,k} = (dm_{o,d,k} / m_t) (\rho_t / \rho_{o,k}) \quad (28)$$

However, $F_{k,j} = dm_{o,d,k,j} / (m_{o,k,j} dD)$ and $dm_{o,d,k} = \sum_{j=1}^{M_k} dm_{o,d,k,j}$
 Therefore,

$$d\zeta_{d,k} = (\rho_t / \rho_{o,k}) \sum_{j=1}^{M_k} \alpha_{k,j} F_{k,j} dD \quad (29)$$

$$\text{Since } dV_{o,d} = \sum_{k=1}^s dV_{o,d,k}$$

$$d\zeta_d = \sum_{k=1}^s (\rho_t / \rho_{o,k}) F_k dD \quad (30)$$

where

$$F_k = \sum_{j=1}^{M_k} F_{k,j} \alpha_{k,j} \quad (31)$$

$$\text{Since } \zeta_o = V_o / V_t, \quad V_o = \sum_{k=1}^s \sum_{j=1}^{M_k} V_{o,k,j}, \text{ and } V = m / \rho,$$

$$\zeta_o = \rho_t \sum_{k=1}^s \sum_{j=1}^{M_k} (\alpha_{k,j} / \rho_{o,k}) \quad (32)$$

$$\text{Since } \rho_t = (V_t / m_t)^{-1}, \quad V_t = \sum_{k=1}^s \sum_{j=1}^{M_k} V_{o,k,j} + V_f, \text{ and } V = m / \rho,$$

$$\rho_t = [\rho_f^{-1} + \sum_{k=1}^s \sum_{j=1}^{M_k} (\rho_{o,k}^{-1} - \rho_f^{-1}) \alpha_{k,j}]^{-1} \quad (33)$$

By definition $NF_{p,k,d} dD = dN_{p,d,k}$. Employing Eq. (14) it is seen that

$$NF_{p,k,d} dD = 6 d \zeta_{d,k} / (\pi D^2) \quad (34)$$

Employing this result and Eqs. (25) and (30), Eq. (10) can be rewritten as

$$\bar{r} \rho_t = \frac{\bar{m}''}{m_t} = \rho_t \sum_{k=1}^s \rho_{o,k}^{-1} \oint_D (\bar{m}_{d,k}''^* / \zeta_{d,k}^*) F_k dD \quad (35)$$

Therefore

$$\bar{r} = \sum_{k=1}^s \rho_{o,k}^{-1} \oint_D (\bar{m}_{d,k}''^* / \zeta_{d,k}^*) F_k dD \quad (36)$$

Eqs. (21 - 24), (31 - 33), and (36) put $\bar{r}$ in terms of real propellant data. Since interest is focused on the BDP model herein,

$$\bar{m}_{d,k}''^* = \bar{m}_{BDP}'' (D, \alpha_{d,k}^*, \rho_{d,k}^*, \zeta_{d,k}^*, \text{etc.}) \quad (37)$$

Modifications to BDP Model

The reason for polydisperse propellants is high total solids. Consequently, with "real" propellants the BDP model must operate in the $\zeta_o \approx 1$ regime. Unfortunately, examination of the model⁽⁶⁾ shows that the b parameter (mean distance from center of oxidizer particle to center of binder separating particles) is given by

$$b = D [1 + \sqrt{3/2} (\delta/D)] / \sqrt{6} \quad (38)$$

where

$$\delta/D = [\pi / (6 \zeta_o)]^{1/3} - (2/3)^{1/3} \quad (39)$$

Clearly, as ζ_o approaches unity, both δ/D and b must approach zero with the proviso that $\delta/D > 0$ and $b > 0$. Examination of Eq. (39) shows that δ/D changes sign at $\zeta_o \approx 0.785$. Consequently, Eqs. (38) and (39) and hence the BDP model cannot be employed for propellants with $\zeta_o \geq 0.785$. This represents no difficulty for monodisperse propellants because packing considerations limit ζ_o to values below this limit.⁽¹¹⁾ However, this is a very real difficulty with monodisperse psuedo-propellants.

The aforementioned difficulty occurs because the fuel surface of an oxidizer particle/fuel surface pair is assumed to be annular with $D_i = \bar{D}$ and $D_o = 2b$. However, in reality the binder surface is not an annulus but an irregular quadrilateral. Consequently, this assumption "loses" the fuel in the corners between the quadrilateral and the "inscribed" annulus. The simplest way to overcome this difficulty is to assume that b is the dimension of an annulus possessing the fuel surface associated with the mean oxidizer particle/fuel surface pair. In other words, b is defined by

$$\pi b^2 - \pi \bar{D}^2 / 4 = \Delta \bar{S}_f \quad (40)$$

The fraction of planar surface occupied by fuel is $1 - \zeta_o$. The number of particles/unit planar surface is given by Eq. (13). Therefore,

$$\Delta \bar{S}_f = (1 - \zeta_o) \pi \bar{D}^2 / (6 \zeta_o) \quad (41)$$

$$b = D / \sqrt{6 \zeta_o} \quad (42)$$

and

$$\delta/D = (\zeta_o^{-1/2} - 1) / \sqrt{6} \quad (43)$$

Examination of the BDP computer program⁽¹²⁾⁽¹³⁾ shows that the FORTRAN expression employed for δ/D is not equivalent to Eq. (39) but represents

$$\delta/D = [\pi/(6\zeta_0)]^{1/3} - (2/3)^{1/2} \quad (44)$$

This expression is positive for $\zeta_0 < 0.961$.

Figure 3 compares Eqs. (39), (43), and (44). It is seen that Eq. (43) has correct behavior for $\zeta_0 \approx 1$ and agrees well with Eq. (39) for $\zeta_0 \approx 0$.

Numerical tests were made to determine the effect of oxidizer mass fraction on burning rate. Tests were made with both Eqs. (38) (44) (denoted as BDP) and (42) (43) (denoted as Mod. BDP). Figure 4 presents results when $D = 1 \mu$ and $p = 932$ psi. It is clear that the solutions are discontinuous at both high and low mass fractions for both normal and modified BDP models. For oxidizer mass fractions greater than the upper discontinuity point and less than the lower discontinuity point, the models gave negative values for the diffusion flame standoff distances in both cases. Consequently, the difficulty appears to stem from the Burke-Schumann solution. Since the BDP model with the single term approximation to the Burke-Schumann solution was employed herein and Sammons multiple term version showed no evidence of discontinuities at a mass fraction of 0.86,⁽¹³⁾ this defect can probably be remedied by employing the Sammons version of the BDP model. However, we did not have this version. Consequently, another remedy was sought. Because the diffusion flame standoff distances increased rapidly to very large values when the discontinuities were approached from the other direction, a negative diffusion flame standoff distance was replaced by a very large value whenever it occurred. This gives continuity with intermediate mass fraction results. Figure 5 illustrates rate versus mass fraction results with this modification.

Calculations at $D = 100 \mu$ and $p = 932$ psi exhibited behavior similar to the aforementioned. However, as will be observed below, the aforementioned results did not completely eliminate "discontinuous" behavior.

Implementation of Polydisperse BDP Model

The modified monodisperse BDP combustion model was extended to non-metallized propellants with a polydisperse oxidizer by embedding the model in the previously described statistical framework. A complete listing of the computer program and a description of its use with a sample problem is provided in Appendix A.

Since parametric studies were anticipated, a log normal distribution of oxidizer particle size was assumed for each mode.

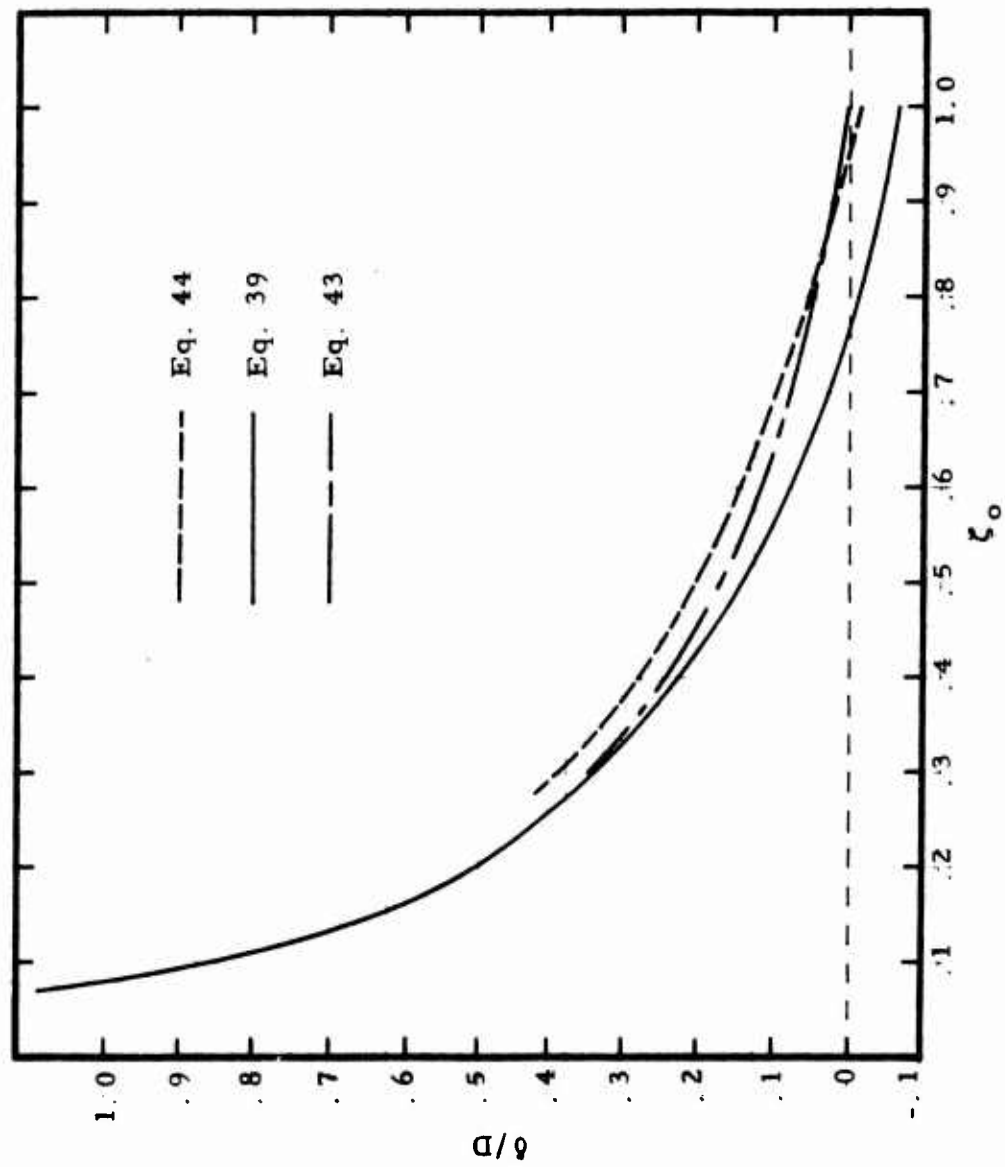


Figure 3. δ/D versus ζ_0 .

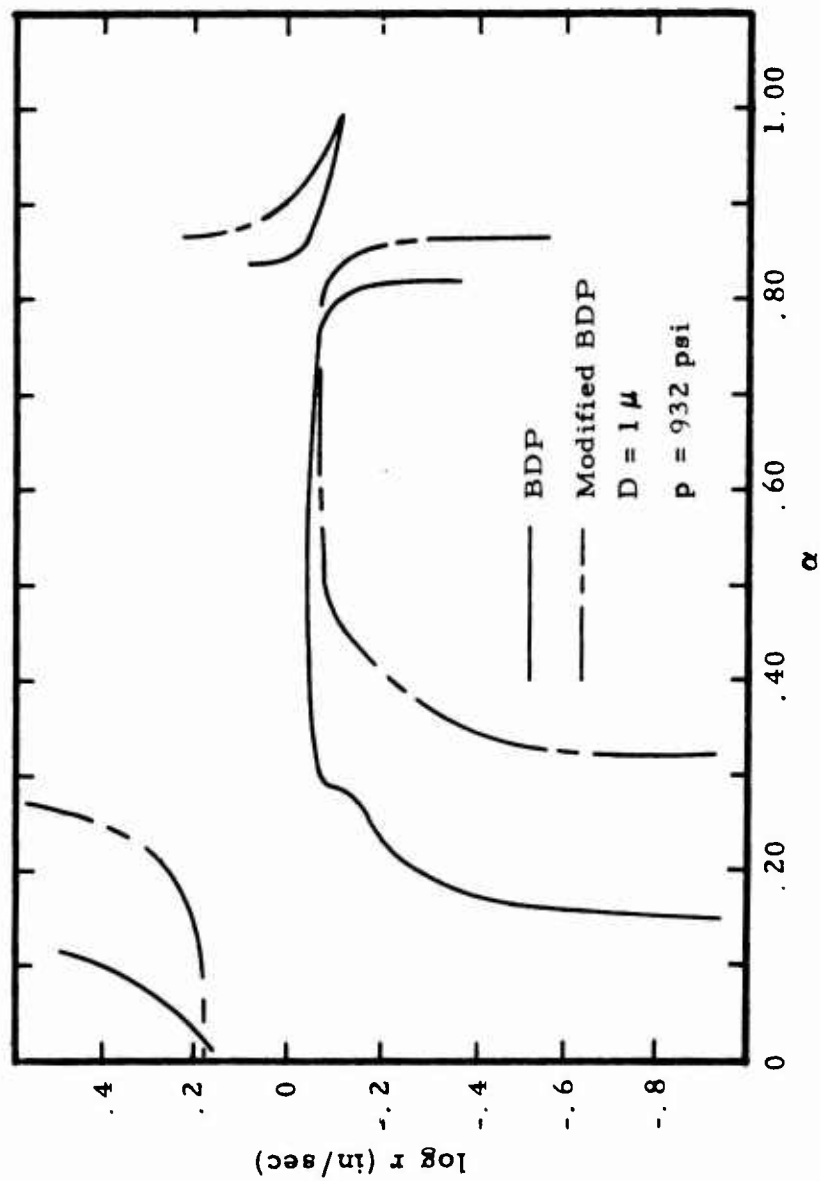


Figure 4. Burning Rate as a Function of Oxidizer Mass Fraction

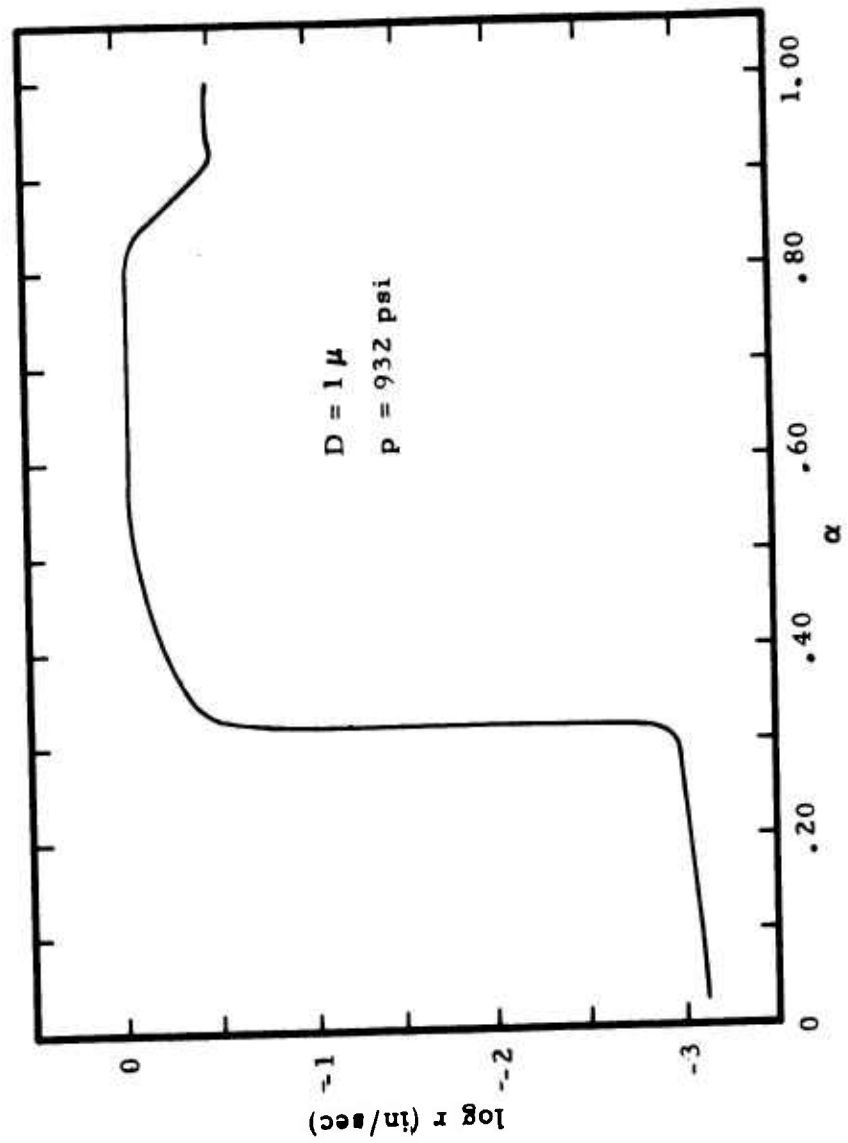


Figure 5. Burning Rate as a Function of Oxidizer Mass Fraction

$$y = \frac{1}{\sigma \sqrt{2\pi}} \exp \left[-\frac{1}{2} \left(\frac{x - m}{\sigma} \right)^2 \right] \quad (45)$$

where

$$x = \ln D$$

$$m = \ln \bar{D}_m$$

$$\sigma = \ln \sigma^*$$

This assumption is reasonably realistic and permits each mode to be characterized with minimum input information, thereby assisting parametric studies of particle size effects. Thus, in addition to the standard BDP input parameters, the number of modes, the weight mean diameter and standard deviation of diameter for each mode and the mass fraction of each mode relative to the total mass of oxidizer are needed to characterize the polydisperse oxidizer size distributions in the computer program.

The initial test of the computer program was made with a polydisperse bimodal AP propellant. Oxidizer size distribution data are shown in Table 1. The distributions are depicted in Fig. 6.

TABLE 1

<u>Mode</u>	<u>Mass Fraction of Total Propellant</u>	<u>$\bar{D}$ [μ]</u>	<u>σ^* [μ]</u>
1	0.45	16	2.0
2	0.45	200	1.4

The computer program solves for the mass flux associated with each monodisperse psuedo-propellant in the propellant and sums these fluxes in accordance with Eq. (36) to determine mean propellant burning rate. Figure 7 presents the monodisperse psuedo-propellant burning rates as a function of particle size for several values of n . * Figure 8 illustrates how oxidizer mass fraction varies in the psuedo-propellant family. Viewing Figures 7 and 8 together shows the following:

*Recall that n is an empirical parameter controlling how oxidizer mass fraction varies in the psuedo-propellant family.

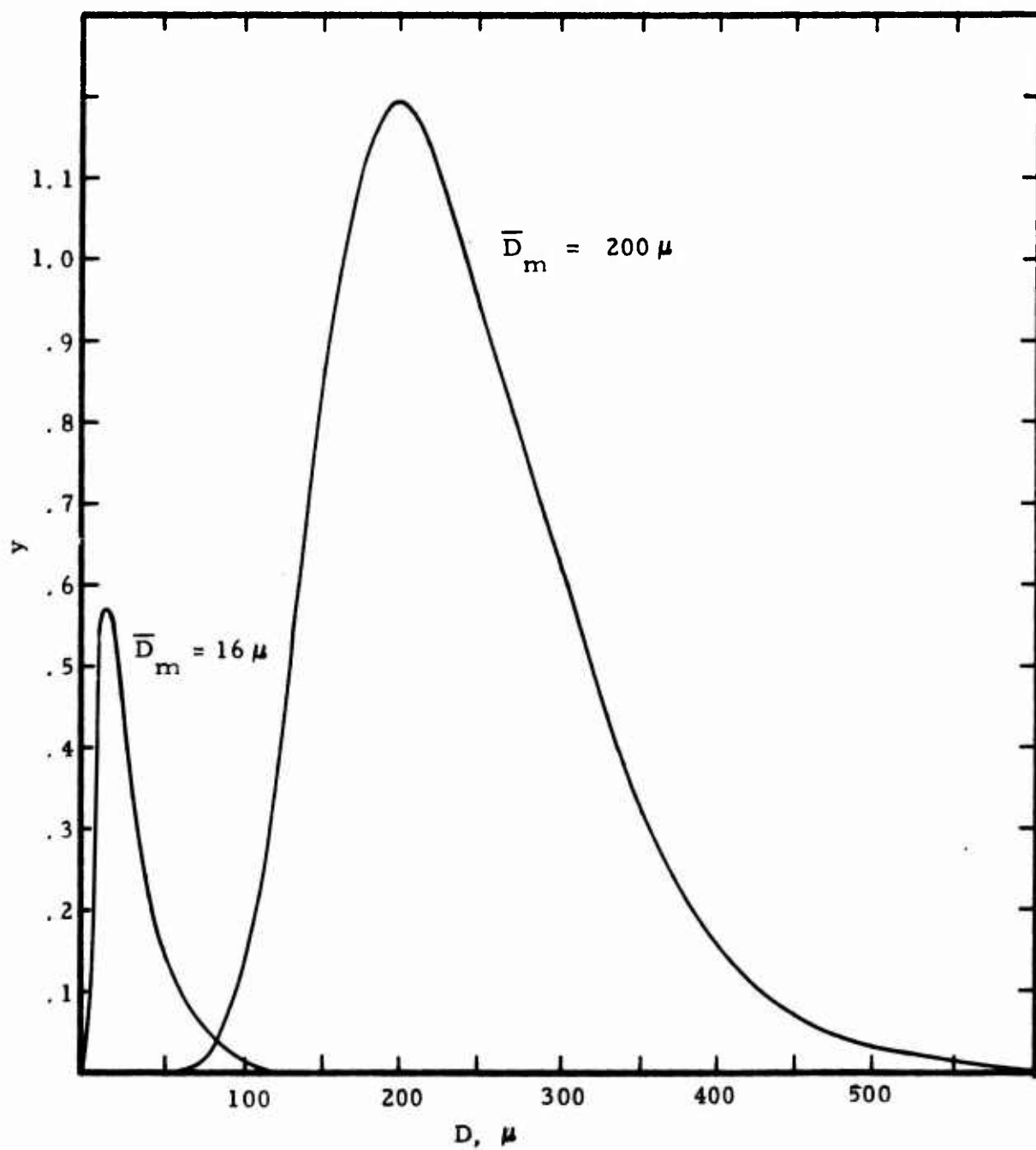


Figure 6. Oxidizer Size Distribution Function

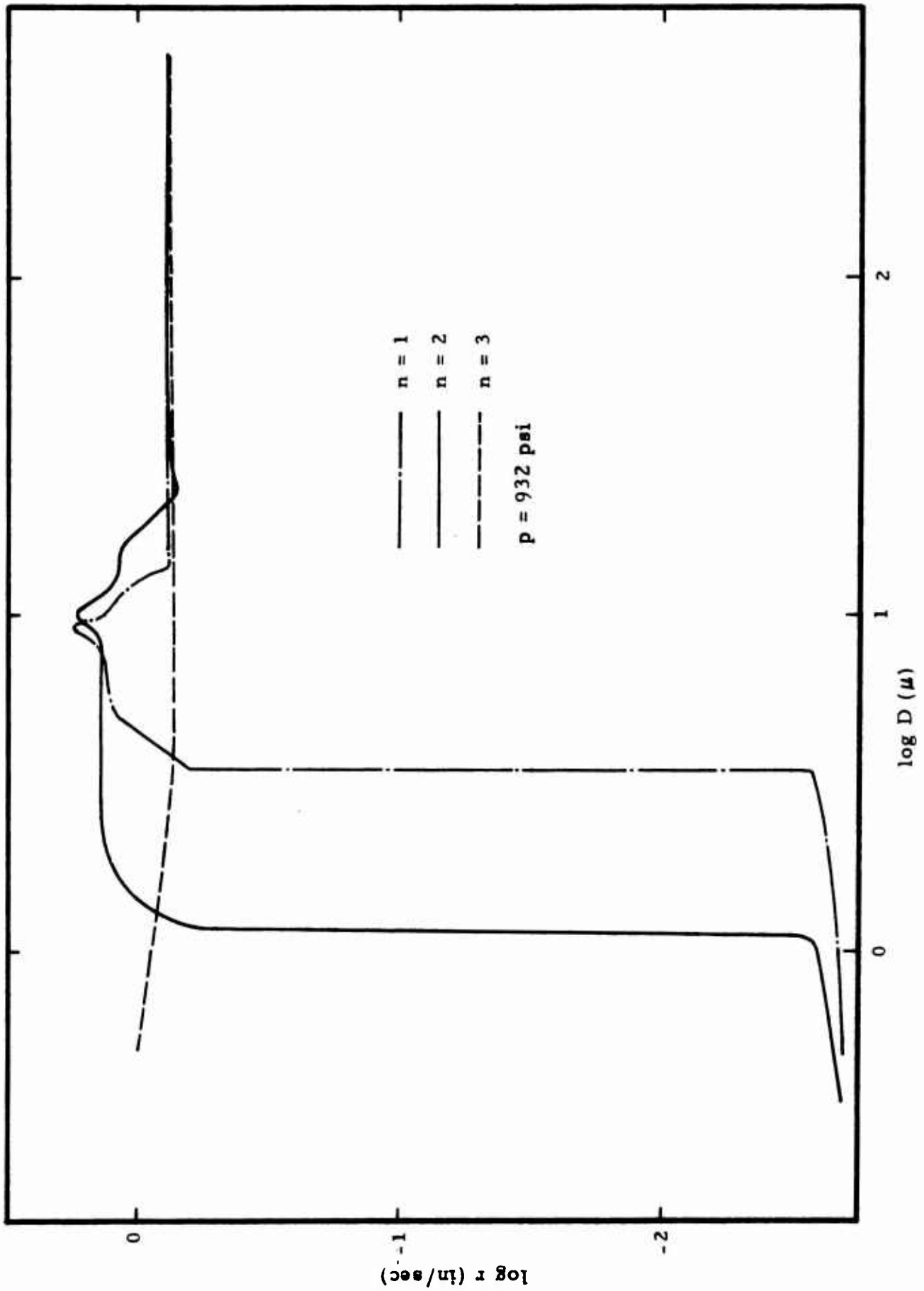


Figure 7. Burning Rate as a Function of Oxidizer Size

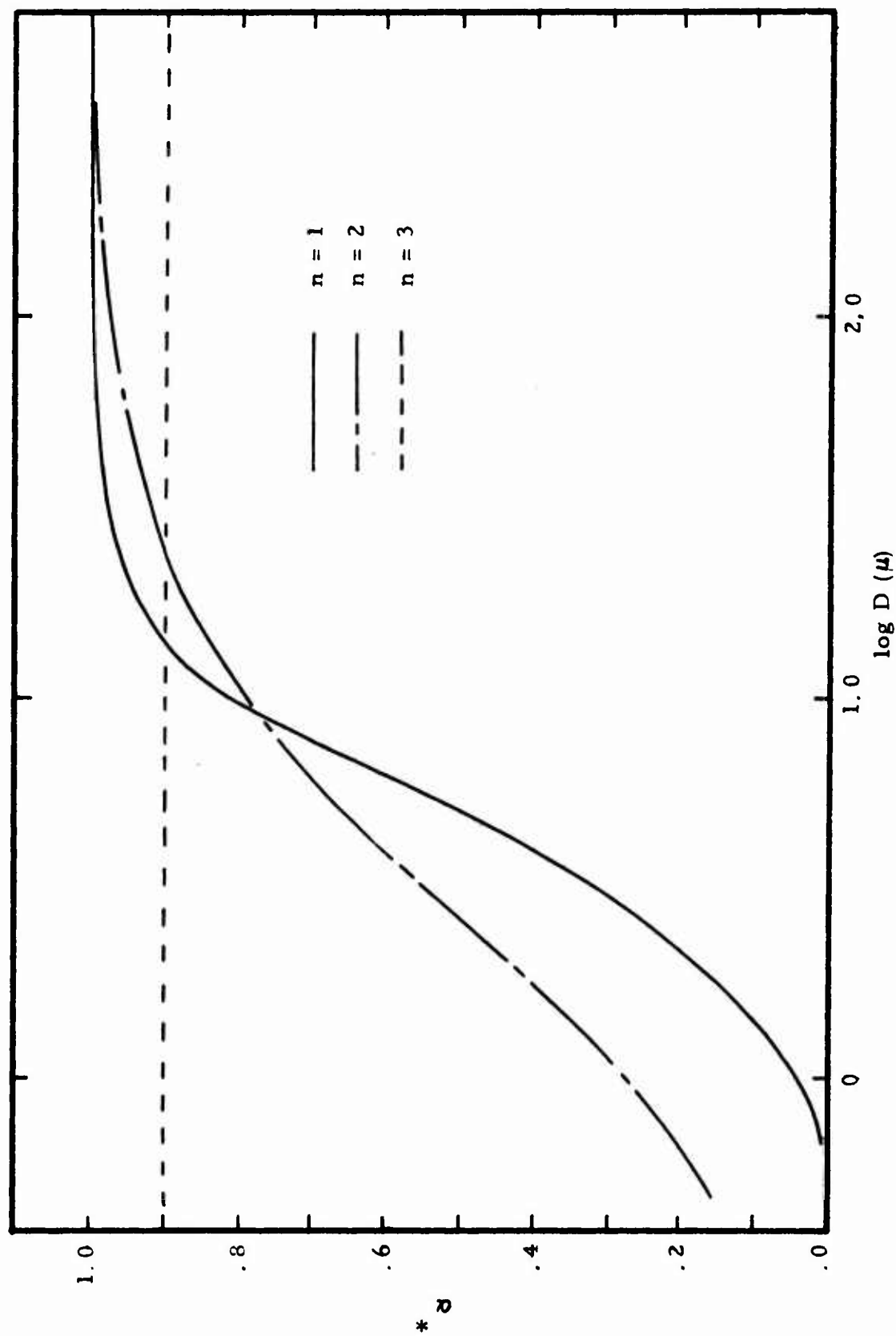


Figure 8. Monodisperse Psuedo-Propellant Mass Fraction as a Function of Oxidizer Particle Size

- o Rate does not vary with particle size by any simple expression reminiscent of the GDF relationship. ⁽¹⁴⁾
- o The way fuel is apportioned among the psuedo-propellants (n) has an enormous effect on the burning rates of the smaller particle sizes.
- o The way fuel is apportioned among the psuedo-propellants (n) has little effect on the burning rates of the larger particle sizes.

The fact that a simple $r \propto D^{-1}$ relationship is not evident suggests that smaller particles do not necessarily augment burning rate by any intrinsically higher rate mechanism. Rather, they appear to partially augment rate by leaning the mixture ratio of the larger particles.

Figure 9 presents the burning rate of the initial case propellant versus pressure. A reasonable exponent is predicted and, somewhat surprisingly, the results are not strongly dependent upon the value of n.

T-BURNER VENT FLOW STUDY

Culick⁽¹⁾⁽¹⁵⁾ has shown, through analysis of the one-dimensional equations of change that a mean flow/acoustics surface interactions term arises naturally in stability analyses. For regions where $d\hat{p}/dz \neq 0$ this term represents a loss of acoustic energy when there is mass addition and a gain of acoustic energy when there is mass subtraction. The latter has led to speculation that the vent of a T-burner yields a gain of acoustic energy for waves in the burner.

However, Culick⁽¹⁵⁾ demonstrates that the adiabatic process leading to a mean flow/acoustic surface interaction loss dissipates acoustic energy into heat. Since acoustic energy is completely available energy, available energy is degraded into heat by this process. Therefore, this process is thermodynamically irreversible. Consequently, the reverse process - the mean flow/acoustics surface interaction gain - is thermodynamically impossible.

This result is almost as surprising as the original mean flow/acoustics surface interaction gain because it contradicts results that arise solely from the equations of change. However, the equations of change do not suffice to define reality because a second law of thermodynamics exists. Therefore, a mean flow/acoustics surface interaction gain process must be a second law violator. Reflection shows that this is the situation because formal reversal of the mean flow/acoustics surface interaction loss implies complete conversion of heat into available energy in an adiabatic process - a phenomena that is disallowed by the second law of thermodynamics.

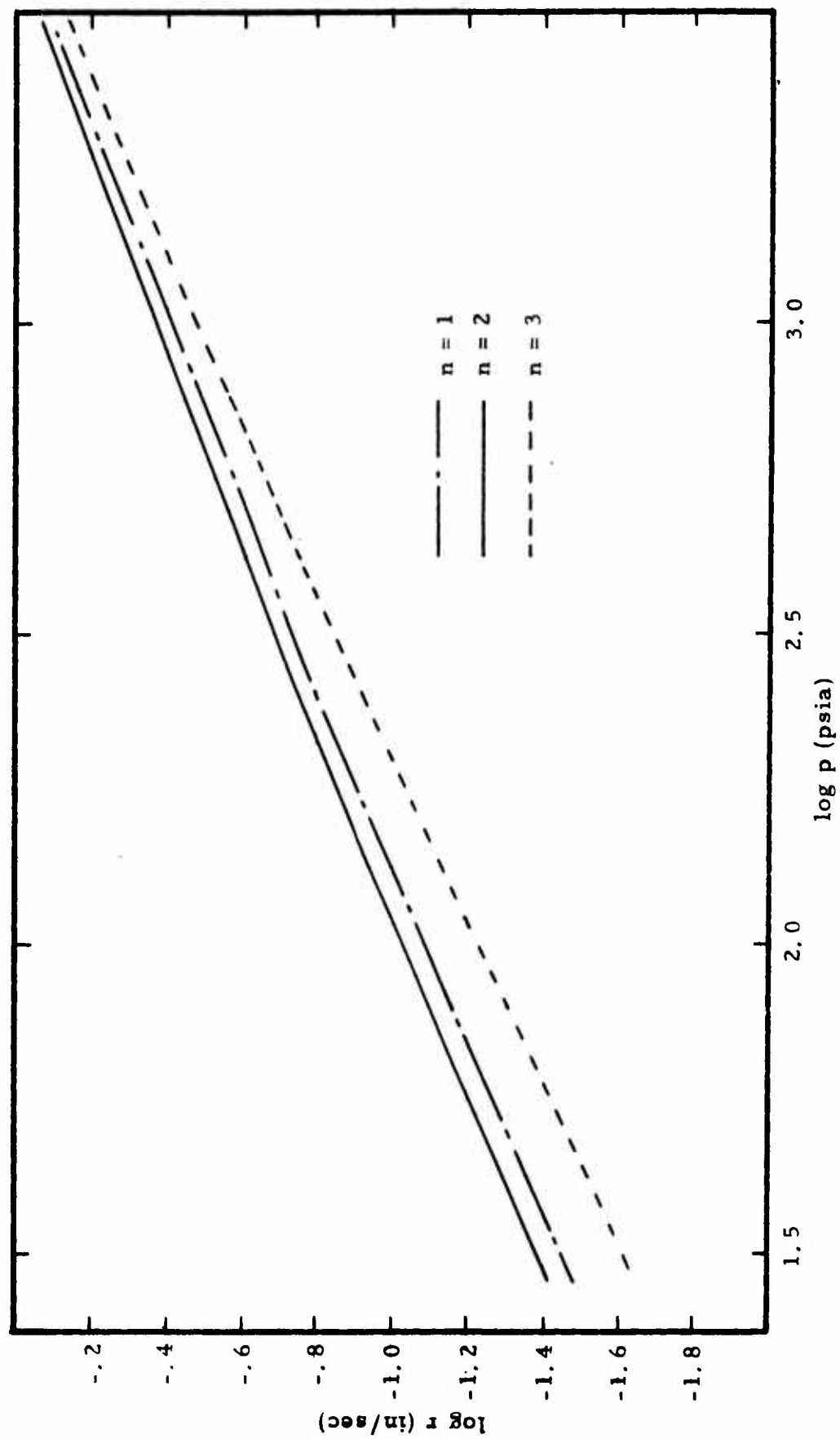


Figure 9. Burning Rate as a Function of Pressure for the Polydisperse Propellant

Why does this result occur and what is the correct result for a mean flow/acoustic surface interaction when there is mass subtraction? The only "arbitrary" assumption in Culick's analysis is that mass enters and leaves with zero velocity. Is this assumption "legitimate"? Since the one-dimensional equations of change must be valid in the quasi-steady limit, is this assumption "legitimate" in steady-flow? Shapiro⁽¹⁶⁾ shows that it is legitimate for mass addition but violates the second law of thermodynamics for mass subtraction. Moreover, Shapiro shows that the second law requires that mass be rejected with free stream conditions in a steady, one-dimensional flow. Clearly, the mean flow/acoustic surface interactions gain arises from this improper boundary condition. For a proper one-dimensional analysis, Culick's equations must be formulated so they are in harmony with these quasi-steady flow constraints because this is the limit as frequency goes to zero. Culick has also solved this problem⁽¹⁵⁾ and finds in this case that the mean flow/acoustic surface interactions term is zero when there is mass subtraction. Therefore, a properly formulated one-dimensional analysis shows that the vent is neither gain nor loss.

It is important to note that this "new" result is in harmony with physical results. First, atmospheric T-burner test results reported by Horton and Coates⁽²⁾ demonstrate conclusively that gases at the vent of a T-burner possess axial velocity. Second, hydraulic analogy tests reported by Glick⁽¹⁷⁾ show that in a T-burner with a vent pipe the gases enter the vent with axial momentum and that that axial momentum is transformed in the vent into a Karman vortex sheet. Third, Culick⁽¹⁸⁾ has shown that a flow field like that revealed by the hydraulic analogy studies leads to a vent condition that is neither gain nor loss.

In summary, theoretical and experimental evidence seems to be converging on a null vent condition.

ON REDUCTION OF SOLID ROCKET DATA WHEN THE PRESSURE-TIME HISTORY IS NON-NEUTRAL

Reducing pressure- and thrust-time, propellant mass and web, and nozzle geometry data to determine mean burning rate, mean characteristic velocity, delivered (mean) specific impulse, mean pressure, and mean nozzle geometry is reasonably straightforward with neutral pressure-time histories and minimal nozzle erosion because pressure and nozzle geometry are unique in this situation. However, when the pressure-time history is non-neutral, pressure (and usually nozzle geometry) is no longer unique and choosing the correct mean pressure becomes a problem. It is important to note that functional relationships exist between dependent (r , C^* , I_{sp}) and independent (p , ϵ , etc.) variables. Indeed, one purpose of performance testing is to determine these relationships experimentally. Consequently, when means of dependent variables are defined, means of the independent variables must be derived from these definitions. In other words, when the independent variables (pressure, etc.) vary during a test firing, their means cannot be arbitrarily defined. In Ref. 19 constraints are placed upon independent variable variations during a test. If variations exceed constraints, that data is unacceptable. Although this approach eliminates non-neutral independent variable problems and yields quality performance data, it is not cost effective.

The objectives of this work are twofold. First, to derive general equations defining consistent independent variable means when motor operation is in the quasi-steady regime and pressure and throat area are the independent variables. Second, to obtain first approximation "solutions" to these equations.

Reference 19 defines mean burning rate, mean characteristic velocity,* and delivered specific impulse as

$$\bar{r} = w/t_b \quad (46)$$

$$\bar{C}^* = g \int_{t_I}^{t_I + t_a} A_t p dt / m_p \quad (47)$$

$$I_{sp, d} = \int_{t_I}^{t_I + t_a} F dt / m_p \quad (48)$$

*Eq. (47) is a generalization of the more commonly employed $\bar{C}^* = g \bar{A}_t$

$$\int_{t_I}^{t_I + t_a} p dt / m.$$

The mean independent variables are defined as*

$$\bar{p}_t = \int_{t_I}^{t_I + t_a} p \, dt / t_a \quad (49)$$

$$\bar{A}_t = \left[A_t (t_I + t_a) + A_t (0) \right] / 2 \quad (50)$$

$$\bar{\epsilon} = A_e (t_I + t_a) / \bar{A}_t \quad (51)$$

Since functionals $r(p)$, $C^*(p)$, and $I_{sp}(p, \epsilon)$ are presumed to exist, consistent means for p and ϵ require that

$$\bar{r} = r(\bar{p}_r) \quad (52a)$$

$$\bar{C}^* = C^*(\bar{p}_C) \quad (52b)$$

$$I_{sp, d} = I_{sp}(\bar{p}_I, \bar{\epsilon}_I) \quad (52c)$$

where $\bar{p}_r$, $\bar{p}_C$, and $\bar{p}_I$ are mean pressures for burning rate, characteristic velocity, and specific impulse, respectively and $\bar{\epsilon}_I$ is the mean expansion ratio for specific impulses. Since $w = \int_0^t r(p) \, dt$, Eq. (46) can be written as

*For non-neutral pressure-time histories, Reference 19 suggests that the mass averaged pressure

$$\bar{p}_m \approx \frac{\int_{t_I}^{t_I + t_a} p^2 \, dt}{\int_{t_I}^{t_I + t_a} p \, dt}$$

replace the time averaged pressure $\bar{p}_t$.

$$r(\bar{p}_r) = \int_{t_I}^{t_I + t_b} r(p) dt / t_b \quad (53)$$

For quasi-steady conditions $I = \int_{t_I}^{t_I + t_a} I_{sp} dm^*$, $m = \int_{t_I}^{t_I + t_a} \dot{m} dt$, and $\dot{m} = A_t p g / C^*$.

Therefore, Eqs. (47) and (48) can be rewritten as

$$C^*(\bar{p}_C) = \int_{t_I}^{t_I + t_a} A_t p dt / \int_{t_I}^{t_I + t_a} [A_t p / C^*(p)] dt \quad (54)$$

$$I_{sp}(\bar{p}_I, \bar{\epsilon}_I) = g \int_{t_I}^{t_I + t_a} [I_{sp}(p, \epsilon) A_t p / C^*(p)] dt \quad (55)$$

Equation (55) does not specify $\bar{p}_I$ and $\bar{\epsilon}_I$ uniquely. Therefore, it is necessary to introduce an arbitrary definition. Since specific impulse and characteristic velocity are both thermodynamic parameters, it is logical that both should possess the same mean pressure. Consequently, assume

$$\bar{p} = \bar{p}_I = \bar{p}_C \quad (56)$$

Examination of Eqs. (53 - 55) shows the following: (a) they are implicit equations; (b) the function desired must be known to determine the desired mean; (c) since r , C^* , and I_{sp} are, in general, neither proportional to p nor independent of p , $\bar{p}_r \neq \bar{p} \neq \bar{p}_m \neq \bar{p}_t$ for non-neutral pressure-time histories; and (d) when the pressure-time history is neutral, $\bar{p}_r = \bar{p} = \bar{p}_m = \bar{p}_t$. Item (b) shows that when the pressure-time history is non-neutral motor test data cannot be reduced on a single firing basis. If the dependent variable is assumed to be an M

*This shows that specific impulse is a mass averaged quantity. Consequently, it has been argued that $\bar{p}_m$ should be employed with $I_{sp, d}^{(21)}$, e.g., $\bar{p}_I = \bar{p}_m$. Following this same argument, $\bar{p}_r = \bar{p}_t$.

parameter function of the independent variables, at least M tests are required and data for the M firings must be reduced simultaneously. Items (c) and (d) show that although the CPIA recommendations are exact for neutral pressure-time histories, they are not precisely valid for non-neutral pressure-time histories.

First approximation "solutions" to Eqs. (53 - 56) are obtained by assuming $r = ap^n$, $\bar{C}^*/\bar{C} = 1 + \alpha(p - \bar{p})$, $I_{sp}/I_{sp,d} = 1 + \beta(p - \bar{p}) + \delta(\epsilon - \bar{\epsilon})$.

Then, Eqs. (53 - 56) become*

$$\bar{p}_r = \left(\int_{t_I}^{t_I + t_b} p^n dt / t_b \right)^{1/n} \quad (57)$$

$$\bar{p} = \frac{\int_{t_I}^{t_I + t_a} A_t p^2 dt}{\int_{t_I}^{t_I + t_a} A_t p dt} \quad (58)$$

$$\bar{\epsilon} = \beta(\bar{p}_m - \bar{p})/\delta + A_e \left[\bar{p}_t (1 + \alpha \bar{p}) + \alpha \int_{t_I}^{t_I + t_a} p^2 dt \right] / \int_{t_I}^{t_I + t_a} A_t p dt \quad (59)$$

If A_t is constant, $\bar{p} = \bar{p}_m$ and $\bar{\epsilon} = A_e/A_t$. Therefore, the CPIA recommendations for non-neutral pressure-time histories are valid as first approximations.

The magnitude of the errors involved with employing $\bar{p}_t$ for $\bar{p}_r$ [Eq. (57)] and $\bar{p}$ [Eq. (58)] can be readily estimated. Expanding the integrands of Eqs. (57) and (58) in a Taylor's series about $p = \bar{p}_t$ gives

$$p^n = \left[1 + n(\Delta p/\bar{p}_t) + n(n-1)(\Delta p/\bar{p}_t)^2/2! + n(n-1)(n-2)(\Delta p/\bar{p}_t)^3/3! + \dots \right] \bar{p}_t^n \quad (60)$$

$$3! + \dots \right] \bar{p}_t^n$$

*Equation (57) has been obtained previously by Brock. (20)

When $n < 1$, this series has alternating sign. Consequently, when convergent,

$$p^n \approx [1 + n (\Delta p / \bar{p}_t) + n(n-1) (\Delta p / \bar{p}_t)^2 / 2!] \bar{p}_t^n \quad (61)$$

with error less than $[n(n-1)(n-2) (\Delta p / \bar{p}_t)^3 / 3!]$. (21) Substitution of Eq. (61) into Eq. (57), integrating, and applying the mean value theorem for integrals gives

$$\bar{p}_r \approx \bar{p}_t \left[1 + n(n-1) \left[(\Delta p / \bar{p}_t)^2 / 2 \right] \right]^{1/n} \quad (62)$$

Substitution of Eq. (61) with $n=2$ into Eq. (58), assuming A_t is constant, integrating, and applying the mean value theorem for integrals gives

$$\bar{p} = \bar{p}_t \left\{ 1 + \left[(\Delta p / \bar{p}_t)^2 \right] \right\} \quad (63)$$

Examination of Eqs. (62) and (63) shows that when $\Delta p / \bar{p}_t$ is small, $\bar{p}_r$ and $\bar{p}$ agree with $\bar{p}_t$ to first order accuracy. However, when $\Delta p / \bar{p}_t$ is large, significant deviations can occur. Calculations presented by Brock⁽²⁰⁾ support this.

In summary, this work has shown that consistent reduction of motor test data when the pressure-time history is non-neutral falls outside conventional procedure. As long as deviations from neutrality are small, errors relative to established procedure are small. However, when deviations become large, significant errors can result. This work has assumed that motor operations falls in the quasi-steady regime and that pressure and throat area are the only independent variables. However, burning rate depends on flow over the burning surface and the thermodynamic parameters depend at least upon stay time and nozzle geometry. Therefore, what has been presented here is just a ripple on the surface of the basic problem of extracting all possible truth from available data.

FUTURE PLANS

Future efforts will be expended in four directions:

- modification of the BDP combustion model
- generation and implementation of propellant burning rate computer codes
- consideration of transient burning phases within the steady-state statistical framework
- application of the hydraulic analogy to determine mean flow effects on mode shape.

In the first, extension of the model to include spheriodal particles and surface tension effects will be explored. In the second, computer codes for predicting burning rates in additive free propellants will be developed. In the third, basic problems in statistical combustion modeling will be explored. Specifically, transient effects and statistical formulations with nonplanar burning surfaces will be pursued. In the latter, hydraulic analogy test sequences with real motor geometry and distributed mass addition will be employed to assess mode shape deviations wrought by mean flow effects. This will be accomplished by determining the resonant frequency and then measuring amplitude and phase along the motor length (light absorption technique). Comparison of results at no flow with acoustic approximation results "defines" analogy errors; comparison of analogy results at various port Mach numbers "indicates" mean flow errors.

PUBLICATIONS DERIVED FROM PROGRAM

1. On Reduction of Solid Rocket Data When the Pressure-Time History is Non-Neutral, accepted for publication, Journal Spacecraft and Rockets, 1975.
2. Hydraulic Analogy Study: T-Burner Vent Gain/Loss, CPIA Publication No. 261, Vol. 1, 1974, pp. 491-498.
3. Comment on "The Stability of One-Dimensional Motions in a Rocket Motor", accepted for publication, Combustion Science and Technology, 1975.

NOMENCLATURE

Latin Symbols

A_e	nozzle exit area
A_t	nozzle throat area
b	$\overline{D} + \Delta$
C	constant defined by Eq. (19)
C^*	characteristic velocity
D	diameter
F	distribution function
g	gravitational acceleration
h	water depth
I	delivered impulse
I_{sp}	specific impulse
$I_{sp, d}$	delivered specific impulse
m	mass
$\dot{m}$	mass flow rate
m''	mass flux
M_k	number of modes associated with k^{th} oxidizer species
n	exponent defined by Eq. (19)
p	pressure
Q	number of subdivisions
r	burning rate
s	number of oxidizer species
S	surface area

t	time
t_a	action time
t_b	burn time
t_I	time when p first becomes $0.05 \bar{p}_t$
u	velocity component in x direction
v	velocity component in y direction
V	volume
w	propellant web or velocity component in z direction
x, y, z	coordinates in inertial reference frame
y	$dm_{o,j,k} / (m_{o,j,k} dD)$
z	distance normal to S

Greek Symbols

α	mass oxidizer/mass propellant
ζ	volume oxidizer/volume propellant
δ	width of fuel annulus surrounding mean oxidizer particle
Δ	denotes a small quantity
$\eta_{d,k}$	fraction of oxidizer particles on burning surface with $D \leq D \leq D + dD$ and species k
ϵ	nozzle expansion ratio
σ^*	standard deviation of oxidizer particle size distribution
ρ	density

Special Symbols

$(\bar{\quad})$	denotes a mean
$(\quad)^*$	pertains to a monodisperse, psuedo-propellant
$(\hat{\quad})$	denotes a fluctuating term such that $(\hat{\quad}) = 0$
$(\quad)^+$	denotes a non-dimensional quantity

Subscripts

b	denotes burning surface
d	denotes oxidizer particles with $D \leq D \leq D + dD$
f	denotes fuel
g	denotes gas
j	denotes oxidizer mode j
k	denotes oxidizer species k
m	denotes weight mean in oxidizer particle size distribution
o	denotes oxidizer or stagnation condition
t	denotes time mean or propellant
p	denotes planar surface
v	denotes per unit volume
w	denotes water

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APPENDIX A

COMPUTER PROGRAM

COMPUTER PROGRAM DATA INPUT FORMAT

CARD 1: Control Card

NUMBER REQUIRED: One card per run

FUNCTION: Specify run options

FORMAT: (2I6)

Columns 1-6: NJOB, if NJOB = 1 read

propellant parameters, if NOB = 2 read namelist data

Columns 7-12: IPLOT, IPLOT = 2, (Plotting routine
presently deleted)

CARD 2: Title Card

NUMBER REQUIRED: One card per run

FUNCTION: Identify run out at

FORMAT: (20A4)

Columns 2-80: May be used to identify run

CARD 3: Data Card

NUMBER REQUIRED: One card per run

FUNCTION: Specify propellant parameters

FORMAT: (6E12.6)

Columns 1-12: TZERO, initial propellant temperature, deg K

Columns 13-24: ALFA, Oxidizer mass fraction

Columns 25-36: TF, adiabatic flame temperature, deg K

Columns 37-48: GMW, molecular weight of final flame

Columns 49-60: XNUI, stoichiometric ratio of the final flame

Columns 61-80: not used

CARD 4: Data Card

NUMBER REQUIRED: One card per run

FUNCTION: Specify propellant parameters

FORMAT: (6E12.6)

Columns 1-12: QFUEL, heat of pyrolysis of the fuel binder, cal/g

Columns 13-24: RHOF, density of fuel binder, g/cm^3

Columns 25-36: AF, arrhenius frequency factor of fuel binder,
 $\text{g/cm}^2\text{-sec}$

Columns 37-48: EF, activation energy of the fuel binder, cal/mole

Columns 49-60: XNUP, primary flame stoichiometric ratio

Columns 61-72: PMW, primary flame molecular weight

Columns 73-80: not used

CARD 5: Data Card

NUMBER REQUIRED: One card per run

FUNCTION: Specify propellant parameters

FORMAT: (6E12.6)

Columns 1-12: QL, latent heat of vaporization of the oxidizer, cal/g

Columns 13-24: RHOX, density of the oxidizer, g/cm^3

Columns 25-36: AOX, arrhenius frequency factor of the oxidizer
 $\text{g/cm}^2\text{-sec}$

Columns 37-48: EOX, activation energy of the oxidizer cal/mole

Columns 49-60: TAP, temperature of the AP flame, deg K

Columns 61-72: AP, AP=1 if oxidizer rate constants specified,

AP = -1 or 0 if oxidizer rate constant to be calculated by
program. If -1, mass flux of oxidizer taken as $1.9 \text{ g/cm}^2\text{-sec}$
in rate constant calculation. If 0, mass flux of oxidizer taken
as $1.66 \text{ g/cm}^2\text{-sec}$ in rate constant calculation.

Columns 73-80: not used

CARD 6: Data Card

NUMBER REQUIRED: One card per run

FUNCTION: Specify propellant parameters

FORMAT: (6E12.6)

Columns 1-12: CIGN, oxidizer ignition delay parameter, sec(atm)^m
 cm^{-n+1} where $m=\text{POWIGN}$ and $n=\text{POWD}$

Columns 13-24: POWIGN, pressure exponent in oxidizer particle
ignition particle ignition delay term

Columns 25-36: POWD, diameter exponent in oxidizer particle ignition
delay term

Columns 37-48: PSTART, pressure to start incremental calcu-
lations, atm

Columns 49-60: PSTOP, pressure to stop incremental calculations, atm

Columns 60-72: CONF, CONF=0 if parabolic flame assumed, CONF=1
if conical flame assumed

Columns 73-80: not used

CARD 7: Data Card

NUMBER REQUIRED: One card per run

FUNCTION: Specify propellant parameters

FORMAT: (6E12.6)

Columns 1-12: KPF, rate constant of primary flame, $\text{g}/\text{cm}^3\text{-sec-atm}$)

Columns 13-24: KAP1, rate constant of AP flame at low pressure,
 $\text{g}/(\text{cm}^3\text{-sec-atm})$

Columns 25-36: KAP2, rate constant of AP flame at high pressure,
 $\text{g}/\text{cm}^3\text{-sec-atm})$

Columns 37-48: XN1, reaction order of primary flame

Columns 49-60: XN2, reaction order of AP flame at low pressure

Columns 61-72: XN3, reaction order of AP flame at high pressure

Columns 72-80: not used

CARD 8: Data Card

NUMBER REQUIRED: One card per run

FUNCTION: Specify propellant parameters

FORMAT: (6E12.6)

Columns 1-12: CSUBP, average heat capacity of solids and gases,
 $\text{cal}/\text{g-}^\circ\text{K}$

Columns 13-24: XLAMB, average thermal conductivity of the combustion gases, $\text{cal}/\text{cm-sec-}^\circ\text{K}$

Columns 25-36: GAMMA, diffusion parameter, cm^2/sec

Columns 37-48: AFH, flame height factor

Columns 49-60: EPS, exponent for diffusion pressure dependence

Columns 61-72: Y, proportionality constant for short diffusion flame

Columns 72-80: not used

CARD 9: Data Card

NUMBER REQUIRED: One per run

FUNCTION: Specify propellant parameters

FORMAT: (6E12.6)

Columns 1-12: BETA, mass fraction of metal

Columns 13-24: RHOM, density of metal, g/cm^3

Columns 25-36: QM, heat release of metal combustion, cal/g

Columns 37-80: not used

CARD 10: Data Card

NUMBER REQUIRED: One per case

FUNCTION: Specify integration parameters

FORMAT: (3I5, 3F10.5)

Columns 1-5: NMODES, number of oxidizer size distribution modes

Columns 6-10: NCOUNT, number of intervals in the numerical integration of total propellant mass flux

Columns 10-15: NXCOUN, number of intervals in the numerical integration for the proportionality constant C in the equation for the volume of fuel associated with a particle in a polydisperse packing

Columns 16-25: XN, diameter exponent in the equation for the volume of fuel associated with a particle in a polydisperse packing.

Columns 26-35: DDO, oxidizer particle size increment in the numerical integration of total propellant mass flux.

Columns 36-45: XDDO, oxidizer particle size increment in the numerical integration for the proportionality constant C

CARDS 10 to 11 + NMODES: Data Card

NUMBER REQUIRED: One per oxidizer mode size, per case

FUNCTION: Specify oxidizer size distribution parameters

FORMAT: (3F10.5)

Columns 1-10: SIGMA, standard deviation of oxidizer size distribution for a particular mode

Columns 11-20: DBAR, mean oxidizer crystal size for a particular mode, microns

Columns 21-30: YI, mass fraction of oxidizer in a particular mode relative to the total mass of oxidizer.

Columns 31-80: not used

CARD 11 + NMODES: Control Card

NUMBER REQUIRED: One card per case

FUNCTION: Start next case or terminate run

FORMAT: (I4)

Columns (1-4): NSTOP, if NSTOP > 1 terminate program, if NSTOP ≤ 1 begin next case

CARD 12 + NMODES: Data Card

NUMBER REQUIRED: One card per additional case

FUNCTION: Specify propellant parameters

FORMAT: NAMELIST/NAM1/

REMARKS: Used only when more than one case is run.

CARD 13 + NMODES: Data Card

NUMBER REQUIRED: One card per additional case

FUNCTION: See Card 10

FORMAT: See Card 10

CARD 13 + NMODES_{case one} to (12 + NMODES_{case one} + NMODES_{case two}):
Data Card

NUMBER REQUIRED: One per mode in case two

FUNCTION: See Cards 11 to 10 + NMODES_{case one}

FORMAT: See Cards 11 to 10 + NMODES_{case one}

CARD 13 + NMODES_{case one} + NMODES_{case two}: Control Card

NUMBER REQUIRED: One per additional case

FUNCTION: See Card 11 + NMODES_{case one}

FORMAT: See Card 11 + NMODES_{case one}

COMPUTER PROGRAM LISTING

AND

SAMPLE CALCULATION


```

FORTRAN IV C LEVEL 21      MAIN      DATE = 75197      09/58/38
C      *****      469 0040
0001      SUBROUTINE CONCAL (J)      469 0041
0002      IMPLICIT REAL*8 (A-H,O-Z)      469 0042
C      THIS SUBROUTINE INCREMENTS THE PRESSURE
      REAL*8 KAP1, KAP2, KPF, MOX, MT
      DIMENSION FAC(10)
      COMMON AL,
1      AZ, AF, AFH, ALFAST,
2      BESS, BESS1(50), BETAF, BSQR,
3      CIGN, CON1, CSUBP, DELDI,
4      EOX, ETA, GAMMA, GNM,
5      HOP, KPF, MOX, MT, KAP1,
6      POWIGN, PSTART, QAP,
      COMMON QFUEL, QPF, R,
1      RHOF, RHOSP, RHOD, RON,
2      TAV, TF, TIT(20), TIT1(20), TZERO,
3      XLAMB, XN1, XN2, XN3, XNU1,
      COMMON XNUP, XALFA, PMW, ETAP, EPS
      COMMON/DOUBLE/TS,C3P,C4P,XS1PF,XSTPD,XSTARD,XSTAP
      COMMON/XINT/IJIM, IPLOT, K, MEM1, NP1
1      IF (J) 2, 2, 15
2      FAC(1)=1.0
0006      FAC(2)=1.77
0007      FAC(3)=3.17
0008      FAC(4)=5.62
0009      FAC(5)=10.0
0010      JJ = 0
0011      I = 1
0012      IF (JJ - 1) 16, 20, 20
0013      16 XMULT = PSTART
0014      JJ = 1
0015      I = 1
0016      IF (1-6) 50,21,21
0017      21 XMULT = XMULT*10.
0018      I = 2
0019      P = XMULT*FAC(I)
0020      I = I + 1
0021      RETURN
0022      END
0023
0024
0025
0026
0027
0028
      *****
      469 0068
      469 0069
      469 0070
      469 0071
      469 0072
      469 0073
      469 0075
      469 0076
      469 0077
      469 0078
      469 0079
      469 0080

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```

0001 C *****
0002 SURROUTINE STEMP
0003 IMPLICIT REAL*8 (A-H,O-Z)
0004 EXTERNAL DYN
0005 REAL*8 KAP1, KAP2, KPF, MOX, MT
COMMON A1,
1 A2, AFH, ALFAST,
2 BESS, BESS1(50), BETAF, BSQR,
3 CIGN, CON1, DELDT, DZERO,
4 EOX, ETA, GAMMA, HON,
5 HDP, HOP, KAP1, KAP2, KPF,
6 KPE, MOX, MT, P,
COMMON QFUEL, PCMIGN, PSTOP, QAP,
1 QHOF, QL, QPF, R,
2 RHOF, RHOSP, RHOX, R, RAP,
3 TAV, TF, TIT(20), TZERO,
4 XLAMB, XN1, XN2, XN3, XNU1,
COMMON XJUP, XALFA, PMW, ETAP, EPS
COMMON/DOUBLE/TS-C3P-CAP,XSTPF,XSTPD,XSTARD,XSTAP
COMMON/XINT/ IJIM, IPLOI, K, MEH1, NPI
COMMON/ETAY/ Y
DIMENSION ARG1ST(20), AN(5)
ALFA = ALFAST
XNU = XNUST
XNU2 = (1.000 - ALFAST)*XNU1/ALFAST
XNUQ = (1.000 - ALFAST)*XNUP/ALFAST
BSQR = RHOSP
BSQR = (DZERO**2/6.000)*(1.000/XNU) *1.00-08
CELOI = (1.000/(DSQRT(XNU)) - 1.000)*(1.000/(DSQRT(6.000)))
CON1 = DSQRT(XNU)
ARG = 3.9300*CON1
CALL BESSEL (0.0, ARG, AN)
BESS = AN(3)
DUM1 = 3.21500*CON1*(1.000 + XNU2)*BESS/(XNU2 - (1.000 + XNU2)*CON
11**2)
41 IF (DUM1) 40, 40, 41
42 ETA = DLOG (DUM1)
GO TO 42
40 ETA = DLOG (-1.29300*DUM1/3.21500)
42 DUM1 = -1.29300*CON1*(1.000 + XNUQ)*BESS/(XNUQ - (1.000 + XNUQ)*CO
11**2)
20 IF (DUM1) 20, 20, 21
21 ETAP = DLOG (3.21500*DUM1/(-1.29300))
GO TO 22
21 ETAP = DLOG (DUM1)
22 QFF = CSUBP*((TF - 298.000) - ALFA*(TAP - 298.000) + (1.000 - ALFA
1)/(CSUBP*QFUEL)/ALFA
QPF = CSUBP*((TF - 298.000) + ALFA*(QL/CSUBP + (1.000 - ALFA) *
1 QFUEL/CSUBP)
QAP = CSUBP*(TAP - 298.000) + QL
ETA = Y/ETA
ETAP = Y/ETAP
CON2 = GAMMA*TAV**0.7500/62.0600*GMW
C3 = 2.000*CON2*ETA*AFH
C4 = (7.6600*CON2)**2/BSQR
32 MNC = XN2
RATC = KAP1
MT = RHOP*R
XNT = 0.0000
469 0081 *****
469 0082
469 0085 ANS1(50), 469 0004
469 0086 DZERO, 469 0085
469 0087 HON, 469 0086
469 0088 KAP2, 469 0087
469 0089 P, 469 0090
469 0090 QAP, 469 0091
469 0091 R, 469 0092
469 0092 SOX, 469 0093
469 0093 TAP, 469 0094
469 0094 XNU1 469 0014
469 0097
469 0185
469 0186
469 0101
469 0102
469 0103
469 0104

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```

C
0001 *****
0002 SUPROUTINE INPUT (M1)
0003 IMPLICIT REAL*8 (A-H,O-Z)
0004 REAL*8 KAP1, KAP2, KPF, MOX, MT
0005 COMMON AL,
1 A2, AF, ALFAST, ANSI(50), 469 0004
2 BESS(50), BETAF, BSQR, 469 0136
3 CIGN, CON1, CSUSP, DELOI, 469 0137
4 EOX, ETA, GAMMA, KAP1, 469 0138
5 HDP, KPF, MOX, MT, 469 0141
6 POMIGN, PSTART, PSTOP, GAP, 469 0142
COMMON QFUEL, QL, QPF, R, RAP, RF, 469 0012
1 RHCF, RHGX, RCHX, RCH, SOX, TAP, 469 0144
2 TAV, TF, TIT(20), TZERO, 469 0014
3 XLAMB, XN1, XN2, XN3, XNU1
COMMON XNUP, XALFA, PMH, ETAP, EPS
COMMON /PBC/ CONF
COMMON /RMN/ BETA, RHOM, QM
COMMON/DNURLE/TS,C3P,C4P,XSTPF,XSTPD,XSTARD,XSTAP
COMMON/XINT/ IJIN, IPLOT, K, MEM1, NP1
COMMON/ETAY/ Y
DIMENSION ANI(4)
NAMELIST /NAME1/ IPLOT, NJOB, ITIT, TZERO, ALFA, TF, GMW, XNU1,
1 DZERO, QFUEL, RHOF, AF, EF, XNUP, PMH, QL, RHGX, AOX, EOX, TAP,
1 AP, CIGN, POMIGN, POWD, PSTART, PSTOP, CONF, KPF, KAP1, KAP2, QM
1 XN1, XN2, XN3, CSURP, XLAMB, GAMMA, AFH, EPS, Y, BETA, RHOM, QM
DATA NJOB/1/
GO TO (1, 2), NJOB
1 READ (5,800) NJOB, IPLOT
READ (5,801) (TIT(I), I=1,8)
READ (5,802) TZERO, XALFA, TF, GMW, XNU1, XDZERO
READ (5,802) QFUEL, RHCF, AF, EF, XNUP, PMH
READ (5,802) QL, RHGX, AOX, EOX, TAP, AP
READ (5,802) CIGN, POMIGN, POWD, PSTART, PSTOP, CONF
READ (5,802) KPF, KAP1, KAP2, XN1, XN2, XN3
READ (5,802) CSURP, XLAMB, GAMMA, AFH, EPS, Y
READ (5,802) BETA, RHOM, QM
NJCB = 2
GO TO 10
2 READ (5,NAME1)
IF (NJCB - 2) 3, 3, 11
3 CONTINUE
4 CONTINUE
10 CONTINUE
11 CONTINUE
ITIT = 0
IF (AP) 22, 21, 20
CALCULATE OXIDIZER RATE CONSTANT, AS NONE WAS GIVEN
22 MOX70 = 1.900
21 MOX70 = 1.6800
23 TS70 = -COX/(1.98700* DLGG(MOX70/ADK))
ZS70 = DLOG ((TAP + QL/CSURP - 298.000)/(OL/CSURP - 298.000 +
1 TS70))
KAP1 = CSURP/XLAMB*MOX70**2/(70.000**XN2*ZS70)
KAP2 = KAP1
V = (TAP + TF)/2.000
20 RETURN
201 FORMAT (30H AP CENTERED PRIMARY FLAME
202 FORMAT (30H AP CENTERED FINAL FLAME
800 FORMAT (212)
801 FORMAT (R10)
802 FORMAT (6E12.6)
END
469 0179
469 0204
469 0205
469 0207
469 0208
469 0212
469 0213
469 0216
469 0217
469 0218
469 0219
469 0220
469 0221
469 0222

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STMP

FORTRAN IV G LEVEL 21

```

0045      C 51      BEGINNING OF COMPETING FLAME CALCULATION
0046      17 = 0
0047      18 = 0
0048      ARGST(1) = TS
0049      ARGST(3) = C3
0050      ARGST(4) = C4
0051      ARGST(5) = RATC
0052      ARGST(6) = XNC
0053      C 80      CONVERGENCE CALCULATION ON TS FOLLOWS
0054      XTS = TS - 808(DON, ARGST)
0055      IF (DABS (1.000 - XTS/TS) - .00100) 60, 60, 61
0056      61      IF (TS - XTS) 86, 85, 85
0057      85      17 = 1
0058      IF (XTS.LT.500.000) XTS = 500.000
0059      XLOW = XTS
0060      GO TO 87
0061      86      18 = 1
0062      IF (XTS-GE.1400.) XUP = 1400.000
0063      IF (XTS.LT.1400.) XUP = XTS
0064      IF (17 + 18 - 2) 88, 89, 89
0065      88      ARGST(1) = XTS
0066      GO TO 80
0067      89      ANS = 0.000
0068      TS HAS BOUNCED -- GO TO BRUTE FORCE
0069      N = 15
0070      XTS = 2(DON, ARGST, XUP, XLOW, ANS, N)
0071      CONTINUE
0072      R = MT/RHOP
0073      RETURN
0074      END

```

```

0001      C ***** FINRAT
0002      SUBROUTINE FINRAT (XMT,D,FZERO,DOO,XXMU,NCOUNT)
0003      IMPLICIT REAL*8 (A-H,O-Z)
0004      COMMON/XRAT/ RHOP,8R
0005      DIMENSION XMT(100), FZERO(100), XXMU(100), D(100)
0006      A = 0.000
0007      LL = 1
0008      2      XL1 = XMT(LL)*XXMU(LL)*FZERO(LL)/D(LL)
0009      XL2 = XMT(LL+1)*XXMU(LL+1)*FZERO(LL+1)/D(LL+1)
0010      IF (D(LL+1).LT.5.000) GO TO 10
0011      IF (D(LL+1).LT.30.000) GO TO 11
0012      IF (D(LL+1).LT.60.000) GO TO 12
0013      IF (D(LL+1).LT.120.000) GO TO 13
0014      IF (D(LL+1).LT.240.000) GO TO 14
0015      GO TO 15
0016      10      DOO = .500
0017      GO TO 3
0018      11      DOO = 1.000
0019      GO TO 3
0020      12      DOO = 5.000
0021      GO TO 3
0022      13      DOO = 10.000
0023      GO TO 3
0024      14      DOO = 20.000
0025      GO TO 3
0026      15      DOO = 40.000
0027      3      APART = (XL1 + XL2)*DOO/2.000
0028      LL = LL + 1
0029      A = A + APART
0030      IF (LL - NCOUNT) 2, 4, 4
0031      4      RR = A/RHOP
0032      RETURN
0033      END

```

```

0001 *****
0002 DOUBLE PRECISION FUNCTION DON (ARGLST)
0003     IMPLICIT REAL*8 (A-H,O-Z)
0004     CALCULATE TS FOR COMPETING FLAMES
0005     REAL*8 KAP1, KAP2, KPF, MOX, MT
0006     COMMON A1, A2, AF, AFH, ALFAST,
0007     BESS, BESS1(50), BETAF, BSQR,
0008     CIGN, CON1, CSUBP, DELDI,
0009     EDX, ETA, GAMMA, GNV,
0010     KAP2,
0011     MT,
0012     P,
0013     QF,
0014     RF,
0015     SOX,
0016     TAP,
0017     TIT(20), TZERO,
0018     XN1, XN2, XN3, XNUST,
0019     XNU
0020     COMMON XNUP, XALFA, PMW, ETAP, EPS
0021     COMMON /PBC/ CONF
0022     COMMON /RWN/ BETA, RHOM, QM
0023     COMMON/DOUBLE/TS,C3P,C4P,XSTPF,XSTPD,XSTARD,XSTAP
0024     COMMON/XINT/ IJIM, IPLOT, K, MEM1, NP1
0025     DIMENSION ARGLST(20)
0026     IF (ARGLST(1).GT.0.230D40) GO TO 99
0027     TS = ARGLST(1)
0028     C3 = ARGLST(3)
0029     C4 = ARGLST(4)
0030     RATC = ARGLST(5)
0031     XNC = ARGLST(6)
0032     WNCP = RHOSP
0033     ALFA = ALFAST
0034     XNU = XNUST
0035     C2P = GAMMA*TS**0.75D0/82.06D0*PMW
0036     C3P = 2.00D0*C2P*ETAP*AFH
0037     C4P = (7.66D0*C2P)**2/RSQR
0038     MOX = AOX*DEXP(-EOX/(1.987D0*TS))
0039     CALL SOXCAL (TS, SOX)
0040     MT = MOX*SOX/ALFA
0041     XSTPF = MT/(KPF**XN1)
0042     DUM2=1.0D0 + C4P/(MOX**2)
0043     IF (DUM2 - 1.01D0) 121, 121, 122
0044     121 DUM3 = 0.5D0*C4P/(MOX**2)
0045     GO TO 124
0046     122 DUM3 = DSQRT (DUM2) - 1.0D0
0047     124 XSTPD = C3P/(MOX*DUM3)
0048     IF(XSTPD-LT.0.0D0) XSTPD = 1.0D0
0049     XSTAP = MOX/(RATC**XNC)
0050     IF (XSTAP - XSTPF - XSTPD/AFH) 51, 51, 52
0051     52 BETAF = 1.0D0
0052     GO TO 55
0053     51 BETAF = AFH*(XSTAP - XSTPF)/XSTPD
0054     IF (CONF) 54, 54, 53
0055     53 BETAF = 2.0D0*BETAF - BETAF**2
0056     COMMON (CONICAL) FLAME
0057     54 IJIM = 2
0058     IF (BETAF) 56, 55, 55
0059     56 BETAF = 0.0D0
0060     55 CONTINUE
0061     DUM2 = 1.0D0 + C4/(MOX**2)

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DON

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0047 IF (DUM2 - 1.0100) 10, 10, 11
0048 11 DUM3 = DSQRT (DUM2) - 1.000
0049 GO TO 91
0050 10 DUM3 = 0.500+C4/(MOX**2)
0051 91 XSTARD = C3/(MOX*DUM3)
0052 IF (XSTARD-LT.0.000) XSTARN = 1.000
0053 DUM2 = 1.000 + C4P/(MOX**2)
0054 IF (DUM2 - 1.0100) 12, 12, 13
0055 13 DUM3 = DSQRT(DUM2) - 1.000
0056 GO TO 92
0057 12 DUM3 = 0.500+C4P/(MOX**2)
0058 92 XSTPD = C3P/(MOX*DUM3)
0059 IF (XSTPD-LT.0.000) XSTPD = 1.000
0060 93 XSTAP = MOX/(RATC*P**XNC)
0061 94 XSTPF = MT/(KPF*P**XN1)
0062 95 ZAP = CSURP*MOX*XSTAP/XLAMB
0063 96 ZAT = ZAP + CSURP*MCX*XSTARD/XLAMB
0064 97 ZPF = CSURP*MT/XLAMB*(XSTPF + XSTPD)
0065 90 ZPF = CSURP*MT/XLAMB*(XSTPF + XSTPD)
0066 GO TO 98
0067 97 ZPF = CSURP*MT/XLAMB*(XSTAP*AFH + XSTPF)
0068 98 IF (ZPF-LT.-164.000) ZPF = -164.000
0069 IF (ZAP-LT.-164.000) ZAP = -164.000
0070 IF (ZAT-LT.-164.000) ZAT = -164.000
0071 IF (ZPF-GT.164.000) ZPF = 164.000
0072 IF (ZAP-GT.164.000) ZAP = 164.000
0073 IF (ZAT-GT.164.000) ZAT = 164.000
0074 XTS = ZERO - ALFA*QL/CSURP - (1.000 - ALFA - BETTA)*QFUEL/CSURP
1 - BETTA*QW/CSURP + (1.000 - BETTA)*QF/CSURP*(ALFA*QAP/CSURP*DEXP(-ZAP) +
2 QFF/CSURP*DEXP(-ZAT)*ALFA) + BETTA*QPF/CSURP*DEXP(-ZPF)
C
0075 XTS = AMAX1 (XTS, 500.)
0076 IF ( XTS.LF.500.000) XTS = 500.000
0077 CON = ARGLS1(1) - XTS
0078 GO TO 100
0079 99 CON = ARGLS1(1)
0080 100 RETURN
END

```

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FORTRAN IV G LEVEL 21          MAIN          DATE = 75197          09/58/38          *****
C          *****          OUTPUT          *****
0001  SURROUTINE OUTPUT (M1)
0002  IMPLICIT REAL*8 (A-H,C-Z)
0003  REAL*8 KAP1, KAP2, KPF, MCX, MT
0004  REAL*8 MOX1
0005  COMMON A1,
1      A2,
2      BESS,
3      CIGN,
4      ENX,
5      KPF,
6      POMO,
COMMON QFUEL,
1      RHOF,
2      TAV,
3      XLAMR,
COMMON XNUP, XALFA, PMW, ETAP, EPS
COMMON /PBC/ CONF
COMMON /RW/ BETA, RHOF, QM
COMMON/DOUBLE/TS,C3P,C4P,XSTPF,XSTPD,XSTARD,XSTAP
COMMON/XINT/ IJIM, IPLOT, K, MEM1, NP1
0006  DIMENSION TIT(20)
1      GO TO 110, 201, M1
10  ERKT = R
PT(K) = P
PTA(K) = PT(K)*14.700
BRA(K) = BR(K)/2.5400
PMAX = K
K = K + 1
RETURN
20  CONTINUE
XNLT = XALFA*100.000
TZIP = TZERO - 273.000
IF (CONF) 150, 150, 151
151  WRITE (6,152)
150  WRITE (6,154)
153  WRITE (6,106)
WRITE (6,107) XNUT
WRITE (6,108) RHOP, RHOF, RHOF
WRITE (6,109) QFUEL, TF, GMW, PMW
WRITE (6,110) GAMMA, XNUI,XNUP
WRITE (6,111)
WRITE (6,112) CIGN, POMIGN, POMD, QL
WRITE (6,113)
WRITE (6,114) EF, EOX, AF, AOX
WRITE (6,115) XN1, KPF, XN2, KAP1, XN3, KAP2
WRITE (6,116)
WRITE (6,117) TAP, XLAMR, CSURP
WRITE (6,118) AFH
WRITE (6,119) TZIP
WRITE (6,121) EPS
WRITE(6,102)
WRITE(6,104)
CC 69 K = 1, KMAX
WRITE(6,103) PT(K),PTA(K),RR(K),BRA(K)
69  CONTINUE
RETURN
0007
0008
0009
0010
0011
0012
0013
0014
0015
0016
0017
0018
0019
0020
0021
0022
0023
0024
0025
0026
0027
0028
0029
0030
0031
0032
0033
0034
0035
0036
0037
0038
0039
0040
0041
0042
0043
0044
0045
0046
0047
0048
ANSI(50),469 0004
469 0330
DZERC,
469 0331
HON,
469 0332
KAP2,
P,
469 0335
OFF,
469 0336
RF,
469 0012
TAP,
469 0338
XNUI
469 0014
469 0342
469 0343
469 0344
469 0352
469 0353
469 0354
469 0367
469 0368
469 0371
469 0376
469 0377
469 0378
469 0380
469 0381
469 0383
469 0384
469 0386
469 0387
469 0388
469 0389
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469 0391
469 0392
469 0394
469 0395

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0049 101 FORMAT (1H1.8A10/)
0050 102 FORMAT (8X,4HPRES,5X,4HPRES,7X,2HBR,9X,2HBR)
0051 103 FORMAT (5X,F7.2,2X,F7.1,2I2X,F9.4)
0052 104 FORMAT (8X,4HATMS,5X,4HPSIA,5X,6HCM/SEC,5X,6HIN/SEC/)
0053 106 FORMAT (19H PROPELLANT DATA IS)
0054 107 FORMAT (6X,20HWT, PERCENT OXID. = ,F6.1)
0055 108 1 9X,16HMOXID. DENSITY = ,F5.2
0056 109 1 9X,16HMOXID. DENSITY = ,F5.2
0057 110 1 F6.2,5X,13HPRI MOL WT = ,F6.2)
0058 111 1 RAT = ,F6.2/)
0059 112 1 6X,14HACT HEAT = ,F7.1/)
0060 113 1 6X,14HACT HEAT = ,F7.1/)
0061 114 1 6X,14HACT HEAT = ,F7.1/)
0062 115 1 6X,14HACT HEAT = ,F7.1/)
0063 116 1 6X,14HACT HEAT = ,F7.1/)
0064 117 1 6X,14HACT HEAT = ,F7.1/)
0065 118 1 6X,14HACT HEAT = ,F7.1/)
0066 119 1 6X,14HACT HEAT = ,F7.1/)
0067 120 1 6X,14HACT HEAT = ,F7.1/)
0068 121 1 6X,14HACT HEAT = ,F7.1/)
0069 122 1 6X,14HACT HEAT = ,F7.1/)
0070 123 1 6X,14HACT HEAT = ,F7.1/)
0071 124 1 6X,14HACT HEAT = ,F7.1/)

0001 *****
0002 SUBROUTINE SOXCAL (TS1, SOX1)
0003 IMPLICIT REAL*8 (A-H,O-Z)
0004 PEAL*9 KAP1, KAP2, KPE, MOX, MT
COMMON A1,
1 A2,
2 BESS,
3 CIGN,
4 EOX,
5 KPF,
6 POWD,
COMMON QFUEL,
1 QHOF,
2 TAV,
3 XLAM,
COMMON XNUP, XALFA, PMW, ETAP, EPS
COMMON DOUBLE/TS,C3P,C4P,XSTPF,XSTPD,XSTARD,XSTAP
COMMON/XINT/ IJIM, IPLOT, K, MEM1, NPI
ALFA = ALFAST
XNU = XNUST
RF = AF*EXPI-EF/(1.98700*TS1)/RHO
RAP = MOX/RHOX
RON = RAP*CIGN*(DZERG*.00100)**POWD/(P**POWIGN)
HDP = A1*(1.000 - RAP/RF) + RON
HON = A2*(1.000 - RAP/RF) + RON
IF (HDP-GE-0.788500) HDP = 0.788500
IF (HON-LE-0.211500) HON = -0.211500
IF (HON-GE-0.211500) HON = 0.211500
IF (HON-LE-0.788500) HON = 0.788500
SOX1 = 3.000*XNU*(HDP**2 + HON**2)
1 XNU*(HDP**2 + HON**2)
RETURN
END

0005 *****
0006 SUBROUTINE SOXCAL (TS1, SOX1)
0007 IMPLICIT REAL*8 (A-H,O-Z)
0008 PEAL*9 KAP1, KAP2, KPE, MOX, MT
COMMON A1,
1 A2,
2 BESS,
3 CIGN,
4 EOX,
5 KPF,
6 POWD,
COMMON QFUEL,
1 QHOF,
2 TAV,
3 XLAM,
COMMON XNUP, XALFA, PMW, ETAP, EPS
COMMON DOUBLE/TS,C3P,C4P,XSTPF,XSTPD,XSTARD,XSTAP
COMMON/XINT/ IJIM, IPLOT, K, MEM1, NPI
ALFA = ALFAST
XNU = XNUST
RF = AF*EXPI-EF/(1.98700*TS1)/RHO
RAP = MOX/RHOX
RON = RAP*CIGN*(DZERG*.00100)**POWD/(P**POWIGN)
HDP = A1*(1.000 - RAP/RF) + RON
HON = A2*(1.000 - RAP/RF) + RON
IF (HDP-GE-0.788500) HDP = 0.788500
IF (HON-LE-0.211500) HON = -0.211500
IF (HON-GE-0.211500) HON = 0.211500
IF (HON-LE-0.788500) HON = 0.788500
SOX1 = 3.000*XNU*(HDP**2 + HON**2)
1 XNU*(HDP**2 + HON**2)
RETURN
END

0009 *****
0010 SUBROUTINE SOXCAL (TS1, SOX1)
0011 IMPLICIT REAL*8 (A-H,O-Z)
0012 PEAL*9 KAP1, KAP2, KPE, MOX, MT
COMMON A1,
1 A2,
2 BESS,
3 CIGN,
4 EOX,
5 KPF,
6 POWD,
COMMON QFUEL,
1 QHOF,
2 TAV,
3 XLAM,
COMMON XNUP, XALFA, PMW, ETAP, EPS
COMMON DOUBLE/TS,C3P,C4P,XSTPF,XSTPD,XSTARD,XSTAP
COMMON/XINT/ IJIM, IPLOT, K, MEM1, NPI
ALFA = ALFAST
XNU = XNUST
RF = AF*EXPI-EF/(1.98700*TS1)/RHO
RAP = MOX/RHOX
RON = RAP*CIGN*(DZERG*.00100)**POWD/(P**POWIGN)
HDP = A1*(1.000 - RAP/RF) + RON
HON = A2*(1.000 - RAP/RF) + RON
IF (HDP-GE-0.788500) HDP = 0.788500
IF (HON-LE-0.211500) HON = -0.211500
IF (HON-GE-0.211500) HON = 0.211500
IF (HON-LE-0.788500) HON = 0.788500
SOX1 = 3.000*XNU*(HDP**2 + HON**2)
1 XNU*(HDP**2 + HON**2)
RETURN
END

0013 *****
0014 SUBROUTINE SOXCAL (TS1, SOX1)
0015 IMPLICIT REAL*8 (A-H,O-Z)
0016 PEAL*9 KAP1, KAP2, KPE, MOX, MT
COMMON A1,
1 A2,
2 BESS,
3 CIGN,
4 EOX,
5 KPF,
6 POWD,
COMMON QFUEL,
1 QHOF,
2 TAV,
3 XLAM,
COMMON XNUP, XALFA, PMW, ETAP, EPS
COMMON DOUBLE/TS,C3P,C4P,XSTPF,XSTPD,XSTARD,XSTAP
COMMON/XINT/ IJIM, IPLOT, K, MEM1, NPI
ALFA = ALFAST
XNU = XNUST
RF = AF*EXPI-EF/(1.98700*TS1)/RHO
RAP = MOX/RHOX
RON = RAP*CIGN*(DZERG*.00100)**POWD/(P**POWIGN)
HDP = A1*(1.000 - RAP/RF) + RON
HON = A2*(1.000 - RAP/RF) + RON
IF (HDP-GE-0.788500) HDP = 0.788500
IF (HON-LE-0.211500) HON = -0.211500
IF (HON-GE-0.211500) HON = 0.211500
IF (HON-LE-0.788500) HON = 0.788500
SOX1 = 3.000*XNU*(HDP**2 + HON**2)
1 XNU*(HDP**2 + HON**2)
RETURN
END

0017 *****
0018 SUBROUTINE SOXCAL (TS1, SOX1)
0019 IMPLICIT REAL*8 (A-H,O-Z)
0020 PEAL*9 KAP1, KAP2, KPE, MOX, MT
COMMON A1,
1 A2,
2 BESS,
3 CIGN,
4 EOX,
5 KPF,
6 POWD,
COMMON QFUEL,
1 QHOF,
2 TAV,
3 XLAM,
COMMON XNUP, XALFA, PMW, ETAP, EPS
COMMON DOUBLE/TS,C3P,C4P,XSTPF,XSTPD,XSTARD,XSTAP
COMMON/XINT/ IJIM, IPLOT, K, MEM1, NPI
ALFA = ALFAST
XNU = XNUST
RF = AF*EXPI-EF/(1.98700*TS1)/RHO
RAP = MOX/RHOX
RON = RAP*CIGN*(DZERG*.00100)**POWD/(P**POWIGN)
HDP = A1*(1.000 - RAP/RF) + RON
HON = A2*(1.000 - RAP/RF) + RON
IF (HDP-GE-0.788500) HDP = 0.788500
IF (HON-LE-0.211500) HON = -0.211500
IF (HON-GE-0.211500) HON = 0.211500
IF (HON-LE-0.788500) HON = 0.788500
SOX1 = 3.000*XNU*(HDP**2 + HON**2)
1 XNU*(HDP**2 + HON**2)
RETURN
END

0021 *****
0022 SUBROUTINE SOXCAL (TS1, SOX1)
0023 IMPLICIT REAL*8 (A-H,O-Z)
0024 PEAL*9 KAP1, KAP2, KPE, MOX, MT
COMMON A1,
1 A2,
2 BESS,
3 CIGN,
4 EOX,
5 KPF,
6 POWD,
COMMON QFUEL,
1 QHOF,
2 TAV,
3 XLAM,
COMMON XNUP, XALFA, PMW, ETAP, EPS
COMMON DOUBLE/TS,C3P,C4P,XSTPF,XSTPD,XSTARD,XSTAP
COMMON/XINT/ IJIM, IPLOT, K, MEM1, NPI
ALFA = ALFAST
XNU = XNUST
RF = AF*EXPI-EF/(1.98700*TS1)/RHO
RAP = MOX/RHOX
RON = RAP*CIGN*(DZERG*.00100)**POWD/(P**POWIGN)
HDP = A1*(1.000 - RAP/RF) + RON
HON = A2*(1.000 - RAP/RF) + RON
IF (HDP-GE-0.788500) HDP = 0.788500
IF (HON-LE-0.211500) HON = -0.211500
IF (HON-GE-0.211500) HON = 0.211500
IF (HON-LE-0.788500) HON = 0.788500
SOX1 = 3.000*XNU*(HDP**2 + HON**2)
1 XNU*(HDP**2 + HON**2)
RETURN
END

```


FORTRAN IV G LEVEL	21	CONVR2	DATE = 75197	09/50/38	PAGE 0002
0034	1	XINC=XINC*0.500		469 0522	
0035		TOP=BOT+XINC		469 0523	
0036		IVAL=IVAL-1		469 0524	
0037		IF (IVAL) 12,12,11		469 0525	
0038	12	CONVR2=TOP		469 0526	
0039		GO TO 99		469 0527	
0040	11	ARGLST(1)=TOP		469 0528	
0041		ATOP=XNAME(ARGLST)		469 0529	
0042		GO TO 50		469 0530	
	C			469 0531	
	C	IN THE NEXT INTERVAL , MOVE AND HALVE		469 0532	
	C			469 0533	
0043	2	XINC=XINC*0.500		469 0534	
0044		BOT=TOP		469 0535	
0045		TOP=BOT+XINC		469 0536	
0046		ABOT=ATOP		469 0537	
0047		IVAL=IVAL-1		469 0538	
0048		IF (IVAL) 22,22,21		469 0539	
0049	22	CONVR2=TOP		469 0540	
0050		GO TO 99		469 0541	
0051	21	ARGLST(1)=TOP		469 0542	
0052		ATOP=XNAME(ARGLST)		469 0543	
0053		GO TO 50		469 0544	
	C			469 0546	
	C	ONE OF THE END POINTS IS EXACT		469 0547	
	C			469 0548	
0054	40	IF (ATOP-ANS) 42,41,42		469 0549	
0055	41	CONVR2=TOP		469 0550	
0056		GO TO 99		469 0551	
0057	42	CONVR2=BOT		469 0552	
0058	99	CONTINUE		469 0553	
0059		ARGLST(1) = CONVR2		469 0554	
0060		ADUM = XNAME (ARGLST)		469 0555	
0061		RETURN		469 0556	
0062		END		469 0557	

```

FORTRAN IV G LEVEL 21
C
0001 *****
0002 SUBROUTINE BESSEL(X,Y,ANS)
0003 IMPLICIT REAL*8 (A-H,O-Z)
      DIMENSION ANS(4)
C
C      CN RETURN
C      ANS(1) = J ZERO (X)
C      ANS(2) = Y ZERO (X)
C      ANS(3) = Y ONE (Y)
C      ANS(4) = Y ONE (Y)
C
C      IF (X-3.0D0) 2,2,4
2 Z=X*X/9.0D0
      IF (X) 20,20,30
20 ANS(1)=1.0D0
      ANS(2)=1.0D0
      GO TO 6
30 CONTINUE
      ANS(1) = (((((-0.002100*Z-.0039444D0)*Z+.0444479D0)*Z-.3163866D0)*Z
1 + 1.2656208D0)*Z-2.2499997D0)*Z+1.0D0
      ANS(2) = -6.3662031* DLG(-5D0*X)*ANS(1)+(((1-0.0024846D0)*Z+
1 -0.00427916D0)*Z-.04261214D0)*Z+.25300117D0)*Z-.74350384D0)*Z+
2 -6.0559366D0)*Z+.36746691
      GO TO 6
4 Z=3.0D0/X
      FZERO = (((((-0.0014476D0*Z-.00072805D0)*Z+.00137237D0)*Z-.00009512
1D0)*Z-.0055274D0)*Z-.7700D-6)*Z+.79788456D0
      THZERO = X+(((1-0.0013558D0)*Z-.00029333D0)*Z-.00054125D0)*Z+.00262
1573D0)*Z-.0003954D0)*Z-.04166397D0)*Z-.78539816D0
      ANS(1) = FZERO*DCOS(THZERO)/DSQRT(X)
      ANS(2) = FZERO*DSIN(THZERO)/DSQRT(X)
      IF (Y-3.18*8.10
8 Z=Y*Y/9.0D0
      IF (Y) 40,40,50
40 ANS(3)=0.0D0
      ANS(4)=0.0D0
      GO TO 80
50 CONTINUE
      ANS(3) = (((((-0.0001109D0*Z-.00031761D0)*Z+.00443319D0)*Z-
1 -0.03954299D0)*Z+.21093573D0)*Z-.56249985D0)*Z+.5D0)*Y
      ANS(4) = (-6.3662031D0*Y* DLG(-5D0*Y)*ANS(3)+(((1-0.0027873D0)*Z-
1 -0.0400976D0)*Z+.3123951D0)*Z-1.3164827D0)*Z+.2.1682709D0)*Z+.221209
2D0)*Z-.6366198D0)/Y
      GO RETURN
80 RETURN
10 Z=3.0D0/Y
      FONE = (((((-0.00200330D0*Z+.00113653D0)*Z-.00249511D0)*Z+.00017105
1D0)*Z+.01659667D0)*Z+1.560D-6)*Z+.79788456D0
      THONE = Y+(((1-0.0029166D0)*Z+.00079824D0)*Z+.00074348D0)*Z-
1 -0.0637879D0)*Z+.0005650D0)*Z+.12499612D0)*Z-2.3561945D0
      ANS(3) = FONE*DCOS(THONE)/DSQRT(Y)
      ANS(4) = FONE*DSIN(THONE)/DSQRT(Y)
      RETURN
      END
C
*****
C      DOUBLE PRECISION FUNCTION B08 (XNAME,ARGLIST)
      IMPLICIT REAL*8 (A-H,O-Z)
      DIMENSION ARLIST(20)
      B08 = XNAME(ARLIST)
      RETURN
      END
0004 *****
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0001 C *****
0002 SUBROUTINE INPUT1(JJ,M,D,FZERO,XNU,NCCOUNT,ODOO)
0003 IMPLICIT REAL*8 (A-H,O-Z)
0004 REAL*8 KAP1,KAP2,KPF,MOX,MT
      COMMON AL, A2, AF, AFH, ALFAST, ANSI(50),
      1 ADX, BESS, CON1, CSUBP, DELDI, DZERO,
      2 FF, HOP, KAP1, KAP2, KPF, MOX, MT,
      3 KPF, POMIGN, QP, QPF, QFF,
      4 COMMON QFUEL, QL, QP, QPF, QFF,
      5 RHOF, RHOSP, RHOP, RHOF, RHOSP, RHOP,
      6 TAV, TF, TIT(20), TIT(20), TZERO,
      7 XLAMP, XN1, XN2, XN3, XNU1
      COMMON XNUP, XALFA, PMW, ETAP, EPS
      COMMON/XPUT/NXCCUN
      COMMON/XRAT/ RHOP,RR
      DIMENSION YI(10), FZERO(100), D(100), XFZERO(1000), XO(1000), DBAR
      1 IFM = 1, 1, 1, 15
      2 READ(5,100) NMODES, NCCOUNT,NXCCUN,XN,ODO,XDDO
      3 DI = 1.000
      4 FSUM = 0.000
      5 JJ = 1
      6 DO 10 II=1,NMODES
      7 READ(5,101) SIGMAI(II), DBARI(II), YI(II)
      8 CONTINUE
      9 DO 12 III=1,NXCCUN
      10 DO 11 JJJ=1,NMODES
      11 CALL DISTF(DI, JJJ, ITT, YVECR, DBART, SIGMAI)
      12 XFSUM = YI(JJJ)/YVECR
      13 FSUM = FSUM + XFSUM
      14 XFZERO(III) = FSUM
      15 XO(III) = DI
      16 DI = DI + XDDO
      17 FSUM = 0.000
      18 CONTINUE
      19 CONTINUE
      20 XNU = 1.000/(1.000 + RHOF*(1.000-XALFA)/(RHOF*XALFA))
      21 RHOF = RHOF*(1.000-XALFA)/(RHOF*XALFA)
      22 CALL CCAL (XFZERO,XO,XN,XNU,C,XDDO)
      23 CONTINUE
      24 RE-COUNT D AND FZERO
      25 DI = .500
      26 DO 22 IZZ=1,NCCOUNT
      27 FSUM = 0.000
      28 DO 21 JZZ=1,NMODES
      29 CALL DISTF(DI,JZZ,IZZ,YVECR,DBART,SIGMAI)
      30 XFSUM = YI(JZZ)/YVECR
      31 FSUM = FSUM + XFSUM
      32 CONTINUE
      33 FZERO(IZZ) = FSUM
      34 C(IZZ) = DI
      35 IF(DI-LT-5.000) GO TO 31
      36 IF(DI-LT-30.000) GO TO 32
      37 IF(DI-LT-60.000) GO TO 33

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DATE = 2157

FORTRAN IV G LEVEL 21 INPUT1

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0047 IF(01.LT.120.000) GO TO 34
0048 IF(01.LT.240.000) GO TO 35
0049 GO TO 36
0050 31 C1 = 01 + .500
0051 32 D1 = 01 + 1.000
0052 33 C1 = 01 + 5.000
0053 34 C1 = 01 + 10.000
0054 35 C1 = 01 + 20.000
0055 36 D1 = 01 + 40.000
0056 22 CONTINUE
0057 15
0058 DZERO = 0(JJ)
0059 XNUST = 1.000/(1.000+(4.000*C*DZERO**((XN-3.000)/3.14159200)
0060 ALFAST = 1.000/(1.000+(6.000*C*RHO)*DZERO**((XN-3.000)/(3.14159200
0061 1*(RHOX)))
0062 RHOXP = RHOX*XNUST/ALFAST
0063 RETURN
0064 FORMAT(3I5,3F10.5)
0065 100
0066 101
0067 END
0068
0069
0070
0001 *****
0002 SUBROUTINE CCAL(XFZERO,XD,XN,XNU,C,XDD0)
0003 IMPLICIT REAL*8 (A-H,O-Z)
0004 COMMON/XPUT/NKCCUN
0005 DIMENSION XFZERO(1000), XD(1000)
0006 A = 0.000
0007 B1 = 3.14159200*(1.000-XNU)/(6.000*XNU)
0008 JZ = 1
0009 XL1 = XFZERO(JZ)*XD(JZ)**((XN-4.000)
0010 XL2 = XFZERO(JZ+1)*XD(JZ+1)**((XN-4.000)
0011 APART = (XL1 + XL2)*XDD0/2.000
0012 JZ = JZ + 1
0013 A = A + APART
0014 IF (JZ - NKCCUN) 2, 4, 4
0015 C = B1/A
0016 RETURN
0017 END
0018
0019 *****
0020 SUBROUTINE DISTF(DI,JJJ,III,YVECR,DBARI,SIGMAI)
0021 IMPLICIT REAL*8 (A-H,O-Z)
0022 DIMENSION DBARI(10), SIGMAI(10)
0023 X = DLG(DI)
0024 XM = DLOG(DBARI(JJJ))
0025 SIG = DLOG(SIGMAI(JJJ))
0026 YVECR = SIG*2.506628275000*DEXP(.500*((X-XM)/SIG)**2)
0027 RETURN
0028 END
0029
0030 *****
0031 SUBROUTINE XSTOR(JJ,XMT,XNUST,XNU,MT,XXNU)
0032 IMPLICIT REAL*8 (A-H,O-Z)
0033 REAL*8 MT
0034 DIMENSION XMT(100), XXNU(100)
0035 XMT(JJ) = MT
0036 XXNU(JJ) = XNU/XNUST
0037 JJ = JJ + 1
0038 RETURN
0039 END
0040
0041 *****
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0070

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P = 2 atm									
JJ	R, C _m /w	FZEROP	DZERO, μ	XSTPF, μ	XSTAP, μ	XSTPD, μ	XSTARD, μ	ALFAST, α [*]	KMUST, f [*]
1	0.0022	0.0000	0.5	0.33	2.14	10000.00	10000.00	0.1600	0.0870
2	0.0025	0.0001	1.0	0.41	2.76	10000.00	10000.00	0.2759	0.1601
3	0.2187	0.0008	1.5	36.86	280.44	5.04	6.31	0.3637	0.2223
4	0.2180	0.0032	2.0	38.37	296.27	3.05	3.57	0.4325	0.2759
5	0.2144	0.0080	2.5	39.11	305.36	2.57	2.99	0.4878	0.3227
6	0.2108	0.0156	3.0	39.65	312.34	2.37	2.77	0.5334	0.3637
7	0.2076	0.0260	3.5	40.08	318.06	2.27	2.69	0.5714	0.4001
8	0.2048	0.0389	4.0	40.46	322.98	2.21	2.66	0.6038	0.4325
9	0.2023	0.0539	4.5	40.78	327.25	2.16	2.65	0.6316	0.4616
10	0.2001	0.0704	5.0	41.06	331.18	2.12	2.66	0.6558	0.4879
11	0.1965	0.1057	6.0	41.56	337.86	2.05	2.68	0.6957	0.5334
12	0.1937	0.1413	7.0	41.98	343.44	1.94	2.70	0.7273	0.5715
13	0.1915	0.1745	8.0	42.35	348.31	1.80	2.69	0.7530	0.6039
14	0.1898	0.2039	9.0	42.71	352.78	1.60	2.65	0.7742	0.6317
15	0.1887	0.2287	10.0	43.10	357.20	1.27	2.58	0.7921	0.6558
16	0.1869	0.2487	11.0	43.22	359.35	1.42	2.47	0.8074	0.6770
17	0.1829	0.2640	12.0	42.76	356.47	2.81	2.31	0.8205	0.6957
18	0.1785	0.2751	13.0	42.15	352.25	4.51	2.09	0.8320	0.7124
19	0.1729	0.2825	14.0	41.17	344.87	7.07	1.77	0.8421	0.7274
20	0.1643	0.2865	15.0	39.45	331.10	11.50	1.02	0.8511	0.7438
21	0.1486	0.2878	16.0	35.91	302.13	21.07	2.65	0.8591	0.7530
22	0.1006	0.2867	17.0	24.48	206.61	56.90	4.09	0.8663	0.7641
23	0.0679	0.2837	18.0	16.61	140.52	10000.00	5.88	0.8727	0.7743
24	0.0673	0.2791	19.0	16.55	140.24	10000.00	8.35	0.8786	0.7836
25	0.0666	0.2732	20.0	16.46	139.67	10000.00	12.06	0.8840	0.7921
26	0.0657	0.2665	21.0	16.31	138.55	10000.00	18.29	0.8889	0.8001
27	0.0642	0.2590	22.0	16.01	136.18	10000.00	30.98	0.8934	0.8074
28	0.0608	0.2509	23.0	15.22	129.60	10000.00	70.68	0.8976	0.8142
29	0.0512	0.2425	24.0	12.86	109.65	10000.00	10000.00	0.9014	0.8206
30	0.0513	0.2339	25.0	12.91	110.18	10000.00	10000.00	0.9050	0.8265
31	0.0513	0.2252	26.0	12.96	110.67	10000.00	10000.00	0.9083	0.8321
32	0.0513	0.2164	27.0	13.04	111.12	10000.00	10000.00	0.9114	0.8373
33	0.0514	0.2077	28.0	13.08	111.54	10000.00	10000.00	0.9143	0.8422
34	0.0514	0.1992	29.0	13.11	111.93	10000.00	10000.00	0.9170	0.8468
35	0.0514	0.1907	30.0	13.25	113.85	10000.00	10000.00	0.9195	0.8511
36	0.0514	0.1521	35.0	13.36	115.02	10000.00	10000.00	0.9302	0.8696
37	0.0514	0.1201	40.0	13.45	115.95	10000.00	10000.00	0.9384	0.8840
38	0.0514	0.0946	45.0	13.51	116.69	10000.00	10000.00	0.9449	0.8956
39	0.0514	0.0746	50.0	13.56	117.31	10000.00	10000.00	0.9501	0.9050
40	0.0514	0.0593	55.0	13.61	117.83	10000.00	10000.00	0.9545	0.9129
41	0.0514	0.0477	60.0	13.67	118.64	10000.00	10000.00	0.9581	0.9196
42	0.0514	0.0344	70.0	13.73	119.26	10000.00	10000.00	0.9639	0.9303
43	0.0514	0.0340	80.0	13.77	119.75	10000.00	10000.00	0.9682	0.9384
44	0.0513	0.0484	90.0	13.80	120.14	10000.00	10000.00	0.9717	0.9449
45	0.0513	0.0798	100.0	13.82	120.46	10000.00	10000.00	0.9744	0.9501
46	0.0513	0.1283	110.0	13.88	121.15	10000.00	10000.00	0.9767	0.9545
47	0.0513	0.1915	120.0	13.91	121.46	10000.00	10000.00	0.9786	0.9581
48	0.0513	0.3402	140.0	13.94	121.91	10000.00	10000.00	0.9816	0.9639
49	0.0512	0.4770	160.0	13.97	122.43	10000.00	10000.00	0.9839	0.9682
50	0.0512	0.5651	180.0	13.99	122.71	10000.00	10000.00	0.9856	0.9717
51	0.0512	0.5932	200.0	13.94	121.91	10000.00	10000.00	0.9870	0.9744
52	0.0511	0.5697	220.0	13.94	121.91	10000.00	10000.00	0.9882	0.9767
53	0.0512	0.5120	240.0	13.97	122.21	10000.00	10000.00	0.9892	0.9786
54	0.0512	0.3596	280.0	13.98	122.43	10000.00	10000.00	0.9907	0.9816
55	0.0511	0.2235	320.0	13.93	122.43	10000.00	10000.00	0.9919	0.9839
56	0.0512	0.1289	360.0	14.01	122.71	10000.00	10000.00	0.9928	0.9856
57	0.0511	0.0710	400.0	14.00	122.71	10000.00	10000.00	0.9935	0.9871
58	0.0511	0.0381	440.0	14.00	122.71	10000.00	10000.00	0.9941	0.9882
59	0.0511	0.0201	480.0	14.03	122.97	10000.00	10000.00	0.9946	0.9892
60	0.0511	0.0105	520.0	14.03	122.97	10000.00	10000.00	0.9950	0.9900

p = 3.54 atm

JJ	$\rho, \text{ gm/cc}$	FZEROP	DZERC, μ	XSTPF, μ	XSTAP, μ	XSTPD, μ	XSTARD, μ	ALFAST, α^*	XNUST, γ^*
1	C-0022	0.0000	0.5	0.14	0.77	10000.00	10000.00	0.1600	0.0870
2	C-0025	0.0001	1.0	0.17	0.99	10000.00	10000.00	0.2759	0.1601
3	C-0166	0.0008	1.5	22.66	148.37	5.04	6.31	0.3637	0.2223
4	C-0198	0.0032	2.0	23.90	158.54	3.05	3.57	0.4325	0.2759
5	C-0155	0.0080	2.5	24.44	163.63	2.57	2.99	0.4876	0.3227
6	C-0136	0.0156	3.0	24.80	167.27	2.37	2.77	0.5334	0.3637
7	C-0060	0.0260	3.5	25.09	170.22	2.27	2.69	0.5714	0.4001
8	C-0389	0.0389	4.0	25.33	172.67	2.21	2.66	0.6038	0.4325
9	C-2983	0.0539	4.5	25.53	174.79	2.16	2.65	0.6316	0.4616
10	C-2951	0.0704	5.0	25.71	176.67	2.12	2.66	0.6558	0.4879
11	C-2899	0.1057	6.0	26.03	179.97	2.05	2.68	0.6957	0.5334
12	C-2858	0.1413	7.0	26.30	182.85	1.94	2.70	0.7273	0.5715
13	C-2828	0.1745	8.0	26.56	185.42	1.80	2.69	0.7530	0.6039
14	C-2806	0.2039	9.0	26.81	187.86	1.60	2.65	0.7742	0.6317
15	C-2795	0.2287	10.0	27.10	190.45	1.27	2.58	0.7921	0.6558
16	C-2765	0.2487	11.0	27.15	191.31	1.42	2.47	0.8074	0.6770
17	C-2682	0.2640	12.0	26.63	188.07	2.81	2.31	0.8205	0.6957
18	C-2591	0.2751	13.0	25.98	183.88	4.51	2.09	0.8320	0.7124
19	C-2472	0.2825	14.0	25.00	177.28	7.07	1.77	0.8421	0.7274
20	C-2592	0.2865	15.0	23.36	165.94	11.50	1.02	0.8511	0.7408
21	C-1970	0.2878	16.0	20.22	143.97	21.07	2.65	0.8591	0.7530
22	C-1324	0.2867	17.0	13.68	97.58	56.90	4.09	0.8663	0.7641
23	C-1087	0.2837	18.0	11.30	80.73	10000.00	5.88	0.8727	0.7743
24	C-1075	0.2791	19.0	11.23	80.33	10000.00	8.35	0.8786	0.7836
25	C-1060	0.2732	20.0	11.12	79.67	10000.00	12.06	0.8840	0.7921
26	C-1039	0.2665	21.0	10.95	78.53	10000.00	18.29	0.8889	0.8001
27	C-1004	0.2590	22.0	10.63	76.33	10000.00	30.98	0.8934	0.8074
28	C-0930	0.2509	23.0	9.88	71.02	10000.00	70.68	0.8976	0.8142
29	C-0807	0.2425	24.0	8.60	61.91	10000.00	10000.00	0.9014	0.8206
30	C-0808	0.2339	25.0	8.64	62.22	10000.00	10000.00	0.9050	0.8265
31	C-0808	0.2252	26.0	8.67	62.50	10000.00	10000.00	0.9083	0.8321
32	C-0809	0.2164	27.0	8.70	62.77	10000.00	10000.00	0.9114	0.8373
33	C-0809	0.2077	28.0	8.73	63.01	10000.00	10000.00	0.9143	0.8422
34	C-0810	0.1992	29.0	8.76	63.25	10000.00	10000.00	0.9170	0.8468
35	C-0810	0.1907	30.0	8.78	63.46	10000.00	10000.00	0.9195	0.8511
36	C-0812	0.1521	35.0	8.88	64.37	10000.00	10000.00	0.9302	0.8696
37	C-0812	0.1201	40.0	8.96	65.06	10000.00	10000.00	0.9384	0.8840
38	C-0813	0.0946	45.0	9.02	65.60	10000.00	10000.00	0.9449	0.8956
39	C-0813	0.0746	50.0	9.07	66.04	10000.00	10000.00	0.9501	0.9050
40	C-0813	0.0593	55.0	9.11	66.40	10000.00	10000.00	0.9545	0.9129
41	C-0813	0.0477	60.0	9.14	66.70	10000.00	10000.00	0.9581	0.9196
42	C-0813	0.0344	70.0	9.19	67.17	10000.00	10000.00	0.9639	0.9303
43	C-0813	0.0340	80.0	9.22	67.53	10000.00	10000.00	0.9682	0.9384
44	C-0812	0.0464	90.0	9.25	67.82	10000.00	10000.00	0.9717	0.9449
45	C-0812	0.0798	100.0	9.27	68.04	10000.00	10000.00	0.9744	0.9501
46	C-0812	0.1283	110.0	9.29	68.23	10000.00	10000.00	0.9767	0.9545
47	C-0812	0.1915	120.0	9.31	68.38	10000.00	10000.00	0.9786	0.9581
48	C-0812	0.3402	140.0	9.33	68.63	10000.00	10000.00	0.9816	0.9639
49	C-0811	0.4770	160.0	9.35	68.81	10000.00	10000.00	0.9839	0.9682
50	C-0811	0.5651	180.0	9.36	68.96	10000.00	10000.00	0.9856	0.9717
51	C-0811	0.5932	200.0	9.38	69.07	10000.00	10000.00	0.9870	0.9744
52	C-0810	0.5697	220.0	9.37	69.07	10000.00	10000.00	0.9882	0.9767
53	C-0811	0.5120	240.0	9.39	69.25	10000.00	10000.00	0.9892	0.9786
54	C-0910	0.3596	280.0	9.40	69.37	10000.00	10000.00	0.9907	0.9816
55	C-0909	0.2235	320.0	9.40	69.37	10000.00	10000.00	0.9919	0.9839
56	C-0810	0.1289	360.0	9.42	69.54	10000.00	10000.00	0.9928	0.9856
57	C-0809	0.0710	400.0	9.42	69.54	10000.00	10000.00	0.9935	0.9871
58	C-0810	0.0381	440.0	9.43	69.64	10000.00	10000.00	0.9941	0.9882
59	C-0910	0.0201	480.0	9.43	69.64	10000.00	10000.00	0.9946	0.9892
60	C-0809	0.0105	520.0	9.43	69.64	10000.00	10000.00	0.9950	0.9900

P=6.34 atm

JJ	R ₂ C ₂ /m	FZEROP	DZERO, μ	XSTPF, μ	XSTPD, μ	XSTARD, μ	ALFAST, α°	XMUST, γ°
1	0.0022	0.0000	0.5	0.06	0.27	10000.00	0.1600	0.0870
2	0.0025	0.0001	1.0	0.07	0.35	10000.00	0.2759	0.1601
3	0.4320	0.0008	1.5	13.50	76.09	10000.00	0.3637	0.2223
4	0.4665	0.0032	2.0	14.54	82.95	5.04	0.4325	0.2759
5	0.4626	0.0080	2.5	14.95	85.87	3.05	0.4878	0.3227
6	0.4563	0.0156	3.0	15.20	87.79	2.37	0.5334	0.3637
7	0.4500	0.0260	3.5	15.39	89.27	2.27	0.5714	0.4001
8	0.4442	0.0389	4.0	15.55	90.49	2.21	0.6038	0.4325
9	0.4391	0.0539	4.5	15.68	91.53	2.16	0.6316	0.4616
10	0.4345	0.0704	5.0	15.80	92.44	2.12	0.6558	0.4879
11	0.4271	0.1057	6.0	16.00	94.03	2.05	0.6957	0.5334
12	0.4215	0.1413	7.0	16.18	95.43	1.94	0.7273	0.5715
13	0.4176	0.1745	8.0	16.36	96.81	1.80	0.7530	0.6039
14	0.4152	0.2039	9.0	16.55	98.20	1.60	0.7742	0.6317
15	0.4148	0.2287	10.0	16.78	99.79	1.27	0.7921	0.6558
16	0.4097	0.2487	11.0	16.79	100.02	1.42	0.8074	0.6770
17	0.3920	0.2640	12.0	16.24	96.94	2.81	0.8205	0.6957
18	0.3727	0.2751	13.0	15.59	93.21	4.51	0.8320	0.7124
19	0.3472	0.2825	14.0	14.65	87.73	7.07	0.8421	0.7274
20	0.3098	0.2865	15.0	13.17	78.99	11.50	0.8511	0.7408
21	0.2345	0.2878	16.0	10.04	60.30	21.07	0.8591	0.7530
22	0.1931	0.2867	17.0	8.32	50.04	56.90	0.8663	0.7641
23	0.1747	0.2837	18.0	7.57	45.58	10000.00	0.8727	0.7743
24	0.1719	0.2791	19.0	7.49	45.14	10000.00	0.8786	0.7836
25	0.1684	0.2732	20.0	7.37	44.47	10000.00	0.8840	0.7921
26	0.1635	0.2665	21.0	7.19	43.41	10000.00	0.8889	0.8001
27	0.1557	0.2590	22.0	6.87	41.54	10000.00	0.8934	0.8074
28	0.1409	0.2509	23.0	6.25	37.79	10000.00	0.8976	0.8142
29	0.1278	0.2425	24.0	5.69	34.42	10000.00	0.9014	0.8206
30	0.1280	0.2339	25.0	5.71	34.60	10000.00	0.9050	0.8265
31	0.1281	0.2252	26.0	5.73	34.77	10000.00	0.9083	0.8321
32	0.1283	0.2164	27.0	5.76	34.92	10000.00	0.9114	0.8373
33	0.1284	0.2077	28.0	5.78	35.07	10000.00	0.9143	0.8422
34	0.1285	0.1992	29.0	5.80	35.21	10000.00	0.9170	0.8468
35	0.1286	0.1907	30.0	5.81	35.33	10000.00	0.9195	0.8511
36	0.1289	0.1521	35.0	5.89	35.86	10000.00	0.9302	0.8696
37	0.1291	0.1201	40.0	5.94	36.27	10000.00	0.9384	0.8840
38	0.1293	0.0946	45.0	5.99	36.58	10000.00	0.9449	0.8956
39	0.1294	0.0746	50.0	6.02	36.84	10000.00	0.9501	0.9050
40	0.1294	0.0593	55.0	6.05	37.05	10000.00	0.9545	0.9129
41	0.1295	0.0477	60.0	6.07	37.22	10000.00	0.9581	0.9196
42	0.1295	0.0344	70.0	6.11	37.50	10000.00	0.9639	0.9303
43	0.1295	0.0340	80.0	6.13	37.71	10000.00	0.9682	0.9384
44	0.1295	0.0484	90.0	6.15	37.87	10000.00	0.9717	0.9449
45	0.1295	0.0798	100.0	6.17	38.00	10000.00	0.9744	0.9501
46	0.1295	0.1283	110.0	6.18	38.11	10000.00	0.9767	0.9545
47	0.1295	0.1915	120.0	6.19	38.20	10000.00	0.9786	0.9581
48	0.1294	0.3402	140.0	6.21	38.34	10000.00	0.9816	0.9639
49	0.1294	0.4770	160.0	6.22	38.45	10000.00	0.9849	0.9682
50	0.1294	0.5651	180.0	6.23	38.53	10000.00	0.9856	0.9717
51	0.1294	0.5932	200.0	6.24	38.60	10000.00	0.9870	0.9744
52	0.1292	0.5697	220.0	6.24	38.60	10000.00	0.9882	0.9767
53	0.1293	0.5120	240.0	6.25	38.70	10000.00	0.9892	0.9786
54	0.1293	0.3596	280.0	6.26	38.77	10000.00	0.9907	0.9816
55	0.1291	0.2235	320.0	6.26	38.77	10000.00	0.9916	0.9839
56	0.1293	0.1289	360.0	6.27	38.87	10000.00	0.9928	0.9856
57	0.1292	0.0710	400.0	6.27	38.87	10000.00	0.9935	0.9871
58	0.1293	0.0381	440.0	6.28	38.93	10000.00	0.9941	0.9882
59	0.1292	0.0201	480.0	6.28	38.93	10000.00	0.9946	0.9892
60	0.1291	0.0105	520.0	6.28	38.93	10000.00	0.9950	0.9900

p=11.24 σ_{rms}

JJ	R _j C ₀ /μm	FZEROP	DZERO, μ	XSTPF, μ	XSTAP, μ	ΔSTDP, μ	XSTARD, μ	ALFAST, α [*]	XNUST, γ [*]
1	0.0022	0.0000	0.5	0.02	0.10	10000.00	10000.00	0.1600	0.0870
2	0.0025	0.0001	1.0	0.03	0.12	10000.00	10000.00	0.2759	0.1601
3	0.6219	0.0008	1.5	7.87	38.39	5.04	6.31	0.3637	0.2223
4	0.6625	0.0032	2.0	8.75	43.19	3.05	3.57	0.4325	0.2759
5	0.6621	0.0080	2.5	9.06	44.97	2.57	2.99	0.4878	0.3227
6	0.6554	0.0156	3.0	9.25	46.04	2.37	2.77	0.5334	0.3637
7	0.6474	0.0260	3.5	9.38	46.81	2.27	2.69	0.5714	0.4001
8	0.6398	0.0389	4.0	9.49	47.42	2.21	2.66	0.6038	0.4325
9	0.6328	0.0539	4.5	9.57	47.93	2.16	2.65	0.6316	0.4616
10	0.6267	0.0704	5.0	9.65	48.38	2.12	2.66	0.6558	0.4879
11	0.6167	0.1057	6.0	9.79	49.17	2.05	2.68	0.6957	0.5334
12	0.6096	0.1413	7.0	9.92	49.90	1.94	2.70	0.7273	0.5715
13	0.6052	0.1745	8.0	10.05	50.63	1.80	2.69	0.7530	0.6039
14	0.6037	0.2039	9.0	10.19	51.45	1.60	2.65	0.7742	0.6317
15	0.6061	0.2287	10.0	10.39	52.51	1.27	2.58	0.7921	0.6558
16	0.5978	0.2487	11.0	10.38	52.51	1.42	2.47	0.8074	0.6770
17	0.5597	0.2640	12.0	9.82	49.76	2.81	2.31	0.8205	0.6957
18	0.5192	0.2751	13.0	9.20	46.65	4.51	2.09	0.8320	0.7124
19	0.4672	0.2825	14.0	8.35	42.38	7.07	1.77	0.8421	0.7274
20	0.3697	0.2865	15.0	6.66	33.81	11.50	1.02	0.8511	0.7408
21	0.3230	0.2878	16.0	5.86	29.77	21.07	2.65	0.8591	0.7530
22	0.2932	0.2867	17.0	5.35	27.22	56.90	4.09	0.8643	0.7641
23	0.2756	0.2837	18.0	5.06	25.75	10000.00	5.88	0.8727	0.7743
24	0.2692	0.2791	19.0	4.57	25.31	10000.00	8.35	0.8786	0.7836
25	0.2612	0.2732	20.0	4.84	24.70	10000.00	12.06	0.8840	0.7921
26	0.2503	0.2665	21.0	4.66	23.79	10000.00	18.29	0.8889	0.8001
27	0.2343	0.2590	22.0	4.38	22.38	10000.00	30.98	0.8934	0.8074
28	0.2101	0.2509	23.0	3.95	20.15	10000.00	70.68	0.8976	0.8142
29	0.1998	0.2425	24.0	3.76	19.24	10000.00	10000.00	0.9014	0.8206
30	0.2001	0.2339	25.0	3.78	19.35	10000.00	10000.00	0.9050	0.8265
31	0.2004	0.2252	26.0	3.80	19.45	10000.00	10000.00	0.9083	0.8321
32	0.2007	0.2164	27.0	3.82	19.54	10000.00	10000.00	0.9114	0.8373
33	0.2009	0.2077	28.0	3.83	19.63	10000.00	10000.00	0.9143	0.8422
34	0.2011	0.1992	29.0	3.84	19.71	10000.00	10000.00	0.9170	0.8468
35	0.2013	0.1907	30.0	3.86	19.78	10000.00	10000.00	0.9195	0.8511
36	0.2021	0.1521	35.0	3.91	20.10	10000.00	10000.00	0.9302	0.8696
37	0.2027	0.1201	40.0	3.95	20.34	10000.00	10000.00	0.9384	0.8840
38	0.2030	0.0946	45.0	3.98	20.53	10000.00	10000.00	0.9469	0.8956
39	0.2033	0.0746	50.0	4.01	20.68	10000.00	10000.00	0.9501	0.9050
40	0.2035	0.0593	55.0	4.03	20.80	10000.00	10000.00	0.9545	0.9129
41	0.2037	0.0477	60.0	4.05	20.91	10000.00	10000.00	0.9581	0.9196
42	0.2039	0.0344	70.0	4.07	21.07	10000.00	10000.00	0.9639	0.9303
43	0.2040	0.0340	80.0	4.09	21.19	10000.00	10000.00	0.9682	0.9384
44	0.2041	0.0484	90.0	4.11	21.29	10000.00	10000.00	0.9717	0.9449
45	0.2041	0.0798	100.0	4.12	21.37	10000.00	10000.00	0.9744	0.9501
46	0.2041	0.1283	110.0	4.13	21.43	10000.00	10000.00	0.9767	0.9545
47	0.2041	0.1915	120.0	4.14	21.48	10000.00	10000.00	0.9786	0.9581
48	0.2041	0.3402	140.0	4.15	21.57	10000.00	10000.00	0.9816	0.9639
49	0.2041	0.4770	160.0	4.16	21.63	10000.00	10000.00	0.9839	0.9682
50	0.2040	0.5651	180.0	4.16	21.68	10000.00	10000.00	0.9856	0.9717
51	0.2040	0.5932	200.0	4.17	21.72	10000.00	10000.00	0.9870	0.9744
52	0.2037	0.5697	220.0	4.17	21.72	10000.00	10000.00	0.9882	0.9767
53	0.2040	0.5120	240.0	4.18	21.76	10000.00	10000.00	0.9892	0.9785
54	0.2040	0.3596	280.0	4.18	21.82	10000.00	10000.00	0.9907	0.9816
55	0.2037	0.2235	320.0	4.18	21.82	10000.00	10000.00	0.9919	0.9839
56	0.2040	0.1289	360.0	4.19	21.88	10000.00	10000.00	0.9928	0.9856
57	0.2038	0.0710	400.0	4.19	21.88	10000.00	10000.00	0.9935	0.9871
58	0.2039	0.0381	440.0	4.20	21.91	10000.00	10000.00	0.9941	0.9882
59	0.2038	0.0201	480.0	4.20	21.91	10000.00	10000.00	0.9946	0.9892
60	0.2037	0.0105	520.0	4.20	21.91	10000.00	10000.00	0.9950	0.9900

JJ	R ₃ Confine	FZEROP	DZERO, μ	XSTPE, μ	XSTAP, μ	XSTPD, μ	XSTARD, μ	ALFAST, α^*	XNUST, ξ^*
1	C.0022	0.0000	0.5	0.01	0.03	10000.00	10000.00	0.1600	0.0870
2	0.0025	0.0001	1.0	0.01	0.04	10000.00	10000.00	0.2759	0.1601
3	0.7242	0.0008	1.5	3.86	16.13	5.04	6.31	0.3637	0.2223
4	C.9148	0.0032	2.0	5.09	21.81	3.05	3.57	0.4325	0.2759
5	0.9258	0.0080	2.5	5.34	22.95	2.57	2.99	0.4878	0.3227
6	0.5211	0.0156	3.0	5.48	23.57	2.37	2.77	0.5334	0.3637
7	C.9176	0.0260	3.5	5.57	23.98	2.27	2.69	0.5714	0.4001
8	0.5014	0.0389	4.0	5.64	24.29	2.21	2.66	0.6038	0.4325
9	C.8946	0.0539	4.5	5.70	24.54	2.16	2.65	0.6316	0.4616
10	C.8868	0.0704	5.0	5.75	24.76	2.12	2.66	0.6558	0.4879
11	0.8745	0.1057	6.0	5.85	25.17	2.05	2.68	0.6957	0.5334
12	C.8668	0.1413	7.0	5.94	25.56	1.94	2.70	0.7273	0.5715
13	0.8636	0.1745	8.0	6.04	25.99	1.80	2.69	0.7530	0.6039
14	0.8657	0.2039	9.0	6.16	26.50	1.60	2.65	0.7742	0.6317
15	C.8762	0.2287	10.0	6.33	27.22	1.27	2.58	0.7921	0.6558
16	0.8604	0.2487	11.0	6.29	27.07	1.42	2.47	0.8074	0.6770
17	0.7807	0.2640	12.0	5.77	24.83	2.81	2.31	0.8205	0.6957
18	C.6980	0.2751	13.0	5.21	22.41	4.51	2.09	0.8320	0.7124
19	0.5606	0.2825	14.0	4.22	16.14	7.07	1.77	0.8421	0.7274
20	0.5177	0.2865	15.0	3.93	16.89	11.50	1.02	0.8511	0.7408
21	0.4796	0.2878	16.0	3.67	15.76	21.07	2.65	0.8591	0.7530
22	0.4509	0.2867	17.0	3.47	14.92	56.90	4.09	0.8663	0.7641
23	0.4289	0.2837	18.0	3.32	14.28	10000.00	5.88	0.8727	0.7743
24	0.4147	0.2791	19.0	3.23	13.89	10000.00	8.35	0.8786	0.7836
25	0.3973	0.2732	20.0	3.10	13.37	10000.00	12.06	0.8840	0.7921
26	C.3751	0.2665	21.0	2.94	12.69	10000.00	18.29	0.8889	0.8001
27	0.3462	0.2590	22.0	2.73	11.76	10000.00	30.98	0.8934	0.8074
28	0.3154	0.2509	23.0	2.50	10.76	10000.00	70.68	0.8976	0.8142
29	0.3108	0.2425	24.0	2.47	10.64	10000.00	10000.00	0.9014	0.8206
30	0.3115	0.2339	25.0	2.48	10.71	10000.00	10000.00	0.9050	0.8265
31	0.3121	0.2252	26.0	2.49	10.77	10000.00	10000.00	0.9083	0.8321
32	0.3127	0.2164	27.0	2.51	10.83	10000.00	10000.00	0.9114	0.8373
33	0.3132	0.2077	28.0	2.52	10.88	10000.00	10000.00	0.9143	0.8422
34	0.3137	0.1992	29.0	2.53	10.93	10000.00	10000.00	0.9170	0.8468
35	C.3142	0.1907	30.0	2.54	10.97	10000.00	10000.00	0.9195	0.8511
36	0.3159	0.1821	35.0	2.58	11.16	10000.00	10000.00	0.9302	0.8696
37	0.3171	0.1701	40.0	2.61	11.30	10000.00	10000.00	0.9384	0.8840
38	0.3180	0.1546	45.0	2.63	11.41	10000.00	10000.00	0.9449	0.8956
39	0.3186	0.1466	50.0	2.65	11.50	10000.00	10000.00	0.9501	0.9050
40	0.3191	0.1393	55.0	2.66	11.58	10000.00	10000.00	0.9545	0.9129
41	0.3195	0.1327	60.0	2.67	11.64	10000.00	10000.00	0.9581	0.9196
42	0.3201	0.1264	70.0	2.69	11.74	10000.00	10000.00	0.9639	0.9303
43	C.3205	0.1200	80.0	2.71	11.81	10000.00	10000.00	0.9682	0.9384
44	0.3208	0.1136	90.0	2.72	11.87	10000.00	10000.00	0.9717	0.9449
45	C.3211	0.1079	100.0	2.73	11.91	10000.00	10000.00	0.9744	0.9501
46	0.3211	0.1283	110.0	2.74	11.95	10000.00	10000.00	0.9767	0.9545
47	0.3212	0.1915	120.0	2.74	11.98	10000.00	10000.00	0.9786	0.9581
48	C.3212	0.3402	140.0	2.75	12.03	10000.00	10000.00	0.9816	0.9639
49	0.3213	0.4770	160.0	2.76	12.07	10000.00	10000.00	0.9839	0.9682
50	0.3213	0.5651	180.0	2.76	12.10	10000.00	10000.00	0.9856	0.9717
51	0.3213	0.5932	200.0	2.77	12.12	10000.00	10000.00	0.9870	0.9744
52	0.3208	0.5697	220.0	2.77	12.12	10000.00	10000.00	0.9882	0.9767
53	0.3213	0.5120	240.0	2.77	12.16	10000.00	10000.00	0.9892	0.9786
54	0.3213	0.3596	280.0	2.78	12.18	10000.00	10000.00	0.9907	0.9816
55	0.3208	0.2235	320.0	2.78	12.18	10000.00	10000.00	0.9919	0.9839
56	0.3213	0.1289	360.0	2.78	12.22	10000.00	10000.00	0.9928	0.9856
57	C.3210	0.0710	400.0	2.78	12.22	10000.00	10000.00	0.9935	0.9871
58	0.3213	0.0381	440.0	2.79	12.24	10000.00	10000.00	0.9941	0.9882
59	0.3211	0.0201	480.0	2.79	12.24	10000.00	10000.00	0.9946	0.9892
60	0.3209	0.0105	520.0	2.79	12.24	10000.00	10000.00	0.9950	0.9900

P = 35.40 ΔT_{ref}									
JJ	$R_{\text{Conf}}/\mu\text{m}$	FIEROP	DZERO, μ	XSTPF, μ	XSTAP, μ	STPD, μ	XSTARD, μ	ALFAST, μ^*	XNUST, μ^*
1	0.0022	0.0000	0.5	0.00	0.01	10000.00	10000.00	0.1600	0.0870
2	C.0025	0.0001	1.0	0.01	0.02	10000.00	10000.00	0.2759	0.1601
3	C.8763	0.0008	1.5	0.01	7.14	5.04	6.31	0.3637	0.2223
4	1.0318	0.0032	2.0	2.49	9.14	3.05	3.57	0.4325	0.2759
5	1.1145	0.0080	2.5	2.73	10.11	2.57	2.77	0.4878	0.3227
6	1.2464	0.0156	3.0	3.15	11.76	2.37	2.69	0.5334	0.3637
7	1.2400	0.0260	3.5	3.22	11.99	2.27	2.66	0.5714	0.4001
8	1.2307	0.0389	4.0	3.26	12.16	2.21	2.65	0.6038	0.4325
9	1.2212	0.0539	4.5	3.31	12.29	2.16	2.65	0.6316	0.4616
10	1.2126	0.0704	5.0	3.34	12.40	2.12	2.66	0.6558	0.4879
11	1.1998	0.1057	6.0	3.41	12.61	2.05	2.68	0.6957	0.5334
12	1.1940	0.1413	7.0	3.47	12.84	1.94	2.70	0.7273	0.5715
13	1.1961	0.1745	8.0	3.55	13.10	1.80	2.69	0.7530	0.6039
14	1.2081	0.2039	9.0	3.65	13.45	1.60	2.65	0.7742	0.6317
15	1.2377	0.2287	10.0	3.80	13.97	1.27	2.58	0.7921	0.6558
16	1.2089	0.2487	11.0	3.75	13.80	1.42	2.47	0.8074	0.6770
17	0.9459	0.2640	12.0	2.97	10.87	2.81	2.31	0.8205	0.6957
18	0.8392	0.2751	13.0	2.66	9.73	4.51	2.09	0.8320	0.7124
19	C.7910	0.2825	14.0	2.53	9.24	7.07	1.77	0.8421	0.7274
20	0.7721	0.2865	15.0	2.49	9.09	11.50	1.02	0.8511	0.7408
21	0.7233	0.2878	16.0	2.35	8.57	21.07	2.65	0.8591	0.7530
22	C.6846	0.2867	17.0	2.24	8.16	56.90	4.09	0.8663	0.7641
23	0.6499	0.2837	18.0	2.14	7.79	10000.00	5.88	0.8727	0.7743
24	0.6200	0.2791	19.0	2.05	7.47	10000.00	8.35	0.8786	0.7836
25	C.5856	0.2732	20.0	1.94	7.09	10000.00	12.06	0.8840	0.7921
26	0.5458	0.2665	21.0	1.82	6.64	10000.00	18.29	0.8889	0.8001
27	0.5034	0.2590	22.0	1.68	6.15	10000.00	30.98	0.8934	0.8074
28	0.4766	0.2509	23.0	1.60	5.84	10000.00	70.68	0.8976	0.8142
29	0.4770	0.2425	24.0	1.61	5.87	10000.00	10000.00	0.9014	0.8206
30	0.4785	0.2339	25.0	1.62	5.91	10000.00	10000.00	0.9050	0.8265
31	0.4798	0.2252	26.0	1.63	5.95	10000.00	10000.00	0.9083	0.8321
32	0.4810	0.2164	27.0	1.64	5.98	10000.00	10000.00	0.9114	0.8373
33	C.4821	0.2077	28.0	1.64	6.01	10000.00	10000.00	0.9143	0.8422
34	0.4831	0.1992	29.0	1.65	6.04	10000.00	10000.00	0.9170	0.8468
35	0.4841	0.1907	30.0	1.66	6.07	10000.00	10000.00	0.9195	0.8511
36	0.4878	0.1521	35.0	1.69	6.18	10000.00	10000.00	0.9302	0.8696
37	0.4904	0.1201	40.0	1.71	6.27	10000.00	10000.00	0.9384	0.8840
38	C.4923	0.0946	45.0	1.73	6.34	10000.00	10000.00	0.9449	0.8956
39	0.4938	0.0746	50.0	1.74	6.39	10000.00	10000.00	0.9501	0.9050
40	0.4949	0.0593	55.0	1.75	6.44	10000.00	10000.00	0.9545	0.9129
41	C.4958	0.0477	60.0	1.76	6.47	10000.00	10000.00	0.9581	0.9196
42	0.4972	0.0344	70.0	1.78	6.53	10000.00	10000.00	0.9639	0.9303
43	C.4982	0.0340	80.0	1.79	6.58	10000.00	10000.00	0.9682	0.9384
44	C.4989	0.0484	90.0	1.80	6.61	10000.00	10000.00	0.9717	0.9449
45	0.4995	0.0798	100.0	1.80	6.64	10000.00	10000.00	0.9744	0.9501
46	0.4999	0.1283	110.0	1.81	6.66	10000.00	10000.00	0.9767	0.9545
47	C.5003	0.1915	120.0	1.81	6.68	10000.00	10000.00	0.9786	0.9581
48	0.5005	0.3402	140.0	1.82	6.71	10000.00	10000.00	0.9816	0.9639
49	C.5007	0.4770	160.0	1.82	6.73	10000.00	10000.00	0.9839	0.9682
50	0.5008	0.5651	180.0	1.83	6.75	10000.00	10000.00	0.9856	0.9717
51	0.5009	0.5932	200.0	1.83	6.76	10000.00	10000.00	0.9870	0.9744
52	C.5001	0.5697	220.0	1.83	6.76	10000.00	10000.00	0.9882	0.9767
53	0.5010	0.5120	240.0	1.84	6.78	10000.00	10000.00	0.9892	0.9786
54	0.5011	0.3596	280.0	1.84	6.80	10000.00	10000.00	0.9907	0.9816
55	C.5004	0.2235	320.0	1.84	6.80	10000.00	10000.00	0.9919	0.9839
56	0.5013	0.1289	360.0	1.84	6.82	10000.00	10000.00	0.9928	0.9856
57	C.5008	0.0710	400.0	1.84	6.82	10000.00	10000.00	0.9935	0.9871
58	C.5013	0.0381	440.0	1.85	6.83	10000.00	10000.00	0.9941	0.9882
59	0.5010	0.0201	480.0	1.85	6.83	10000.00	10000.00	0.9946	0.9892
60	C.5037	0.0105	520.0	1.85	6.83	10000.00	10000.00	0.9950	0.9900

p = 63.40 α

JJ	$P, C_{\text{col/line}}$	FZEROP	DZERO, μ	XSTPE, μ	XSTAP, μ	XSTPD, μ	XSTARD, μ	ALFAST, α^*	XNUST, γ^*
1	C.0022	0.0000	0.5	0.00	10000.00	10000.00	10000.00	0.1600	0.0870
2	0.0025	0.0001	1.0	0.00	10000.00	10000.00	10000.00	0.2759	0.1601
3	1.0707	0.0008	1.5	1.01	5.04	3.31	6.31	0.3637	0.2223
4	1.3090	0.0032	2.0	1.29	3.05	3.57	3.57	0.4325	0.2759
5	1.3722	0.0080	2.5	1.40	4.68	2.57	2.99	0.4878	0.3227
6	1.3923	0.0156	3.0	1.47	4.68	2.37	2.77	0.5334	0.3637
7	1.3967	0.0260	3.5	1.51	4.81	2.27	2.69	0.5714	0.4001
8	1.3946	0.0389	4.0	1.54	4.91	2.21	2.66	0.6036	0.4325
9	1.3903	0.0539	4.5	1.57	4.98	2.16	2.65	0.6316	0.4616
10	1.3859	0.0704	5.0	1.59	5.05	2.12	2.66	0.6558	0.4879
11	1.3804	0.1057	6.0	1.64	5.16	2.05	2.68	0.6957	0.5334
12	1.3835	0.1413	7.0	1.68	5.29	1.94	2.70	0.7273	0.5715
13	1.4002	0.1745	8.0	1.74	5.45	1.80	2.69	0.7530	0.6039
14	1.4422	0.2039	9.0	1.82	5.71	1.60	2.65	0.7742	0.6317
15	1.7087	0.2287	10.0	2.19	6.88	1.27	2.58	0.7921	0.6558
16	1.4827	0.2487	11.0	1.92	6.01	1.42	2.47	0.8074	0.6770
17	1.2550	0.2640	12.0	1.64	5.12	2.41	2.31	0.8205	0.6957
18	1.1944	0.2751	13.0	1.58	4.91	4.51	2.09	0.8320	0.7124
19	1.1709	0.2825	14.0	1.56	4.85	7.07	1.77	0.8421	0.7274
20	1.1819	0.2865	15.0	1.59	4.93	11.50	1.02	0.8511	0.7408
21	1.0916	0.2878	16.0	1.48	4.58	21.07	2.65	0.8591	0.7530
22	1.0248	0.2867	17.0	1.40	4.32	56.90	4.09	0.8663	0.7641
23	C.9624	0.2837	18.0	1.32	4.08	10000.00	5.88	0.8727	0.7743
24	0.9044	0.2791	19.0	1.25	3.85	10000.00	8.35	0.8786	0.7836
25	0.8439	0.2732	20.0	1.17	3.61	10000.00	12.06	0.8840	0.7921
26	0.7841	0.2665	21.0	1.09	3.36	10000.00	18.29	0.8889	0.8001
27	0.7374	0.2590	22.0	1.03	3.18	10000.00	30.98	0.8934	0.8074
28	0.7258	0.2509	23.0	1.02	3.14	10000.00	70.68	0.8976	0.8142
29	0.7291	0.2425	24.0	1.03	3.16	10000.00	10000.00	0.9014	0.8206
30	0.7322	0.2339	25.0	1.03	3.19	10000.00	10000.00	0.9050	0.8265
31	C.7349	0.2252	26.0	1.04	3.21	10000.00	10000.00	0.9083	0.8321
32	0.7375	0.2164	27.0	1.05	3.23	10000.00	10000.00	0.9114	0.8373
33	0.7398	0.2077	28.0	1.05	3.25	10000.00	10000.00	0.9143	0.8422
34	0.7419	0.1992	29.0	1.06	3.27	10000.00	10000.00	0.9170	0.8468
35	0.7439	0.1907	30.0	1.06	3.28	10000.00	10000.00	0.9195	0.8511
36	C.7517	0.1521	35.0	1.09	3.35	10000.00	10000.00	0.9302	0.8696
37	0.7572	0.1201	40.0	1.10	3.40	10000.00	10000.00	0.9384	0.8840
38	0.7614	0.0946	45.0	1.11	3.44	10000.00	10000.00	0.9449	0.8956
39	0.7645	0.0746	50.0	1.13	3.48	10000.00	10000.00	0.9501	0.9050
40	0.7671	0.0593	55.0	1.13	3.50	10000.00	10000.00	0.9545	0.9129
41	0.7691	0.0477	60.0	1.14	3.52	10000.00	10000.00	0.9581	0.9196
42	C.7723	0.0344	70.0	1.15	3.56	10000.00	10000.00	0.9639	0.9303
43	0.7745	0.0340	80.0	1.16	3.59	10000.00	10000.00	0.9682	0.9384
44	0.7762	0.0484	90.0	1.17	3.61	10000.00	10000.00	0.9717	0.9449
45	0.7775	0.0798	100.0	1.17	3.62	10000.00	10000.00	0.9744	0.9501
46	0.7785	0.1293	110.0	1.18	3.64	10000.00	10000.00	0.9767	0.9545
47	C.7794	0.1915	120.0	1.18	3.65	10000.00	10000.00	0.9786	0.9581
48	0.7806	0.3402	140.0	1.18	3.67	10000.00	10000.00	0.9816	0.9639
49	0.7813	0.4770	160.0	1.19	3.68	10000.00	10000.00	0.9839	0.9682
50	C.7817	0.5651	180.0	1.19	3.69	10000.00	10000.00	0.9856	0.9717
51	0.7820	0.5932	200.0	1.19	3.70	10000.00	10000.00	0.9870	0.9744
52	C.7808	0.5697	220.0	1.19	3.70	10000.00	10000.00	0.9882	0.9767
53	C.7824	0.5120	240.0	1.20	3.71	10000.00	10000.00	0.9892	0.9786
54	0.7827	0.3596	280.0	1.20	3.72	10000.00	10000.00	0.9907	0.9816
55	C.7815	0.2235	320.0	1.20	3.72	10000.00	10000.00	0.9919	0.9839
56	C.7831	0.1289	360.0	1.20	3.73	10000.00	10000.00	0.9928	0.9856
57	0.7824	0.0710	400.0	1.20	3.73	10000.00	10000.00	0.9935	0.9871
58	C.7833	0.0381	440.0	1.20	3.74	10000.00	10000.00	0.9941	0.9882
59	C.7828	0.0201	480.0	1.20	3.74	10000.00	10000.00	0.9946	0.9892
60	0.7824	0.0105	520.0	1.20	3.74	10000.00	10000.00	0.9950	0.9900

$P = 112.40 \text{ atm.}$

JJ	R, cm/sec	FZEROP	OZEROP, μ	XSTPF, μ	XSTAP, μ	XSTDP, μ	XSTARD, μ	ALFAST, μ	XNUST, μ
1	C.0022	0.0000	0.5	0.00	0.00	10000.00	10000.00	0.1600	0.0870
2	C.0025	0.0001	1.0	0.00	0.00	10000.00	10000.00	0.2759	0.1601
3	1.2389	0.0008	1.5	0.50	1.32	5.04	6.3	0.3637	0.2223
4	1.6207	0.0032	2.0	0.68	1.87	3.05	3.7	0.4325	0.2759
5	1.7298	0.0080	2.5	0.75	2.08	2.57	2.99	0.4878	0.3227
6	1.7707	0.0156	3.0	0.79	2.19	2.37	2.77	0.5334	0.3637
7	1.7864	0.0260	3.5	0.82	2.26	2.27	2.69	0.5714	0.4001
8	1.7914	0.0389	4.0	0.84	2.31	2.21	2.66	0.6038	0.4325
9	1.7917	0.0539	4.5	0.86	2.35	2.16	2.65	0.6316	0.4616
10	1.7903	0.0704	5.0	0.87	2.39	2.12	2.66	0.6558	0.4879
11	1.7881	0.1057	6.0	0.90	2.44	2.05	2.68	0.6957	0.5334
12	1.7911	0.1413	7.0	0.92	2.50	1.94	2.70	0.7273	0.5715
13	1.8036	0.1745	8.0	0.95	2.56	1.80	2.69	0.7530	0.6039
14	1.8331	0.2039	9.0	0.98	2.64	1.60	2.65	0.7742	0.6317
15	1.9104	0.2287	10.0	1.04	2.78	1.27	2.58	0.7921	0.6558
16	1.8713	0.2487	11.0	1.03	2.75	1.42	2.47	0.8074	0.6770
17	1.7378	0.2640	12.0	0.96	2.57	2.81	2.31	0.8205	0.6957
18	1.7099	0.2751	13.0	0.96	2.55	4.51	2.09	0.8320	0.7124
19	1.7154	0.2825	14.0	0.97	2.57	7.07	1.77	0.8421	0.7274
20	1.7840	0.2865	15.0	1.02	2.70	11.50	1.02	0.8511	0.7408
21	1.5957	0.2878	16.0	0.92	2.42	21.07	2.65	0.8591	0.7530
22	1.4728	0.2867	17.0	0.85	2.24	56.90	4.09	0.8663	0.7641
23	1.3637	0.2837	18.0	0.79	2.08	10000.00	5.98	0.8727	0.7743
24	1.2664	0.2791	19.0	0.74	1.94	10000.00	8.35	0.8786	0.7836
25	1.1776	0.2732	20.0	0.69	1.81	10000.00	12.06	0.8840	0.7921
26	1.1084	0.2665	21.0	0.65	1.71	10000.00	18.29	0.8889	0.8001
27	1.0782	0.2590	22.0	0.64	1.67	10000.00	30.98	0.8934	0.8074
28	1.0814	0.2509	23.0	0.64	1.68	10000.00	70.68	0.8976	0.8142
29	1.0880	0.2425	24.0	0.65	1.70	10000.00	10000.00	0.9014	0.8206
30	1.0940	0.2339	25.0	0.65	1.71	10000.00	10000.00	0.9050	0.8265
31	1.0995	0.2252	26.0	0.66	1.72	10000.00	10000.00	0.9083	0.8321
32	1.1045	0.2164	27.0	0.66	1.74	10000.00	10000.00	0.9114	0.8373
33	1.1092	0.2077	28.0	0.67	1.75	10000.00	10000.00	0.9143	0.8422
34	1.1135	0.1992	29.0	0.67	1.76	10000.00	10000.00	0.9170	0.8468
35	1.1174	0.1907	30.0	0.68	1.77	10000.00	10000.00	0.9195	0.8511
36	1.1335	0.1521	35.0	0.69	1.81	10000.00	10000.00	0.9302	0.8696
37	1.1450	0.1201	40.0	0.71	1.84	10000.00	10000.00	0.9384	0.8840
38	1.1535	0.0946	45.0	0.72	1.87	10000.00	10000.00	0.9449	0.8956
39	1.1601	0.0746	50.0	0.72	1.89	10000.00	10000.00	0.9501	0.9050
40	1.1655	0.0593	55.0	0.73	1.90	10000.00	10000.00	0.9545	0.9129
41	1.1698	0.0477	60.0	0.73	1.92	10000.00	10000.00	0.9581	0.9196
42	1.1765	0.0344	70.0	0.74	1.94	10000.00	10000.00	0.9639	0.9303
43	1.1813	0.0340	80.0	0.75	1.96	10000.00	10000.00	0.9682	0.9384
44	1.1850	0.0484	90.0	0.75	1.97	10000.00	10000.00	0.9717	0.9449
45	1.1878	0.0798	100.0	0.76	1.98	10000.00	10000.00	0.9744	0.9501
46	1.1901	0.1283	110.0	0.76	1.99	10000.00	10000.00	0.9767	0.9545
47	1.1920	0.1915	120.0	0.76	1.99	10000.00	10000.00	0.9786	0.9581
48	1.1948	0.3402	140.0	0.77	2.00	10000.00	10000.00	0.9816	0.9639
49	1.1969	0.4770	160.0	0.77	2.01	10000.00	10000.00	0.9839	0.9682
50	1.1984	0.5651	180.0	0.77	2.01	10000.00	10000.00	0.9856	0.9717
51	1.1992	0.5932	200.0	0.77	2.02	10000.00	10000.00	0.9870	0.9744
52	1.1973	0.5697	220.0	0.77	2.02	10000.00	10000.00	0.9882	0.9767
53	1.2003	0.5120	240.0	0.78	2.03	10000.00	10000.00	0.9892	0.9786
54	1.2010	0.3596	280.0	0.78	2.04	10000.00	10000.00	0.9907	0.9816
55	1.1992	0.2235	320.0	0.78	2.04	10000.00	10000.00	0.9919	0.9839
56	1.2020	0.1289	360.0	0.78	2.04	10000.00	10000.00	0.9928	0.9856
57	1.2009	0.0710	400.0	0.78	2.04	10000.00	10000.00	0.9935	0.9871
58	1.2027	0.0381	440.0	0.78	2.05	10000.00	10000.00	0.9941	0.9882
59	1.2019	0.0201	480.0	0.78	2.05	10000.00	10000.00	0.9946	0.9892
60	1.2012	0.0105	520.0	0.78	2.05	10000.00	10000.00	0.9950	0.9900

$p = 200 \text{ atm.}$

JJ	$R_s \text{ cm/sec}$	FZEROP	DZERO, μ	XSTPF, μ	XSTAP, μ	XSTPD, μ	XSTARD, μ	ALFAST, α^*	XMUST, β^*
1	0.0022	0.0000	0.5	0.00	0.00	10000.00	10000.00	0.1600	0.0870
2	0.0025	0.0001	1.0	0.00	0.00	10000.00	10000.00	0.2759	0.1601
3	1.3484	0.0008	1.5	0.23	0.52	5.04	6.31	0.3637	0.2223
4	1.9047	0.0032	2.0	0.34	0.80	3.05	3.57	0.4325	0.2759
5	2.0972	0.0080	2.5	0.38	0.92	2.57	2.99	0.4878	0.3227
6	2.1844	0.0156	3.0	0.41	0.99	2.37	2.77	0.5334	0.3637
7	2.2296	0.0260	3.5	0.43	1.03	2.27	2.69	0.5714	0.4001
8	2.2553	0.0389	4.0	0.45	1.06	2.21	2.66	0.6038	0.4325
9	2.2711	0.0539	4.5	0.46	1.09	2.16	2.65	0.6316	0.4616
10	2.2821	0.0704	5.0	0.47	1.11	2.12	2.66	0.6558	0.4879
11	2.2989	0.1057	6.0	0.49	1.14	2.05	2.68	0.6957	0.5334
12	2.3168	0.1413	7.0	0.50	1.17	1.94	2.70	0.7273	0.5715
13	2.3413	0.1745	8.0	0.52	1.20	1.80	2.69	0.7530	0.6039
14	2.3787	0.2039	9.0	0.54	1.24	1.60	2.65	0.7742	0.6317
15	2.4498	0.2287	10.0	0.56	1.29	1.27	2.58	0.7921	0.6558
16	2.4478	0.2487	11.0	0.57	1.30	1.42	2.47	0.8074	0.6770
17	2.3815	0.2640	12.0	0.56	1.27	2.81	2.31	0.8205	0.6957
18	2.3955	0.2751	13.0	0.57	1.29	4.51	2.09	0.8320	0.7124
19	2.4508	0.2825	14.0	0.58	1.33	7.07	1.77	0.8421	0.7274
20	2.6385	0.2865	15.0	0.63	1.44	11.50	1.02	0.8511	0.7408
21	2.2505	0.2878	16.0	0.54	1.23	21.07	2.65	0.8591	0.7530
22	2.0339	0.2867	17.0	0.49	1.11	56.90	4.09	0.8663	0.7641
23	1.8604	0.2837	18.0	0.46	1.02	10000.00	5.88	0.8727	0.7743
24	1.7207	0.2791	19.0	0.42	0.95	10000.00	8.35	0.8786	0.7836
25	1.6172	0.2732	20.0	0.40	0.89	10000.00	12.06	0.8840	0.7921
26	1.5658	0.2665	21.0	0.39	0.86	10000.00	18.29	0.8899	0.8001
27	1.5607	0.2590	22.0	0.39	0.86	10000.00	30.98	0.8934	0.8074
28	1.5787	0.2509	23.0	0.39	0.88	10000.00	70.68	0.8976	0.8142
29	1.5915	0.2425	24.0	0.40	0.89	10000.00	10000.00	0.9014	0.8206
30	1.6032	0.2339	25.0	0.40	0.90	10000.00	10000.00	0.9050	0.8265
31	1.6139	0.2252	26.0	0.41	0.90	10000.00	10000.00	0.9083	0.8321
32	1.6237	0.2164	27.0	0.41	0.91	10000.00	10000.00	0.9114	0.8373
33	1.6328	0.2077	28.0	0.41	0.92	10000.00	10000.00	0.9143	0.8422
34	1.6412	0.1992	29.0	0.42	0.93	10000.00	10000.00	0.9170	0.8468
35	1.6490	0.1907	30.0	0.42	0.93	10000.00	10000.00	0.9195	0.8511
36	1.6809	0.1521	35.0	0.43	0.96	10000.00	10000.00	0.9302	0.8696
37	1.7042	0.1201	40.0	0.44	0.98	10000.00	10000.00	0.9384	0.8840
38	1.7220	0.0946	45.0	0.44	0.99	10000.00	10000.00	0.9449	0.8956
39	1.7356	0.0746	50.0	0.46	1.01	10000.00	10000.00	0.9501	0.9050
40	1.7464	0.0593	55.0	0.46	1.02	10000.00	10000.00	0.9545	0.9129
41	1.7554	0.0477	60.0	0.46	1.02	10000.00	10000.00	0.9581	0.9196
42	1.7691	0.0344	70.0	0.47	1.04	10000.00	10000.00	0.9639	0.9303
43	1.7792	0.0340	80.0	0.48	1.05	10000.00	10000.00	0.9682	0.9384
44	1.7869	0.0484	90.0	0.48	1.05	10000.00	10000.00	0.9717	0.9449
45	1.7930	0.0798	100.0	0.48	1.06	10000.00	10000.00	0.9744	0.9501
46	1.7979	0.1283	110.0	0.48	1.07	10000.00	10000.00	0.9767	0.9545
47	1.8019	0.1915	120.0	0.49	1.07	10000.00	10000.00	0.9786	0.9581
48	1.8080	0.3402	140.0	0.49	1.08	10000.00	10000.00	0.9816	0.9639
49	1.8125	0.4770	160.0	0.49	1.08	10000.00	10000.00	0.9839	0.9682
50	1.8159	0.5651	180.0	0.49	1.08	10000.00	10000.00	0.9856	0.9717
51	1.8185	0.5932	200.0	0.50	1.09	10000.00	10000.00	0.9870	0.9744
52	1.8164	0.5697	220.0	0.50	1.09	10000.00	10000.00	0.9882	0.9767
53	1.8219	0.5120	240.0	0.50	1.09	10000.00	10000.00	0.9892	0.9786
54	1.8238	0.3596	280.0	0.50	1.10	10000.00	10000.00	0.9907	0.9816
55	1.8210	0.2235	320.0	0.50	1.10	10000.00	10000.00	0.9919	0.9839
56	1.8261	0.1289	360.0	0.50	1.10	10000.00	10000.00	0.9928	0.9856
57	1.8244	0.0710	400.0	0.50	1.10	10000.00	10000.00	0.9935	0.9871
58	1.8276	0.0381	440.0	0.50	1.10	10000.00	10000.00	0.9941	0.9882
59	1.8264	0.0201	480.0	0.50	1.10	10000.00	10000.00	0.9946	0.9892
60	1.8254	0.0105	520.0	0.50	1.10	10000.00	10000.00	0.9950	0.9900

PARABOLIC FLAME ASSUMED

PROPELLANT DATA IS

WT. PERCENT OXID. = 90.0
 PROCP. DENSITY = 0.0
 QFUEL = 25.0
 DIFF PARAM = 1000.0000
 ST PAT = 16.50
 PPI ST PAT = 8.30
 BINDER DENSITY = 0.98
 MOL WT = 20.87
 OXID. DENSITY = 1.95
 PRI MOL WT = 28.00

OXIDIZER IGNITION AND BURNING DATA IS

CIGN = 190.0
 POWIGN = 0.721
 POWD = 0.8
 LATENT HEAT = -110.0

ACTIVATION ENERGIES AND RATE FACTORS ARE

EF = 15000.
 ORDER, PF = 1.500
 ORDER, HP = 1.800
 E OX = 26000.
 RT CON, PF = 0.2500
 RT CON, HP = 0.2310
 AF = 0.2700
 ORDER, LP = 1.800
 RT CON, LP = 0.2310
 A OX = 0.3000

FLAME PROPERTIES ARE

OXID. FLM TEMP = 1400.0
 AV FLM HT FACT = 0.3000
 GAS CONDUCT = 0.00020
 CP(AVE) = 0.3000

PROPELLANT INITIAL TEMP IS 21.1 DEG CENTIGRADE

n (exponent in Eq. 19) = 2

EXPONENT FOR DIFFUSION PRESSURE DEPENDENCE IS 1.000

PPFS ATMS	PRES PSIA	JR CM/SEC	BR IN/SEC
2.00	29.4	0.1006	0.0396
3.54	52.0	0.1515	0.0597
6.34	93.2	0.2287	0.0900
11.24	165.2	0.3405	0.1341
20.00	294.0	0.5047	0.1987
35.40	520.4	0.7357	0.2896
63.40	932.0	1.0400	0.4095
112.40	1652.3	1.4896	0.5860
200.00	2940.0	2.1296	0.8384

Appendix B

HYDRAULIC ANALOGY

The analogy between one-dimensional, nonsteady flows of inviscid gases and inviscid liquids with free surfaces and between two-dimensional, steady flows of inviscid gases and inviscid liquids with free surfaces is well documented in the literature⁽²²⁾. As one might expect in this situation, the analogy also extends to two-dimensional, nonsteady flows. However, although this analogy has been exploited in several studies,⁽²²⁾ no explicit derivation of the analogy for the nonsteady, two-dimensional situation has apparently been presented.* The object of this appendix is to present a derivation for this situation.

For nonsteady, two-dimensional, irrotational flow of a perfect gas the governing equations are⁽²⁴⁾

$$\partial \rho / \partial t + \partial \rho u / \partial x + \partial \rho v / \partial y = 0 \quad (\text{B-1})$$

$$\partial u / \partial t + u \partial u / \partial x + v \partial u / \partial y + \rho^{-1} \partial p / \partial x = 0 \quad (\text{B-2})$$

$$\partial v / \partial t + u \partial v / \partial x + v \partial v / \partial y + \rho^{-1} \partial p / \partial y = 0 \quad (\text{B-3})$$

$$p / p_o = (\rho / \rho_o)^\gamma \quad (\text{B-4})$$

Employing a_o , ρ_o , p_o , l_g , t_g as reference dimensions and Eq. B-4 to eliminate p from Eqs. B-2 and B-3 yields the non-dimensional equations

$$\partial \rho^+ u^+ / \partial x^+ + \partial \rho^+ v^+ / \partial y^+ + [l_g / (a_o t_g)] \partial \rho^+ / \partial t^+ \quad (\text{B-5})$$

$$[l_g / (a_o t_g)] \partial u^+ / \partial t^+ + u^+ \partial u^+ / \partial x^+ + v^+ \partial u^+ / \partial y^+ + [\partial (\rho^+) \frac{\gamma-1}{\gamma} / \partial x^+] / (\gamma-1) = 0 \quad (\text{B-6})$$

$$[l_g / (a_o t_g)] \partial v^+ / \partial t^+ + u^+ \partial v^+ / \partial x^+ + v^+ \partial v^+ / \partial y^+ \quad (\text{B-7})$$

$$+ [\partial (\rho^+) \frac{\gamma-1}{\gamma} / \partial y^+] / (\gamma-1) = 0$$

A three dimensional, nonsteady flow of inviscid liquid over a planar surface perpendicular to the gravity vector g is governed by the equations⁽²⁴⁾

* Loh⁽²³⁾ indicates in a footnote that the analogy extends to this case.

$$\partial u / \partial x + \partial v / \partial y + \partial w / \partial z = 0 \quad (B-8)$$

$$D_u / D_t + \rho^{-1} \partial p / \partial x = 0 \quad (B-9)$$

$$D_v / D_t + \rho^{-1} \partial p / \partial y = 0 \quad (B-10)$$

$$D_w / D_t + \rho^{-1} \partial p / \partial z + g = 0 \quad (B-11)$$

Assuming that vertical water accelerations are small compared to g Eq. B-11 becomes

$$\partial p / \partial z = -\rho g \quad (B-12)$$

Integration yields

$$p(x, y, z, t) = \rho g \int_h^z dz + p(x, y, h, t) \quad (B-13)$$

where $h(x, y, t)$ is the depth of the water. However, since only pressure differences are encountered in Eq. (B-9) to (B-11) and since $p(x, y, h, t) =$ constant, that constant can be set to zero without loss of generality. Consequently,

$$p(x, y, z, t) = \rho g (h - z) \quad (B-14)$$

and

$$\rho^{-1} \partial p / \partial x = g \partial h / \partial x \quad (B-15)$$

$$\rho^{-1} \partial p / \partial y = g \partial h / \partial y \quad (B-16)$$

Analysis is directed at inviscid motion. Assume $u = u(x, y, t)$ and $v = v(x, y, t)$. Therefore, terms containing w are eliminated from Eqs. (B-9) and (B-10). However, since $w = w(z)$, $\partial w / \partial z \neq 0$. Formally integrating Eq. (B-8) from $z=0$ to $z=h$ yields (after application of Liebnitz's rule⁽²¹⁾) and the above assumption

$$\partial h u / \partial x + \partial h v / \partial y + w(x, y, h, t) = u(x, y, h, t) \partial h / \partial x + v(x, y, h, t) \partial h / \partial y \quad (B-17)$$

$$\text{Since } w(x, y, h, t) = \partial h / \partial t + u(x, y, h, t) \partial h / \partial x + v(x, y, h, t) \partial h / \partial y, \text{ Eq. (B-17)}$$

becomes

$$\partial h / \partial t + \partial h u / \partial x + \partial h v / \partial y = 0 \quad (B-18)$$

Nondimensionalizing Eqs. B-9, B-10, and B-18 with reference dimensions h_0 , $g h_0$, l_w , and t_w yields the non-dimensional hydraulic equations

$$\partial h^+ u^+ / \partial x^+ + \partial h^+ v^+ / \partial y^+ + [l_w / (\sqrt{gh_o} t_w)] \partial h^+ / \partial t^+ = 0 \quad (B-19)$$

$$[l_w / (\sqrt{gh_o} l_w)] \partial u^+ / \partial t^+ + u^+ \partial u^+ / \partial x^+ + v^+ \partial u^+ / \partial y^+ + \partial h^+ / \partial x^+ = 0 \quad (B-20)$$

$$[l_w / (\sqrt{gh_o} l_w)] \partial v^+ / \partial t^+ + u^+ \partial v^+ / \partial x^+ + v^+ \partial v^+ / \partial y^+ + \partial h^+ / \partial y^+ = 0 \quad (B-21)$$

Comparison of Eqs. (B-5) to (B-7) with Eqs. (B-19) to (B-21) shows that when $\gamma=2$ and $l_w / (\sqrt{gh_o} t_w) = l_g / (a_o t_g)$ the non-dimensional equations are equivalent if $h^+ = \rho^+$. Consequently, under these conditions an analogy exists between the gas and free surface liquid flows. In this analogy

$h^+ = \sqrt{p^+}$ [or $p^+ = (h^+)^2$], $a = \sqrt{gh}$, $h^+ = \rho^+$, $u_w^+ = u_g^+$, and $v_y^+ = v_g^+$. For conditions where $0(l_w) \sim 0(l_g)$, $0(t_w) < 0(t_g)$. In other words, time is effectively slowed in the analogy. This means that transient phenomena can often be studied visually in the hydraulic analogy. It is this fact that makes the analogy valuable for nonsteady situations.

It has been shown that an analogy exists between irrotational flow of gas with $\gamma=2$ and irrotational flow of liquid over a horizontal surface. Flows in nature are not irrotational. Therefore, of what practical value is this analogy? First, numerous experiments⁽²²⁾ have demonstrated excellent agreement with theory for simple flows. Second, there seems to be no question that the analogy provides a relatively simple way to obtain information on complex flow situations.⁽²²⁾

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19 REPORT DOCUMENTATION PAGE		READ INSTRUCTIONS BEFORE COMPLETING FORM	
1. REPORT NUMBER AFOSR TR-75-1553	2. GOVT ACCESSION NO.	3. RECIPIENT'S CATALOG NUMBER 9	
4. TITLE (and Subtitle) STEADY-STATE COMBUSTION OF NONMETALLIZED COMPOSITE SOLID PROPELLANT,		5. TYPE OF REPORT & PERIOD COVERED INTERIM 1 May 74 - 30 Jun 75	
7. AUTHOR(s) R. L. GLICK		6. PERFORMING ORG. REPORT NUMBER U-75-27	
9. PERFORMING ORGANIZATION NAME AND ADDRESS THIOKOL CORPORATION HUNTSVILLE DIVISION HUNTSVILLE, ALABAMA		8. CONTRACT OR GRANT NUMBER(s) F44620-74-C-0086	
11. CONTROLLING OFFICE NAME AND ADDRESS AIR FORCE OFFICE OF SCIENTIFIC RESEARCH/NA 1400 WILSON BOULEVARD ARLINGTON, VIRGINIA 22209		10. PROGRAM ELEMENT, PROJECT, TASK AREA & WORK UNIT NUMBERS 681308 AF-9711-01 61102F	
14. MONITORING AGENCY NAME & ADDRESS (if different from Controlling Office)		12. REPORT DATE Jul 75	
		13. NUMBER OF PAGES 76	
		15. SECURITY CLASS. (of this report) UNCLASSIFIED	
		15a. DECLASSIFICATION/DOWNGRADING SCHEDULE	
16. DISTRIBUTION STATEMENT (of this Report) Approved for public release; distribution unlimited.			
17. DISTRIBUTION STATEMENT (of the abstract entered in Block 20, if different from Report)			
18. SUPPLEMENTARY NOTES			
19. KEY WORDS (Continue on reverse side if necessary and identify by block number) MONODISPERSE BDP COMBUSTION MODEL NONMETALLIZED PROPELLANTS HYDRAULIC T-BURNER ANALOG VENT FLOW PHENOMENA NON-NEUTRAL PRESSURE-TIME HISTORY			
20. ABSTRACT (Continue on reverse side if necessary and identify by block number) Monodisperse BDP combustion model was extended to nonmetallized propellants with mixed, polydisperse oxidizers by embedding monodisperse model in statistical framework including mixture ratio effects. Basically, polydisperse propellant is "disassembled and rearranged" to form sequence of monodisperse pseudo-propellants whose rates are computed via monodisperse model. Reassembly provides real propellant's burning rate. Approach provides information pertaining to distribution of regression rates and surface structure among different size oxidizer particles. Preliminary results suggest that significant factor in rate increases wrought by			

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introduction of small oxidizer modes is mixture ratio alterations in larger modes. Hydraulic T-burner analog was constructed and employed to visualize vent flow phenomena. Studies showed that flow enters vent with axial momentum and that momentum is partially transformed to vent into Karman vortex sheet. Fact that flow enters vent with axial momentum invalidates boundary condition of Culick analysis for flow turning gain; "correct" boundary condition leads to null vent gain. Experimental facts consistent with proof that in formal one-dimensional flow vent gain violates second law of thermodynamics. Logical and consistent way to reduce solid rocket data when pressure-time history is not neutral was derived. Since current techniques are not self-consistent in this situation, these results open door to reclamation of performance data heretofore rejected.

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