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## OPERATING MANUAL FOR COAXIAL INJECTION COMBUSTION MODEL

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;E. SUPPLEMENTARY NOTES

## 16. ABSTRAJT

This report is an operating manual for the Coaxial Injection Combustion Model (CiCM) and is submitted as the final report for an eleven-month effort designed to provide improvement, verify and document this comprehensive computer program for analyan, the performance of thrust chamber operation with gas/liquid coaxial jet injection. 'ilie' effort culminated in delivery to MSFC of an operational FORTRAN IV computer progratm and associated documentation pertaining to the combustion conditions in the Space shut: Main Engine. In addition, the computer program is structured for compatibility with the standardized JANNAF performance evaluation procedure. Use of the CICM in conjutchion with the JANNAF procedure will allow engine systems using coaxial gas/liquid injuction to be analyzed.

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This manual, describing the computerized coaxial injection combustion model, was prepared in support of the continuing JANNAF effort to develop systematic performance prediction techniques.

In 1565, the Interagency Chemical Rocket Fropulsion Group (ICRPG) Working Group was formed for the purpose of improving and recommending method0logy suited to eventual adoption as national standards for the analytical and experimental evaluation of the performance of liquid propellant rocket engines. By 1968, the Working Group (made up of members from government, industry, and academia) had:

Developed a physical model of rocket engine thrust chamber performance Selected computer programs to perform the mathematical calculations required by the physical model

Developed recommended practices for test measurements

Developed a model for uncertainty in measurements

Documented the effort in three procedures manuals (CPIA No. 178, 179, and 180 ) and several computer program manuals.

In 1968, the ICRPG was reincorporated as part of the Joint Army-Navy-NASAAir Force (JANNAF) Interagency Propulsion Committee. The major JANNAF achievement to that time was the publication of standard Thermochemical Tables for rocket exhaust products. The ICRPG Performance Standardization Working Group became the JANNAF Rocket c̈ngine Performance Woriing Group.

Other JANNAF Working Groups cover such areas as Combustion Instability (originally part of the ICRPG), and Air-Breathing Propulsion and Environmental Effects. Each Working Group has a four-person steering committee (each Government agency being represented), a program manager to coordinate the Group's efforts, members from Government agencies, and participants from outside the Government.

Since the reinstitution of the Rocket Engine Performance Working Group in 1968, this Working Group has:

Extended the methodology from the thrust chamber to the entire engine Developed a detailed injector analysis procedure to replace the earlier ICRPG method

Developed a rigorous step-by-step analysis procedure and a simplified procedure using efficiency definitions

Replaced the approximate boundary layer model with a more rigorous model

Established new overall procedures and documentation consisting of a Performance Prediction and Evaluation Manual, a User's Guide based upon experience pertaining to the manual and recently a CPIA publication (245) dealing with JANNAF Rocket Engine Performance Test Data Acquisition and Interpretation.

Continued to update and improve all methods and procedures.

The documentation of the coaxial injection combustion model contained in this manual is indicative of constant updating and improvement to JANNAF performance prediction procedures. Specifically, this report describes the
use of a reference computer program developed for the rigorous analysis of rocket thrust chambers with coaxial propellant injection. An earlier version of the nodel described herein was referenced in CPIA Publication 245 (page 13.2B) as the CSS model, a "coaxial element model that replaces LISP and 3DC for coaxial elements". This report describes an improved computer program which supersedes CSS. The improved model is named CICM.

This report has been prepared in fulfillment of contract NAS8-29664 from the National Aeronautics and Space Administration. The effort was com. pleted during the period from 2 May 1973 to 15 April 1974. Mr. K. W. Gross of the NASA Marshall Space Flight Center was the Technical Monitor. The Rocketdyne Program Manager was Mr. L. P. Combs, initially, and later M1. J. Friedman. Dr. Robert D. Sutton served as the Rocketdyne Project Engineer.

## ACKNOWLEDGEMENT

In addition to the authors, other technical personnel participated in the effort or served as consultants regarding specific aspects of the program. Mr. K. W. Fertig, in particular, was instrumental in formulation and programming of the finite difference equation describing the droplet heating and diffusion model. Additionally, his advice, and knowledge of numerical analysis techniques were invaluable in overcoming numerical problems encountered in many portions of the computer program. Mr. M. Moriarty lent considerable aid in development of specific techniques to allow calculation of the pressure variation from the manifold to the injector face.

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## ITTRODUCTION

The performance of a thrust chamber depends greatly on the combustion and injection processes including atomization, evaporation, and mixing. The individua: processes are highly complex, especially for coaxial liquid-gas streams. Over a period of several years, Rocketdyne has developed an analytical model to simulate these processes; the model has been used extensively in the Space Shuttle engine development effort.

The JANAF Performance Standardization Working Group has directed the development of reference computer programs for evaluation of liquid rocket engine performance. Current capability includes the ability to simulate the behavior of various injection elements such as doublets, triplets, pentads, showerheads, etc., for liquid-liquid propellants with the JANNAF Distributed Energy Release (DER) computer program. However, the ability to simulate coaxial liquid-gas jet injection and combustion was needed in the JANMAF methodology.

The objective of this technical effort was to provide NASA/MSFC with an operational FORTRAX IV computer program and associated documentation applicable to analysis of coaxial injection and combustion of liquid-gas propellants in the Space Shuttle engire. In addition, the computer program was to be structured to fit into the standardized JAlwaf evaluat ion procedure, so that other engine systems using coaxial injection could be analyzed. These objective, have been met.

The effort was divided into two tasks. The first concerned improvements io the existing Rocketdyne model: program modularization, improvement of the numerical analysis, modification of program tables, changes to the input and output format, ant inclusion of punched card output compatible with the JANNAF DER program input requirements. The second task involved documentation of the model.

This report has been prepared to provide sufficient information to allow MSFC to adequately use the model. This report includes overall descriptions of the equations, the overall program and its subroutines (including flow charts that emphasize the inte:actions of the subroutines rather than the detail of their internal structure), the program input and output, internal checks, guidelines, and error analysis.

SCOPE AND LIMITATIONS OF THE COMPUTER PROGRAM (CICM)

This report describes a very comprehensive and complicated computer program to predict the combustion within rocket thrust chambers of gas/liquid propellants injected from coaxial elements. The model is capable, when used with applicable intra-element mixing data, of predicting the performance of any size of concentric coaxial element using any propellant combination.

The program is designed to use the injector and chamber configuration, the propellant and the operating conditions as the input. In a sing!e run, the program will calculate the state of flow conditions within each element's "cup" (volume formed by recessing the oxidizer propellant delivery post
into the fuel sleeve). The calculated flow conditions include the important fuel side "cup" pressure drop. This pressure loss is defined to be the difference between the pressure in the fuel annulus $8 a^{2}$ compared to that at the injector face, The program then automatically stores and uses all data as input to the chamber calculation sequenco. If the injector ias more than one element design (or zones representing a group of elements eách having similer inlet conditions) the model performs automated repetitive analysis until the element (zone) with the longest predicted jet length is located. At his point spray gas information from all of the elements, or groups of elements, are internally input into an auxiliary pregram that organizes the data, in terms of punched card output, for subsequent analyses of the completion of combustion, etc. via other computer programs (JANAF DER, et sca.). The zones of element inlet conditions (i.e., injector feed maldistribution) must of course be part of the input to DER.

This rocket engine combustion model is unique because it calculates both the rate of atomization of the injected liquid jet, resulting from the sheer force between the jet and the surrounding gas, and the axially varying mean druplet size produced by the atomization. Thus, it dees not require experimentally determined correlations for the droplet size distribution, which are rocuired in other models.

Integration of the computer program into the DER methodology was formulated after considering many alternative methods for handing intra-element mixing. It was tecided that the most accurate way to compute the total effect of this phenomenon is to divide the spray and gas flows for each coaxial element
zone into multiple mixture ratio sub-zones. The manner in which the element zones axe further subdivided to simulate the intra-element mixing loss is determined from cold flow measurements. These cold flow measurements relate the element geometry and flow condition to its mixing efficiency. Such information may be input to the CICM program in terms of mass fraction as a function of the total fuel and oxidizer flowrate for each element zone. This analysis is used in an auxiliary program that interfaces CICM with the streamtube portion of $D E R$.

The streamtube portion (STC) of DER must, of course, be provided with more information than the punched card output from CICM provides. In essence, STC contains multiple concentric streamtubes representing each zone and the further breakdown of each zone into additional concentric streamtubes to account for intra-element mjxing efficiency. Although mass fraction as a function of the fuel and oxidizer flowrates for each element zone is calculated, the user must decide, shen inputing $D E R$, which spatial concentric streamtube to use to represent each zone, and further, what mixture ratio profile to assign to the additional concentric streamtubes within each overall zonal streamtubes. These same decisions are required for analysis of other element types when using the JANNAF DER (STC) program and, therefore, they do not represent additional complexity.

The computer program also has capability for bypassing DER (STC) entirely and continuing the spray/gas combustion computations for single streamtubes to the nozzle throat. In such a case the area of the streamtube varies as a constant proportion of the total cross-sectional area, whish is usually based
on the ratio of element flowrate to total flowrate. Unlike DER (STC), in constant area sections of the chamber the streamtube area does not change, rather it retains a constant area. This simplification occurs because only one streamt whe is being consiciered, whereas in STC many streamtubes are considered and adjustments are made to their individual areas so that they sum to the chamber area.

All physical properties in the program are supplied by generalized property table subroutines for all droplet liquid and vapor, combustion gas, nonburning gases and droplet film properties. The program utilizes an advanced droplet vaporization and reating model which includes real gas effects regarding vapor-liquid equilibrium and solubility of external gases into the droplet. To describe these non-ideal gas effects, the Redlich-Kwong equation of state and the mixing rules of Chueh and Prausnitz* have been utilized. Rocketdyne has developed separate programs to calculate the non-ideal effects required in the CICM program. Although the program has been generalized to accept any propellant combination, non-ideal properties have been supplied only for the $\mathrm{LO}_{2} / \mathrm{GH}_{2}$ propellant combination. Additional effort would be required to supply properties for other propellants.

During the current effort, the non-ideal physical properties for the $\mathrm{LO}_{2} / \mathrm{GH}_{2}$ propellant system were evaluated to ensure that the program is adequate for computations to at least 5000 psi . Non-ideal effects (where applicable) of temperatures from $100^{\circ} \mathrm{R}$ to $10,000^{\circ} \mathrm{R}$ have also been included.

[^1]As noted earlier, the program contains an advanced droplet vaporization and heating model (similar to, but an improvement on, that contained in the current DER/STC droplet heating program). This model was developed to permit analysis of both subcritical and supercritical temperature and pressure conditions. The model predicts continuous variation of burning rate with pressure. It computes a "wet bulb" temperature for subcritical pressures while allowing the droplet to continue heating through and past the critical temperature for supercritical pressures.

The portion of the program that deals with the "cup" region (that volume created by recessing the oxidizer post within the fuel sleeve upstream of the injector face) permits analysis of both non-burning or ignited gas flows. Ignition of the injected gas (usually fuel) and atomized and vaporized oxidizer (the liquid jet) is believed to occur primarily as a result of recirculatica of hot gas which is promoted by a highly flared fuel sleeve (such as on the $J-2$ and $J-2 S$ ). With such a flare, an ignition front is established across the gas flow path at an angle determined by the cup gas propellant flow and flame speeds. Ignition is considered to occur at the beginning of the flare on the fuel sleeve and propagates downstream toward the liquid jet. For a non-flared cup, a similar analysis is used for ignition of non-burning gases as they enter into the chamber. Ignition occurs by local recirculation of hot gas around or between elements. Determination of the chamber gas flame speed is not exact; generally a value of $600 \mathrm{feet} / \mathrm{sec}$ ond is recommended.

Other ignition mechanisms are possible but no high performance coaxial injected engine is known to have been (or is ever likely to be) built which has a gas injection velocity low enough to allow a turbulent flame to propagate upstream into the cup and maintain combustion there. Similarly, no engine is known to have been built or designed with gas injection temperatures high enough to cause auto-ignition to occur. Even in the case of the SSME, tests have been made with hydrogen-rich gas injected at $2000^{\circ} \mathrm{R}$ (considerably hotter than that planned for the actual engine) without indications of cup ignition. Ignition is unlikely because the induction time for auto-ignition at these extreme conditions is some 30 times greater than cup gas residence time.

Additionally, the computer program has been modified from previous versions to improve the calculation of the "cup" pressure drop. With this modification, the pressure at the downstream end of the fuel gap annulus is predicted rather than at the propellant contact point downstream of the oxidizer post. This change is of significant importance to the accurate prediction of the overall fuel pressure drop, fuel manifold to injector face. The program will accurately predict the pressure recovery or loss (if any) in the flow from the annulus to the point of propellant contact, as well as the pressure drop from that point to the injector face. Three different methods are provided to compute the pressure differences between the point of contact and the fuel annulus. These three methods are discussed in detail under the General Program Outline section of this report. Of these three methods, one is recommended, but the others may be used with easily made changes to certain atomization rate and dropsize diameter correlation inputs which depend on the method
selected. Flame speed effects, whether in the cup or in the chamber, are relevant only with respect to use of the third (presently recommended) method.

The primary limitation of the program is its essentially one-dimensional nature. Within any streantube at a given axial location, the droplet spray and gas flow are considered uniform within the cross-section. Also, the program does not directly consider secondary droplet breakup. Conly the initial atomization rate and mean dropsize variation as a result of vaporization between axial steps are calculated.) However, neither of these restrictions seem to have any significant influence on the ability to model observed behavior.

Non-uniformities are handed by the intra-element mixing technique described earlier. For the cup regjon, the method of predicting the atomization rate and initial dropsize is believed to account implicitly for what secondary droplet breakup occurs because the rates and dropsizes are adjusted to obtain the best values of model parameters based on experimental information. The same statement can be made concerning the chamber, although for this region computations indicate secondary breakup is far less likely. In the chamber, the droplets are larger initially because the flow is not constrained by the cup fuel sleeve walls. However, the computations indicate that the droplets rapidly vaporize in the surrounding hot combusting gas and are rapidly accelerated by droplet drag to a critical relative speed where further breakup (beyond the initial atomization) does not occur.

An additional restriction of the program is its inability to analyze coaxial injectors incorporating propellant swirl.

Over a period of several years, an integrated method for analyzing bipropellant liquid spray combustion has been developed and applied to steady-state wall heating and performance analyses (Ref. 2, 2, and 3). The approach was developed at Rocketdyne under a series of contracts supported by the Air Force and by NASA and was guided by JANNAF Performance Working Group recommendations and requirements. For injection elements other than coaxial elements, this method is based on initializing the combustion field for the entire combustor (or a representative geometric segment of it) at a plane located a short distance downstream of the injector by summing the spray flux contributions from individual injection elements to each of a large number of flow-net mesh points. Individual element behavior is described analytically by empirical correlations of data from single-element, cold-flow experiments. Subsequent to that, combustion is described in a rapid combustion zone (if strong transverse gradients are produced) followed by a streamtube combustion zone, as shown in Fig. 1. The computer program (Ref. 3) necessary to analyze this flow field is schematically illustrated in Fig. 2.

To date, this approach has been primarily applied to liquid-liquid systems. While cold-flow characterization of gas-liquid injection provides valid empirical correlations for many injector types, this approach may not be sufficiently accurate for injector types that exhibit strong coupling betwcen the atomization processes and the spray combustion or vaporization processes. This is particularly true in regard to the dropsize distribution and location at which spray droplets are formed. Coaxial jet injection is subject to such coupling in at least two ways: (1) gas-liquid interaction in any elemental recesses


Figurc. 1. Schematic of General Liquid Rocket Engine Steady State

(e.g., such as recessing the liquid propellant injection post) accelerates the initial atomization, produce; finer sprays, and increases injection pressure losses and (2) completion of jet atomization is accelerated and finer sprays are produced by the buildup of axial combustion gas velocity. Therefore, it was anticipated that some form of coupled atomizationcombusticn analysis of individual elements would be required for initializing the more global chamber combustion analyses. This is schematically implied in Fig. 3. The jet atomization may extend considerably into the combustion chamber, interacting strongly with (and producing) the surrounding combustion flow field. Thus, a jet atomization-combustion zone would replace the injection-atomization and rapid combustion zones of fig, 1. This requires an addition or alteration to the present computer program of Ref. 3, such as shown in Fig. 4.

The Rocketdyne-developed coaxial injection combustion model (CICM) predicts the atomization, mixing, and (if present) combustion within the coaxial element recessed cup as well as the jet atomization and combustion within the combustion chamber. The basic program analyzes a single coaxial element or "element zone" composed of similar elements which can be considered to be a single element. If manifold feed maldistribution is present (or if some of the elements differ in design) an internal multiple analysis is performed for each element zone that represents a different operating condition. Each element zone is assigned its proper proportion of the chamber area and propellant flow. These element zones may be further divided into subzones to include the offects of intra-element mixing losses.


Figure 3. Schematic of Typical Gas/Liquid Coaxial Injected Engine


Figure 1. Proposed Restructuring of DIA Program to Include Gas/ Liquid Coaxial Injector
analytical features of Single-element, COAXIAL
INJECTION COMBUSTION

As in most combusticn analyses, inputs are required regarding the propellants' physical and thermochemical properties, equilibrium combustion products, and injector, chamber and nozzle designs. The analysis of the injector element, as far as prediction of the vaporization efficiency is concerned, may proceed from a flow field formulation such as that depicted in Fig. 5. The element shown here is flared such as on a J-2 engine. (Most elements are not flared.) Only three axisymmetric flow fields need be considered, as shown: (1) the liquid jet, (2) the spray/gas-burning (or nonburning) flow field surrounding the jet, and (3) bleed flow through the injector face, "Rigimesh flow", surrounding the gas/spray flow field and mixing with it. The flow within each of these fields is taken to be quasi-one-dimensional (i.e., the radial mass flux concentration and pressure gradients are assumed to be insignificant).

The actual analysis begins with initial contact between gas and liquid jet (Fig. 5). This contact may, for some injectors, occur in the cup formed by recessing the liquid oxidizer injection post. The conditions of this initial contact depend on the method chosen to describe the fuel flow from the fuel annulus gap to the liquid jet. In this region, the constrained highvelocity gas stream begins the initial stripping and atomization of the jet. Small drops are formed and, depending on local flow and geometric conditions (i.e., gas temperature, velocity, oxidizer vapor concentration, pressure and flame speeds), the propollants may initially ignite


Figure 5. Conceptual Model of Uniformly Flowing Coaxial Injector Element
within the cup. Whether or not this occurs depends either on hot gas recirculation in the flare (if the element is flared) or on kinetic ignition delay times. Even if burning does not occur in the cup region, the recess of coaxial injectors has a significant effect on subsequent atomization and combustion in the chamber, thereby ontrolling the performance efficiency. In addition, significant cup burning often radiraliy changes injection delta pressures and injection temperatures and must be accounted for in initial design.

The program is based on the use of conservation equations for both the liquid jet and combustion gas/spray flow in the cup region and chamber flows. They include spray droplet atomization, heating, burning, and droplet drag. ieat transfer to tice walls, injector facs, and liquid jet are neglected. In the chamber, uniform radial pressure is assumed at each axial location and the sum of the areas of the liquid jet, combustion' spray field and "Rigimesh flow" must fill the portion of the chamber area allotted to the element. In the absence of "Rigimesh flow", the combustor flow field emanating from an element is allowed to expand at constant pressure until the flow fills the "chamber". This is not an assumption bur represents the limit of axial pressure variation as the ex'ernal (Rigimesh) flow is reduced to zero. These equations are described more fully later in this report.

Equations are also included which describe liquid jet stripping rates and drop-size distribution. This is the only known model which calculates stripping rates, atomization, and combustion of liquid jets in gas-liquid coaxial injectors. The current model represents a significant advance over the first attempt at modeling coaxial injectors (Ref. 4). The model does not require input data regarding dropsize information because the distribution is calculated as a function of flow field conditions and jet axial position. The controlling parameters of the model are: (1) the local stripping rate of the liquid jet, $M_{A}$, (2) the local mean drop size being produced when $M_{A}$ is etripped from the jet, $\bar{D}$, (3) the droplet heating and burning rates, (4) the droplet drag coefficient, and (5) for the chamber flow, the rate of mixing of the external "Rigimesh flow" (for low percentage flow, this parameter will be shown to be of little importance).

A corrclation for the droplet drag coefficient was utilized which was obtained for accelerating, burning droplets in a convective flow field (Ref. 5). While it lacks particle interaction effects, it appears to be fairly accurate.

The rate of mixing of the "Rigimesh flow" is important only if that flow is abnormally large. This mixing of the "Rigimesh flow" is not accomplished by turbulent mixing of striated parallel gas flows but is primarily "caught" or entrained between adjacent elements. As combustion of the spray
proceeds, the reacting flow field expands radially as it progresses downstream as computed from the entire interrelated set of conservation equations describing each flow field. The assumption of uniform pressure at each axial location is utilized to iteratively solve the equations. These iterations, coupled with the proportioned chamber area constraint, determine the pressure level (pressure varies axially but not radially), velocity and area of each flow field. Computations have been performed for extremes in "Rigimesh flow" mixing from complete mixing to no mixing. Results show that rapid spreading of the combusting flow field from adjacent elements (with the presence of "Rigimesh flow", mixing or not) causes a decreasing axial pressure. The "Rigimesh flow" accelerates rapidly so that, within approximately 2 inches downstream from the injector face, its flow area is reduced to only approximately 3 percent of its injection area. Because this area is in the form of an annulus trapped between elements, the average thickness of this annulus (for typical injectors) is on the order of 0.01 inch. Thus, the "Rigimesh flow" allows a single turbulent eddy to sweep the flow into the adjacent element flow fields. Consequently, with normal 2nounts of "Rigimesh flow" (approximately 5 percent of the total fuel flow, the axial variation of the expansion area of the combusting flow field of adjacent elements is relatively unaffected by the presence of the "Rigimesh flow". Hence, the rate of mixing of the "Rigimesh flow" is not of importance and is usually taken to be a linear functinn between the injector face and the 95 -percent closure point of two adjacant elements computed under no Rigimesh mixing
conditions. If this approach requires too much computer time, an arbitrary downstream distance may be chosen with no significant change in accuracy. Naturally, when the axial rate of mixing is prescribed, the mixed "Rigimesh flow" is spread uniformly over the cross-sectional area of the element's flow field and becomes part of the fuel to be reacted.

An important aspect of this program was the development of a continuous sub- and supercritical burning (and heating) rate drop model that allows steady-state combustion analyses and performance predictions to be made to $>5000$ psia. The equations are similar to the El Wakil equations (Ref. 6). However, the boundary condition was changed to allow the existence of an external mass flux (i.e., surface regression effects of the droplet). This change allows smooth computation through the critical point. Additionally, high-pressure effects due to the presence of other gases were included for the computation of the vapor surface mole fraction and the 'heat of vaporization". This involved use of the Redlich-Kwong equation of state, fugaciic relationships, and solubility effects of the external gas in the droplet (Ref. 7).

Equations for the jet stripping rate and drop size production are presented below:
A. Stripping Rate

B. Mean Irop Size

$$
\left.\overline{\mathrm{D}}_{j}=\mathrm{B}_{\mathrm{A}}\left[\frac{\mu_{j}\left(\sigma_{j} / \rho_{j}\right)^{1 / 2}}{\rho_{g} U_{r}^{2}}\right]_{\substack{\text { Drop Size } \\ \text { Coefficient }}}^{2 / 3}\right]^{2}
$$

where

$$
\begin{aligned}
& D_{j}=\text { diameter of jet } \\
& U_{r}=\text { expanded relative gas velocity in cup (or chamber) } \\
& \text { between gas and spray }
\end{aligned}, \begin{aligned}
& \mathrm{Z}=\text { axial location } \\
& \rho_{g}=\text { gas density } \\
& \rho_{j}=\text { jet density } \\
& \mu_{j}=\text { jet viscosity } \\
& \sigma_{j}=\text { jet surface tension }
\end{aligned}
$$

The equations include an atomization coefficient, $C_{A}$, and a drop size coefficient, $B_{A}$. It is not expected that the values for $B_{A}$ and $C_{A}$ be the same inside the cup region as out in the chamber since the fuel is not constrained in the chamber as it is in the cup. Thus, the values of $B_{A}$ and $C_{A}$ in the cup may reflect droplet breakup, etc. However, the equations are general in nature and the values of $B_{A}$ and $C_{A}$ determined
for either regime have been found to be the same for any engine uperating condition. This is significant in that the extremes range from burning to non-burning propellant cup conditions, various chamber shapes, etc., and even different propellants.

Methods of evaluating $C_{A}$ and $B_{A}$ for the cup and chamber regions are required and the validity of these equations has been verified.
$B_{A}$ and $C_{A}$ for the cup region were determined by analytical comparison of four to seven different cases where the pressure drop from the end of the fuel gap annulus to the injector face (cup pressure drop) had been measured. Four of these cases were from subscale firings of LOX/hydrogen coaxial injection engines: (1) the SSME straight oxidizer post preburner, $P_{c}=$ 1500 psia; (2) the SSME tapered oxidizer post preburner, $\mathrm{P}_{\mathrm{c}}=1500 \mathrm{psia}$; (3) the stability preburner-like uni-element motor, $P_{c}=500-1000 \mathrm{psia}$, in which the delta $P$ between the fuel gap annulus static pressure and the injector face pressure was measured directly; and (4) the SSME uni-element tests, $P_{c}=1500$ psia which consisted of a uni-element preburner and a unielement main injector containing an oxidizer post capable of being recessed from flush mounting to $0.3+$ inch from the injector face. The remaining cases were full-scale firings of three similar engines also using $\mathrm{LOX} / \mathrm{GH}_{2}$ propellants: (1) the $J-2$, (2) the $J-2 S$, and (3) a variable-oxidizer-postrecessed aerospike (segment) engine, $P_{c}=750$ psia. The J-2 and J-2S are the only ones in which the propellants ignite and burn within a flared fuel cup sleeve.

The number of experimental cases used to determine $B_{A}$ and $C_{A}$ depended on the method used to compute the pressure profile from the fuel gap annulus to the point of propellant contact. At least two sets of data are needed to determine $B_{A}$ and $C_{A}$; these resultant values are then used to predict the cup $\Delta \mathrm{Ps}$ of the remaining engines. The adequacy of the chosen $B_{A}$ and $C_{A}$ is determined by comparing predicted and measured cup $\Delta P$ values. Acceptable accuracy has been taken to be $\pm 20$ percent (except at very low cup $\Delta P^{\prime}$ 's where predicted differences of only a few psi can result in apparent high percentage deviations).

Three methods have been used for computing total cup delta pressures and for obtaining $B_{A}$ and $C_{A}$. This computation concerns the process through which the gas is assumed to flow from the gap annulus into the recessed portion of the injector element. In the first of these methods, the gaseous fuel was assumed to flow around the post thickness and fill the entire annulus between the liquid jet and the fisel sleeve walls. The liquid jet was not allowed to expand, and therefore does not have the bulge as shown in Fig. 5. The fuel pressure in the annulus gap is calculated by assuming that the fuel static pressure did not change in the expansion from the annulus gap to the cup. $B_{A}$ and $C_{A}$ for the cup region were determined by comparison of predicted and measured cup $\Delta P$ values for the $\mathrm{J}-2$ and $\mathrm{J}-2 \mathrm{~S}$.

Sets of values of $B_{A}$ and $C_{A}$ were calculated that yielded the correct pressure drop for each engine. When these were plotted, they produced a cross point of two curves that was sharp and yielded the cnly values of $B_{A}$ and $C_{A}$ that satisfied the pressure drop of both engines. It was necessary for these calculations to assume burning to occur within the cup. A nonburning assumption caused over 90 percent of the jet to be atomized in the 0.200 -inch recess of this cup to yicld the correct pressure drop; clearly this was a nonrealistic assumption. Additional engine cup $\Delta P$ data were then used to verify the validity of the chosen $B_{A}$ and $C_{A}$. Although this method of obtaining $B_{A}$ and $C_{A}$ (combined with the fact that ignition of the flowing gas was assumed to occur at a cross-sectional plane just downstream of the oxidizer post) gave satisfactory agreement with most existing cup pressure drop data, it does not properly conserve gas momentum and, therefore, was considered unsatisfactory. Further, this technique failed to properly predict the directly measured cup $\Delta P^{\prime}$ s of the stability preburner like-element injector.

The second method involved the use of an iterative procedure to predict a "sudden expansion" of both the gas and liquid (requiring the equations of motion for both propellants to be satisfied) with compressibility factors being used to allow for nonideal gas behavior. The iteration was used to find the allowable areas of expansion for the two propellants subject to the constraint of the total cup flow area. As expected, the results indicated that as the thickness of the LOX post is increased the pressure recovery approaches zero. Again values for $B_{A}$ and $C_{A}$ were obtained from the J-2 and J-2S data allowing ignition to occur as in the previous case.

It became evident at this point that ignition of the cup gases upstream of the flare was not possible because of the high gas velocity in the unflared section of the cup. However, assuming ignition to occur at a cross-sectional plane located at the beginning of flare, failed to produce a common solution when the $B_{A}$ 's and $C_{A}$ 's were plotted. (The assumption that ignition occurred in the flare was also used to obtain a set of values for $B_{A}$ and $C_{A}$ with the first method but the change in the results was insignificant.) Although the proper values for $B_{A}$ and $C_{A}$ could not be adequately defined by this second method, comparisons were made to other engines. Using this approach the measured subscale SSME preburner total manifold-to-injector end pressure drop was accurately predicted. However, when predicted pressure drops were compared with other available large engine cup $\Delta P$ data the comparison was again less than satisfactory. Further, the trends of the directly measured cup pressure drop of the subscale preburner-like unielement firings could not be properly predicted with this method.

The third method corresponds to a significantly different concept of the flow behavior within a recessed oxidizer post coaxial injector. The previous methods considered the gas and liquid static pressures to be equal (and radially uniform) at the end of the oxidizer post. Consequently the radial liquid and gas expansions predicted by the second method always occurred within the radial thickness of the oxidizer post. However, base bleed analyses of the injection process with, e.g., a coaxial element, suggested that the fuel pressure and oxidizer pressure (and the intermediate pressure at the tip of the post) may not be equal
at the end of the post and that adjustment of the streams to reach a radially uniform pressure would occur. Further investigation led to the concept previously illustrated in Fig. 5. The liquid jet pressure at the end of the oxidizer post is believed to be initially iess than that of the surrounding gas. Relaxation of the radial pressure frofile to a uniform pressure occurs due to initial expansion of the liquid jet flow area and subsequent contraction of the fuel flow area. Consequently the liquid jet flow gains static pressure and the gas flow loses static pressure until the pressure is radially uniform. In the analysis this initial liquid expansion is allowed to occur in approximately one oxidizer post thickness downstream from the post. Propellant contact begins at the point marked 1 in Fig. 5 and subsequent atomization of the liquid begins. Total cup $\Delta \mathrm{P}$ is still defined as the difference between pressure in the fuel gap annulus and injector face chamber pressure.

To compute $B_{A}$ and $C_{A}$ for this third method at least four sets of engine data are needed, because the equations used to predict the liquid area expansion also contain two empirical constants. Actually, data from all of the engines were used to obtain a "best-fit" correlation for injector cup pressure losses under non-burning cup conditions, as shown on Fig. 6.


Figure 6. Injector Cup Pressure Loss Correlation (Nonburning Cups)

Conservation and correlation equations were used to calculate the liquid jet area (and the contracted area of the fuel). Because the manifold-to-injector-face pressure loss for the fuel has the most significant effect on engine design, the conservation equations (mass, momentum, energy, and state) for the fuel were applied to calculate this fuel flow field from the end of the post (i.e., from the fuel gap annulus) to the point of propellant contact. The area of the contracted gas flow was correlatcu ins. the following equation:

$$
\frac{A_{c p}}{A_{A N N}}=0.982+0.0337 \mathrm{Ln}\left(\frac{A_{\text {post I.D. }}}{A_{\text {fuel sleeve }}}\right)
$$

where $A_{c p}$ is the area of the gas at the initial stream contact point and $A_{A N N}$ is the area of the fuel gap annulus.

In addition, the constraint was used that the sum of the areas of the gas and liquid at the contact point equaled the total area of the cup (fuel sleeve). Simultaneous with the determination of the two constants in the above equation, the cup $B_{A}$ and $C_{A}$ values were also determined by computing cup pressure losses downstream from the propellant contact point.

The $B_{A}$ and $C_{A}$ values for this were determined from non-burning cup gas data. Resulting were the first values for $\operatorname{cup} B_{A}$ and $C_{A}$ that yielded predicted pressure losses in agreement with data from the stability unielement injector. Because the values for $B_{A}$ and $C_{A}$ were obtained assuming a non-burning cup, the $J-2$ and $J-2 S$ cup pressure losses were computed by assuming cup gas ignition to occur at a conical surface based at the upstream edge of the flare on the fuel sleeve and sloping downstream toward the liquid jet. Also, because $B_{A}$ and $C_{A}$ and the $J-2$ and J-2S pressure losses are all known, this method aliowed the flame speed in this reacting two-phase LOX/hydrogen flow to be predicted. The value obtained for the $J-2$ was $382 \mathrm{ft} / \mathrm{sec}$. The fiame speed for the J-2S was prodicted to be slightly greater than its gas velocity at the beginning of the flare. Consequently, the latter flame speed was reduced to this gas velocity. As a result, the predicted cup pressure loss for the J-2S qoes not precisely match the measured loss (as shown in Fig. 6). Nevertheless, this third method is preferred and is recommended over the first two methods. It is believed that as more accurate non-burning cup gas pressure loss data becomes available, it will be possible to adjust $B_{A}$ and $C_{A}$ to allow prediction of the measured loss within +10 percent.

Although a nonplanar ignition front has been introduced, the program is still one-dimensional. Flame propagation is computed using an "averaged" or pseudo mixture ratio in the gas flow field region surrcunding the liquid jet. This region is composed of unburned propellant (gas flow near the jet that has not yet passed through the "flame front") and burned propellant which has passed through the flame front. To compute the mixture ratio under such quasi-two-dimensional conditions the folluwing equations were utilized.

$$
M R_{(x)}=\mathbb{M R}_{I}\left(\frac{y_{I}^{2}-y_{f(x)}^{2}}{y_{I}^{2}-y_{j e t(x)}^{2}}\right)
$$

and

$$
y_{f(x+\Delta x)}=y_{f(x)}-\frac{V_{f}}{V_{I}} \Delta x
$$

where

$$
x=\text { axial distance }
$$

$\mathbb{R}_{(x)}=$ the pseudo mixture ratio at axial location $x$
$\mathbb{R}_{\mathrm{I}}=$ the mixture ratio at the ignition point
$y_{I}$ = the radial distance from the centerline of the liquid jet to the ignition point on the fuel sleeve
$y_{f(x)}=$ the radial distance from the conterline of the liquid jet to the flame front at location ( x )
$y_{j e t(x)}$ - the radial distance from the centerline of the liquid jet
to the outside surface of the jet at location ( $x$ )

$$
\begin{aligned}
& V_{f}=\text { the flame speed } \\
& V_{1}=\text { the gas velocity at the ignition point. }
\end{aligned}
$$

Should part of the gas flow at the injection point be composed of fuel rich combustion products (i.e., topping cycle engines) then appropriate adjustment to the mixture ratio equation is performed by the program. The program uses the local mixture ratio (MR (x) with the combustion gas properties table to calculate corresponding pseudo gas stagnation lemperature, etc., to the local pressure through interpolation techniques. This stagnation temperature is then reduced in the program by the corresponding amount of energy stored within the unreacted oxidizer vapor and droplets at location $x$. Static temperature is computed assuming "frozen" composition as will be described later.

Values for $C_{A}$ and $B_{A}$ are also needed for the chamber. To obtain these, comparisons were made with data from two difierent engines. In this case the comparisons were made of measured and predicted combustion efficiencies of short chamber length, non-burning-cup segment engines. Utilizing the third method developed for the cup, curves of $B_{A}$ and $C_{A}$ which give the correct performance level for each engine were obtained. These were obtained by calculating the gas and spray flow and combustion in the chamber. Nonburning cup exit flows were ignited it the cup exit on the fuel sleeve and a flame speed of 600 fect/sec was utilized. Flame speed in the chamber is not precisely known, however, parametric
studies show that flame propagation is complete in no more than .15 inches (three normal axial steps) for flame speeds as low as 350 feet/ second. Cross plots of $B_{A}$ and $C_{A}$ for the proper chamber conditions yielded a single cross point. The final point selected was checked by predicting an independent segment engine efficiency and also predicting the liquid jet lengths of the $J-2$ and $J-2 S$. Combustion within the latter two engines had been observed and photographed in subscale transparent hot-firing tests (Ref. 8). The model predictions are in good agreement with the test results when the computations are Performed without using $D E R / S T C$ but using the CICM program to compute combustion efficiency $\eta_{C}$ * down to the engine throat. Computation of $B_{A}$ and $C_{A}$ for the chamber was performed in a similar manner since the segment engines used to obtain the values of the parameters were especially chosen. None of the engines had Rigimesh flow, all had 100 percent efficient intraelement mixing characteristics, and no manifuld flow maldistribution. Consequertly the engines could be viewed as single streamtubes in which the mixture ratio was uniform. Additionally a great deal of measured performance efficiency data were available for these selected segment engines.

SIIMMARIZATION OF THE CONSERVATION EQUATIONS FOR SINGLE ELEMENT COAXIAL INJECTION COMBUSTION

As stated previously the program is based on the use of conservation equations for both the liquid jet and combustion gas/spray flow in the cup region and chamber flows. Where appropriate, as in the cup, these
equations have been used with other correlation equations to determine the propellant contact point and the flow conditions of the propellants at that point. In addition, the effects of flame propagation in flared cups and in the chamber (from flow exiting from non-burning cups) have been introduced. Values for $B_{A}$ and $C_{A}$ in the cup and chamber have been determined.

The analysis of the injector element, as far as prediction of vaporization efficiency is concerned, proceeds from a flow field such as that depicted in Fig. 5. Three axisymmetric flow fields must be considered; (1) the liquid jet, (2) the spray/gas burning (or non-burning) flow surrounding the jet; and (3) the Rigimesh flow (in the chamber) surrounding the spray/gas flow and mixing with it. Flow within each of these fields is considered to be one-dimensional.

Four sets of conservation equations are used, one each for the combustion (or non-burning) gas, the spray, the liquid jet, and the Rigimesh flow. The four sets of equations are related by expressions which describe the transport phenomena between the flow streams. It is quite possible and convenient to sum the conservation equations for each constituent and obtain one overall set of combined equations replacing one of the four original sets of equations. Numerical techniques and practice indicate that this set of combined equations should replace the combustion gas conservation equations. Terms for transport phenomena between streams are decoupled from the combined conservation equations
so that they can be directly integrated. The entire set of all equations (and their derivations) can be found in Ref. 8. For this user's manual only a verbal description of the conservation equations are presented. However, the expressions representing the transport phenomena of mass, energy and drag force are presented in detail.

## A. The Overall Combined Equations

1. The local mixture ratio equation.
2. The overall continuity equation expressing conservation of the mass of the gas, spray, jet and Rigimesh flow at every increment. The sum of the mass of each flow is a constant.
3. The overall momentum equation
4. The overall energy equation
a) This equation can be rigorously written for the flow entha!pies and velocities and with the use of tabulated gas equilibrium properties as a function of mixture ratio and pressure solved iteratively with the other equations. This requires extensive triple interpolation and produces an inefficient program. Experience indicates that the equilibrium combustion gas properties are weak functions of the stagnation
pressure; hence the overall energy equation is replaced by a set of combustion stagnation properties dependent only on the injection pressure and temperature and the local (axial varying) mixture ratio. Stagnation temperature, etc., (as a function of axial location) is then directly and easily computed from the properties tables. This temperature is adjusted (reduced) for the energy contained in the spray and remaining oxidizer vapor. Reduction to static flow temperature is accomplished by assuming that no species change takes place between stagnation and flow conditions. Thus, except for temperature, gas properties (specific heat ratio, viscosity, etc.) in the flowing stream are assumed to be the same as at stagnation. The equation

$$
T=T_{0}\left[1-\left\{\frac{i_{0}^{-1}}{2} \cdot \frac{v^{2} M N_{0}}{R \gamma_{0} g T_{0}}\right\}\right]
$$

is used to compute the static temperature.
Here $\quad T=$ static temperature
$T_{0}=$ stagnation temperature
$\gamma_{0}=$ specific heat ratio
$\mathrm{MW}_{\mathrm{O}}=$ stagnation molecular weight

$$
\begin{aligned}
& R=\text { universal gas constant } \\
& V=\text { velocity of gas }
\end{aligned}
$$

Good agreement results when this method is compared with the rigorous equation (and its attendant comi'....uted properties tables).
5. Equation of state
B. The Jet Equations

Expressions for continuity, momentum and energy are considered;
drag on the jet is neglected in the momentum equations since the effect is accounted for in the production and acceleration of droplets. Similarly, the jet temperature is considered to be constant since the surface stripping prevents conduction to the jet core.
C. The Rigimesh Flow

This flow is considered to be isentropic. The continuity equation contains a mixing rate expression, but this does not affect the conditions required to have isentropic flow.
D. The Spray Equations

It is this set of conservation equations, along with the expressions for the stripping rate and dropsize production tha. essentially control the program. of particular importance
in the spray equations is the vaporization rate, drag force and heating rate expressions in the continuity, momentum and energy equations, respectively. These equations are principally initial value problems in that a new initial condition is formed at each axial increment along the jet.

All of these conservation equations are required for simultaneous solution on a digital computer to predict engine performance. Iteration of the initial assumed injector face pressure is required until the throat velocity is sonic. The computation of the combusticn gas is considered to be composed of constituents in thermodynamic equilibrium. This is in agreement with the accepted approximation that, for well designed engines, drop vapor diffusion rates are very much more limiting than gas phase chemical kinetic rates.

## Expressions Describing the Transport Phenomena

1. Drag Force on Droplets

The expression describing this droplet dynamic transport term appears in the spray momentum equation. The drag force is defined as:

$$
F^{n}=\frac{\pi}{8 g}\left[\rho\left(D^{n}\right)^{2} \quad\left(u-u^{n}\right)\left(\left|u-u^{n}\right|\right) C_{D}^{n}\right]
$$

$-24 \pi\left(D^{n}\right)^{3} \frac{d p}{d x}$
where

```
Cn n - <mol!rt irag corfficiont,
    initial drop group size n.
i)" - droplet diameter
F
| - gas pressure
u - gas velmeity
un
x - axial location
f - gas frec-stream density
```

The drag force includes both frictional drag and the drag due to volume forces across the drop arising from any existing gas pressure gradients. Other terms in the drag force equation, such as the acceleration of the "apparent mass" of the gas displaced by the droplet and the Basset term (non-steady condition) have been neglected because

```
\rho
n' - the density of the droplet
```

The validity of the equation is limited to the applicability of the existing correlations for the droplet drag coefficient. The review of existing corrclations in Ref. 8 indicate that Rabin's, et al, work in Ref. 5 is still considered to be the best correlation for describing drag coefficients whon applied to droplete in a rockot commbetion chamher flow. Ralin's work
shows that $C_{D}^{n}$ is a function of the relative Reynolds number. The correlation includes (1) the effect of gassification in a convective flow field and the effects of distortion of the drop.

$$
\begin{aligned}
C_{D} & =24 \mathrm{Re}^{-0.84} \\
& =.271 \mathrm{Re}^{0.217} \\
& =2
\end{aligned}
$$

$$
\begin{aligned}
\operatorname{Re} & \leq 80 \\
80<\operatorname{Re} & \leq 10^{4} \\
\operatorname{Re} & >10^{4}
\end{aligned}
$$

where

$$
\operatorname{Re}=\frac{\rho D^{n}\left|u-u^{n}\right|}{g \mu}
$$

and $\mu$ is the gas free-stream viscosity.
2. Droplet Vaporization and Heating Rate*

Background. The quasi-steady evaporation coefficient approach to droplet heating and burning, while empirically based on the observation that a burning droplet's diameter squared varies linearly with time, has been expressed analytically in increasingly comprehensive formulations. These models are based on the concept that a spherical flame surface surrounds a spherical droplet, with simultaneous heat transfer to and evaporation from the droplet being enhanced by the presence of the flame. These models have all been formulated as quasi-steady problems (i.e., time variation has been neglected in writing the conservation equations), although there are no assumptions in the models that preclude droplet heating. Relatively recent work at

[^2]Rocketdyne (using the addition of diffusion equations) has culminated in the added develonment of a tlin-flame model that includes uniform droplet heating. A problem that arises in applying such a model, however, is that the initial heating and burning rates may be over-predicted by assuming a flame exists when the vapor concentrations are too low to support it. Another problem is that the derived formulae for the burning rate (or the evaporation coefficient), in all of these models have singularities (blow-up logarithmically) if droplet temperatures approach propellant critical temperatures. One final problem is that exposing the droplet to even mild forced convection is likely to blow the flame into the droplet wake or extinguish it, so that flameenhancement of vaporization does not occur.

As a consequence of these limitations and problems, propellant droplet gasification and burning has also been analyzed from a vaporization standpoint, with vapors diffusing into and mixing with a high-temperature gas stream. So far as the droplet is concerned, combustion reactions within that gas stream serve to keep the gas temperature high and the vapor concentration low. (In practice, reaction to local thermodynamic equilibrium is usually assumed.) To the extent that the freestream gas temperature is lower than the stoichiometric flame temperature (the thin-flame modcl's driving temperature), a vaporization model will predict lower droplet burning rates than will a thin-flame model.

An evaporation model that is commonly used for analyzing spray gasification in rockets is that of El Kuiil (Ref. 6) and others at the

University of Wisconsin. By solving spherically symmetric, quasisteady conservation equations for simultaneous heat and mass transfer, droplet mass evaporation rate and (uniform) heating rate expressions have been developed.

It is possible to calculate nonuniform temperature distributions within a droplet undergoing heating (e.g., Ref. 8), but it is usually assumed that internal temperature gradients are prevented from building up by strong internal circulation. Under convective flow conditions, surface shear does promote circulation and this simplification is probably quite valid. Then the uniform droplet temperature is obtained from:

$$
\left\lceil\mathrm{d}^{\mathrm{T}} \mathrm{~T}^{\mathrm{n}}\right]^{\frac{\pi}{h}} \rho_{\ell}^{\mathrm{n}} \quad\left(\mathrm{C}_{\mathrm{pl}} \quad\left(D^{n}\right)^{3}\right]=Q^{n}
$$

Forced convection and resultant nonspherical transfer processes are accounted for through empirical Nusselt number correlations for both heat and mass transfer. The Nusselt number correlations used in the mass transport equation were obtained by Ranz and Marshall (Ref. 9); based on droplet film (f) conditioris.

$$
\begin{aligned}
& N u_{m}=2\left(1+0.3 \operatorname{Sc}_{f}^{1 / 3} \operatorname{Re}_{f}^{1 / 2}\right) \\
& N u_{h}=2\left(1+0.3 \operatorname{Pr}_{f}^{1 / 3} \operatorname{Re}_{f}^{1 / 2}\right)
\end{aligned}
$$

They verified this correlation with data from vaporization of water droplets in heated air. The equations derived thus account for both droplet heating and evaporation.

The foregoing droplet heating and evapcration model is capable of computing droplet behavior to complete combustion at subcritical chamber pressures, althcugh the vaporization rate blowstog logarithmically as droplet temperatures approach the boiling temperature $\left(X_{v_{1}}^{i} \rightarrow 1\right)$. For most conditions, the "wet bulb" effect suppresses the equilibrium droplet temperature enough below the boiling point to avoid the singularity. There, however, the evapoiction rate is strongly dependent upon droplet temperature and, because an implicit solution $n f$ the system of equations is required, many iterations may be needed to obtain convergence. Recent work, summarized in Ref. 8, gives good correlation with experimental data under such conditions, even up to high pressures, if the effects of the presence of other gases on the vapor pressure and "heat of vaporization" are taken into account.

Real Gas Effects. For vapor-liquid equilibrium, the free energy is the same on either side of a phase interface. This fundamental relationship for vapor-liquid equilibrium is conveniently written in terms of fugacities; for each component $i$, the fugacity of the vapor $f_{i}^{V}$ is equal to that of the liquid $f_{i}{ }^{L}$ (Ref. 7). Since the liquid senses the total pressure while the vapor senses only its partial pressure, the equiiibrium relationship can be written as

$$
f_{i}^{v}\left(P_{v}\right)=f_{i}^{L}\left(P_{T o t a l}\right)
$$

Hence, at constant temperature, as the total pressure increases, the partial pressure of the vapor has to increase to maintain the required relationship for equilibrium. For a non-ideal gas, the entha+ $p y$ is a function of the partial pressure of the gas (Ref. 10). Hence, the heat of vaporization, $\Delta H_{v a p}$, will be a function of total pressure since

$$
A_{v a p}=H_{v}-H_{\ell}
$$

In the calculation of vapor-liquid equilibrium, the vapor has to be considered a non-ideal gas. Of the four two-constant equations of state which have been widely used, the Redlich and Kwong equation is more accurate and the best at high pressures. The Redlich-Kwong equation is:

$$
P=\frac{R T}{(v-b)}-\frac{a}{T^{0.5} v(v+b)}
$$

where $a$ and $b$ are determined from mixing rules (Ref. 7). To match data over wide ranges, $a$ and $b$ have been programmed as functions of temperature.

These "real gas" corrections have been neglected in most prior applications of the El Wakil droplet vaporization model. Under supercritical pressures, some conditions led to calculated equilibrium temperatures below the critical temperature, but usually no equilibrium temperature was reached and the droplets were heated through the critical temperature. The model could be used beyond this point, but it usually was not because a physical model was lacking for $X_{v}^{n}$ at the "surface" of the pure supercritical vapor pocket. Instead, most users either assumed instantancous mixing of such supercritical vapors with
the surrounding gases, which is obviously unsatisfactory, or switched to a supercritical burning model due to Spalding (Ref. 11). This latter model, however, treats only the mass transfer and assumes that the vapor pocket remains at its critical temperature. As a result, no prior combustion model employin the El Wakil vaporization formulation can be adopted carte blanche for supercritical spray heating and combustion.

Interestingly, introduction of the real gas corrections for vapor pressure and heat of vaporization caused the El Wakil solution for droplet temperature to reach a subcritical equilibrium temperature for all conditions. This is known from photographic evidence (Ref. 12) to be unreal, so the need for an improved formulation was apparent.

New Droplet Heating and Diffusion Model. The El Wakil model has been extended and improved to overcome this physically unrealistic result. The new model is referred to as the droplet diffusion model. The main difference between it and the old model is this: In the El Wakil formulation, only the propellant vapor is considered to have a non-zero net flux in the film surrounding the droplet, while in the new model the radial mass flux of combustion gas in the film surrounding the droplet is no longer assumed to be squal to zero. Instead, the molar flux of combustion gas is defined at the droplet surfare through a moving control volume formulation such that changes in the droplet radius, die to droplet dersity changes and mass diffusion, cause it to be greater than or less than zero. The droplot surface boundary condition is determined through use of the species continuity equation. This is one of the major changes developed since the initial version of this model was programmed into the droplet heating and vaporization version of the current DER (STC) computer program. (The other major change is the inclusion of
solubility, using the methods of Ref. 7 , of the external gas in the droplet surface layers; this latter change allows computation of the droplet surface vapor concentration to extremely high pressures.) The droplet surface boundary. condition equations are:
a) $M W_{E_{d}} N_{E_{d}}=\rho_{E_{d}} \frac{\partial r_{d}^{n}}{\partial \tau}$
b) $\dot{\pi}_{v_{d}}^{n}+4 \pi\left(r_{d}^{\prime \prime}\right)^{2} \quad \rho_{v_{d}} \frac{\partial r_{d}^{n}}{\partial \tau}=4 \pi\left(r_{d}^{n}\right)^{2} M N_{v_{d}} N_{v_{d}}$

Thus, as the droplet "burns" the external diffusing combustion gas is allowed to enter the control volume and occupy that fraction of the volume vacated by the receding droplet surface.

The diffusion rate, or burning rate, is defined by the diffusion equation and is

$$
\dot{m}_{v}^{n}=\left(\frac{2 \pi D^{n}}{A B}\right)\left(\frac{i^{N} v_{f}}{R r_{f}}\right) \mathcal{D}_{v_{f}}\left(\frac{N u_{m}}{2}\right) \quad L n\left[\begin{array}{l}
1-B x_{v_{\infty}} \\
1-B x_{v_{d}}^{n}
\end{array}\right]
$$

where

$$
B \equiv\left[A+\left(\frac{M v_{f} \rho_{E_{d}}}{M N_{E_{f}}^{\rho_{v_{d}}}}\right)(A-1)\right] / A
$$

(NOTE: Here fifers to "film" conditions.)
an 1

$$
A=1+\frac{4 \pi\left(r_{d}^{n}\right)^{2} \rho_{v_{d}}}{\dot{m}_{v}^{n}} \frac{\partial r_{d}^{n}}{\partial t}
$$

The droplet heatup rate is defined to be

$$
Q^{n}=\pi k_{f} N u_{h} D^{n} z_{z}\left\{\frac{T_{E_{\infty}}-T_{d}^{n}}{e^{z}-1}-\frac{\Delta H_{v a p}}{\left[A C_{p_{v_{f}}}+C_{p_{E_{f}}}(A-1) \frac{\rho_{E_{d}}}{\rho_{v_{d}}}\right]}\right\}
$$

where

$$
z=\frac{\dot{m}_{v}^{r_{i}}}{\pi k_{f} D^{n} N u_{H}}\left[\left(C_{P_{v_{i}}}\right) A+C_{p_{E_{f}}}(A-1) \frac{{ }^{\circ} E_{d}}{\rho_{v_{d}}}\right]
$$

The droplet diffusion model no longer has the logarithmic singularity at either the droplet boilin: or propellant critical temperatures because, as droplets are heated through these temperatures, the value of $B$ is such that (1-Bx $V_{d}^{n}$ ) does not vanish. It thus becomes possible to continue analyzing spray droplets' behavior after they have become fully gasified, but have not yet been diffused and mixed into the surrounding combustion gas stream.

Comparison of the foregoing droplet diffusion model equations with the old model equations, e.g., as given by El Wakil, shows them to be very similar. The major differences are the appearance of the parameters $A$ and $B$. Examination of the equations shows, however, that $A$ and $B$ depend upon the heating and vaporization rates so that the droplet diffusion model must be solved implicitly by iterative methods. If the heating and vaporization rates are low enough that $\partial r_{d}^{n} / \partial t$ vanishes, $A \rightarrow 1, B \rightarrow I$ and the droplet diffusion model reduces rigorously to the E Wakil model. Chemical reactions are not taken into account directly in the droplet heating and diffusion model, but combustion is simulated by specifying a bulk gas cquilibrium flame temperature and zero droplet vapor mass fraction in the local free stream (except where a flame front is around the $j e t$ ).

| $a, b$ | parameters in Redlicn-Kwong state equation |
| :---: | :---: |
| B | parameter in droplet diffusion model |
| $\mathrm{C}_{\mathrm{p}}$ | specific heat at constant pressure |
| 0 | molecular diffusivity |
| D | droplet diameter |
| f | fugacity |
| H | enthalpy |
| $\Delta H_{\text {vap }}$ | heat of vaporization |
| k | thermal conductivity |
| NW | molecular weight |
| $\dot{m}$ | rate of change of mass |
| N | the absolute gas molar flux |
| Nu | Nusselt number |
| P, p | pressure |
| Pr | Prandtl number |
| Q | spray or droplet heating rate |
| Re | Reynolds number |
| R | universal gas constant |
| r | radial coordinate (drop radius) |
| Sc | Schmidt number |
| T | temperature |
| t | time |
| $v$ | molar or specific volume |
| x | mole fraction of droplet vapor |
| 2 | heat transfer blockage term |

## Greek Letters

```
0 density
Superscripts
L liquid
n concerned with the n }\mp@subsup{}{}{\mathrm{ th}}\mathrm{ droplet size group
y vapor
```


## Subscripts

```
d droplet (droplet surface)
E external gas
f droplet film
h heat or heating
\(\ell \quad\) liquid (usually referring to droplet properties)
m mass
\(v\) droplet vapor, vaporization rate
```


## INTERFACING WITH DER

Integration of the computer program into the DER methodology was formulated after considering many alternative methods for handling intra-element mixing. It was decided that the most accurate way to include intra-element mixing was to divide the spray and gas flows for each coaxial element zone into multiple mixture ratio zones. The manner in which the zones are subdivi. : to simulate the intra-element loss is determined from cold flow measurements. These cold flow measurements relate the element geometry and flow conditions to its mixing efficiency. Such information is input to the CICM program in terms of mass fraction as a function of the total fuel and oxidizer flowrate fo. each coaxial element zone. An auxiliary program (subprogram) is used to perform this analysis and interface CICM with the streamtube portion of DER. The auxiliary program organizes the spray/gas information generated by the coaxial element zone calculations in terms of punched card output. The streamtube portion (STC) of DER must, of course, be provided with more information than this punched card output.

During a coaxial element zone CICM analysis, as many as 100 droplet groups can be generated by the stripping process. However, to interface with the STC portion of DER, the droplet groups must be condensed to fewer than 12 equivalent droplet groups (restricted by STC program). The auxiliary program condenses the number of CICM droplet groups to those necessary ( $n_{D E R}$ ) through use of input variables which define the mass fraction of the spray in each DER droplet group. The DER droplet group temperature, velocity, and droplet diameter are determined by requiring conservation of droplet energy, droplet momentum, and droplet spray vaporization rate, i.e.,

$$
\begin{aligned}
& \dot{W}_{D E R}=\sum_{i=i_{s t}}^{i_{j}} \dot{W}_{\text {CICM }_{i}} \\
& \dot{W}_{D E R_{j}} h_{D E R}=\sum_{i=i}^{i} \dot{W}_{\text {CICM }_{i}} h_{C_{i C M}} \\
& \dot{W}_{D E R} V_{D_{D E R}}=\sum_{i=i}^{i} \quad \dot{W}_{\text {CICM }_{i}} V_{C_{C I C M}^{i}}
\end{aligned}
$$

where the lower and upper limits of summation are determined by

$$
\dot{W}_{D E R}={\underset{\mathrm{S}}{\mathrm{SPRAY}}}^{\mathrm{DER}_{j}}\binom{\dot{W}_{\mathrm{SPRAY}}}{\text { TOTAL }}
$$

The amount of fuel and oxidizer for each DER zone are specified as mass fractions of the total fuel and total oxidizer flowrates for each coaxial element zone calculation. The $D E R$ start plane pressure, zone areas, and gas velocities are determined by requiring conservation of the gas mass, momentum, and energy in the coaxial element zone with the constraint that the sum of the DER zone areas must be equal to the chamber cross-sectional area.

The output of the auxiliary program consists of streamtube initialization punched cards for use in the supercritical version of the DER program.

The order in which the streamtube initialization cards are punched depends on the order in which the coaxial elenent zone calculations were performed. The first set of streamtube cards corresponds to the first coaxial clement zone calculation, the second set corresponds to the second coaxial element zone calculation, etc. The user can, if he chooses, reorder the streamtube cards in any manner that he selects before executing the DER program.

A logic diagram of the CICM main computer program is shown in Fig. 7. Also shown in Fig. 8 through 11 are logic diagrams for several important subroutines. The method of solution used in the main program is summarized in the following paragraphs.

Input data required are: (1) tables of propellant and combustion gas properi:es, (2) properties of the equilibrium combustion gas at stagnation conditions, (3) miscellaneous program control information, (4) case information data. The input data are printed as tiney are read by the program, which permits a full documentation of the computer run conditions.

The input data are used in an initialization section to calculate a number of program variables which include updating the stagnation equilibrium combustion gas properties (CGTBI2), defining the cross-sectional area as a function of axial distance (AVAR or AVARP), and velocities and properties (INIR) at the start plane. Initialized data are printed out before entering the main computational iteration loop.

The main computational loop solves the model iterations at each axial position using sequential marching numerical methods. At each axial location, the liquid jet stripping rate and mean droplet size generated by the stripping are calculated based upon the local combustion gas velocity and combustion gas properties (ATØM); a new spray droplet size group is initiallized from these local data. Droplet acceleration (DRAG), heating, and vaporization (DINS) are then calculated for each droplet group present in the combustion


Figure 7. CICM Main Program Flow Chart


Figure 7. CICM Main Program Flow Chart (cont)


Figure 8. Subroutine CGAT Flow Chart


Figure 8. Subroutine CGAT Flow
Chart (cont)


Figure 3. Subroutine CGAT Flow Chart (cont)


Figure 9. Subroutine DHVS Flow Chart


Figure 10. Subroutine zran flow Chart


Figure 11. Subroutine FDTDX Flow Chart


Figure 11. Subroutine FDTDX Flow Chart (cont)
gas. A portion of the "Rigimesh" gas is then mixed into the combustion gas and downstream gas velocities and properties are calculated based upon the total droplet vaporization rate, amount of "Rigimesh" gas added, and the cross-sectional area (CGAT). Initialization of parameters for the next step is then perfrmed (INIW) and, at selected axial locations, complete gas and propellant spray group data are printed (øUTPUT).

Upon completion of the main iteration loop, if the case was a cup calculation, the program then checks to see if the cup exit pressure is within a tolerance (which is input) of the chamber pressure. If the cup exit pressure is outside the tolerance, the case is rerun with a new estimated cup delta pressure. If the cup exit pressure is within the tolerance and the case is a coupled cup/ chamber calculation, the calculated cup exit conditions are used as initial conditions for the chamber calculation along with chamber information (INCHA). Also, if the DER option was specified in the input, cup exit conditions are saved on a scratch tape (ØUTCUP). If the case is not a coupled cup/chamber calculation, the program branches to a read location specified by the variable IREAD to begin a new case or terminates the calculations.

If the DER option was specified, spray and gas data are saved ( $\varnothing$ UTDER) on a scratch tape unit. If all the DER zones have not been executed, the program branches to the case input statements to read in new zone data. If all the $D E R$ zones have been executed, the program checks to see if each chamber case was continued to the axial position required for $D E R$ punched card output. If any of the zone chamber cases was terminated before reaching the axial position required for $D E R$ punshed card output, the program recalculates these
zone chamber cases (INCUP). Upon completion of all zone calculations, the program calculates the DER punched card information (DERINI), punches the DER cards, and lists the DER punched card output. The program then branches to a read location specified by the variable IREAD to begin a new case or terminates the calculations.

The version of CICM described in this report consists of a main or calling program together with 33 subroutines. A listing of the CICM program, together with its subprograms and function routines, is shown in Appendix $A$.

This subroutine calculates the portion of the liquid jet that is atomized over one axial computational increment. A droplet spray group is calculated, and the initial weight flow rate and initial mean droplet diameter of the group are determined.

In this subroutine, the cross-sectional area per injection element is calculated at each axial computational step for an axisymmetric combustion chamber.

In this subroutine, the cross-sectional area per injection element is calculated at each axial computation step for a combustion chamber specified by a table of areas at specific axial distances.

In this subroutine, the portion of the "Rigimesh" flow which is mixed with the combustion gas stream is calculated. Combustion gas properties are reevaluated as a function of local mixture ratio. Division of the constrained area between the liquid jet, combustion gas, and "Rigimesh" streams are solved iteratively.

In this subroutine, the combustion gas stagnation temperature and properties are calculated from tabulated values and the local mixture ratio of burned propellants. Droplet and non-reacted liquid vapor energies are subtracted from the tabulated stagnation temperatures.

CGTBIN In this subroutine, the stagnation equilibrium combustion gas properties are read into program as a function of mixture ratio.

CGTBI2 Subroutine entry point in CGTBIN which adjusts properties read by CGTBIN for changes in propellant inlet energy.

CPLF In this subroutine, the liquid specific heat is obtained by a a double interpolation of values tabulated as a function of pressure and temperature.

CUBIC In this subroutine, the real roots, and the number of them, are determined fron the coefficients of a cubic equation.

DERINI This subroutine is used, if the option is selected for DER output, to recall data from a scratch data set. Spray droplet groups and gas flows are setup and parameters punched out for initial vaiues to each stream tube in DER.

DHVS In this subroutine, the heating and vaporization of each spray drop group are calculated with the support of several subroutines.

DINTRP In this subroutine, a linear double interpolation is performed using points and slopes which have been previously determined in subroutine LØCFAC.

DRAG

EQSTAT

FDTDX

FGPR $\emptyset P$ In this subroutine, mean droplet film physical properties and film diffusivity are calculated for subprograms FDTDX and DHVS.

FT This function subprogram is used by subroutine DHVS, which also transmits it to subroutine ZERD, for determining the value of a function based on a predicted value of droplet temperature. This function goes to zero when the correct droplet temperature is found. The bulk of the calculations performed by FTare done in its subprogram FDTDX.

HEAD This subroutine prints a header page to identify the computer program.

INCHA

LøCFAC In this subroutine, the location of the first of two sequential values in an array which bracket a specified value are found, and a scale factor, $\left(X-x_{1}\right) /\left(x_{2}-x_{1}\right)$, is calculated. The values in the array must be arranged in either ascending or descending order, and the validity of the order is checked if the option is specified.

ØUTCUP This subroutine causes cup exit conditions from an injector cup element analysis to be stored on a scratch data set.

QUTDER If the option is sclected for DER punched output, this subroutine causes spray and gas fiow data to be saved on a scratch data set for processing at the end of the job.

ØUTPUT This subroutine causes the solution at specified axial locations to be printed. This is the primary output routine of CICM.

RHØGF In this subroutine, the gas density is calculated. A compressibility factor is used, which is obtained by a double interpolation of values tabulated as functions of temperature and pressure.

STLF In this subroutine, the liquid surface tension is determined by performing a double interpolation of tabulated values as a function of temperature and pressure.

TABIN This subroutine causes the propellant liquid and vapor physical property tables to be read into the program and printed out, if the option is specified.

VISiF In this subroutine, liquid viscosity is obtained by a double interpolation of values tabulated as functions of pressure and temperature.

In this subroutine, the mole fraction of vapor at the droplet surface, heat of vaporization, and Redlich-Kwong $A$ and $B$ parameters are obtained by interpolation of tabulated values.

In this subroutine, droplet temperature is found, starting with upper and lower limits, by successive solutions of a function of droplet temperature with subprogram FT being used. The final value of the function must approach zero. If the primary numerical solution is unable to converge on a solution, a secondary numerical solution is automatically reverted to which has better numerical stability, but is less accurate than the primary numerical method.

Specific input data for the CICM computer program are listed in Tables 1, 2, 3, and 4, which have been structured in the format of a typical input punched-card data deck. The input consists of blocks of cards describing the propellant and combustion gas, stagnation equilibrium combustion gas, control data, and case data. In these tables, the "CARD NO." is a suggested card identification number (punched in columns 73-80) which is consistent with sequence numbers on the sample data cards listed in Appendix $B$. Where ranges of ID sequence numbers are given, consecutive integers are implied. (Note that the different blocks of the CICM program input data deck so sequenced should not be sorted with each other, as there is overlap and/or duplication of sequence numbers hetween these blocks.)

The "FORMAT" in the tables of input instructions denotes the type of FORTRAN input (integer, floating point derimal, alpha-numeric) and the subdivision of each card's first 72 columns into fields. Standard FORTRAN input formats are used. Specifically used are:Comment cards (A-format)18A4Integer variables with variable names beginning withletters $I$ through $M$ (no decimal points, 12 space fieldwidths, last digit in last space of field, 6 consecutivevalues per card until READ statement is finished).

TABLE 1 . INSTRUCTIONS FOR PROPFLLANT AND COMBUSTION GAS INPUT DATA

| and lo. $\therefore \because 0.0 \leq T$ | Vaciable <br> CODE | DESCRIPTION |
| :---: | :---: | :---: |
| $\begin{aligned} & 10 \\ & (6 I 12) \end{aligned}$ | IPTAB | Print control integer: " 0 " to suppress printout, " 1 " to print out table of propellant properties. |
|  |  | Cards 20-264: input oxidizer droplet mele fraction, heat of vaporization, ana Redlich-Kwong equation of ztate parameters. |
| $\begin{aligned} & 20 \\ & (6 I 12) \end{aligned}$ | NPTP (1) | Number of pressures in oxidizer mole fraction table. Limit: 2 to 30. |
|  | NPTP (2) | Required to be zero(0) |
|  | NPTT (1) | Number of temperatures in oxidizer mole fraction table. <br> Limit: 2 to 20. |
|  | NPTT (2) | Required to be zero (0) |
| $\begin{aligned} & 30,31, \text { etc. } \\ & (6 E 12.8) \end{aligned}$ | $\begin{aligned} & \mathrm{TP}(I, 1) \\ & \mathrm{I}=1, \operatorname{NPTP}(1) \end{aligned}$ | Pressure array in ascending order for oxidizer table. <br> Units: psia |
| 40,41, etc. | $\begin{aligned} & \operatorname{TT}(I, 1) \\ & I=1, \operatorname{NPTT}(1) \end{aligned}$ | Temperature array in ascending order for oxidizer table. Units: ${ }^{\circ} \mathrm{R}$ |
| $\begin{aligned} & 50,51, \text { etc. } \\ & (6 E 12.8) \end{aligned}$ | $\begin{aligned} & (\operatorname{TXV}(I, K, 1) \\ & I=1, \operatorname{NPTP}(1)), \\ & K=1, \operatorname{NPTT}(1) \end{aligned}$ | Mole fraction of oxidizer vapor at surface of oxidizer droplet. <br> Array of values at each pressure must be entered for each temperature. <br> Enter NPTP(1)xNPTT(1) number of values, 6 per card with no embedded blank fields. |
| $\begin{aligned} & 150,151, \mathrm{etc} \\ & (6 E 12.8) \end{aligned}$ | $\begin{aligned} & (\operatorname{TDHV}(I, K, 1) \\ & I=1, \operatorname{NPTP}(1)), \\ & K=1, \operatorname{NPTT}(1) \end{aligned}$ | Ox: dizer heat of vaporization. Units: BTU/ 1 bm Muitiple arrays using same order as for cards 50, etc. |
| 250, 251, etc | $\begin{aligned} & \operatorname{TA}(I, 1) \\ & I=1, \operatorname{NPTT}(1) \end{aligned}$ | Redlich-Kwong parameter "a" array used in the equation of state for oxidizer. Units: $f t^{4}-R^{1 / 2} / 1 \mathrm{bm}$. |
| $\begin{aligned} & 260,261, \text { etc } \\ & (6 E 12.8) \end{aligned}$ | $\begin{aligned} & \mathrm{TB}(I, 1) \\ & I=1, \mathrm{NPTT}(1) \end{aligned}$ | Redlich-Kwong parameter, " $b$ " array used in the equation of state for oxidizer. Units: $\mathrm{ft}^{3} / \mathrm{lbm}$ |
|  |  | Cards 570-737: input oxidizer liquid heat capacity and oxidizer liquid enthalpy |
| $\begin{aligned} & 570 \\ & (6 I 12) \end{aligned}$ | NPCP (1) | ```Number of pressures in liquid oxidizer table. Limit: 2 to 20 Required to be 22ro(0) Number of temperatures in oxidizer table. Limit: 2 to 20 Required to be zero(0)``` |
|  | NPCP (2) |  |
|  | NTCP(1) |  |
|  | NTCP (2) |  |
| $\begin{aligned} & 580,581, \text { etc } \\ & (6 E 12.8) \end{aligned}$ | $\begin{aligned} & \operatorname{TPCPL}(K, 1) \\ & K=1, N P C P(1) \end{aligned}$ | Pressure array in ascending order for oxidizer table. <br> Units: psia |

TARTF 1. INSTRUCTIONS FOR PROFELIANT ANI
COMRIISTION GIAS INTITT DATA (COHT.)

| $\left.\left\lvert\, \begin{array}{ccc} \cdots & \cdots & \ddots \\ \because & \because & \ddots \end{array}\right.\right]$ | $\because \because \mathrm{OL}$ <br> COH | Drecination |
| :---: | :---: | :---: |
| $\begin{aligned} & 590,591, \text { etc. } \\ & (6512.8) \end{aligned}$ | $\begin{aligned} & \operatorname{TTCPL}(K, 1) \\ & K=1, \operatorname{NTCP}(1) \end{aligned}$ | Temperature in ascending order for oxidizer tahie. Units: ${ }^{\circ} \mathrm{R}$ |
| $\begin{aligned} & 600,601, \text { etc. } \\ & (65.12 .8) \end{aligned}$ | $\begin{aligned} & (\operatorname{TCP}(I, K, 1) \\ & K=1, \operatorname{NTCP}(1)), \\ & I=1, \operatorname{NPCP}(1) \end{aligned}$ | Specific heat at constant pressure uf liquic oxidizer. Units: BTU/lbm-R. An array of values corresponding with temperature array must be entered to correspond with each pressure. Enter NYCP (1) xNTCP (1) number of values, 6 per card. Do not skip any fields. |
| $\begin{aligned} & 670,671 \text {, etc. } \\ & \text { (6F12.8) } \end{aligned}$ | $\begin{aligned} & (\operatorname{THดL}(I, K, 1) \\ & K=1, \operatorname{NTCP}(1)), \\ & 1-1, \operatorname{NFCP}(1) \end{aligned}$ | Enthalpy of liquid oxidizer. Units: BTU/lbm Multiple arrays using same input order as cards 600, etc. |
|  |  | Cards 940-1477: input tables of oxidizer and fuel vapor properties in which values of three dependent variables correspond with the same temperature array and at various pressure levels. |
| $\begin{aligned} & 940 \\ & (6,12) \end{aligned}$ | NPV(1) | Number of pressures for oxidizer vapor tables. limit: 2 to 20. |
|  | NPV (2) | Number of pressures for fuel vapor table. limit: 0 to 20 |
|  | NTV (1) | Number cí temperatures in oxidizer vapor tahle. <br> Limit: 2 to 20 |
|  | NTV (2) | Number of temperatures in fuel vapor tahle. <br> Limit: 0 to 20 |
| $\begin{aligned} & 950,951, \text { etc } \\ & (6 E 12.8) \end{aligned}$ | $\begin{aligned} & \operatorname{TPV}(K, 1) \\ & K=1, N P V(1) \end{aligned}$ | Pressure array in ascending order for oxidizer vapor table. Units: psia |
| $\begin{aligned} & 960,961, \text { etc } \\ & (6: 12.8) \end{aligned}$ | $\begin{aligned} & \operatorname{TTV}(K, 1) \\ & K=1, \operatorname{NTV}(1) \end{aligned}$ | Temperature array in ascending order for oxidizer vapor table. Units: $R$ |
| $\begin{aligned} & 970,976, \text { etc } \\ & (6 F 13,8) \end{aligned}$ | $\begin{aligned} & (\operatorname{TCPV}(K, 1,1) \\ & 1=1, \operatorname{NTV}(1)), \\ & K=1, \operatorname{NrV}(1) \end{aligned}$ | Specific heat at constant pressure for oxidizer vapor. Units: BTU/lbm. An array of values corresponding with temperature array must be entered to correspond with each pressure level. Do not ship any fields. |
| $\begin{aligned} & 1040,1041 \\ & \text { ctc: } \\ & (6 E 12.8) \end{aligned}$ | $\begin{aligned} & (1=1 / N(K, I, 1) \\ & I=1, N I V(1)), \\ & K=1, N P V(1) \end{aligned}$ | Viscosity of oxidizer vapor. Uifts: $1 \mathrm{bm} / \mathrm{ft}$-sec. Multiple arrays using same anput order as for cards 070 , etc. |
| $\begin{aligned} & 1110,1111 \\ & \text { etc } \\ & (6 E: 2.8) \end{aligned}$ | $\begin{aligned} & \left(T H \emptyset V^{\prime}(K, 1,1)\right. \\ & I=1, N \operatorname{NV}(1)), \\ & K=1, N P V(1) \end{aligned}$ | Enthalpy of oxidizer vapor. Units: BTU/lbm. Multiple arrays using same input order as for cards 970,etc. |
|  |  | Onait cards 1250-1477 if NTV (2) $=1$. |

TABLE 1. INSTRUCTIGNS FOR PROPELLANT AND COMBUSTION GAS INPUT DATA (COnt.)

| C.MRD NO. ; Ponelt | $\begin{aligned} & \text { VARIABLE } \\ & \text { CODE } \end{aligned}$ | DESCRIPTION |
| :---: | :---: | :---: |
| $\begin{aligned} & 1250,1251 \\ & \text { etc. } \\ & \left(6 F_{2}, 8\right) \end{aligned}$ | $\begin{aligned} & \operatorname{TPV}(K, 2) \\ & K=1, \operatorname{NPV}(2) \end{aligned}$ | Pressure array in ascending order for fuel vapor table. Units: psia |
| $\begin{aligned} & 1: 60,1261 \\ & \text { etc. } \\ & (6 E 12.8) \end{aligned}$ | $\begin{aligned} & \operatorname{TTV}(K, 2) \\ & K=1, \operatorname{NTV}(2) \end{aligned}$ | Temperature array in ascending order for fuel vapor table. Units: ${ }^{\circ}$ R |
| $\begin{aligned} & 1270,1271 \\ & \text { etc. } \\ & (6 \mathrm{E} 12.8) \end{aligned}$ | $\begin{aligned} & (T C P V(K, I, 2) \\ & I=1, N T V(2)), \\ & K=1, \operatorname{NPV}(2) \end{aligned}$ | Specific heat at constant pressure for fuel vapor. Units: BTU/lbm. Multiple arrays using input order per card 970, etc. |
| $\begin{aligned} & 1340,1341 \\ & \text { otc. } \\ & (6 \mathrm{E} 12.0) \end{aligned}$ | $\begin{aligned} & (\operatorname{TMUV}(K, I, 2) \\ & I=1, \operatorname{NTV}(2)), \\ & K=1, \operatorname{NPV}(2) \end{aligned}$ | Viscosity of fuel vapor. Units: BTU/lbm. <br> Multiple arrays using input order per card 970 ,etc. |
| $\begin{aligned} & 1410,1411 \\ & \text { etc. } \\ & (6 E 12.8) \end{aligned}$ | $\begin{aligned} & (T l i \emptyset V(K, I, 2) \\ & I=1, \operatorname{NTV}(2)), \\ & K=1,1, \operatorname{NPV}(2) \end{aligned}$ | Enthalpy of fuel vapor. nits: BTU/lbm. Multiple arrays using input order per card 970 ,etc. |
|  |  | Cards 1500-1554: input oxidizer tables of diffusion parameters. |
| $\begin{aligned} & 1500 \\ & (6 I 12) \end{aligned}$ | NTDF (1) NTDF (2) | Number of temperatures in the oxidizer table. Limit: 2 to 20. <br> Required to be zero( 0 ) |
| $\begin{aligned} & 1510,1511 \\ & \text { etc. } \\ & (6 E 12.8) \end{aligned}$ | $\begin{aligned} & \operatorname{TTDIF}(I, 1) \\ & I=1, \operatorname{NTDF}(1) \end{aligned}$ | Temperature array in ascending order for oxidizer table Units: $R$ |
| $\begin{aligned} & 1520,1521 \\ & \text { ctc. } \\ & (6: 12.8) \end{aligned}$ | $\begin{aligned} & \operatorname{TDIFF}(I, 1,1), \\ & I=1, \operatorname{NTDF}(1) \end{aligned}$ | Oxicizer binary diffusior parameter array (see page 86) for specie to stoichiometric sombustion products. <br> Units: $\mathrm{ft}^{2} / \mathrm{sec}$ |
| $\begin{aligned} & 1530,1531 \\ & \text { etc. } \\ & \text { ( } 6: 12.8 \text { ) } \end{aligned}$ | $\begin{aligned} & \operatorname{TDIFF}(1,2,1) \\ & I=1, \operatorname{NTDF}(1) \end{aligned}$ | Oxi,izer binary diffusion parameter array for specie to fuel. Units: $\mathrm{it}^{2} / \mathrm{sec}$ |
| $\begin{aligned} & 1540,1541 \\ & \text { ctc. } \\ & (6 \mathrm{E} 12.8) \end{aligned}$ | $\begin{aligned} & \operatorname{TDIFF}(1,3,1) \\ & I=1, \operatorname{NTCr}(!) \end{aligned}$ | Oxidizer binary diffusion parameter array for specie to oxidizer. Units: $\mathrm{ft}^{2} / \mathrm{sec}$. |
| $\begin{aligned} & 1550 \\ & (6 E 12.8) \end{aligned}$ | $\begin{aligned} & (\operatorname{TPRF}(1, K) \\ & K=1,3), \\ & (\operatorname{TTRF}(1, K) \\ & K=1,3) \end{aligned}$ | Reference prossures used with the three corresponding oxidizer hinary diffusion parameters. Urits: psia Reference remperatures used with the three corresponding oxidizer bindary diffusi: $n$ parameters. Unies: ${ }^{\circ}$ R |


| $\begin{aligned} & \because \vdots . \\ & \because \because \ldots \\ & \because \end{aligned}$ | $\begin{gathered} \text { Mo, } B L E \\ \text { Co, }: \end{gathered}$ | LHSCRIITIOS |
| :---: | :---: | :---: |
| $\begin{aligned} & 1(1010 \\ & (6 F 12.8) \end{aligned}$ | PCRIT(1) | Critical pressure of oxidizer. Units: psia. |
|  | TCRI . (1) | Critical temperature of oxidizer. Units: R |
|  | FMWL (1) | Nolecular weight of oxidizer as liquid. Units:lbm/ lb-mole |
|  | Eawl (1) | Molecular weight of oxidizer as vapor. Units: $1 \mathrm{bm} /$ 1b. mole |
| $\begin{aligned} & 1620 \\ & (6 E 12.8) \end{aligned}$ | PCRI' ${ }^{(2)}$ | Critical pressure of fuel. Units: psia |
|  | TCRIT (2) | Critical temperature of fuel. Units: R |
|  | EMNL (2) | Molecular weight of fuel as Molecular weight of fuel as vapor. Inits: $1 \mathrm{bm} / 1 \mathrm{~h}-\mathrm{mole}$ |
|  | EMWV (2) | Molecular weight of fuel as vapor. |
| $\begin{aligned} & 1630 \\ & \text { (6F:12.8) } \end{aligned}$ | STØCMR | Stojchiometric mixture ratio |
|  | Friwl'r | Molecular weight of products at STDCMR. <br> Units: $1 \mathrm{hm} / 1 \mathrm{~b}-\mathrm{mole}$ |
|  |  | Cards 1640-2254: input table of combustion gas properties with mixture ratio and temperature as the independent variables. This table is used to detemine droplet film properties at the mean temperature between the droplet and free stream gas |
| $\begin{aligned} & 1640 \\ & (6112) \end{aligned}$ | NMRCCF | Number of mixture ratio levels Limit: 2 to 20 |
|  | NTCGF | Nunber of temperatures at each mixture ratio level. <br> i.imit: $2 t, 20$ |
| $\begin{aligned} & 1650,1651 \\ & \operatorname{ctc} \cdot(6 E 12,8) \end{aligned}$ | [MRCGF (1) | Mixture ratio array in ascending order. |
|  | $1=1, \operatorname{NMRCGF}$ |  |
| $\begin{aligned} & 1660,1661 \\ & \text { etc. }(6 \mathrm{E} 12.8) \end{aligned}$ | $\begin{aligned} & \operatorname{TTCGF}(\mathrm{I}) \\ & \mathrm{I}=1, \mathrm{NTCGF} \end{aligned}$ | Temperature array in ascending order. Units: ${ }^{\circ} \mathrm{R}$ |
| $\begin{aligned} & 1670,1671 \\ & \text { etc. }(6 \mathrm{~F} 12.8) \end{aligned}$ | $\begin{aligned} & \operatorname{TMWCGF}(1, \mathrm{~J}), \\ & . j=1, \mathrm{NTCGF} \end{aligned}$ | Molecuiar weight array for combustion gas at the first mixture ratio level and corresponding with TTCGF array. <br> Units: $1 \mathrm{bm} / 1 \mathrm{~b}$-mole |
| $\begin{aligned} & 1680,1681 \\ & \text { etc. }(6 \mathrm{~F} 12.8) \end{aligned}$ | $\begin{aligned} & \text { TMUCGF }(1, \mathrm{~J}) \\ & \mathrm{J}=\mathrm{J}, \mathrm{NTCGF} \end{aligned}$ | Viscosity array for combustion gas at the first mixture ratio levcl and corresponding with TTCGF array. Units: $1 \mathrm{bm} / \mathrm{ft}-\mathrm{sec}$. |
| $\begin{aligned} & 1690,1691 \\ & \text { etc. } \\ & (6 \mathrm{~F} 12.8) \end{aligned}$ | $\begin{aligned} & \operatorname{TCFCGF}(1, \mathrm{~J}) \\ & \mathrm{J}=1, \operatorname{NTCGF} \end{aligned}$ | Specific heat array for combustion gas at the first mixture ratio level and corresponding in order with TTCGF. Units: BTU/lbm-R |
| $\begin{aligned} & 1700,1701 \\ & \text { etc. }(6 E 12.8) \end{aligned}$ | TMNCGF (2,J), J=1, NTCGF | Repeat arrays of TMNCGF, TMWCGF and TMUCGF for each mixture |
| 1 | 1 |  |
| 1 | 1 |  |


|  | variable CODE | DESCRIPTION |
| :---: | :---: | :---: |
| etc. | etc. | Unit conversion options: <br> If $\operatorname{TMUCGF}(1,1)$ is negative then the TMUCGF array is divided by 3600 . <br> If $\operatorname{TMUCGF}(1,2)$ is negative, then the TMUCGF array is multiplied by 32.16 . |
|  |  | Cards 2260-2427: input tables of oxidizer liquid surface tension and viscosity as functions of temperature and pressure. |
| $\begin{aligned} & 2260 \\ & (6 \mathrm{I} 12) \end{aligned}$ | NPST(1) <br> NPST(2) <br> NTST (1) <br> NTST (2) | Number of pressures in oxidizer table. Limit: 2 to 20. <br> Required to be zero ( 0 ) <br> Number of temperatures in oxidizer table. Limit: 2 to 20 <br> Required to be zero ( 0 ) |
| 2270, 2271 | $\operatorname{TPST}(K, 1)$ <br> $K=1$ NPST(1) | Pressure array in ascending order for liquid oxidizer. Units: $1 \mathrm{bf} / \mathrm{in} .^{2}$. |
| etc. (6E12.8) | $\mathrm{K}=1, \mathrm{NPST}(1)$ | Units: lbf/in. ${ }^{2}$. |
| 2280,2281 | $\operatorname{TTST}(\mathrm{K}, 1)$ | Temperature array in ascending order for liquid. |
| etc. (6E12.8) | $\mathrm{K}=1, \mathrm{NTST}$ (1) | Units: R. |
| 2290,2291 | (TST ( $\mathrm{I}, \mathrm{K}, 1$ ) | Oxidizer liquid surface tension. Units: lbf/ft. |
| etc. (6E12.8) | $\begin{aligned} & \mathrm{K}=1, \operatorname{NTST}(1)), \\ & \mathrm{I}=1, \operatorname{NPST}(\mathrm{I}) \end{aligned}$ | An array of values corresponding with temperature array must be entered to correspond with each pressure level. Do not skid fields. |
| $\begin{gathered} 2360,2361 \\ \text { etc. }(6 \mathrm{E} 12.8) \end{gathered}$ | (TVISL (I, K, 1) | Oxidizer liquid viscosity. Units: $1 \mathrm{bm} / \mathrm{ft}-\mathrm{sec}$ |
|  | $\begin{aligned} & \mathrm{K}=1, \operatorname{NTST}(1)), \\ & \mathrm{I}=1, \operatorname{NPST}(1) \end{aligned}$ | Multiple arrays using same input order as cands 2290, etc |
|  |  | Cards 2600-2687: input tables of fuel compressibility factor as a function of temperature and pressure. |
| $\begin{aligned} & 2490 \\ & (6 \mathrm{I} 12) \end{aligned}$ | NP2(1) | Required to be zero (0) |
|  | NPZ ${ }^{\text {(2) }}$ | Number of pressures in fuel table. Limit: 2 to 20. |
|  | $\begin{aligned} & \text { NTZ (1) } \\ & \text { NTZ (2) } \end{aligned}$ | Required to be zero (0) <br> Number of temperatures in fuel table. Limit: 2 to 20. |
| $\begin{gathered} 2600,2601 \\ \text { etc. }(6 E 12.8) \end{gathered}$ | TPZ ( $\mathrm{K}, 2$ ) , | Pressur. array in ascending order for fuel. |
|  | $\mathrm{K}=1, \mathrm{NPZ}(2)$ | Units: psia |
| $\left\lvert\, \begin{gathered} 2610,2611 \\ \text { etc. }(6 \mathrm{E} 12.8) \end{gathered}\right.$ | TTZ (K, 2) | Temperature values in ascending order for fuel. |
|  | $\mathrm{K}=1, \mathrm{NTZ}$ (2) | Units: R |
| $\left\lvert\, \begin{gathered} 2620,2621 \\ \text { etc. }(6 \mathrm{E} 12.8) \end{gathered}\right.$ | (TZ (I, K, 2) | Compressibility factor of fuel. An array of values cor- |
|  | $\begin{aligned} & \mathrm{K}=1, \mathrm{NTZ}(2)), \\ & \mathrm{I}=1, \mathrm{NPZ}(2) \end{aligned}$ | ponding with temperature array must be entered to corpond with each pressure value. Do not skip fields. |

TARLE 2 ．INSTRUCTTONS FOR STAGNATION EOIITIIRRTIMM COMBISTIION CAS INPUT IAATA

|  | VAETAILE CODE | MSSCPIPIION |
| :---: | :---: | :---: |
|  |  | Combustion gas properties are entered as dependent variables of propellant $0 / F$ weight mixture ratio at a pressure roughly near the case chamber pressure． <br> Fach card contains a mixture ratio followed with corres－ ponding values of the dependent variables． <br> Cards must be entered in order of ascending values of mixture ratio． |
| $\begin{aligned} & 5 \\ & (6112) \end{aligned}$ | NTAB | Number of mixture ratio values．Limit： 2 to 18. |
| $\begin{aligned} & 10 \\ & (5 \mathrm{~F} 12.8) \end{aligned}$ | $\operatorname{TMR}(1)$ <br> TTG（1） <br> TMW（1） <br> TGAM（1） <br> TVIS（1） | ```Propellant O/F weight mixture ratio Combustion temperature. Units: }\mp@subsup{}{}{0}\mp@subsup{\mathbf{R}}{R}{ Nolecular weight. Units: lbm/lb-mole Frozen specific heat ratio Viscosity. Units: lhm/ft-sec``` |
| $\begin{aligned} & 180 \\ & (5 E 12.8) \end{aligned}$ | $\begin{aligned} & \operatorname{TMR}(18) \\ & \operatorname{TTG(18)} \\ & \operatorname{TMW}(18) \\ & \operatorname{TGAM}(18) \\ & \operatorname{TVIS}(18) \end{aligned}$ | Enter NTAR number of cards |
|  |  | Options：If sign on TTG（1）is negative，TTG array is multiplied by 1.8. <br> If sign on TVIS（1）is negative，TVIS array is divided by 3600 ． <br> NOTE：Values from this Table are modified during com－ puter execution to allow for differences in propellant injection energy from those assumed in Table to those in a specific analysis． |

\begin{tabular}{|c|c|c|}
\hline Cand 10. ¢ Foncta \& VARIABLE CODE \& DESCRIDTION <br>
\hline \multirow[t]{2}{*}{$$
\begin{aligned}
& 10 \\
& (1,112)
\end{aligned}
$$} \& IDER
ICUPC

NCHAMC
M2C

NCØN4C \& | Control indicator: value $\leq 0$ to bypass DER option; value $>0$ for number of injector fiow zones analyzed |
| :--- |
| Control indicator: value of " $O$ " for one cup or a chamber calculation, value of "I" for both cup and chamber calculations. If IDER $>0$, program sets ICUPC $=1$. |
| NOTE: If IDER $=0$ and ICUPC $=0$, then $\mathrm{NCHAMC}, \mathrm{M2C} \mathrm{and}$ NCØN4C are ignored. |
| Control indicator for type of chamber geometry input: value of " 0 " for conventional geometry (card 50), or an integer for the size of a cross-sectional area array (card 60, 61, etc.) |
| Print control indicator: solution printed at calculation step intervals of M2C. |
| Print control indicator to fnrce printul of each step for first NC $\varnothing \mathrm{N} 4 \mathrm{C}$ chamber calculations. | <br>

\hline \& \& Include cards 30-60 only if either IDER or ICUPC $>0$. This card group is used to define chamber parameters when the computer run includes the analyses of both injector element cup(s) and chamber. <br>

\hline \[
$$
\begin{aligned}
& 30 \\
& (6 E 12.8)
\end{aligned}
$$

\] \& | WGJC |
| :--- |
| EMRGJC |
| STGJC |
| EMWGJC |
| GAMGJC |
| XLMC | \& | Total chamber "rigimesh" (or gas mantle) flowrate at injector face. Units: $1 \mathrm{bm} / \mathrm{sec}$. |
| :--- |
| Weight mixture ratio (oxidizer/fuel) of WGJC flow. Stagnation temperature of WGJC. Units: ${ }^{\circ} R$. |
| Molecular weight of WGJC. Units: $1 \mathrm{bm} / 1 \mathrm{~b}$-mole. |
| Specific heat ratio, $\gamma$, of WGJC. |
| Length of mixing region. Rigimesh flow is mixed into the combustion region linearly over this region. Units: in. | <br>

\hline \multirow[t]{4}{*}{$$
\begin{aligned}
& 40 \\
& (6 \mathrm{E} 12.8)
\end{aligned}
$$} \& DELTXC \& Axial step size for chamber calculations, Units: in. Rerommended value $=0.05 \mathrm{in}$. <br>

\hline \& BSPRC \& Droplet formation size parameter in chamber.* Recommended value $=120.0$ <br>
\hline \& CSPRC \& Liquid jet stripping rate parameter in chauber.* Recommended value $=0.08$ <br>
\hline \& XMINDE \& Minimum axial distance for DER punch card output (not required if $I D E R \leq 0$ ). Units: in. <br>

\hline \multirow[t]{3}{*}{\[
$$
\begin{aligned}
& 50 \\
& (6 \mathrm{E} 12.8)
\end{aligned}
$$

\]} \& ACSC \& | Incinde card 50 only if $\mathrm{NCHAMC}=0$. |
| :--- |
| Cross-sectional area of chamber at the injector end. Units: sq. in. | <br>

\hline \& CLNTC \& Chamber length from injector face to the throat plane. Units: in. <br>
\hline \& CONRAC CCANGC \& Chamber contraction ratio (area of chamber/area throat). Nozzle angle of convergence. Units: degrees <br>
\hline
\end{tabular}

TARLE 3. INSTRICTTONS FOR CONTROI INIUT DATA (CONCl B BI)

|  | $\begin{gathered} \because \quad \text { inele } \\ \text { CODE } \end{gathered}$ | DESCPIPTION |
| :---: | :---: | :---: |
| 50 <br> (Cont.) <br> 60, 61, etc. (6E12.8) | RCRCC RCTC XCILAMC (1) ACHAMC (1) XCHAMC (2) ACHMCC (2) 1 1 1 etc. | Wall radius of curvature at beginning of nozzle convergence. Units: in. <br> Wall radius of curvature entering throat. Units: in. <br> Include these cards only if NCHAMC $>0$. <br> First value in array of axial distances from injector face for specifying chamber geometry. Units: in. <br> First value in array of chamber cross-sectional areas corresponding with position XCHAM(1). Units: sq.in. Enter NCHAMC pairs of values, 3 per card with XCHAMC $i_{1}$ : ascending order |

TABLE 4 . INSTRUCTIONS FOK CASE indut data


| Cind : 0 <br> $\therefore$ FOEDT | VARIABLE CODE | DESCRIPTION |
| :---: | :---: | :---: |
| 130 (cont.) | TFXPGL | Control indicator for expansion around liquid post for cup calcul"tion only)* <br> " 1 " constant gas expansion <br> " 2 " 1iquid and gas expansion <br> "3" liquid expansion and gas contraction <br> Recommended: IEXPGL $=3$ |
|  | IATめ | Atomization control indicator. Fnter value of "l". |
| $\begin{aligned} & 140 \\ & (6 \mathrm{~F}, 12.8) \end{aligned}$ |  | Include card 140 only if $\mathrm{NCHAM}=0$. |
|  | ACSI | Cross-sectional area of injector cup or chamber at upstream end. Units: sq. in. |
|  | CLNT | Injector cup or chamber length. Units: in. |
|  | CONRAT | Area ratio of injector cup or chamber: ACSI over cup exit or nozzle throat area. |
|  | CCANG | Angle of convergence: for cup, a negative value specifies angle of divergence; for chamber, value is nozzle angle of convergence. Units: degrees. |
|  | RCBC | Wall radius of curvature leading into convergent section. Units; in. For cup, set $\mathrm{RCBC}=0$. |
|  | RCT | Wall radius of curvature entering nozzle throat. Units: in. For cup, set RCT $=0$. |
| $\begin{aligned} & 150,151, \text { etc. } \\ & (\text { GE12.8) } \end{aligned}$ |  | Include th se cards only if NCHAM $>0$. |
|  | XCHAM (1) | First value in array of axial distances from the beginning of either injector cup for cup analysis or injector face for chamber analysis. Units: in. |
|  | ACHAM (1) | First vaiue in array of cross-sectional areas corresponding with position XCHM(1). Units: sq. in. |
|  | $\begin{aligned} & \text { XCHAM (2) } \\ & \text { АCHAM (2) } \end{aligned}$ | Enter NCHAM pairs of values, 3 per card, with XCHAM in ascending order. |
|  |  |  |
|  | etc. |  |
| $\begin{aligned} & 160 \\ & (6 \mathrm{E} 12.8) \end{aligned}$ | WCGI | Flowrate per element of gas stream surrounding liquid jet at start position of case. Units: $1 \mathrm{bm} / \mathrm{sec}$. |
|  | EMRCGI | Weight mixture ratio ( $0 / F$ ) of WCGI. |
|  | ACGI | Initial cross-sectional flow area of WCGI. Units: sq.in. Weight mixture ratio of gas in manifold. EMRII = ENRCG! |
|  |  | when gas is fully reacted at start position of case. Stagnation temperature of WCGI at a reference mixture ratio AMRT. Units: ${ }^{\circ} R$ |
|  | AMRT | Reference weight mixture ratio for WCGI temperature of STT. |

*See text page 22 for descri; ion.

| Cand do. $\mathrm{C}_{\mathrm{F}}$ :ORNT | variable CODE | DESCRIPTION |
| :---: | :---: | :---: |
| $\begin{aligned} & 170 \\ & (6 \mathrm{E} 12.8) \end{aligned}$ | WLJ I | Flowrate per element of oxidizer liquid jet at start position. Units: $1 \mathrm{bm} / \mathrm{sec}$. |
|  | TLI | Temperature of WLJI. Units: ${ }^{\text {O }} \mathrm{R}$ |
|  | VLJ I | Velocity of WLJI. Units: ft/sec. (If VLJI < 0, area of WLJI. Units: sq in.) |
|  | DØDMAX | Maximum dropsize permitted in atomization of liquid jet. Units: microns. |
|  | BSPR | Droplet formation size parameter.* <br> Recommended: BS IR $=120.0$ (Chamber), 3.0553 (Cup) |
|  | CSPR | Liquid jet stripping rate parameter.* Recommended: $\operatorname{CSPR}=0.08$. (Chamber), 0.037854 (Cup) |
| $\begin{aligned} & 180 \\ & (6 \mathrm{E} 12.8) \end{aligned}$ | WGJ I | Flowrate per element of gas stream surrounding WCGI at start position. Units: lbm/sec. |
|  | EMRGJI | Weight mixture ratio (0/F) of WGJI. $0^{\text {a }}$ |
|  | STGJ | Stagnation temperature of WGJI. Units: ${ }^{\text {R }}$ |
|  | EMVGJ 1 | Molecular weight of WGJI. Units: lbm/lb-mole. |
|  | GAMGJ 1 | Specific heat ratio, $\gamma$, of WGJI. |
|  | XLM | Length of region for WGJI to be mixed with WCGI. Units: in. |
| $\begin{aligned} & 190 \\ & (6 \mathrm{E} 12.8) \end{aligned}$ | PCI | Injector end static pressure. Units: $16 f / \mathrm{sq} . \mathrm{in}$. |
|  | CUPDP | Estimated static pressure drop in injector cup. For cup analysis only. Units: nsi |
|  | CUPDPL | Tolerance on matching cup exit pressure with PCI. Units: psi. |
|  | STX2 | Start plane position; either distance from liquid injection post for cup or distance from injector face for chamber. Units: in. |
|  | DELTX2 | Axial step size for case computations. Units: ir. |
|  | FCHA | Fraction of chamber cioss-sectional area taken by this flow zone case. |
| $\begin{aligned} & 191 \\ & (6 \mathrm{E} 12.8) \end{aligned}$ | RFLAME | Radial location of the pseudo flame front. Recommended: RFLAME = radius of the fuel sleeve. Units: in. |
|  | XFLAME | Axial location of the start of the pseudo flame front. Recommended: XFLAME $=0.0$ (injector face). Units: in. |
|  | VFLAME | Turbulent flame speed. Units: ft/sec |
| $\begin{aligned} & 200,201 \\ & \text { etc. }(4 \mathrm{E} 12.8) \end{aligned}$ |  | Include these cards only if NDSCI $>0$ |
|  | VODI (1) | Droplet velocity of spray group 1. <br> Units: ft/sec |
|  | TøDI (1) | Droplet tempegature of spray group 1. Units: $R$ |
|  | DODI (1) | Droplet diameter of spray group 1. <br> Units: microns |
|  | WSPRI (1) | Spray group 1 flowrate. Units; $1 \mathrm{bm} / \mathrm{sec}$ Enter NDSCI number of spray groups. |

*See text page 13 for description.


Decimal variables with variable names beginning with letters other than $I$ through $M$
(Use decimal point or account for implied decimal location, one value every 12 spaces, 6 consecutive values per card.)

The "VARIABLE CODE" column gives the FORIRAN code names of input variables as they appear in the program listing. A single value is to be entered for each coded variable unless it is subscripted. Array sizes for subscripted integer and decimal variables are also indicated within parenthesis in this column, following the variable name. For most of the data, all of the values of one variable are read before proceeding to the next variable. Note that some arrays with multiple subscripts are "packed", i.e., values for each subscript level start immediately in the next field, not skipping fields to start on a new card.

Variable names and/or descriptions of variables are given together with appropriate dimensions and limits, in the "DESCRIPTION" column. Geverally, the program is written in units of $1 b-i n-s e c-{ }^{0} R$, but there are some exceptions.

## PROPELLANT AND COMBUSTION GAS INPUT DATA

The rirst block of data required as input to the CICM computer program comprises the propellant and combustion gas properties (Table 1). Printout of this block during execution is controlled by the variablo IPTAB: "O" to suppress ${ }^{2}$ rintout, " 1 " to print the data block.

## Liquid, Vapor and State Properties of Propellants (Card No. 20 et seq.)

Fixensive tables of propellant properties are provided as input to tha droplet diffusion model. The first of these tables gives values for the vapor mass fraction, $X_{v}$, at the droplet surface (equivalent to a reduced partial pressure), the heat of vaporization, $\Delta H_{v}$, and parameters $a$ and $b$ of the Redlich-Kwong equation of state. Tables of $X_{v}$ and $\Delta H_{v}$ as functions of both total pressure and temperature are provided, while $a$ and $b$ are provided as functions of temperature only. As noted in Tahle 1 , only oxidizer properties are required.

Values in these tabies should correspond to temperatures ranging from injection temperature to the critical temperature only. Pressure ranges should cover the pressure variation occurring in the subsonic flow portion of a combustor under analysis. It is probably preferable to input data for much wider variation so that the same tables can be used for other engines using the same oxidizer. This approach was taken in structuring the liquid oxygen tables supplied with the example case, Appendix $B$.

Values of $X_{v}$ and $\Delta H_{v}$ should include real gas effects, i.e., dependence upon total pressure level. For vapor-liquid equilibrium, the free energies of the vapor and the liquid are equal. This fundamental relationship for vapor-liqui: equilibrium is conveniently expressed in terms of fugacities; for each component $i$ the fugacity of the vapor, $f_{i}{ }^{v}$, is equal to that of the liquid, $f_{i}{ }^{l}$, (Ref. 7 ), Because the liquid senses the total pressure
while the vapor senses only its partial pressure, the equilibrium relationship may be written as

$$
f_{i}^{V}\left(P_{v_{i}}\right)=f_{i}^{i}\left(P_{\operatorname{Totai}}\right)
$$

Hence, at constant temperature, as the total pressure increases the partial pressure of the equilibrium vapor also increases.

In the calculation of vapor-liquid equilibrium, the vapor must be considered a non-ideal gas. Of the four two-constant equations of state which have been widely used, the Redlich-Kwong equation is accurate throughout the pressure and temperature range and is the most ascurate at high pressures. The Redlich-Kwong equation is:

$$
P=\frac{P . T}{(v-b)}-\frac{a}{T^{0.5} v(v+b)}
$$

The parameters $a$ and $b$ are determined from mixing rules (Ref. 7). To match data over wide ranges, $a$ and $b$ may be expressed as functions of temperature.

Data for these tables may te obtained by solving simultanecus:y four equations given in Ref. 7 , which are expressions for the iquid and vapor fugarities and liquid and vapor states. Note that, at supercritical pressures, $\Delta H_{v} \rightarrow 0.0$ at temperatures well below tie critical temperature.

For a non-ideal gas the species vapor enthalpy is a function of its partial pressure in the gas (Ref. 10), and is thus depentent on the intal pressure. lence, the heat of vaporization

$$
A H_{v}=H_{\text {vapor }}-H_{\text {liquid }}
$$

is a function of total pressure as well as cf liquid temperature.

Liquid Specific lleat and
Enthalpy (Card No. 570 et seq.)
The next nlock of propellant property data provides liquid specific heat and liquid enthalpy as functions of pressure and liquid temperature. Again, only oxidizer properties are required. Note that. although these are denoted as "liquid" properties, the tables should provide data to temperatures as high as the combustion gas temperature; for temperatures higher than the saturation temperature corresponding. to the tabulated pressure, the pure vapor properties are used.

## Vapor Specific lleat, Viscosity, and

 I:nthalpy (Card No. 940 et seg.)The next data to be input are tables of vapor specific heat at constant pressure, vapor viscosity, and vapol enthalpy as functions of pressure and temperature. These may be derived from tabulations of experimental data or from standard correlation methods, 0.g., such as those given in Ref. 10 .

## Binary Ditfusion Coefficient Parameter (Card No. 1500 eq seq.)

Oxidizer binary molecular diffusion coefficients are calculated in the program froni the data input in the TDIFF ( $1, K, 1$ ) tables. This param. eter is assumed to be a function of temperature; tabulated values correspond to temperatures in the array $\operatorname{TTDIF}(\mathrm{I}, 1)$. The subscript I denotes the various temperature livels. The subscript $:$ indicates the gaseous specie into which the oxidizer is diffusing into, as noted in the description in Table 1 .

The TDIFF ;arameter has the following meaning: An equation for binary diffusion coefficients, based on use of the Lennard-Jones potential in a kinetic theory model, is given in Ref. 10 as:

$$
D_{12}=\frac{0.001858 \mathrm{~T}^{3 / 6}\left[\left(M_{1}+M_{2}\right) / M_{1} M_{2}\right]^{\frac{1}{2}}}{p \sigma_{12}^{2} \Omega_{D}}
$$

Multiplying and dividing this equation by a reference temperature and reference pressure gives:

$$
D_{12}=\frac{0.001858 T_{\text {ref }}^{3 / 2}\left[\left(M_{1}+M_{2}\right) / M_{1} M_{2}\right]^{\frac{1}{2}}}{P_{\text {ref }}{ }_{12} 2^{2} \Omega_{D}}\left(\frac{T}{T_{\text {ref }}}\right)^{3 / 2}\left(\frac{P_{r e}}{P^{\prime}}\right)
$$

The product

$$
\frac{0.001858 \mathrm{~T}_{\text {ref }}^{3 / 2}\left[\left(M_{1}+M_{2}\right) / M_{1} M_{2}\right]^{\frac{1}{2}}}{P_{\text {ref }}{ }^{{ }^{2} 12}{ }^{2} \Omega_{D}}
$$

is tavulated as the TDIFF parameter.

This is assumed to vary with temperature, but not with pressure.

Note that TDIFF (I, 1, 1) are for the oxidizer species diffusing into comhustion products at stoichiometric mixture ratio. For lower or higher mixture ratio combustion gases, the multicomponent diffusion coefficient is approximated by the program for the oxidizer species diffusing into a mixture of stoichiometric products and excess fuel or oxidizer vapor, respectively.

## Propellant Critical Properties and

Molecular Weight (Cards No. 1610, 1620, 1630)
The critical temperature, critical pressure, stoichiometric mixture ratio, and molecular weight of the stoichiometric products are input in ihis data block. The vapor molecular weight will differ from that for the liquid only if there is vapor phase decomposition. If this occurs, it is recommended that the heat of dissociation be included in the tabulated values of heat of vaporization.

## Combustion Gas Properties at

Film Conditions (Card No. 1640 eq seq.)
Combustion gas film properties required in subroutine FGRRøP for calculating film gas properties are molecular weight, viscosity, and specific heat. These are tabulated as functions of mixture ratio and gas temperature. For the oxygen/hydrogen data deck supplied with the sample case, these data were obtained from the Rocketdyne free energy
equilibrium performance program by specifying different values of mixture ratio and product temperature (rather than mixture ratio and initial enthalpy).

Oxidizer Liquid Surface Tension and Viscosity (Card No. 2260 et seq.)

The next propellant properties to be input are tables of liquid surface tension and liquid viscosity as functions of pressure and temperature. The tables should include temperatures ranging from injection temperature to the oxidizer critical temperature.

## Fuel Compressibility Factor

 (Card No. 2490 et seq.)Tables of fuel compressibility factor are input as a function of pressure and temperature. The tables should include temperatures ranging from fuel injection temperature to the combustion gas temperature.

STAGNATION EQUILIBRIUM COMBUSTION GAS INPUT DATA

The second block of data required as input to the CICM computer program comprises the stagnation equilibrium combustion gas (Table 2). Combustion gas properties, tabulated as functions of gas mixture ratio, are obtained from prior peripheral computation using a thermodynamic equilibrium performance prograin. Rocketdyne's free energy performance program was used to generate the table supplied in the reference case, but any comparable program would be sufficient. The combustion temperature,
molecular weight, specific heat, and viscosity entered in this table are properties for equilibrium combustion products at stagnation conditions corresponding to the mean expected chamber pressure. The properties are assumed to be functions only of mixture ratio and not pressure.

CONTROL INPUT DATA

The third block of data required as input to the CICM computer program comprises control data and also chamher conditions íTable 3 ).

Indicator Card (Card No. 10)
The first control input data card contains indicators for controlling:
(1) the DER ontion (IDFR), (2) coupled cup-chamher calculations (ICUPC),
(3) the type of chamber geonetry input (NCHAMC), and (4) the chamber solution printout intervals (M2C and NC $\cap \mathrm{N} 4 \mathrm{C}$ ). For execution of the クrogram using the $D E R$ option, IDER specifies the number of injector flow zones (or number of different element types) to be used in the analysis of the engine. If IDER and ICUPC are both less than or equal to zern, this card is the only control card required as input.

## "Rigimesh" (or Gas Mantle) Conditions

(Card No. 30)
The next card of control data spec: fies the "Rigimesh" flow conditions in the chamber. Even if the "Rigimesh" ilowrate is zero, it is recommended that values for the "Rigimesh" stagnation temperature (STGJC), molecular
weight (EMWGJC), and specific heat ratio (GAMGJC) be entered in order to avoid possible execution errors. At present, the CICM program mixes the "Rigimesh" flow into the combustion region linearly with position from the injector face to the axial location specified by XLMC.

Parameter Card (Card No. 40)
The next control data card specifies the axial step size for the chamber calculations (DELTXC), the chamber droplet formation size and liquid jet stripping rate parameters (BSPRC and CSPF $($ ) , and the minimum axial distance for DER punched card output (XMINDE).

During execution of the program using the DER option, all IDER flow zones are executed to an axial location specified by the length of the longest liquid jet or to the axial distance specified by XMINDE, depending on which is larger, before DER punched cards are generated.

Chamher Geometry (Card No. 50, 60, etc.)
The last set of control cards specify the chamber area as a function of axial distance. Two different methods of input are possible, depending on the value of $N C H A M C$. The first method, $N C H A M C \leq 0$, requires the cross-sectional area of the injector face (ACSC), chamber length (CLNTC), chamber contraction ratio (CØNRAC), nozzle angle of convergence (CCANGC), and the radii of curvature of the beginning of convergence (RCBCC) and at the throat (RCTC) to describe the combustor area as a function of length.

With the second method, NCHAPK> 0 , the geometry of the combustor is specified through the array ACHAMC. At selected axial positions (XCHAMC), the chamber pea is given by ACHAMC. For axial locations between the selected values of XCHAMC, the program linearly interpolates for the combistor area.

## CASF INPUT DATA

The final block of data required as input to the CICM computer program comprises the case input data (Table 4). If the DER option of the program is beinf utilized, the nrogram requires IDFR number of case-input data blocks.

Comment Cards (Card No. 110 and 111)
Two alphanumeric (A-formatted) comment cards are provided to permit the user to document the case with such information as injector name, drawing number, element description, propellant combination, nominal chamber pressure and mixture ratio, date of the computer run, etc.

Indicator Cards (Card No. 120 and 130)
The next two case data cards contain variables (indicators) for:
(1) specifying the number of spray drop sizes at the start plane (NDSCI),
(2) specifying the number of injector elements in the case (NELEM),
(3) controlling the type of injector cup (or chamber) geometry input (NCHAM), (4) controlling the type of case analysis (ICUP), (4) controlling the gas expansion for the first incremental step (ICPE), (5) controliling
the input to be read for next case (IREAD), (6) controlling the case solution printout intervals (M2 and $N C \emptyset N 4$ ), (7) sperifying the method of describing the gas expansion around the liquid post (IEXPGL), and (8) controlling the atomization process (IAT $\varnothing$ ). A constant pressure expansion option (ICPE $=1$ ) has been included in the CICM computer program to allow the combustion gas, in the absence of "Rigimesh" flow, to expand at constant pressure in the chamber. For cup calculations, this indicator should be set equal to zero. The different options for expansion around the liquid oxidizer post (IEXPGL) are discussed on page 22. This indicator is required only for cup calculations.

Case Geometry (Card No. 140,150 , etc.)
The next set of case cards describe the flow area as a function of axial distance. This set of cards is very similar to the chamber geometry cards described in the control input data block. For most coaxial engines, the case geometry will describe the cup geometry. Two different methods of input are possible depending on the value of NCHAM. The first method, $N C H A M \leq 0$, uses the cross-sectional area of the injector cup or chamber at the upstream end (ACSI), injector cup or chamber length (CLNT), ratio of inlet area to exit area of the injector cup or chamber (CØNRAT), angle of convergence (negative value specifies angle of divergence), and the radii of cirvature at the beginning of convergence ( $R C B C$ ) and at the injector ctp or chamber exit (RCT).

In the second method, $N C H A M>n$, the geometry of the injector cup or chamber is described through the array ACHAM. At selected axial positions (XCHAM), the injector cup or chamber cross-sectional area is jiven by ACHAM. For axial locations between the selected values of XCHAM, the program linearly interpolates for the injector cup or chamber area. For cup calculations, XCHAM is the distance from the upstream end of the iniector cup. For chamber calculations, XCHAM is the distance from the injector face.

Combustion Gas Conditions (Card No. 160)
The next card for the case data specifies the combustion gas, or fuel, flow conditions at the computational start plane. The combustion gas, or fuel, flowrate at the start position (WCGI), the weight mixture ratio at the scart plane of the gas (FMRCGI), the initial cross-sectional flow area of the gas (ACGI), the weight mixture ratio of the gas in the manifold (EMRII), and a reference stagnation temperature (STT) and mixture ratio (AMRT). For cup calculations, the mixture ratio at the start plane (EMRCGI) wiil he the same as the mixture ratio in the manifold (FARII).

For chamber calculations, generally the mixture ratio at the start plane will not be equal to the manifold mixture ratio. The reference temperature (STT) and reference mixture ratio (AMRT) are used to update the equilibrium stagnation gas tables (Table 2 ) to account for differences in propellant energies. Nominally, these reference values are equal to the comhustion gas, or fuel, manifold stagnation temperature and mixture ratio.

The next card for the case data specifies the liquid jet flow conditions ai the start plane and droplet parameters. The liquid jet flowrate (Wi,JI), temperature (TLI), velocity (VLJI), maximum dropsize permitted in atomization of the liquid jet ( $D \varnothing D M A X$ ), and parameters describing the droplet formation size ( $B S P R$ ), and liquid jet stripping rate (CSPR) are included. If a negative value is input for the liquid jet velocity, (VLJI), the program will interpret this value to be the liquid jet crosssectional area (AL.JI $=-V L J I)$. If the local droplet diameter produced by the stripping process is larger than $D \triangle D M A X$, stripping of the liquid jet will cease until the local droplet diameter is smaller than $D \emptyset D M A X$.
"Rigimesh" (or Gas Mangle) Conditions

## (Card No. 180)

The next case data card specifies the "Rigimesh" flow conditions in the chamber. This card is very similar to the "Rigimesh" condition card described in the control input data block. Although, for cup calculations, the "Rigimesh" flowrate (WGJI) must be set equal to zero, it is recommended that arbitrary values for the stagnation temperature (STGJ), molecHlar weight (EMWGJI), and specific heat ratio (GAMGJl) be entered to avoid possible execution errors. At present, the CICM program mixes the "Rigimesh" flow into the combustion region linearly from the injector face to the axial location specified by XLM.

The next case data card specifies the injector face static pressure (PCI), estimated cup static pressure drop (CUPDP), the tolerance o. matching the cup exit pressure with the injector face pressures (CUPDPL), start plane position (STX2), axial step size (DELTX2), and the fraction of the chamber cross-sectional area represented by this flow zone case ( $F C H A$ ). For cup calculations, it is recommended that the start plane location be chosen as equal to one liquid post thickness (STX2 $=t_{\text {liquid post }}$ ) and the axial step size be set equal to 0.005 inch. For chamher calculations, it is recommended that the start plane he chosen as the injector face $(S T X 2=0.0)$ and the axial step size he set equal to 0.05 inch.

## Flame Propagation Conditions (Card No. 191)

The next case data card specifies the radial location of the pseudoflamefront (RFLAME), the axial location of the start of the flamefront relat ive to the injector face (XFLAME), and the turbulent flame speed (VFLAME). It is recommended that the radial location of the flamefront be set equal to the fuel sleeve radius and the axial location of the start of the flamefront be set equal to zero (injector face). If IDFK and NDSCI are both less than or equal to zero, this card is the last case data card.

## Droplet Spray Groun Description

## (Card No. 200, etc.)

The next set of case data cards specify the droplet spray groups present at the start plane. This set of cards is needed only if NDSCI>0. The droplet velocity (VØDI), temperature ( $T \emptyset D I$ ), diameter ( $D \varnothing D I$ ), and spray group flowrate (WSPRI) are included. Each droplet group is entered on a separate card, i.e., there will be NDSCI cards in the set.

DER Parameters (Card No. 300, etc.)
The last set of cards for the case input data specify the parameters used in interfacing the CICM program with the STC section of DER. These cards are included only if IDER>0. Included is the number of mixing zones per element (NMIXZ), the number of oxidizer droplet spray groups for DER punched card output $(N G \emptyset)$, fractions of the total fuel and oxidizer flowrate for the case in each mixing zone (FFMIX and FQMIX), and the fraction of total spray flowrate for the case in each DER spray group. Cold flow data are required to $d ? f i n e$ the number of mixing zones and the fractions of fuel and oxidizer in each zone. This is the last set of cards in the case input data block.

## FROGRAM DUTPITT

The output of the CICM computer program is provided as the usua' t:m'ar printout. A sample case is included in Appendix C. Input da are erirled as they are read ishich permits both a full documentation of the sirutor ren cunditions for later analysis and a convenient method to check the input for errors if unusual results are calculated. The input sections should be examined for each case run to be sure that the intended input data were actually used.

During CICM analysis, data are written out as they are genrated. At selected axial incremental positions, complete gas and propellant spray group data are printed. Additionally, the percintages of propellants atomized, vaporiced and rearted are listed. At the top of each axial station printout, two comment cards (from the case data input block) are listed and an identification line is written to inform the user whether the calculation was a cup or chamber case.

Upon completion of the case, the program writes out an identification line informing the user that the case calculation is finished. For calculations, the program checks to see if the cup exit pressure is equal to the chamber pressure, If the two pressures are different, the program prints out this fact and reruns the cup case with a now estimated cup delta pressure.

If the jER optior has been specified, after all zone cases have been executed the program checks to see if each chamber case was continued to the axial position required for DER punched card output. If any of the zone chamber cases was terminated before reaching the axial position required for $D E R$ punched card output, the program automatically recalculates these zone chamber cases. Upon completion of all zone calculations, the program lists the DER punched card output.

Upon analyzing all of the input data, the program writes an identification line informing the user that the program is terminating in the normal fashion.


#### Abstract

The most commen callse of errors during execution of the CICN computer program are mistakes in the input information. The program contains certain spesial printouts if input limits are exceeded (subroutine TABIN) and if interpolation beyond reasonable limits of tabulated rahles is attemped (sumroutine lacrac). The usual reason for these error messages is had inpott data.


If the model calculations are allowed to proceed to the nozzle throat, the program may terminate calculations before the throat plane is reached if the calculated combustion gas velocity exceeds the local sonic velocity. This early termination will not effect sequenced model calculations and should no: be encountered during execution with the $I[R$ option. The early termination can be corrected by adjusting the injector static pressure.

In executing the program with the DER option being used, the user should verify that the number of DER dropler spray groups (variable NG円) is the same for all DER zones. If the number of spray groups are different, the resuleing punched card output will be inconsistent.

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## APPENDIX A

COMPUTER CODE LISTING

## APPINDIX A

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SAMPLE CASE INPUT DATA LISTING


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SAMPLE CASE FRINTED OUTPUT

C-i

CONTENTS OF
SAMPLE CASE OUTPUT
Approx. No.of Pages
Title Page Identifying Computer Model ..... 1
Propellant and Combustion Gas Input Data ..... 42
Control Innut Data ..... 1
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1st Axial Pass
Case Input Data (cup) ..... 2
Solution at Selected Axial Stations ..... 18
2nd Axial Pass with Estimated Cutp $\Delta \mathrm{P}$ Adjusted
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Gas and Spray Data Which Were Calculated \& Punched for DER/STC Program ..... 2

## SURMARY OF SAMPLE CASE SPECIFICATION

## Injection Elements

|  | Units | Type \#1 | Type \#2 |
| :---: | :---: | :---: | :---: |
| Number of Elements | - | 30 | 36 |
| Distance From Convergence of Streams to Injector Face | in. | 0.10 | 0.10 |
| Cup Cross-Sectional Area | in. ${ }^{2}$ | 0.028055 | 0.028055 |
| Depth of Cup Flare | in. | 0 | 0 |
| Liquid Jet Injection Area | in. ${ }^{2}$ | 0.0088247 | 0.00860 |
| Annular Injection Area of Gas Stream | in. ${ }^{2}$ | 0.013953 | 0.013953 |
| Liquid Jet Flowrate | $1 \mathrm{bm} / \mathrm{sec}$ | 0.220 | 0.220 |
| Gas Stream Flowrate | $\mathrm{lbm} / \mathrm{sec}$ | 0.003663 | 0.003663 |
| Gas Stream Mixture Ratio | - | 0 | 0 |
| Rigimesh Gas Flowrate | $1 \mathrm{bm} / \mathrm{sec}$ | 0 | 0 |

## Chamber

| Area at Injector Face | 16.86 | in. ${ }^{2}$ |
| :--- | :---: | :---: |
| Area at Throat | 5.12 | in. ${ }^{2}$ |
| Chamber Length | 5.0 | in. |

Full Taper
(Area change linear with distance)

SAMPLE CASE ELEMENT AND CILAMGER GEOMETRY
Injector Elements


Number of Elements $=\mathbf{3 0}$

Type \#2


Number of Elements = $\mathbf{3 6}$

Chamber Geometry

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$$

$$
\text { TEMPERATUES ITFG :. } \quad \text { VELOCITIES (FT/SEC) }
$$

FLOWOATES (LR/SEC)

$$
\begin{aligned}
\text { LIOUIDJ } & =0.218 .63 \\
\text { COMIUSTION GAS } & =0.03506
\end{aligned}
$$

COMB GAS MOL WT $=2.0$ RT 13/LB-MOLE FRACTICN LYOHD IUNATOBITES= $=0$

7
CRAYJAL IVJFGTION CEA, BUETIOR MOREL

CHFCKCHIT CASE EOR CICA NASA VERSIIN
ELEAFHT TVPE HI, THTAL NUMQER OF ELE
AXIAL DISTANCE (IMCHES)
$x=$ -
FROM IVJPCTOR FACE
STHSLE CIP CZLTILATIR:


CriaxiAl INJECTIMN CEMgIJSTIri＇J NEOFL SINGLE CLIO！IV－C，AC\}

## SINGLE CIF CAISHLTICN

C－HCKCUT CAS？ETR GJCM NASA VERSIT：A ELEAENT TYPE El，TITTAL
OVIIL ISTANCE（INEHESI

TE＇IFERATILES（INEG K）
ヶロ・19＝$=17 \mathrm{C}$ UInU17
FLONFATES（LS／SEC）
$\begin{aligned} \text { LIDUIO JET } & =0.21075 \\ \text { COMDUETIUN GAS } & =0.04538\end{aligned}$

## MISCELLANFOUS

－－ー－ー－ー－ー－



COMB GAS IDNIC VELOCITV $=3825.62$ FT／SEC
FRACTID：CIGIIISVAPTRITES $=0.042 \times 3$
COAXIAL IPJECTIOH ECNAPISTICN WCECL
AXIAL TISTAMCE IINE4ESI

| こんCのKCUT CAs：＝7p ELEWENT TYPE Fi．T <br> AXIAL JISTAACE IINEHE | $\begin{aligned} & \text { A: MSA VERSICA! } \\ & \text { IIPMPER TF ELEWEMTS = } 6 . \text {. } \end{aligned}$ | E＝THISCASE＝30 |
| :---: | :---: | :---: |
| ＊＝－．－i＋3 FRSM IVJECTO？FACE |  |  |
|  |  |  |
| $\begin{aligned} \text { CHAMBER STATIC } & =757.77 \\ \text { COMF GAS STGN } & =772.77 \end{aligned}$ | COMS ras STAT $=519.97$ | LIOMI＇JET $=62.4 \%$ |
|  | CSW5 T5S STSN $=525.77$ | CTM5USTITK－6世5＝959．7．7 |
| RADII（IVCHES） | AREAS（SコーINくHES） | FLSNRATES（LẼ／SEC） |
| LIOUIO JET $=3.34725$ | LIOUI：JET $=0.7 \therefore 1249 \mathrm{~F}$－ 2 | LIQUID JET $=0.2 \% 6 \% \%$ |
| COMELSTIOV GAS $=2 . .945 \%$ | COW3 TAS $=$ S．21：427E－51 | CSMRIISTICN GAS $=5.04714$ |

MESCELLANFIBUS

COAXIAL INJECTECH EOUG:ISTION MONEL

Single cup cilisel


 VELCCITIES (FT/SEC) Liniln Jri $=05.7 \%$ flustinil crs $=$ Quncen (LF/SFE)



 MISCRTLAN:MES
$\square$

COAXIAL INJECTIOA COMBIISTICN TODFL (LIOQ10-64S) AXILL OISTAMC: (IVCHES) FEOM LiJECT:S face
 4xila

TEMPERATMRES (DEGR)

$$
\begin{aligned}
& \text { CCIG GAS STAT }=512.07 \\
& \text { COME CAS STSN }=519.19
\end{aligned}
$$

$$
\begin{aligned}
& \text { AFEAS (SO-1HCtSS) } \\
& \text { LIOUIO JET }=0.626624 E-02 \\
& \text { COHE GAS }=3.217990-61
\end{aligned}
$$

MISCELLANIC:S

$$
\begin{aligned}
& \text { Crime GAS ML WI }=2.854 L T / L R-M O L E
\end{aligned}
$$

$$
\text { FRACTIMM URUM UNATringiEn }=0.02348
$$

CRACTSONLICUMQEACTER=:0

CCAXIA: INJEETINY ERMRISTICV MRO=L
(LIOUIO-GQSI TVTEF GIF CALCEEATIM
 AXILL $二$ ISTANCF (IVCHES)

$$
x=-0.0: J \text { CRJU INJCCTCR } \overline{\mathrm{O}} \mathrm{AC}
$$

| $\begin{gathered} \text { CHAMSEO STATIC }=751.5 ? \\ \text { COME EAS STGN }=30.25 \\ \text { RADII (INCHES) } \end{gathered}$ | AS STAT $=510.5$ | LIDUIS JET $=69.75$ |
| :---: | :---: | :---: |
|  | CTM GAS -TGT $=517.72$ | CTMETETIMM TAE $=023.67$ |
|  | AREAS (SQ-INCHES) | FLENRATES (LQ/SECI |
| LIQIIC JET $=0.74429$ | LIOUIT JET $=$ C.S13944E-D2 | LITUIT JET $=0.20205$ <br> COMEUSTINV GAS $=3.05457$ |
| COMSUSTIO', CAS $=0.39450$ | 57M9 GAS $=0.219168 \mathrm{E}-01$ | COMEUSTI.N GAS $=$ O.0s45 | MISCELLANEOUS

 COMB GAS LIDUID HNATTMIZED = =.01843 FRACTION IITUID QLACTED = ?.J
GCAXIAL IVJFCTIO丹 COUOUSTISン AFOL

AXTiL OISTADCE IIPCHESI
$X=-3 . C: 5$ FRES IR:JECTEF FACE
TEAPERATURES (FEG R)

EPACTITN CHAMEPD LNFILLED = O.C

FRACTION LIOHIF
(LIClio-Gis)
CHECRCUT CASE EDE RICM BIASA VEDSIOUS

PRESSURES TPSIAI
PRESSURES TPSIA CHAMEIR STATIC $=75$ J. EF TOAF GAS STAT $=5 C G, r$
$=-516.27$
AFEAS (SO-If:CUSS)
MISCELLADE ILS
… ..........
ERAXIAL IMJECTIC: EEVAESTICQ MORL
ILIR:1O-f.s

- TJGLE ctit calmeatir:
CHECKDUT CASE EาD EIEA JASA YEGSIMA

AXIAL DISTANCE (INEHES)
- .OC: FROA I:JECTS2 FACE

 FRACTIN GAS WOL MT $=3.231 L E / L E M C L E$
COMS GAS FOACTION LIDUID IJAATVMIZEO $=0.90741$ FRACTICN LITUY REACTET: $=0.0$
CUP EXIT PRESSUQE HAS NOT CONVERGES OV CHAMBES PRESSUOE CCP CACCULLTIDG CTITIMUING NITH NEW CUF PRESSURE LCSS
85
NI ヨSVO
NCHAM $=n$

$$
\text { - }-\cdots+
$$

$$
2
$$



- $\because$ T DATA

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i 8
$$



$$
\begin{aligned}
& \text { - collomit- -ats) } \\
& \begin{array}{l}
\text { CHECYOUT CASE FO? CICM NATA VEPSJM: } \\
\text { CLEAENT TYPE \#, TUTAL NIMAER OF ELE }
\end{array} \\
& \text { GLEAENT TYPE \#1, TGTAL NIDYEFR OF ELEMENTS = 66, NUMEFF THIS CSSE }=30 \\
& \text { SIVGLF CU: CALEIUATIEV } \\
& \text { S19 ( } \\
& \cdots
\end{aligned}
$$


CRIAYIAL IHSECTICA: CRUOOUCTICA MEAFL




COAXIAL IYJECTIOM COMBUS:IGON NCOEL
sinetrocirneralen
CHESKOUT CASE FOR CEM YASA YERSIOT:

AXIAL DISTANCE (INSHES)
FQn:i InJECTMa face

2e.95 = 13 F Jlivicit

-------------------

MISCELLANTOUS
FRACTICVCFIMEER UIITILLED $=0.0$
COMS FAS MOL WT = ?.?シ4 LRALE-MOLE
FRACTIC'S LIGUIS UPIATGIITER = 5.03157


 MISCELLAA:ECIIS
COME GAS MRL :VT $=2.291$ LOMLE-QALE
GOACTICV LIJUID UMATMITIED $=0.9755$ R
FRACTIUN LIUUTO EEATTET = =.?




35
－・リッロッ TWIS CASE － ！ICII－cas

Y＝－3．LES FRMM I：JSRTVE CAEE DRESEUFES（PEIAJ
VELNCITIES（FT／SECI
2I？117 if1 $=66.53$
FLON？ATES（LG／SECI

LITI：I＇JET GAS GAS $=0.04463$
पISEELLAN：JUS पISEELLAN－JUS


 $\square$
$\square$
$\square$
$\square$
$\square$
$\square$

$$
\mathrm{zi}-19=1 F[\text { Ulliil }
$$

Crixial Iovection covolictinn wront

$$
F \in C E
$$ (LTO•1J-iss)

AYI:L DISTANEE (INCHES)

$$
\text { VEIRCITIES }(F T / E F C)
$$

$$
\text { gubretmre GR }=-96 E .89
$$

FLOW ATES (LQ/EFC)

$$
\begin{aligned}
& =5.21075 \\
& =4.24507
\end{aligned}
$$

$$
=6.04507
$$

$$
5799
$$


 (LIOMD-CAS) riHCES CID

AXIAL DISTEACE (INCHES)
$x=-9.035$ FQGM 1::JこCTCQ FACS TEMPERATMRES (DFG


ETST1OM 6FS = 95z.
FLTVRATES (LE/AFC)
LIOU17 JET = 1.208 .23
GイE115T10: cos $=2.0494$

MJSCELLANEOUS
FEACTICN RHADE!S UNEILLFD=0.0
-


(LICMID-CAS)
SINGLE CUS CALCUTATINA
EHCCKCAT CASF FOR CICM HASA YERSION

AXIAL DISTANCE (INCHES)

$$
-3.525 \text { FZOM INJECTCF FACE }
$$

VELOCITIES (FT/SEC)
54.59 = 1Jr ulficil
COMFUSTMTGAS $=939.3 \%$
FLTWRATES (LS/SEC)
$\begin{aligned} \text { LIOBIF JET } & =0.20574 \\ \text { COMBUSTICN GAS } & =0.0508 \mathrm{CO}\end{aligned}$ MISCELLABEDUS


FRACTRONTOT10 REACTE $=6.0$



CRAMIAL INJESTION ERMBHETICN ATEFI


 CYIAL DISTANCE (INSUES)

EROM I!!J:CT:~ト: $\quad$ :
VILOCITIFS (FT/SEC)


$n l 5$
$246 i$
$\ldots$
MISCELLARETUS


CI:AXIAL IVJFCTICA: CQ:3iISTIDA vonE:




$$
2-10
$$

AXIAL IISTANCT（DrPESS

$$
-.2 .9 C 5 \text { न2丁口 :UJこCTK=F }
$$

— FRESSIITES TFEIA
FACS

$$
=-.2 .3 C 5 \text { F2r:A 1:JECTS=FACE }
$$

CRAYTAL INJFCEION FIMBISTION MOMEL
CHECOLT CASE ENR CICM MASA VERSJNA
COME

$$
\text { TEMLERLTIRES PEPCR } 1
$$

AREAS (SQ-:NCHIS)

$$
----\cdots-1
$$

MISCELLSNEOUS
VFLITITIES (FT/SES)

$$
\text { LIVIT } 157=69.72
$$

$$
\begin{aligned}
\text { LIOUIO IET } & =C .20 C H E \\
& =C O 550^{\circ}
\end{aligned}
$$

$$
\begin{aligned}
& =315: 47 \\
& (!P / S F C)
\end{aligned}
$$

$$
\text { FL(ivr } A T F S \text { (I:Q/SFC) }
$$

$$
\text { COMEUSTIM CAS }=6.6557^{\circ}
$$

$$
+
$$

ERAXIAL PQJECTIOR ELPRIJETIGA MCESL (LIn!lin-5f )

|  | $\begin{aligned} & \because A S A \text { YERSISA! } \\ & \text { MUES GF ELEMEATS = } 5 C \end{aligned}$ | PTHIS CASE=3: |
| :---: | :---: | :---: |
|  |  |  |
|  |  |  |
|  | CCME GAS ETAT $=597.52$ | LIOUIN JET $=70.67$ |
|  | -JTE JAS STCN $=31403$ | TMKETSTTMKTEE $=$ CIEC95 |
| 2دJII (TNCHES) | QREAS (S?-IAT,HRSS) | FLEMOATES (LE/SEC) |
| LIOUID JFI $=0.04334$ | LIVUID JET $=0.50$ ご 76 E -62 | LIMIIC JFT $=0.19964$ |
| COMEUSTII\% GAS = U.UC4. | CCMP GAS $=0.221544 \mathrm{E}$ - $)^{1}$ | COYPI'STICR: CAS $=2.15690$ |



 CHAMEFR CATCUMATICRAS!
MISCRLLAN: Ul!S

FPRCTICN CFAMGRR GMIILLEN $=0.889$

$$
\begin{aligned}
& \text { FPACTICN LIGUIN INAATYIIZEC1 }=0.90744 \\
& \text { FRACTICN LINUID RFACTFT }=5.0
\end{aligned}
$$

2.14.23 FT/SEC $=6.0 .9255$


AXIAL DIETANCE (INCHES)
ERCY INJECTCR FACE
-ONN-OIMF:S! THIAL
XTH = ËOOC: FROM THFITAT

- PQESSIRES (PSIAI
VFLCCITIE (FT/SEC)

F!nH?AT=S ILEASECI


$4: 20,-2$
R284
:Iaf:


${ }^{2}=0,0,2$
Non

$$
S E
$$

$$
\text { --........- }-
$$



$$
3 \%
$$

 Cherins? calculatiror ? GHECKCUT CASE ETH GICN :ASA VERSIOM TVTAL :VIAL TISTATES ITVCHESI
riaylal ivjretios comentstion want


$$
\text { TEYDEKATURES (D:G } 21
$$ MInJTM

PLUEPATES ILF:
 CGMPUCTIM GAS $=734.2 \mathrm{~h}$ flunpates (Lfi/SEC)


 FOACTIGU I.IVII REACTE $=1.10767$
spear rita

 MISCELLAAFOUS

$$
\begin{aligned}
& x \\
& x / 15 \\
& x i 4
\end{aligned}
$$

$$
\text { PQRSSIMES }(P S I A)
$$



$$
\mathrm{T} / \mathrm{SEC} \mathrm{C}
$$

DROP HEATUP




CHAMES (LICIJIN-CNS)
CHMMEK こAICULATICA, FER FLFITENT

GXIGL HIETANCE IJNHESI
FRIM IR:IECTCF FASE
ACIA- IIMENSIT:AL

X
X/RT
XTH
$\cdots$
CHANS
COMI.

$$
\begin{array}{r}
0.0669 \\
\because \quad 3256 \\
\therefore 29055
\end{array}
$$

$$
C * F F F I C I F N C Y=3.3=0
$$

MTSCELLANJOHS FPACIIDY LIQU! V VAPREIZES

$$
\therefore 2704
$$

S
aŋya

$$
. \quad-\quad .
$$


COiASUSTINN GAS SDPAV

SDPAV $\quad A T A$

remozratalue
CONS GAS WR $=1$ RELLTG
COMB GAS SNAIC VELOCITY $=6134.25 \mathrm{FT} / \mathrm{SEC}$.
----------

$$
\begin{aligned}
& 1.2756+21 \\
& 1.922 c+i 1 \\
& 2.530 t+1 \\
& 3.1305+i 1
\end{aligned}
$$

aDe duxa
.
 C* EFFICI NCY =

$$
\begin{aligned}
& \text { - - }
\end{aligned}
$$

PRESSIMES (PS:A) マARII (1asCHES)

AREA RATIC $=1.1166$
 COMEUSTJCN GAS $=0.74 .3^{75}$ CHANSSR STATIC $=75.20 \mathrm{C}$
COMI GSS STG: CHANSSR STATIC $=75.20 \mathrm{C}$
COMI GSS STG: CHAMEIP STATIC $=753.0$


$$
\begin{aligned}
& \text { COME GAS STAT } \\
& \text { COMO GAS STGY }
\end{aligned}
$$


AREAS IST-1A.
CPACTIOY CHAMBFS UHETLLED $=0.184$

Gers gronip

$$
\begin{aligned}
& \text { LNARAT } \\
& \text { LP/SiC } \\
& \text { O } 536-1
\end{aligned}
$$

$$
\begin{aligned}
& 1.536-03 \\
& 20+760 \\
& 3.774150
\end{aligned}
$$

$$
\begin{aligned}
& 3.17475-3 \\
& 4.74 \\
& 3.5241-23
\end{aligned}
$$

$$
\begin{aligned}
& 5 \cdot 5 c 5-63 \\
& =2306-62
\end{aligned}
$$

$$
\cdots-\cdots
$$




 aYIAL OISTAREE (INE-ES)
= 1-CC: FQT;: INJ=CTIT FACF

X/RT $=$ FAR FROM THERAT
PQEFSURES IPSIA) TEMPERATURES (DEGR) VELOCITIES (FT/SFC)
IOU1!: JET $=71.57$
LIOU1!:
COEDETI:
$54 \%$.
FLTAFATES (LF.SEC)



FRARTICA LIGUD B:ACTE! = 6.2717
CRIGUSTINN CHS SFKAY
IFIGP HEATUR
DRUF




CrAYIAL INJICTICO CMROSTIUN ？ORFL



1Y12L HISTANE PINCR－
Jこと」 bujifnl aujs js？i＝

$x$
$\times / 27$
$\times 14$

 RANII（INCH：5）
 TE：MPEGATURES ITFS Si VFLrirITIE（FT／SES）
 AQLAS（ST－J：EHES）FLRUPATES（LS／SEC） AQLAS 1－T－Ja．ches
 MI SCELLANFOUS




## CrNFISTION GAS SUPAY SATA

GRDP HEATIO FRACTINA FOrN G：CHIT
nros ginit
FLOS：AT：
LS／S：C


$m$
$\because$
1
$\vdots$
$\vdots$
$\vdots$
$n$
$\because$
$i$
$\vdots$
$\vdots$
$\vdots$


AREA FATI：$=1.21: 3$
 COASUSTJO＇Y CAS $=\ddot{\circ}$ ？EOIS CIIB GAS STAT
COME GAS STSN －－～－－



 AXIAL こISTENCE（ITJCト：S）
FAこt
1.45 FRON INJ！

COPMAL TNJECTICN COMEMETIC: MCOFL


$\forall 1 \quad 11] \quad 1110$ if 113515
IDEAR $=6$ ST×Z $=2 \cdot \hat{S r C r} \boldsymbol{O}$


FMEJJ $=2 \cdot \hat{O A C E}+30$

FSTRR = A AOCL-C:
 CrNRAT $=1 . \operatorname{BCOE}+\mathrm{B}$
PCT $=0.0$
$\begin{aligned} \text { ACSI } & =3.3953 F-C ? \\ \text { AIDT } & =0\end{aligned}$
$V L . I T=-5 \cdot 6: F-3$
$C S P R=4.294+. I-72$
STGJ $=1.25 E+03$
CuDH0L = 2-0!!e-9.


$[6-33] 2-y=x 1611$
Frict = 1. noc: NF-it

i:-32:3: $\because=4301$ FSOER =





NDSCI $=$


[^6]
 AXILL OISTAME (IHEHES)
A.CE
MOLICTITE (FT/AEC)
$$
\text { LIMUSOJTT }=53.42
$$
$$
\text { CCHESTI } 6 \times 5=145501=
$$
FLOHRATES (HASEES)
\[

$$
\begin{aligned}
& \text { LInllit J:T }=0.200 r \\
& \text { craselustan EAS }=0.3605
\end{aligned}
$$
\]



 -



velecitif: (fi/sec)

flourates MESSEC)
LTOUIN JET = こ..つ2000


MISCELLAVEMUS
CONG GAS NHL WT $=$ ? OLE LO, LE-NCLE


F
COMS GAJ $=0.104552=-01$
AREAS (SO-I CHES)
(FIJd) S3int553i.



$$
\cdots
$$ २AOII (INCHSS)



COAXIAL INJTOTION: CRMBHCTICR MCTHL


AXIAL DIETAHCE (INEAES)
$x=$-T.nTE FROM INJECTR FACE
VELOCITIES (FT/SFC)
LInuIT J1T $=54.73$
Co4EUSTHETGAS =
FLDXESTES (LESECS

 MISCELABETHOS
LIOUIO JEI $=0.8344545-02$
COM2 TAS $=0.107178-\therefore 1$
FRACTICN CHAMBR UNFILLED $=000$

$$
\text { FRCTMUNLIGURマACTO= } 6.0
$$

Checraut case fos cign nasa verstoni

## PRESSUFES IPSIA:

CHAMBEQ STgJIC $=718$

- COME GAS STGN $=-80.10$
DADII (INCHES)

IITUIL: $3 \mathrm{~F}=$ U.35,154
-IMUIt: JET
iGMEUSTIOM
AREA GATIO $=1.00$
COMR GAS: $\because R=0.03539$
COME GAS SOT:IC VELOCITY $=4221.75=\mathrm{T} / \mathrm{SEC}$
$+\quad 1$

(し!い!n-ras)

 - Sivolir cip calculatim:
reckreit rast fon rich visa veisine

AXIAL EJSTANCF (INCHES)
-3.r.65 FROM J!IJECTOR FAOE
$x=$
$x$
 (LICい! - (AS)

 （LIGHn－EAS）
 FL：以ฐ：！T TYPE EZ。 TVTA
QYIAI．OISTANCE IIUCHEC।
－セロ：J FROM IT：JI：T：H FACE

VELORTTIES（HT／SEC）


FL＇INATES（LF／SFC）


 CRAT fos NIL



EL=AEPT TYJE Z


|  |  |  |
| :---: | :---: | :---: |
| - 3n-sSup=s (YSI: | TEMPERATIRES (JEG F | VELCPITIES (FT/SFC) |
| CHAMEL? SIETIC = 75j.14 | COUR GAS STAT $=5.507$ | LI2U17 JET $=710$-5 |
|  | CTAEGAS STEM 三- F-.7 |  |
| YACII (INCHESI | AREAS (SO-I*SHES) | FLOWFATES (L?/SEC) |
| LIE1IS JET $=0.04327$ | LINIID JET $=3.5033105-52$ | LInlin jry $=0.7 n 0 z 4$ |
|  | Cang SAS = C.? $1721 \mathrm{ECN1}$ | CnoptUSTITAJ GAS $=5$. LSES |

MISCELLANEOUS

SI*



(LIC1:IO-r, $=$ )




GOXIAL INJFOTICR CRMBMETICN MROEL

 AXIAL DISTANC: (INCHES)
y UOLJPNI HO甘」 $5<0^{\circ} 0-=\lambda$
$x=-0.075$ FROM INJECTCR FACE PRESSUSFS IPSIEI


 MISCELLANTJUS
MI SCE:LANFOUS
 ELnUQatrs (LE/SFC) $\begin{array}{ll}\text { LIQ!1J JEt } & =3.2186 ? \\ \text { COMUUSTIG }\end{array}$

$$
\text { FTACTIOY LIOUIS REACTED= }=0
$$



$$
\text { AXI \& } 1 \text { IISTANCE (INGHES) }
$$



## $x=-$ J．U7）EROQ INJSET「O FACE

MMNET THIS CASE

$$
=\div t
$$

FLTWPATSS (LS/SFC)

$$
\because 1695 \quad 1 \quad 1 \div r \text { (IN.. } 17
$$

$$
\begin{aligned}
& \text { FIETYAJSES TGCO: } \\
& \text { FLSUPATSS (LG/SFC) }
\end{aligned}
$$

$$
\text { COAR GAS MCL WT = } 2.15 \mathcal{L C M} \text { MOMCLE }
$$

$$
\text { FRACTINI LIOUIA JOATCAIZEN= }=008759
$$

FRロCTIJJ CIगIN शーSETET=?

$$
\begin{aligned}
& \text { STMGEETJP CALENETTINA }
\end{aligned}
$$

CRAXIAL IVJECTINA COMBHSTION NOR:CL

- smote cu calcma

AVIEL DISTENCE (IVCHESI
$X=-$-jeZis FROM IPIJECTIR FACS



MISCELLAA:ECUS

$$
\text { ML NT }=\text { ? } 536 L E / L E-4 \cap L E
$$

$$
\text { LIrUIT INATT:IIES = C. } 95339
$$

$$
\begin{aligned}
& \text { 110191 } \\
& \text { Cri4: }
\end{aligned}
$$

LE:TENTS
--..-.
------------
143

## 

ilimuid-ats) calculatirn


$$
x=-\frac{\text { AXIAL OISTANCE IINCHES? }}{-0.2: 0 \text { FRC! INJFCTOR FACE }}
$$

$$
0 \dot{\alpha}
$$

PRESSURES (DEIA)

$$
\begin{aligned}
& \text { CHAMEFR STATIC=751. } \\
& \text { CRUE GAC OTCN }
\end{aligned}
$$



RADII (ITCHES)


$$
\text { COVB GAS :UL WT }=2.055 \text { IFMS-MILE }
$$




$$
\begin{aligned}
& 9 \varepsilon= \\
& \text { NUBEKTHIS CASE }
\end{aligned}
$$



| simele cho calcillation <br> CHFCKIUT CAES FOR CICA NASA VERSJON <br>  |  |  |  |
| :---: | :---: | :---: | :---: |
| CASE IMPUT DATA |  |  |  |
| MDSCI $=$, NEL | 36 NCHAM $=0$ | ICIP $=$ ? ITPE | $\therefore \quad$ IREAD $=0$ |
| ME $=-5 \times$ NCTN4 $=$ - IEXPGL $=1 \quad$ IATO $=1$ |  |  |  |
| ACSI $=2.50558-02$ | $\begin{aligned} & C 1 P T=1.030] F-31 \\ & Q C E C=6.0 \end{aligned}$ |  | crang $=0.6$ |
| HCG1 $=3.2630 \mathrm{~F}-02$ | $\begin{aligned} & \text { Firccl }=6 \\ & \mathrm{STH}=5.40 \mathrm{C}+52 \end{aligned}$ | $\begin{aligned} \triangle C G I & =3.3953 E-r 2 \\ A N R T & =1 \end{aligned}$ | $E \mathrm{HRO} 11=0.0$ |
| WLJI $=2.2000 \mathrm{~F}-1$ | TLI $-S D E$ | VLJI $=-\mathrm{E}, 0.9 n 0 F-\mathrm{S}$ $C S P R=4.2946 E-62$ | noemay $=6.0 \mathrm{nctaz}$ |
| wGuI $=0 . \%$ |  |  | CMwCJ1 $=2.01620+50$ |
| $P C I=7.510 \mathrm{E}+j 2$ |  | $\begin{aligned} & C P P D L=2.5 C O E-C ? \\ & C C H=5.4545 E-C! \end{aligned}$ | STX2 $=2.0000-6 \%$ |
| RFLAME $=9.450 \cdot 50$ | XELAMS $=0.0$ | VFLLAE $=6$. nonorm? |  |
| $\text { NHIXZ }=2 \quad \text { UNO }=11$ |  |  |  |
| FFMil $=4.0$ Mibje-31 | $\begin{aligned} & \text { rasy }=5.0 \text { oge- } \\ & \text { fitix }= \end{aligned}$ | FFinct $=6 . \operatorname{cosen}$ - 1 | FCMIX $=5.00005-30$ |
| FSDEF = TOSTSEESI |  | $\begin{aligned} & \text { ESDER }=1 \\ & \text { SSOER } \end{aligned}$ |  |
|  |  | $\begin{aligned} & \angle S D=K=1.0 \operatorname{SanE-G} \\ & \text { FSDEP }= \end{aligned}$ | Fsoce $=5.6000 \mathrm{~F}-\mathrm{s}$ |

CCAXIA! ZNJFCTJON CRMADISTIC: verule sivale (liculo-c.as)
ELEMENT TYPE :Z 2 , TGTAL N!IMDEK OF ELEHENTS $=$ OE, AUMB $=$ THIS CAST $=36$
AXIAL DISTA:CE (IUCHES)
RQan IMJKCTRP FRCE
VFlocitils (ft/sec)


FLTENATE: ILTSERCI

--.....


 MI SCELLANEGUS
COVE CAS MOL WT $=20: 1 t$ LPALPGOLE FRACTICN LIDUIO JPIATOMIZED $=1$. NOOOC FRACTICN CIOSIC REACTEN $=\cdots \cdot$ ?

 SIVCLE EIF CALCULATIFA



$$
\cdots \cdots-\cdots
$$


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[^7]
## $y$

EEFEEOH.ES IPS:A!




CПAXIAL IVJFETITA CT：4～IIGTISA ИAESEL

 AXIAL rISTAPICE（IPACHES）
$x=-3.34$ FQOM INIEr，TLS EASF．
PRESSURES（PSIA）
（0．2う01．Sシとl1ャとうdWう1

COMS GAS NOL HT $=2$ 2．535 LFILG－IAOLE
ERACTIJI LIOIIIO UMATYIMIZET $=0.95341$
FRACTIIN LIJJIV REACTED $=5.0$
CORXIAL IHJFCTICV CNAKUSTIOU BODEL

## A M I AL UISTANCF (INEHES)

$x=-0.215$ fROA INJECTOR FACE
TEMPERATHRES MEG $=1$
VELOC:TIES (FI/SEC)
LIO!17n JTT $=69.6$.


> FLOURATES (LS/SEC)
LIOUIN JET $=0.20245$ COASUSTIM GLS $=0.05418$ iAISCELLANEDUS FRLCTIGA CHAMSEQ UHFILLET $=0.0$ Conctur $=2.005$ LS/LR-AOLF


- Singer ciliolncras) cal:ul
ramial ivjertion erugisticy monel



1） 105
CRAMAL IMJECTIMY COMBNSTIOH MREFL
GHATEER CALCILATIO：PER GEDENT
（all


1FEAD $=0$
ACHAM $=5.12 C C F+00$
ICPE $=1$
IATH＝$=\mathrm{I}$

$5: A B 11=0.3$
$=0.12$
$=0.3$
$\operatorname{ncosin}=6.9 \operatorname{coc}+3 ?$
ncomar
FMINRJI $=2.2160 E+0 \%$ －ーール
STYE＝$\because!$

CONXIAL INSECTION COMQUSTICN UNREL
chantre catcuiniontas)
ETMENT TYOE qZ; THTAL NUEED OF ELEMENTS = 66. NUMBER THIS CASE=-26
AXIAL OISTANCE (INCHES)
FEn:A INJECTCR FACE
$\begin{array}{ll}\text { X/RT } & = \\ \text { XTH } & =0 \quad \text { MON-DI:AEASICYAL }\end{array}$ PRESSUFES (PSIA) $x=8 \cdot 0$
$\times / R T=-0$
$X T H=$ temperituris (deg p) veincitite (fi/cec)

$$
x^{\cdots}
$$

CHECKBIT EASF FOR CIC:A Y:SA VERSION
PRESSHFES (PSIA)


## 


EXIAL OISTANFE（IVIFUESI
EXIAL DISTANCE（I：るこムESI

| EMAPGER STATIC $=755.33$ COME GAE STGM $=755.05$ | $\begin{aligned} & \text { COMS GAS STAT }=1211.79 \\ & \text { COMS GAS STGN }=1216.50 \\ & \hline \end{aligned}$ | LIOUIN JET $=71.51$ COMGUSTINN GAS $=933.82$ |
| :---: | :---: | :---: |
| QADEI（IVCHESI | AOEAS（S2－INCHES） | FLCHOATES（LB／SEC） |
| CTOUID JET CNMEUSTIUN GAS $=0.0 .13550$ | $\begin{aligned} \text { TMIIIO JET } & =6.6 E 0582 E-i / 2 \\ \text { COMP GAS } & =0.527 P 0 C E-01 \end{aligned}$ | CIOWIN JET $=0.16775$ COMBUSTIEII GAS $=0.05677$ |

MISCELLINECUS
nKOP
TEFPERATIT:

$$
\text { FRACTIEY CHAMEFR UNFILLEN }=0.773
$$


DATA
DRJP HEATIID FRACTIOA
DRCP r．SOUP
COMRUSTITN GAS SPRAY

$$
\begin{aligned}
& \text { FRACTION LICLID UNATOHIZEO }=0.762 \\
& \text { FRACTION LIGUID REATTED }=0.06424
\end{aligned}
$$

PATE

$$
\begin{aligned}
& \text { PATE } \\
& \text { DEG.R./IN } \\
& 3.2 G G E+B 2 \\
& 3.23 \angle F+22 \\
& 3.237 E+52 \\
& 3.433 F+2.2 \\
& 4 . C 67 E+C 2
\end{aligned}
$$

$$
\begin{aligned}
& \text { FLOUFATE } \\
& \text { LB/SES }
\end{aligned}
$$

$$
4.371 \mathrm{E}-\mathrm{C} 3
$$

$$
\begin{aligned}
& 7.3905-03 \\
& 7.657 F-03
\end{aligned}
$$

$$
\begin{aligned}
& 5.85 \varepsilon E-C 3 \\
& 6.853 E-03 \\
& 7.396 F-03
\end{aligned}
$$

$$
7.65 \div F-03
$$


:anc
:":





## 

AXIRL DIETAF:CE ITNCLESI

 $\operatorname{Hix} x$
$\operatorname{sic} x$
$x$



CHICKOUT CASE Ene CJEU MASA VFOSICM
AXIAL IISTANCC (INCHIS)

$$
\begin{aligned}
& \text { YTH }=\text { ROENS FROIF THRCA: }
\end{aligned}
$$

 AISCELLANEOT3


FRACTICH LIU,II! PEACTER= $\because .14466$

$$
\begin{gathered}
7 \\
8 \\
0 \\
10 \\
11 \\
12 \\
13 \\
14 \\
15 \\
16 \\
17
\end{gathered}
$$








#  

 (LIU1!n-GAS) AXIAL DISTANCE (IJCHE: AXIAL DISTANEE (IJCHES)

## FACE

$=6.7 E 3$ N:CN-DJMCtisTMJLL

PQESSUEES (PSIA)
 TEMPERATUPES (VrCR)
VFLSCITIES (FT/SEC)





CH? (LIGHIO-GAS)
EL AMPNT TYPE SO, TOTA! NUMTER OF ELEMEMTS = GG, NUMSER TUIS CASE = 36
AXIAL [ISTANEE (INCHESI

- ver FROM IrsjFitra facE
$=\therefore \bullet 974$ NON-NIMFNEIONAL
XIH $=2.75$ FRIFH THPLAT
VEIMCITIES (FT/SEC)
Invin JFT $=74.43$
COMPU:T1FMG:S $=G 5 E .01$
FLCiPATES (L3/SEC)




FRACTISN LIOI!TRF:CTER = $\therefore=3=650$
COME:STINY GAS SPRAY
DRIJP HFATI:D FEACTION
RIP COOUP
LOWFATF
LS $\angle E B C$


> D:חP
TSijorntha;
DRGG
y LrCITY
ก 27.0 .4
27.4
$1.519-6$
2.192 E- 3


MISCELLANFOUS
T/SEC
6.16.4.70 FT/SFC
C*EFCICIINCY = 4?.34
AREA $\because A T I!=1.215 \%$
PRESSPH:SS (PSJI)
CHAMEER STATIC $=7.5 .2 Q$
CTNE CAS STGN $=151.57$
QAEII (INEHES)





To: jlit iは)
CHANR CAELILATIOM PIR FLIAFAT

AYIAL CISTAHIC (IVEMESI
F丹न) $1 A \leq C T(: 9$ FAEF
FIMOX-NMENOSJCIVAL


vencime (fissel)


 FRACTION IIOUI! 2EACT: $=i .0$ Cras cias sfiple VELiEIIY $=3+14.23$ EI/SFC
 C. FFICI.YCY = 17.5?


## EXAL MICTANE (ITCHES

$=-174$ NGN-TMESSIOMAL
$=-4.50 G$ FEOMTHEOAT TEMPERTHRES (DRGA) VELOCITITC (FT/SFC)

FLOWPATES (LS/SFC)
MISCILLANEMUS

$$
\text { ITHIE JiT }=0147:
$$

$$
\text { cultisfint ous = } 6.0576
$$


FIACTIMA CHANCER UNYILITO = 0.708 coup ras urit uT = 3.17E
 Drop grouk TeDp G!
rLDMEATE
LEAS! 4, 6. E20.-: 3 $7.3651-02$
$7.572 r-1.3$


SDEAY
$\qquad$ 8
0
0
0
0
0
DATA


CEAXIA! INJFETIGN CEMBIISTICN MS:FL

EXIAL NISTANCE (INCHES)

CHECKCUT CASt EOR CICM NAS Y VESICS:
$=$ C. 150 FOUIA INJECTIO FICL
 XRT
$\times 1 / 2 T$
$-H 1 X$
FRESSURFS (PSIA) VELOCITIFS (FT/EFC)
$\begin{array}{ll}\text { LIOUII: JFT } & =70.64 \\ \text { COMEUSTIS: GAS } & =811.33\end{array}$ FLCNRATES (LE/SEC)
$\begin{aligned} \text { LTQUIF JET } & =0.130 \text { R: } \\ \text { Crindus IOU } & =0.35830\end{aligned}$
COMDUSTION GAS $=0.35830$

FUACTIN CIAMLEF INJFILLEO $=0.640$

FOCCTION II!U! REACTEI = r.ncpel
CrAJOSTICY CAS SPYAY CATA
OFOP HEATIO FRACTEON DRIPP GBOUP
$066 . R-14$
$2.3746+2$
$2.277 E+2$
$2.160 E+02$
$2.0756+12$
$2.02-E+2$
$2.017 E+2$


 (SGHJNI) II UVC

> TEMPERATURTS (DEG R
 ARFAS (SO-IULHES)
 (n): -... COME GAS SOUIC VELSLITY = ETET. $\because$ F FTASEC

AREA RATII = $1.0 ? 3$

$$
06650
$$ MTSCFLLATITMIS

    .............................
    



$$
-\ldots----
$$


FLJSTITF
LB/SEC
$4.2745-33$
$5.74-5-63$
$7.2795-63$
$7.54 \div 1-22$
6.5A

-




ELIATIT TPE :
A!IAL GISTA irf IIvt

$\therefore=92$ arIN-TIVE:SITNAL
4.t.it F\&nsw THOLAT

Vflnctiles (fi/sec)

FPACTINV CHLMPE LUCILLFO $=0.444$
COS GAS MOCWT $=-3 . F 1 \angle$ LTILE-:OLE
ERCCTINO LICUIW EARCTEDEE $=0.26410$
ERCTIN LICUIV EfACTED $=0.14840$
reno conum


SDKAY TATA

## $\therefore \therefore S$

C.JMidisTIMN!
meris
micita

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\operatorname{rnnp}
$$

pro.?
200.9
255.2

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| N |
| N |



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\text { Ivalysach } B 1 \\
\text { duar }
\end{gathered}
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$\cdots$
$\cdots$
$\sigma$
$\cdots \sim$
1
$3 \% \angle う \cdot 1=1$ IIV; yin7
FResslints (PSIA)
 ? LOH - -

$6.32=-3$
$6.22=-3$



 =

247.7
243.9
242.5
$245 \cdot 4$
238.4
231.2
223.0
216.3
238.1
145.4
$19=.7$

- ज - nnNommoo

NNNNNNman




## DRAP

80

- $\square$



## AYIAL IISTANEE (IVE.HES)

$=$ l.Soi FRO: IVJ!ctm: fecf

frne thriat



FRACTIGM LICUIS REACTEH =.$: 3760$

H
$=0.27180$



 ...s $r=$
COMOUSTIN GAS SPRAY EATA

 QSNII INCHESI

LImpir st
Crimstestive AREAS ISA ITNHEST

 $\begin{array}{lll}2 & 2 \\ \vdots & 2 \\ 0 & 2 \\ 0 & 0 \\ \vdots & 0\end{array}$
MI SCFLL AMEOUS
とい－ーくした。

 NonNunNonrunañ


$$
\begin{aligned}
& 1.5 \\
& 4.2 \\
& 5.4 \\
& 4.7 \\
& 5.9 \\
& 8.1 \\
& 1.7 \\
& 6.5 \\
& 2.5 \\
& 2.5 \\
& 7.5 \\
& 7.7 \\
& 6.5 \\
& 6.1 \\
& 6.3 \\
& 6.8 \\
& 7.8 \\
& \hline 2.6 \\
& \hline 0.6 \\
& \hline 0.7
\end{aligned}
$$




 MISCILLANEDIS
 CRHEIETIMI GAS SPRAY OATA مerprenup
Feriment FlnbrAT
in／sic 1．7471－24
$-7475-5$ 3．ज氏日F－：13


 gafip hicatip
 nETP TEYPEのATIM：
い日GR•
$n$
$\vdots$
$\vdots$
$\vdots$
$\vdots$


莫
 SPRAY
GRIGLG ーかいいかん

$$
\begin{aligned}
& =1 \cdot 45 ? \\
& = \\
& =\cdots \cdot 1 \cdot 36 \\
& =
\end{aligned} \quad .52
$$

RAOII (INCHES)
MT SCELLAME CIS
 FRACTIMN tIOU1D RFACTES = $\because 43.95$
SDQAY TPTE
dine

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0 E \varsigma 巳^{\circ}
$$

$$
-=-=-=-=-
$$

PRESSURTS (PSIA)

$$
\begin{aligned}
& 742.05 \\
& 749.91
\end{aligned}
$$

1ERABCA TUR:

rurnmmaman r.C3843 $\quad 4.4115-6$



$$
\begin{aligned}
& \text { CHAMEC? SI:YIL }=7.9 .07 \\
& \text { Cries GAS STGN }=760.44
\end{aligned}
$$

$$
\begin{aligned}
& \text { tinning JF } \\
& \text { COAS GAS }
\end{aligned}
$$

$$
-\cdots---
$$

AREAS (SO-INCHCS)

13



$=1.5$ FOOM HJECTO？FAC．


VELNCITIFS（FT／SEC）

FLOURATES（LR／SEC）
L！OUIの 1F7 $=$ N．0
cantetirn GR $=$ POB3274 ：AISCLLLANETUS FRI


ACTE $=0.42608$


RAOII（INCHES
PRESSITES 1PSIA;
：

$$
\begin{aligned}
& \text { FRACTIGN LIOHIC } \\
& \text { ERCOTIF LIOHI }
\end{aligned}
$$

AREA ：ATI：$=1.2641$
589．3njo

 の品：

$$
\begin{aligned}
\text { CriAS G2S STAT } & =4346.24 \\
\text { Crils GAS STCN } & =4350.16
\end{aligned}
$$

grioustion res SOEAY RATA
 ค号

このをテこロ＝
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$$
\begin{aligned}
& \text { DROP HEAT:2 } \\
& 7.92 \mathrm{aitc}
\end{aligned}
$$



 r．TU1 $=204=25+2$ 2．452らE＋ $2 \cdot 351 \frac{1}{2}[+1) 2$ $2 \cdot 2651 E+5$ $=1 \cdot \operatorname{rifl} E+02$
$=2.7353 F+i)$
 $2 \cdot 72-1 E+B ?$
$2 \cdot 7046 F+U ?$ ご $+7: 7 \angle 9^{\circ}$ ての＋ラみことの・




 $1.79695-62$
$1 \cdot r 4765-92$
$1-479 F-92$
$1-5866 F-72$
$1.2622 F--1 ?$ If if if li li $C D I D I$
Gritan $5 \%$
 $r \cdot$ rVELil＝2．24：3E4

：Vr
$++1+$ $\begin{array}{ll}a & m \\ m a n \\ c\end{array}$ $N N \rightarrow$ $C$
2
2
2


 1
GHSFR
GHSFF
CHSFR
GWSFR
GHSPR
GWSFR
GWSDR
GISPR
GWSPR
GWSPR
GWSPR
GWSPR


$$
\begin{aligned}
& \text { RNS OF INOITT NATA - NERKLEITFOOA PRITRAM }
\end{aligned}
$$


[^0]:    NASA-GEORGE C. MARSHALL SPACE FLIGHT CENTER Marshall Space Flight Center, Alabama 35812

[^1]:    *Chuch, P. L., and J. M. Prausnit., "Calculation of High-Pressure VaporLiquid Equilibria," Industrial and Engineering Chemistry, Vol. 60, 1968, pp. 34-52.

[^2]:    For clarity, notation has been changed in this section; nomenclature is placed at end of section.

[^3]:    
    
    $\square$

[^4]:    $39 \mathrm{Cr}+7$
    $.39382=+\square$

[^5]:    MISCELLコ*FSU3 COMS GAS ッCL WT $=2.667$ LS/LB-MCLE CQACTITA! LICI!IS I'NATCMIZET, = $=94138$

[^6]:    

[^7]:    - YIL IISTA:ICE (IICuF:
    -2...iE FROM If:JECTRG FACE
    $=$

