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Development and Implementation of a Scramjet Cycle Analysis Code with a Finite-Rate-Chemistry Combustion Model for Use on a Personal Computer

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THESIS

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THESIS

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List of Symbols

A	frequency factor
A	area
A_0	inlet capture area
A_6	nozzle exit area
C_f	empirically determined constant used with the Arrhenius equation
$\hat{C}_p$	molar specific heat at constant pressure
C_p	specific heat at constant pressure
E_{act}	activation energy
F	stream thrust
g	gravitational constant
h	enthalpy
$\hat{h}_o$	molar reference enthalpy of each species
I_{sp}	specific impulse
k	rate constant
k_b	backward reaction rate coefficient
k_f	forward reaction rate coefficient
K_c	equilibrium constant based on concentration
K_p	equilibrium constant based on pressure
$\dot{m}$	mass flow
M_i	denotes the individual species
M	Mach number
N	number of moles of each species in the system
NR	total number of reactions in system
NS	total number of species in the system
p	pressure

p_0	free stream pressure
q	free stream dynamic pressure
ΔQ	heat loss in the diffuser
R	specific gas constant
$\hat{R}$	universal gas constant
s	entropy change from a reference entropy state
$\hat{s}_o$	molar reference entropy
S	combustor gap height
T	overall engine thrust
T	temperature
T_o	reference temperature of the system
U	velocity
V	volume of the combustor
[X]	equilibrium molar concentration of each species
x_1	length for complete mixing with equivalence ratio equal to 1.0
x_ϕ	length for complete mixing with equivalence ratio not equal to 1.0
$\dot{w}_f$	weight flow of fuel

Greek Symbols

α	inclination angle from the horizontal
ε	Crocco index
η_b	compression efficiency
η_{kd}	process efficiency
η_{ke}	kinetic energy efficiency
η_m	mixing efficiency
η_{pt}	total pressure recovery efficiency
η_t	empirically determined constant used with the Arrhenius equation

Θ_d	characteristic temperature for dissociation
ν	stoichiometric coefficient of the reactants
ν'	stoichiometric coefficient of the products
ν_r	stoichiometric coefficient of each species
ρ	density
τ_w	wall-shearing stress
Φ	Bray's nozzle rate parameter
ϕ	equivalence ratio

Subscripts

a	properties at the combustor inlet
b	properties at the combustor exit
o	reference state
r	the reaction number
s	species
t	stagnation properties
0	free stream conditions
4	properties at the diffuser exit
5	properties at the combustor exit
6	properties at the nozzle exit

Superscripts

*	equilibrium properties

Abstract

This study compared the performance of an equilibrium combustion model to a finite-rate-chemistry combustion model for a fixed geometry Scramjet flying at the flight conditions of Mach 12, 15, and 18 with a constant dynamic pressure of 50,000 Pa. An integrated PC-based code, developed specifically for this study, models the combustor as an equilibrium combustion process or as finite-rate-chemistry combustion process. This integrated program is based on two existing programs, Ramjet Performance Analysis (RJPA) and 3STREAM. The effects of mixing schedule, combustor length, and combustor exit area were investigated. The results of this study indicate that inefficient mixing is the primary cause of Scramjet performance loss regardless of the flight speed. Combustor length and combustor exit area also had a strong impact on performance.

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Chapter 1 - Introduction

1.1. - Background

Ever since the Wright brothers showed the world that heavier than air flight was possible, engineers have strived to make faster and more efficient aircraft. By 1945, aircraft had evolved beyond recognition from the Wright Flyer. The Wright Flyer, with an average speed of 16 kph, was far out-performed by the piston engine fighters of World War II which flew at speeds of 750 kph (Rand McNally Encyclopedia of Military Aircraft, 1990:165).

Piston engine aircraft were still setting new speed records when the turbojet engine was introduced by the Germans in 1944. It was that year that the Messerschmitt Me.262A-1a became the world's first operational jet fighter. With a top speed of 869 kph, this primitive jet aircraft was already the fastest airplane in the world (Rand McNally Encyclopedia of Military Aircraft, 1990:206).

Once proven as a viable propulsive device, jet engine technology grew by leaps and bounds. The climax to manned atmospheric flight came on June 27, 1962 when the rocket powered Bell X-15 achieved hypersonic speeds (Anderson, 1985:245). Since that historic day, hypersonic propulsion has been the subject of

many government, university, and industrial research projects. A great deal of data concerning hypersonic propulsion has been obtained from the X-15 and Space Shuttle programs. However, predicting experimental results continues to be a formidable task. Real gas effects encountered at Mach numbers greater than 5 result in numerous difficulties in estimating engine performance (Curran et al., 1992).

The governing equations for hypersonic flow are quite arduous to solve without the aid of high speed computers. However, when hypersonic research was in its infancy, c.1950, computers were not available to most of the scientists and engineers. Therefore, they developed simpler, less labor intensive methods to model the combustion process and determine engine efficiency (Curran et al., 1992).

Many methods of estimating Scramjet engine performance were devised during the 1950/1960 time period. One such method was the overall engine kinetic energy efficiency introduced by Evans in his 1951 paper ***Analytical Investigation of Ramjet Engine Performance in Flight Mach Number Range from 3 to 7***. Another was the development of integral solutions to the governing equations. These integral solutions became known as the equilibrium-combustion-model for reacting flows. The equilibrium assumption assumes that "all molecular processes take place within the gas infinitely rapidly, that is, that the gas can adjust instantaneously to changes in its environment" (Vincenti & Kruger, 1965:178).

Large amounts of physical information about the combustion process are sacrificed in order to obtain the closed form equilibrium-combustion-model integral equations. Although relatively simple to use, the integral equations only provide information about the beginning and the end of the combustion process. All of the physical and chemical reaction data in between the end points of the combustion process is lost.

On the other hand, the finite-rate-chemistry (FRC) combustion model is based on the differential equations of motion for a gas. These equations allow the engineer to consider the effects of combustor length and area changes, fuel-air resident time, fuel and air mixing schedules, collision efficiencies, and chemical reaction equations (Vincenti and Kruger, 1965:228). The differential equation approach solves for the resultant properties by using finite step sizes and evaluating the chemical and thermodynamic properties at each step location.

Despite the wealth of information available from the FRC-combustion-model, it could not effectively be utilized on the mainframe computers of the late 1950's. While these computers allowed engineers to automate the task of repetitious calculations, these early computers were very limited in their capabilities. Limited internal memory for data storage and the tedious task of punch card programming hindered the development of sophisticated combustion programs. Therefore, the relatively simple equilibrium-combustion-model was the first combustion mechanism to be automated. As mentioned earlier, equilibrium-combustion-model computer codes are based on the integral solutions for the equations of motion of a gas and provide information only about the beginning and the end of the combustion process.

As computers improved, computational FRC-combustion-models became possible. Most of these early FRC-combustion-models were one-dimensional and modeled only a small number of the many possible chemical reactions. Furthermore, limited computer memory restricted the models to very coarse grids for geometric representations of the Scramjet components. However, by the early 1980's, very refined and complex component grids were being used to model the combustion process.

With the introduction of the personal computer (PC) in the 1980's, equilibrium-combustion-model codes moved from the mainframes and into the

realm of the individual engineer (Pandolfini, 1986). Where a team of engineers and programmers once was needed to prepare, execute, and evaluate a single configuration for a Scramjet, a single engineer could compute and analyze several Scramjet configurations per day.

1.2. - Purpose

Based on the current needs of the hypersonic research community, two objectives have been established for this study. First, develop a one-dimensional integrated PC-based Scramjet analysis code capable of modeling a Scramjet engine which provides the individual engineer access to the realism of the FRC-combustion-model. Second, demonstrate the robustness of the code by performing a parametric study to determine the salient parameters for efficient operation of a fixed geometry Scramjet.

With today's high end PC's it is now possible to put the realism of the FRC-combustion-model in the hands of the individual engineer at a fraction of the cost of a mainframe computer. Finite-rate-chemistry has long been the domain of mainframe computers. However, today's high end PC's are comparable to many of the current mainframes in use today. Furthermore, PC's can be purchased, operated, and maintained at a fraction of the cost of a mainframe.

Despite the obvious benefits of putting FRC in the hands of the individual engineer, there is a general lack of availability of integrated PC-based FRC-combustion-model analysis codes capable of modeling supersonic combustion. Most of the PC-based codes that model the entire Scramjet use equilibrium-combustion-models, while most of the available PC-based FRC-combustion-model codes only model the combustor. The code developed for this research project will help fill some of the void by providing an integrated PC-based code capable of modeling a Scramjet engine with an FRC-combustion-model for the combustor.

The need for a PC-based code becomes even more evident when one considers the limited availability of super computer time and hypersonic test facilities. A significant portion of the super computer capability in the United States is being utilized to validate enormous computational-fluid-dynamic (CFD) codes to predict the inlet, combustor, and nozzle operation of hypersonic vehicles (Barthelemy, 1990). Furthermore, hypersonic flow test facilities have steadily decreased from 82 wind tunnels in 1963 to only 24 wind tunnels in 1987 (Wittliff. 1987). An integrated PC-based FRC-combustion-model code will enable hypersonic research to continue at a much lower cost and allow better utilization of the remaining test facilities by testing only well designed concepts.

1.3. - Scope of Research

The development of the Scramjet analysis code required the integration of two computer codes. An equilibrium-combustion-model Scramjet analysis code served as the shell for the final product, and a finite-rate-chemistry combustor model code was added as an additional option to the existing equilibrium-combustion-model in the shell program.

Figure 1a is a block diagram of a typical Scramjet engine illustrating the air flow through the engine and the flow of data in the shell engine analysis program (Pandolfini, 1986). Free stream air enters the engine through the inlet/diffuser at station 0. The inlet/diffuser slows, compresses, and guides the air into the combustor entrance at station 4 (Hill and Peterson, 1992:226). Fuel is added to the air and is mixed and combusted in the combustor (Hill and Peterson, 1992:257). Next, the combusted mixture leaves the combustor and enters the nozzle at station 5. Finally, the air leaves the engine through the nozzle exit at station 6. The nozzle creates thrust by accelerating the gas mixture to very high velocities (Hill and Peterson, 1992:520).

The operation of the free stream module, the inlet module, and the nozzle module of the shell program remain unchanged in the integrated program. However, as illustrated in Figure 1b, an option has been added to allow the equilibrium combustor module to be bypassed and the gas properties of the inlet/diffuser to be sent to the FRC combustor module. Once combusted, the gas properties are passed from the FRC combustor module to the shell code equilibrium nozzle module for thrust (T) and specific impulse (I_{sp}) calculations.

Once the computer codes were integrated, the final product's robustness was demonstrated by characterizing the performance of a typical fixed geometry Scramjet over a number of different flight conditions. The performance of the Scramjet was characterized by comparing the thrust output of the equilibrium-combustion-model to the thrust output of the FRC-combustion-model for several different combustor lengths and combustor exit areas at various flight Mach numbers.

When a short combustor length is used, it is reasonable to expect that some of the fuel and air mixture may not be completely mixed or reacted at the combustor exit (Northam and Anderson, 1986). When this mixture enters the equilibrium nozzle module of the integrated code, any unmixed and uncombusted fuel and air remaining in the mixture will be instantly mixed and combusted (Pandolfini, 1986). Of course, this is physically unrealistic (Bray, 1959). Therefore, since this study's objective is to compare the differences in the combustor models, the effects of the nozzle are suppressed by considering only the thrust results for frozen flow in the nozzle. Frozen flow assumes that no chemical reactions take place, i.e. no further reactions occur once the mixture leaves the combustor (Vincenti and Kruger, 1965:190).

For this study a constant area combustor, suitable for a typical Scramjet flying at Mach 15, was selected as the baseline (Leingang, 1993). While holding

the baseline geometry constant, the Scramjet's thrust performance was characterized for several flight conditions above and below the baseline flight conditions.

The flight conditions examined were limited to Mach 12, Mach 15, and Mach 18. These were selected because, for high speed flows, inlet efficiencies are fairly constant over this range of flight Mach numbers (Leingang, 1993).

In addition to characterizing the performance at the different flight conditions, a parametric study to characterize the performance of different combustor exit area geometries was performed. During the parametric study the baseline geometry of the Scramjet was held constant at stations 0-4 and at station 6. Referring to Figure 1a, these stations correspond to the Scramjet's inlet/diffuser, combustor entrance, and nozzle exit. Therefore, only the geometry of station 5, the combustor exit, was varied.

Currently, there are not any acknowledged hypersonic vehicles in operation whose geometry can be used as a starting point for this study. However, combustors for hypersonic, sub-orbital vehicles are expected to be about 3 m in length (Leingang, 1993). Unfortunately, overall vehicle design constraints usually require the geometry for any one component to be different than the optimum dimensions for that component (Raymer, 1989). Therefore, during the parametric study the combustor length was varied above the baseline length to 5 m, and below the baseline length to 1 m. These lengths should be representative of combustor lengths that might be considered for the design of a hypersonic vehicle (Leingang, 1993).

Additionally, combustor geometries are generally designed with either a constant area combustion process or a constant pressure combustion process in mind. However, as with the combustor length, the combustor exit area is subject to geometric design constraints. Therefore, engineers often compromise and

design combustor geometries that result in combustion processes somewhere in between the constant pressure combustion process and the constant area combustion process (Leingang, 1993). Therefore, to encompass the entire spectrum of likely combustion processes during the parametric study, the exit area was varied from the baseline value of a constant area to an exit area that resulted in a combustor exit pressure equal to the combustor entrance pressure.

Although this study investigated a wide range of combustor goemetries, it did not consider the effects of heat transfer to the surrounding area, skin friction, or shock and momentum losses. This was strictly an inviscid, adiabatic flow characterization of the differences between the equilibrium-combustion-model and the FRC-combustion-model for different combustor geometries at varying flight Mach numbers.

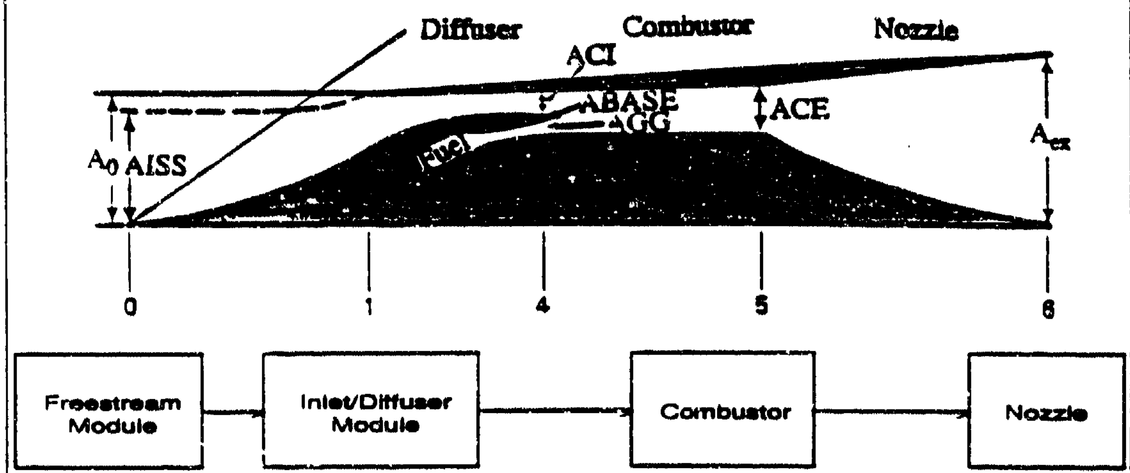


Figure 1a - Functional Block Diagram of a Scramjet

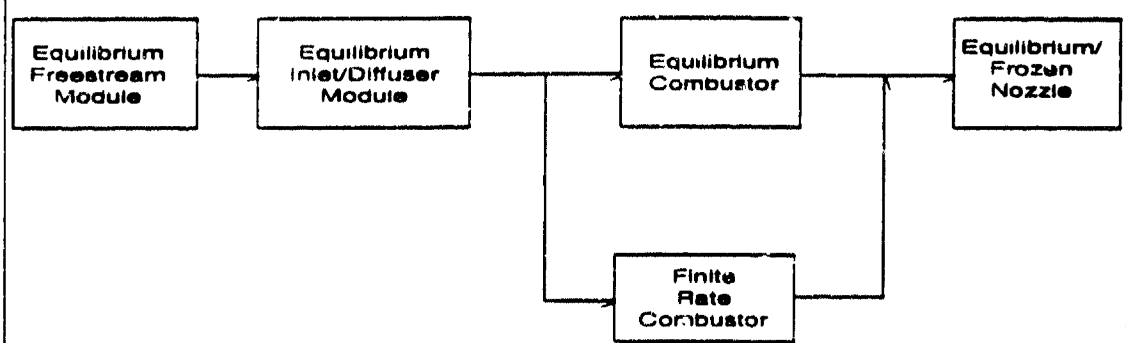


Figure 1b - Functional Block Diagram of the Equilibrium-FRC Code

Chapter 2 - Theory

2.1. - Introduction

Scramjets are the simplest of all air-breathing engines (Hill and Peterson, 1992:155). They do not use any turbomachinery or complex gearing for synchronization of turbines and fans. They simply consist of an inlet or diffuser, a combustor, and a nozzle. A great deal of effort has been put forth to characterize the operation of these components and excellent discussions concerning the operation and efficiencies of the components are available in papers by Waltrup et al., 1981, and Lee and Boedicker, 1983.

The uncertainty of whether to model the flow through a particular Scramjet component as a frozen flow, an equilibrium flow, or as a finite-rate-chemistry flow has always been an underlying question of all characterizations of Scramjet components. The simplicity of the governing equations when using the equilibrium flow assumptions or the frozen flow assumptions has many advantages. However, many of the assumptions made to achieve the closed form, integral solutions of the equilibrium and frozen flow models lead to unrealistic results for thrust, pressure, temperature, etc. Only the FRC-combustion-model consistently gives realistic results for the chemical and thermodynamic properties.

2.2. - Chemistry

2.2.1. - The Elementary Chemical Reaction

Regardless of whether an equilibrium flow assumption model or a FRC model is used to model the combustion process, a set of chemical reactions must be defined to describe the combustion process. An elementary reaction is a single step reaction process that is part of a larger, more complex reaction (Segal,

1985:952). Many common representations for reactions are not elementary reactions. Anderson points out that ". . . the reaction

$$2H_2 + O_2 \leftrightarrow 2H_2O \tag{1}$$

is not an elementary reaction. Two hydrogen molecules do not come together with one oxygen molecule to directly yield two water molecules, . . ."(Anderson, 1989:495). The elementary reactions defining the formation of water from its constituent parts are given as: (Anderson, 1989:495)

$$\begin{aligned} H_2 &\leftrightarrow 2H \\ O_2 &\leftrightarrow 2O \\ H + O_2 &\leftrightarrow OH + O \\ O + H_2 &\leftrightarrow OH + H \\ OH + H_2 &\leftrightarrow H_2O + H \end{aligned} \tag{2}$$

These elementary reactions, as well as any other possible reactions, can be represented by the following equation:

$$\sum_{i=1}^{NS} \nu'_{i,r} M_i \underset{k_b}{\overset{k_f}{\rightleftarrows}} \sum_{i=1}^{NS} \nu''_{i,r} M_i \tag{3}$$

where:

k_b	= backward reaction rate coefficient
k_f	= forward reaction rate coefficient
M_i	= denotes the individual species
NS	= total number of species in the system
r	= the reaction number

ν' = stoichiometric coefficient of the reactants

ν'' = stoichiometric coefficient of the products

It is not always necessary to use elementary reactions to describe the combustion process. The equations governing a reacting flow can be solved using global reaction equations like Eq. 1. However, if elementary reaction equations are not used, potentially vital information about the minor species may be lost. For example, if Eq. 1 was used to describe the combustion process of H_2 and O_2, only information pertaining to H_2, O_2, and H_2O would be available. However if the reactions given in Eq. 2 were used, information for H_2, O_2, H_2O, H, O, and OH is available. Knowledge of the concentration, pressure, and temperature of the minor species can be of vital concern to the structural and material engineers, since many minor species can be extremely corrosive (Askeland, 1984: 670).

2.2.2. - Equilibrium and Frozen Flow Assumptions

The equilibrium flow assumption was defined in Section 1.2 as a flow where ". . . all molecular processes take place within the gas infinitely rapidly, that is, that the gas can adjust instantaneously to changes in its environment. " (Vincenti & Kruger, 1965:178). Since complete and instantaneous mixing and combustion of the gases is assumed, the equilibrium flow assumption represents the upper bound in terms of how far reactions can proceed for a given set of initial conditions (Anderson, 1989:527). In other words, the equilibrium flow assumption predicts the theoretical maximum extent of possible reactions for a reacting flow.

On the other hand, the frozen flow assumption represents the lower bound of how far reactions can proceed. The frozen flow assumption states that no chemical reactions take place (Vincenti and Kruger, 1965:190). Therefore, assuming a thermally perfect gas, calculations using the frozen flow assumption

are carried out with the perfect gas relations using appropriate values for specific heats, C_p and C_v, and gas constant R (Vincenti and Kruger, 1965:190).

While not as simple as the frozen flow assumption, the equilibrium flow assumption is relatively easy to model and is dependent only on temperature and pressure. From the law of mass action for fully- reacting flows, a relationship for the partial pressures and the equilibrium constant is given as (Vincenti and Kruger, 1965:82):

$$\prod_{s}\left(p_s^*\right)^{\nu_s} = K_p(T) \tag{4}$$

where:

K_p	= equilibrium constant based on pressure
p_s^*	= partial pressure of each species at equilibrium
T	= initial temperature of reaction
ν_s	= stoichiometric coefficient of each species

This relationship can also be expressed in terms of molar concentration as (Vincenti and Kruger, 1965:82):

$$\prod_{s}[X_s]^{*\nu_s} = K_c(T) \tag{5}$$

where:

K_c	= equilibrium constant based on concentration
T	= temperature of reaction
$[X_s]^*$	= equilibrium molar concentration of each species
ν_s	= stoichiometric coefficient of each species

These two equations can be related by using the equation of state in the form $p_s^* = [X_s]^* \hat{R}T$ where $\hat{R}$ is the universal gas constant. After substituting the

equation of state into Eq. 4, solving the resulting expression for $[X_s]^*$, and then equating it to Eq. 5, the relation for $K_c(T)$ and $K_p(p)$ is found to be (Vincenti and Kruger, 1965:82):

$$K_c(T) = \frac{K_p(T)}{\left(\hat{R}T\right)^{\sum_s \nu_s}} \tag{6}$$

An equation of this form, for each elementary reaction, coupled with the continuity equation allows for the solution of the pressures. Using the equation of state as given above, the other thermodynamic properties of the gas can then be found (Hill and Peterson, 1962:55).

Since the equilibrium and frozen flow assumptions represent the extreme conditions for the extent of reaction in the combustion process, neither one can be applied to an arbitrary flow condition because some mixtures of gases react very fast while others react very slowly. This statement can be illustrated by Figures 2 and 3 (Hill and Peterson, 1992:580)

The solid line in Figure 2 is a curve fit of experimental data for the corrected specific impulse (I_{sp}) of a rocket engine using H_2 as the fuel and O_2 as the oxidizer. The combustion process for the data plotted in Figure 2 took place at chamber pressures of 0.27, 0.14, and 0.5 MPa. The dashed lines represent the I_{sp} calculated using the equilibrium and frozen flow assumptions for this particular fuel. The results indicate that the propellant H_2-O_2 reacts very quickly and approximates the equilibrium-combustion-model.

The solid line in Figure 3 is also a curve fit of experimental data for corrected I_{sp}. However, the fuel used for Figure 3 is JP4 aviation fuel. This fuel was combusted along with oxygen in a rocket combustion chamber at a pressure of 4 MPa. Once again the dashed lines represent the I_{sp} calculated using the equilibrium and frozen flow assumptions for this particular fuel. Unlike the

propellant H_2-O_2, Figure 3 indicates that the aviation fuel JP4 reacts very slowly and is well approximated by frozen flow assumptions (Hill and Peterson, 1992:580).

2.2.3. - Finite-Rate-Chemistry

As seen in Figures 2 and 3, some flows react very quickly and closely approximate the equilibrium flow assumption. Others react very slowly and closely approximate the frozen flow assumptions. However, neither of the fuels illustrated in these figures actually achieve the reaction rates assumed by the equilibrium flow or the frozen flow assumptions. The true reaction rates are somewhere in between the extremes. In fact, they proceed at a finite-rate, governed by a set of non-linear differential flow equations, subject to a set of initial and boundary conditions, and are modeled by a complex set of elementary chemical reactions. This reaction process is known as finite-rate-chemistry.

Finite-rate-chemistry is a tool that allows the engineer to mix gases and predict the results of the combustion process with only the knowledge of the elementary reactions, the rate constants for the reactions, and the initial and boundary conditions for the flow (Vincenti and Kruger, 1965:228). The finite-rate is the time it takes one particle to find another particle with sufficient energy to react. Chapter 6 of Vincenti and Kruger's book Introduction to Physical Gas Dynamics gives a detailed discussion of FRC and it is summarized here where each chemical reaction is defined by a number of elementary chemical reactions.

The law of mass action for non-fully-reacted flows defines the forward reaction rate as (Anderson, 1989:493):

$$\left.\frac{d[X_s]}{dt}\right)_f = \left(\nu_{s,r}'' - \nu_{s,r}'\right) k_{f,r} \prod_{i=1}^{NS} [X_i]^{\nu_{i,r}'} \qquad (7)$$

and the backward reaction rate as (Anderson, 1989:493):

$$\left.\frac{d[X_s]}{dt}\right)_b = \left(\nu_{s,r}{}' - \nu_{s,r}{}''\right) k_{b,r} \prod_{i=1}^{NS} [X_i]^{\nu_{i,r}''} \tag{8}$$

The total rate of change of species X_s can be found by combining Eqs. 7 and 8, and summing over all possible reactions. The equation for the total rate of change of species X_s, can be expressed as:

$$\frac{d[X_s]}{dt} = \sum_{r=1}^{NR} \left(\nu_{s,r}{}'' - \nu_{s,r}{}'\right) \left[k_{f,r} \prod_{i=1}^{NS} [X_i]^{\nu_{i,r}'} - k_{b,r} \prod_{i=1}^{NS} [X_i]^{\nu_{i,r}''} \right] \tag{9}$$

where:

$k_{b,r}$	= backward rate constant for reaction "r"
$k_{f,r}$	= forward rate constant for reaction "r"
NR	= number of reactions in system
NS	= number of species in the reaction
$[X_i]$	= molar concentration of each species containing the elements of species "s" in reaction "r"
$[X_s]$	= molar concentration of the species of interest
$\nu_{i,r}{}'$	= reactant stoichiometric coefficient of species "i" in reaction "r"
$\nu_{i,r}{}''$	= product stoichiometric coefficient of species "i" in reaction "r"
$\nu_{s,r}{}'$	= reactant stoichiometric coefficient of reaction "r" of species whose rate is being determined

$\nu_{s,r}''$ = product stoichiometric coefficient of reaction "r" of species whose rate is being determined

The rate constants k_f and k_b are related by the equilibrium constant K_c by the relation:

$$k_f = k_b K_c \tag{10}$$

where K_c is given by:

$$K_{c,r} = \frac{\prod_{i=1}^{NS} [X_i]^{\nu_{i,r}''}}{\prod_{i=1}^{NS} [X_i]^{\nu_{i,r}'}} \tag{11}$$

The equilibrium constant K_c is readily available in various sources (i.e., JANNAF Tables).

In 1889 the Swedish chemist Svante Arrhenius proposed an empirical equation describing the temperature dependence of any specific rate constant and is given as follows (Segal, 1985:728):

$$k = Ae^{-E_{act}/RT} \tag{12}$$

where:

A	= frequency factor
E_{act}	= activation energy
k	= rate constant
R	= gas constant
T	= absolute temperature

After taking the natural logarithm of both sides of Eq. 12, a plot of ln k versus $1/T$ will be linear with a slope of $-E_{act}/R$. However, very accurate

measurements have indicated that ln k versus $1/T$ is not always a straight line. Therefore, a modified form of the Arrhenius equation is used to find either k_f or k_b. The form for k_f is given as (Vincenti and Kruger, 1965:215):

$$k_f = C_f T^{\eta_f} e^{-\Theta_d/T} \tag{13}$$

where C_f, Θ_d, *and* η_f are empirically determined constants. The value of these constants vary with source and are not exactly determined for most reactions. Some accepted sources for these constants are Byron, 1959, Wray and Teare, 1962, Dunn and Kang, 1973, and Jachimowski, 1988. With k_f and K_c known, k_b can now be determined. From this point forward, the thermodynamic properties of the system are determined in a similar manner as for the equilibrium properties.

2.3. - Scramjet Components

The major Scramjet components were introduced in Section 2.1 as the inlet/diffuser, the combustor, and the nozzle (see Figure 1). The inlet/diffuser slows and compresses the incoming air, increases the temperature and density of the incoming air, and guides the incoming air into the combustor (Seddon and Goldsmith, 1985:110). Once in the combustor, the incoming air is mixed with fuel and combusted, thereby increasing the temperature and internal energy of the gas (Hill and Peterson, 1992:257). Finally, the nozzle converts the internal energy of the gas into kinetic energy by reducing the pressure of the gas and increasing its velocity (Hill and Peterson, 1992:264). While the function of each component is easy to grasp, the physical processes that make up the operation of each component is governed by a complex relationship between thermodynamics, gas dynamics, and finite-rate-chemistry.

2.3.1. - The Inlet

The primary function of the inlet is to compress the incoming air and guide the air into the combustor. Scramjets do not have turbo-compressors to compress the incoming air nor compressor exit guide vanes to direct the flow into the combustor. Therefore, the inlet must perform these operations.

2.3.1.1. - Inlet Operation

The inlet compresses the incoming air through a series of oblique shocks and a diffusion process through a converging area duct (Seddon and Goldsmith, 1985:154). Inlets often use a moveable spike or ramp to change the throat area of the duct and the shock impingement location on the cowl of the inlet (Seddon and Goldsmith, 1985:154). This is illustrated in Figure 4 (Walton, 1988). Figure 4 shows an inlet in three difference modes of operation: on-design, underspeeding, and overspeeding. The inlet shown is comprised of a forebody, located at the front of the inlet; an inlet ramp, located about two-thirds of the inlet length behind the front of the inlet; and the cowl, located under the vehicle.

Figure 4b shows the shock pattern for an inlet operating in the on design condition. During on design operation the oblique shock from the forebody of the vehicle and the oblique shocks from any of the inlet ramps will impinge on the inlet cowl lip (Walton, 1988). This is referred to as shock-on-lip (SOL) operation. During SOL operation, all of the compressed air enters the combustor.

Figure 4a shows the shock pattern for an inlet that is undersped. An undersped inlet is one that is operating at a speed lower than its design point. When an inlet is undersped, the shocks from the forebody and inlet ramps do not impinge anywhere on the cowl. Therefore some of the compressed air will not be captured and this excess air will be spilled out around the sides of the cowl creating additive or spillage drag (Walton, 1988). Of course, additive drag is a

detriment to overall vehicle performance (Mattingly, 1987:185). Underspeeding can be prevented by utilizing a moveable cowl. With such a device, the cowl lip can be moved forward and down to capture all of the compressed air, thus avoiding many of the problems associated with air flow spillage (Mattingly, 1987:187).

Figure 4c shows the shock pattern for an inlet that is oversped. An oversped inlet is one that is operating at a speed faster than its design point. When an inlet is oversped, the shocks from the forebody and inlet ramps impinge inside of the cowl. In this situation, not only is all of the compressed air captured, but some of the free stream uncompressed air is captured (Walton, 1988). This mixture of compressed and uncompressed air will contribute to the formation of very complex shock and expansion patterns in the inlet duct. These shock and expansion patterns will result in velocity and pressure gradients in the flow as it enters the combustor (Mattingly, 1987:187). These non-uniform flow conditions can retard fuel and air mixing and combustion in the combustor (Billig et al., 1990). The importance of mixing on combustion will be discussed in Section 2.3.2.

During the compression process, the incoming flow's static density, pressure, and temperature is increased and the velocity is decreased. The compression of the air is required because a hot, dense mixture of air combusts more readily than a cool, sparse mixture (Vincenti and Kruger, 1965:223). This is readily apparent when the FRC governing equations, Eqs. 9 - 11 and Eq. 13, are examined. Clearly, when pressure, temperature, and density increase, so does the rate of combustion.

Inlets for hypersonic vehicles usually have either an axisymetric cone or a planar wedge for the forebody and an inlet cowl just prior to the combustor entrance (Walton, 1988). For inviscid flow over an axisymetric or planar wedge

shaped forebody, the flow is independent of the azimuthal angle of the cone or the depth of the wedge. In other words, the flow is uniform or homogeneous for inviscid flow (Anderson, 1989:103). Unfortunately, viscous effects cause flow gradients as the air moves across the forebody surface (White, 1989). In addition to lateral and azimuthal flow gradients, there are velocity and thermal flow gradients in the direction normal to the surface (Anderson, 1989:245).

Fortunately, hypersonic forebodies tend to be very long (Walton, 1988). This long length allows the severe gradients at the leading edge of the forebody to be homogenized prior to the flow's entrance to the inlet cowl. As shown in Figure 5, much of the flow is uniform near the inlet cowl entrance, with most of the non-uniform flow occurring near the edge of the vehicle. Since the flow inward from the edge of the vehicle is relatively uniform, numerous small modular engines can be placed along the underside of the vehicle. Each engine will receive air at similar or mean flow conditions (Walton, 1988).

2.3.1.2. - Inlet Efficiency

The inlet efficiency is a measure of how effectively the inlet compresses and directs the incoming flow. This parameter has long been a concern of the engine designer and much effort has been put forth to define efficiency parameters. One of the simplest and earliest parameters developed is the "total pressure recovery efficiency" defined as: (Raymer, 1989)

$$\eta_{pt} = \frac{p_{t,4}}{p_{t,o}} \qquad (14)$$

where $p_{t,o}$ and $p_{t,4}$ represent stagnation pressure values for the free stream air and the diffuser exit at the stations defined in Figure 1.

Figure 6 is a classic "h-s" or "Mollier" diagram and will be used throughout this section to help define inlet efficiency parameters. In this figure enthalpy is plotted on the abscissa and entropy on the ordinate. Also plotted on the diagram are lines of constant pressure. Pressure lines are plotted for the free stream pressure p_o, the free stream total pressure $p_{t,o}$, the static diffuser exit pressure p_4, and the total diffuser exit pressure $p_{t,4}$. Also shown is a line representing a general compression process between states "0" and "4".

The "total pressure recovery efficiency" is useful for subsonic and moderate supersonic flight conditions if three criteria are met : the reference state $p_{t,o}$ is determined by the equation of state $p_{t,o} = f(h_{t,o}, s_{t,o})$, the state of $h_{t,4}$ is found from the energy equation $h_{t,4} = h_{t,o} - \Delta Q/\dot{m}$, where $\Delta Q/\dot{m}$ is some specified amount of heat loss, and the mean flow parameters are representative of the over all flow (Billig and Van Wie, 1987).

During the X-15 test program (1958-1967) it quickly became apparent that η_{pt} was inadequate for hypersonic flows because the stagnation state at the inlet entrance and the inlet exit is not well defined. For a hypersonic flow, the change of the stagnation pressure across the inlet is difficult to calculate because real gas effects cause the isentropic relationship between the inlet entrance and exit to break down. Therefore, there is not a well defined reference state for this parameter.

The ambiguity of the stagnation state was quickly addressed by a number of engineers who defined efficiency parameters with a reference state not requiring knowledge of the equation of state. One of the earliest attempts to address this problem was the "process efficiency" which is defined as:

$$\eta_{kd} = \frac{h_4 - h_{4e}}{h_4 - h_0} \qquad (15)$$

Referring to Figure 6, h_{4e} would be the state of the flow if it were isentropically expanded from state 4 to state 4e (Molder, 1962). This expression uses h_4 as the reference state, which is the static enthalpy at the diffuser exit. This efficiency parameter indirectly accounts for viscous losses, shock losses, heat losses, and all other loss mechanisms with the end state property h_4.

Unlike the process efficiency, the "kinetic energy efficiency" parameter η_{ke}, directly accounts for heat loss. The heat loss is accounted for by including the total enthalpy $h_{t,4}$ at the diffuser exit in the definition of the parameter. The definition of the kinetic energy efficiency is given as:

$$\eta_{ke} = \frac{h_{t,4} - h_{4e}}{h_{t0} - h_0} = \frac{U_{4e}^2}{U_0^2} \tag{16}$$

Similar to the expression for η_{kd}, h_{4e} would be the state of the flow if it were isentropically expanded from state 4 to state 4e (Molder, 1962).

The "kinetic energy efficiency" parameter is widely used and has been modified by several researchers to enhance its usefulness. For example, Billig, Orth, and Lasky's 1968 paper suggests that for inviscid compressible flows, η_{ke} can be approximated as:

$$\eta_{ke} = 1 - 0.2\left[1 - \frac{M_4}{M_0}\right]^5 \tag{17}$$

Whereas, for viscous compressible flows, Curran and Bergsten, 1964, suggest that η_{ke} can be approximated as:

$$\eta_{ke} = 1 - 0.4\left[1 - \frac{M_4}{M_0}\right]^4 \tag{18}$$

However, a convincing argument to discard all of the aforementioned parameters is made by Billig and Van Wie's 1987 paper "Efficiency Parameters for Inlets Operating at Hypersonic Speeds". In this paper the authors argue that a new "compression efficiency" parameter η_b should be defined as:

$$\eta_b = \frac{h_{4b} - h_0}{h_4 - h_0} \tag{19}$$

The authors very effectively illustrate how η_b accounts for viscous effects and other mechanical losses not accounted for by previous efficiency parameters. However, most compelling is the "compression efficiency" parameter's insensitivity to heat loss. Figure 7 shows the effects of heat loss on η_{ke} and η_b. Notice that η_b is practically invariant to the heat loss while η_{ke} changes significantly. The insensitivity of η_b to heat loss is a result of the way the parameter is defined. Essentially, the engineer specifies a desired compression ratio across the inlet and then calculates the appropriate value for the compression efficiency.

2.3.2. - The Combustor

2.3.2.1. - Combustor Operation

As mentioned earlier, the inlet guides the air into the combustor. Once in the combustor, the air is mixed with fuel, ignited, and combusted. The combustion process increases the temperature and internal energy of the gas mixture. The degree of combustion is dependent on numerous parameters including, but not limited to, incoming velocity, pressure, and temperature of the gases, mixing schedule, and combustor geometry (Hill and Peterson, 1992:257).

By far, the combustor is the most difficult of the three Scramjet components to optimize. This is largely due to the number of independent parameters involved (Billig, 1967). Indeed, one might want to optimize the combustor length to achieve fully-reacted flow conditions at the combustor exit, or optimize the cross sectional area change to produce constant pressure combustion or to achieve a desired exit velocity. Additionally, one might want to optimize the fuel-to-air ratio to obtain a desired combustor exit temperature.

Despite the difficulties in combustor design, a fair amount of success has been achieved in characterizing the operation of the combustor. It is generally accepted that subsonic combustion is no longer practical past flight speeds of about Mach 6 (Hill and Peterson, 1992:21). Past this flight speed, one must rely on supersonic combustion to avoid the large pressure increase and temperature rise associated with creating subsonic flow conditions. During the compression process to reach subsonic flow conditions, it is not unreasonable to expect the incoming static temperature to reach values on the order of 2000K - 4000K. These temperatures are high enough to cause the incoming fuel and air to dissociate rather than combust (Anderson, 1989: 374).

2.3.2.2. - Combustor Efficiency

Combustor inefficiency is primarily the result of two phenomenon. The first is "incomplete mixing and heat release" and the second is "entropy rise". "Incomplete mixing and heat release" is caused by a nonhomogeneous mixture on the macroscopic level and non-chemical equilibrium of the reacting species on a microscopic level. "Entropy rise" is the result of losses in the injection process, wall shearing, and heat addition at the incorrect Mach number, the latter being the most significant contributor to entropy rise (Billig, 1967).

2.3.2.2.1. - Fuel-Air Mixing

Of the two factors influencing combustor efficiency, mixing is arguably the more critical of the two. In fact, the 1975 paper by McClinton et al. claims that the degree of mixing and the mixing efficiency is paramount to supersonic combustion. The paper goes on further to point out that supersonic combustion is mixing limited, meaning that the degree of combustion is limited to the degree of mixing of the fuel and air.

The degree of mixing is dependent on a number of variables including, but not limited to, the injection angle, fuel penetration, shock wave severity, boundary layer thickness, ignition regions, and wall effects (Northam and Anderson, 1986). Of particular importance is the injection angle. The injection angle determines how far the fuel will penetrate into the air stream. If the injection angle is too shallow, fuel penetration may be too low to breach the boundary layer and the result could simply be a layer of fuel flowing between the air stream and the wall. On the other hand, if the fuel is injected at an angle nearly perpendicular to the wall, the fuel will have significant penetration, but the axial momentum contribution from the fuel will be lost, resulting in a decrease in thrust.

An experimentally-based mixing model for different injection angles has been developed at NASA Langley (Northam and Anderson, 1986) for supersonic hydrogen/air combustion with sonic fuel injection. This model predicts an exponential mixing rate for perpendicular fuel injection, a linear rate for parallel fuel injection, and a weighted average of the two rates for angles between 0° and 90°.

Figure 8a, Houck et al., 1990, is an illustration of a typical constant area combustor with a possible configuration for parallel fuel injection and shows how the injector spacing parameter, S, is defined. Also shown is the definition of the duct height, 2H. Figure 8b is an illustration of a typical constant area combustor

with a possible configuration for perpendicular fuel injection. This figure also shows how the injector spacing and the duct height is defined.

The governing equations for this mixing model are taken from Northam and Anderson's 1986 paper and are given as follows: the length for complete mixing is x_l where $x_l \approx 60$ injector gaps for complete mixing for an equivalence ratio, ER, of 1.0. The injector spacing, S, is defined as the gap spacing, where the gap spacing is equal to the duct height, 2H. If the fuel is to be injected perpendicularly from both walls the mixing efficiency is defined as:

$$\eta_m = 1.01 + 0.176 ln\left(\frac{x}{x_\phi}\right) \tag{20}$$

Whereas, if the fuel is to be injected parallel to the walls, the mixing efficiency is defined as:

$$\eta_m = \frac{x}{x_\phi} \tag{21}$$

where both Eq. 20 and Eq. 21:

$$\begin{aligned} x_\phi &= x_l 0.179\, e^{1.72\phi} \quad \text{for } \phi < 1 \\ x_\phi &= x_l 3.33\, e^{-1.204\phi} \quad \text{for } \phi > 1 \end{aligned} \tag{22}$$

Northam and Anderson experimentally showed that a single jet can spray gaseous fuel into an area about twice as wide as the penetration height. Therefore, with injection from both sides of the passage, supersonic combustion with sonic injection will completely mix in approximately 60 injector gaps. Referring to Figure 8, (Houck et al., 1990) for complete mixing the length of the combustor should be about 120 times the half height of the passage.

Even though the combustor may be long enough for the fuel and air to completely mix, it may not be long enough for the flow to completely react. Recall from Eq. 9 that the rate of reaction is a function of time and therefore, the length of the combustor. The rate of reaction is also a function of the molar density, which is a function of the combustor pressure, temperature, and volume, or in the case of one-dimensional flow, the cross-sectional area (Vincenti and Kruger, 1965:222).

2.3.2.2.2. - Entropy Rise

Pressure, temperature, and molar density (or degree of reaction) are all major contributors to "entropy rise" as is readily seen below in Eq. 23. Recall, "entropy rise" is the second of the major contributors to combustor inefficiency (Billig, 1967). The entropy of a system with respect to a common reference value is given below as: (Vincenti and Kruger, 1965:80)

$$s = V\sum_{i=1}^{NS}[X_i]\left(\int_{T_0}^{T}\hat{C}_{p_i}\frac{dT_i}{T_i} - \hat{R}ln\frac{p}{p_0} + \hat{s}_{s_0}\right) - \hat{R}V\sum_{i=1}^{NS}\left([X_i]ln\left(\frac{[X_i]}{\sum_{i=1}^{NS}[X_i]}\right)\right) \quad (23)$$

where:

$\hat{C}_{pi}$	= molar specific heat at constant pressure of species "i"
NS	= number of species in system
p	= pressure of system
p_o	= reference pressure
$\hat{R}$	= universal gas constant
$\hat{s}_o$	= molar reference entropy

s = entropy of the system with respect to a common reference value

T_i = temperature of species "i"

T_o = reference temperature of gas

V = volume of the combustor

$[X_i]$ = molar concentration of species "i"

Figure 9 represents a family of combustion processes mapped in the pressure-ratio/area-ratio plane and will be used to help illustrate the "entropy rise" phenomenon. The data in this figure is based on a combustor with an initial Mach number of 2, static pressure of 1 atm (101325 Pa), static temperature of 1800 °R (1000 K), and a stagnation temperature of 2970 °R (1650 K). The combustor exit-to-entrance area ratio A_b/A_a, is given on the ordinate of this figure where "a" and "b" are the combustor inlet and exit stations respectively. A constant area combustor corresponds to an area ratio A_b/A_a equal to one, while values of A_b/A_a greater than one correspond to a diverging exit area and values less than one correspond to a converging exit area. Given on the abscissa of the figure is the combustor exit-to-entrance pressure ratio p_b/p_a. A constant pressure combustor corresponds to a pressure ratio p_b/p_a of one. When p_b/p_a is greater than one, an adverse pressure gradient is present in the combustor and when p_b/p_a is less than one, a favorable pressure gradient is present (Billig, 1967).

Plotted on this figure are lines of constant Crocco index "ε". The Crocco index is a particularly useful parameter for characterizing the combustion process. For example, $\varepsilon = 1$ is a constant area process, while $\varepsilon = 0$ is a constant pressure process (Crocco, 1958). The Crocco index is derived from the pressure-area integral of the one-dimensional momentum equation given below.

$$p_a A_a - p_b A_b + \int_a^b p dA - \tau_w A_w = \rho_b A_b U_b^2 - \rho_a A_a U_a^2 - \dot{w}_f U_f \cos\alpha / g \quad (24)$$

where:

A	= area
a	= properties at the combustor inlet
b	= properties at the combustor exit
g	= gravitational constant
p	= pressure
U	= velocity
$\dot{w}_f$	= weight flow of fuel
α	= inclination angle from the horizontal
ρ	= density
τ_w	= wall shearing stress

Crocco defined the pressure-area relationship as:

$$pA^{\frac{\varepsilon}{\varepsilon-1}} = constant \quad (25)$$

Using the above relationship, the integral in Eq. 24 can be evaluated as: (Billig, 1967)

$$\int_a^b p dA = (1-\varepsilon)\left(p_b A_b - p_a A_a\right) \quad (26)$$

Once the integral has been evaluated, one can use the continuity equation and perfect gas assumptions to show that:

$$\varepsilon = \frac{\ln\left(\frac{p_b}{p_a}\right)}{\ln\left(\frac{A_b}{A_a}\frac{p_b}{p_a}\right)} \tag{27}$$

Also plotted in Figure 9 is the entropy limit and lines of constant equivalence ratio (ER). The entropy limit is the line representing the minimum entropy rise possible for a given Crocco index and ER. Of course, the intersection of the line of constant Crocco index and the line of constant ER determines the combustor geometry. Processes near the lower bound of the entropy limit correspond to systems with significant amounts of heat removal. The actual lower bound of the entropy limit corresponds to a "zero" entropy change for the system and values to the left of the lower bound represent a physically impossible, negative entropy change for the system. The upper bound of the entropy limit corresponds to a heat addition process that results in sonic flow at the exit of the combustor (Billig, 1967). As pointed out by Billig, 1967, "Heat-addition processes can exist to the right of this limit but, since the Mach number would be subsonic, a second 'throat' would be needed to reaccelerate the flow."

Families of curves similar to this have been generated for a large variety of Mach numbers and pressures to help engineers determine starting points for combustor designs and to determine problems with existing designs. For example, an engineer might choose to design a combustor with a Crocco index of 0.3 and an ER of 0.75 for the flow conditions of Figure 9. These values place the operating point of the engine near the upper entropy limit. However, the engineer might decide that flow instabilities would require a complex control mechanism to prevent the flow from choking before it reaches the nozzle throat. Therefore, the engineer might choose to redesign the engine based on a Crocco index of 0.2, while maintaining the same ER. This would move the engine operating point

somewhat to the left of the upper entropy limit thereby, thereby possibly alleviating the need for the complex control mechanism.

2.3.3. - The Nozzle

As stated earlier, the combustor increases the temperature and internal energy of the gas. Combustor temperatures generally are in excess of 2000K (Hill and Peterson, 1992:263) and dissociation of O_2 and H_2O is common at these high temperatures (Anderson, 1989:374). Dissociation of most molecules, including H_20 and O_2, is endothermic (requiring energy input), while recombination is exothermic (releasing energy) (Segal, 1985:166). The energy released during the recombination process often takes the form of kinetic energy. Therefore, kinetic energy (i.e., thrust) is lost every time a dissociated molecule leaves the engine (Hill and Peterson, 1992:40).

The nozzle provides extra time for the gas molecules to recombine and reach a fully-reacted state. This is accomplished by providing additional length to the overall engine. However, the nozzle's primary function is to expand the gases to lower pressures and temperatures, thereby converting the internal energy to kinetic energy and thrust. Like the inlet, a large amount of effort has been put forth to characterize the chemical reactions that occur in the nozzle. In his 1959 paper, K.N.C. Bray introduced the nozzle rate parameter Φ, where the value of Φ ranges from 0 for frozen flow, to ∞ for equilibrium flow. This parameter is defined as:

$$\Phi = \frac{C T_0^{\eta} \rho_d}{2\sqrt{\pi}\tan\theta}\sqrt{\frac{A_{\text{throat}}}{R_{A_2}\Theta_d}} \tag{28}$$

where:

A_{throat} = throat area

C = constant describing the rate of reaction

R_{A_2} = gas constant of the flow

T_o = reservoir temperature

η = constant describing the rate of reaction

ρ_d = gas density

Θ_d = characteristic temperature for dissociation

θ = angle of the nozzle wall with respect to the horizontal

Figure 10 (Vincenti and Kruger, 1965:297) is a representative diagram for a reacting air flow in a nozzle for varying degrees of dissociation (α) and throat-area to exit-area ratio as characterized by Bray's constant. The results presented in this figure are based on flow through a nozzle for which the reservoir stagnation properties of the oxygen are 5900 K at 115 atm (11.65 MPa) and the reservoir stagnation properties of the nitrogen are 11,300 K at a pressure of 215 atm (21.78 MPa). When Bray's constant is plotted against the degree of dissociation (α) and area ratio, the constant Φ is a level straight line for frozen flow and is a downward sloping curve for equilibrium flow.

Bray concluded that for a given set of initial conditions, the flow initially follows the equilibrium flow assumptions. However, as the flow moves further down the nozzle, the degree of dissociation begins to lag behind the dissociation value for equilibrium flow conditions. In fact, the flow quickly begins to exhibit follow frozen flow assumption characteristics. Therefore, the flow can be characterized as one that initially approximates the equilibrium flow assumptions and then approximates the frozen flow assumptions for some intermediate value of α. This phenomenon is clearly seen in Figure 10a where the flow approximates the equilibrium flow assumptions until the exit area ratio is about 10 with a degree

of dissociation of 0.44. At this point the flow is essentially conforming to the frozen flow assumptions. This is primarily the result of the relation (Vincenti and Kruger, 1965: 298):

$$u\frac{d\alpha}{dx} = -CT^{\eta}\frac{\rho^2}{\rho_d}\alpha^2 \tag{29}$$

"Thus, for any finite value of C, the density will eventually become sufficiently low as a result of the expansion that for all practical purposes $d\alpha/dx = 0$" (Vincenti and Kruger, 1965:298). Based on Bray's results, it is not unreasonable to model the reacting flow through the nozzle as some percentage of frozen flow and equilibrium flow.

2.4. - Summary

The chemistry model for a particular component of the Scramjet can have significant effects on the vehicle's overall performance. Whether the frozen flow model, the equilibrium flow model, or the finite-rate-chemistry model is used is dictated by the flow conditions encountered. The flow through the inlet is well understood and one-dimensional flow is adequately modeled the equilibrium-combustion-model the appropriate efficiency parameter. The high temperatures, pressures, and area variations of the combustor dictate that finite-rate-chemistry be used to model the flow. Finally, for the nozzle, a combination of equilibrium and frozen flow assumptions should be used.

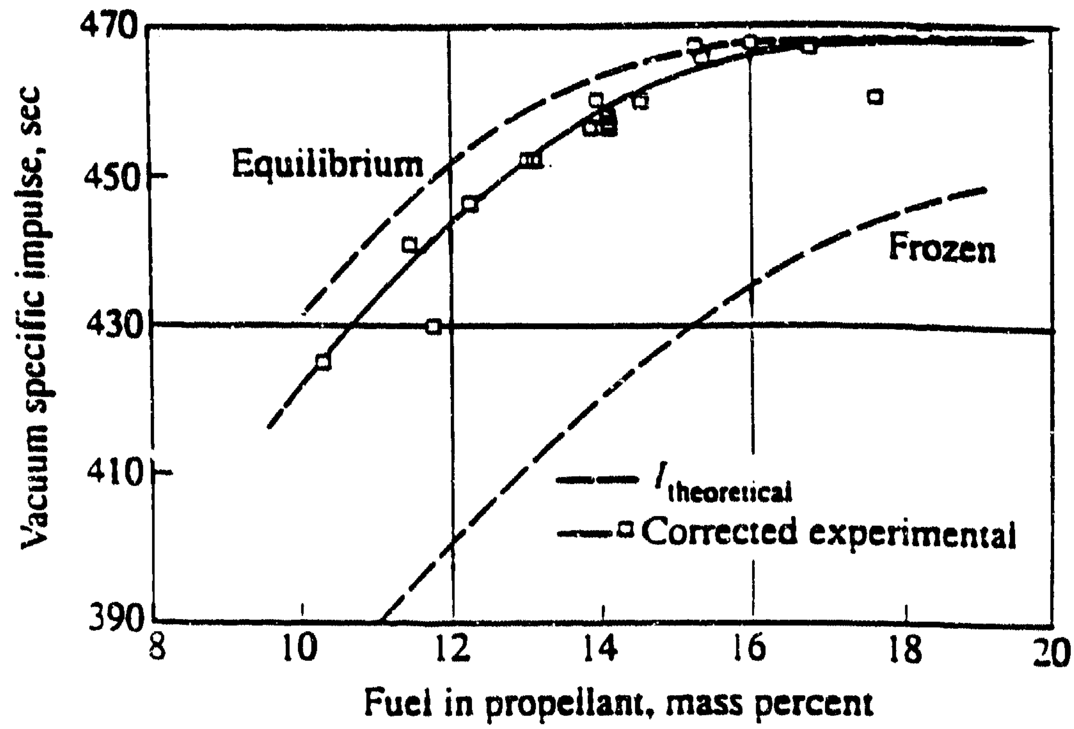


Figure 2 - "Corrected" Specific Impulse of Hydrogen-Oxygen Rocket (Hill and Peterson, 1992:580)

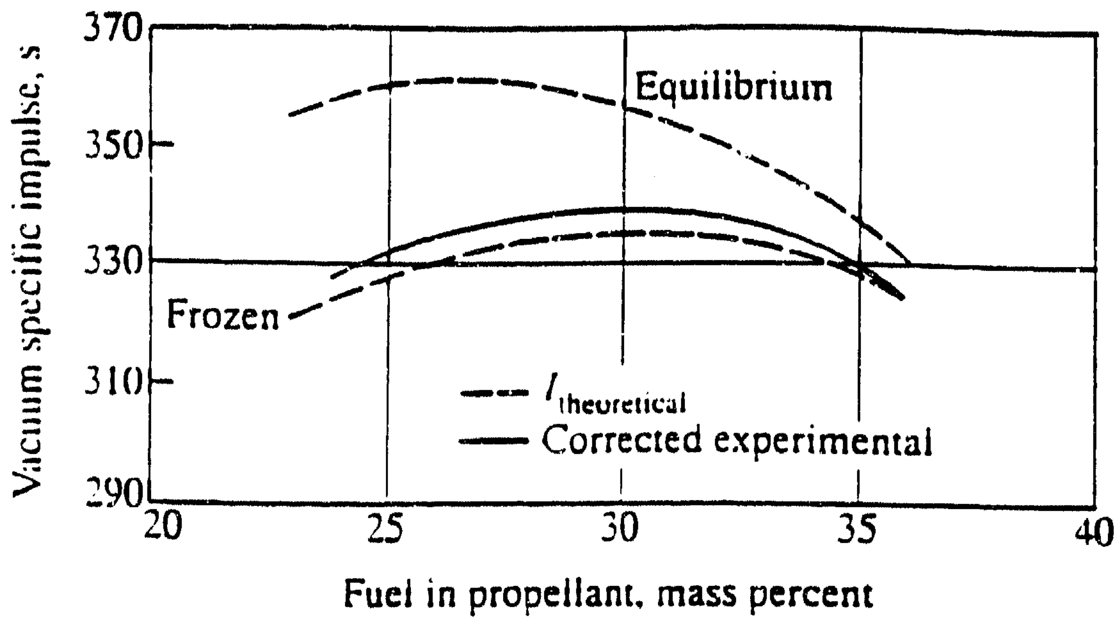


Figure 3 - "Corrected" Specific Impulse of JP4-Oxygen Rocket (Hill and Peterson, 1992:581)

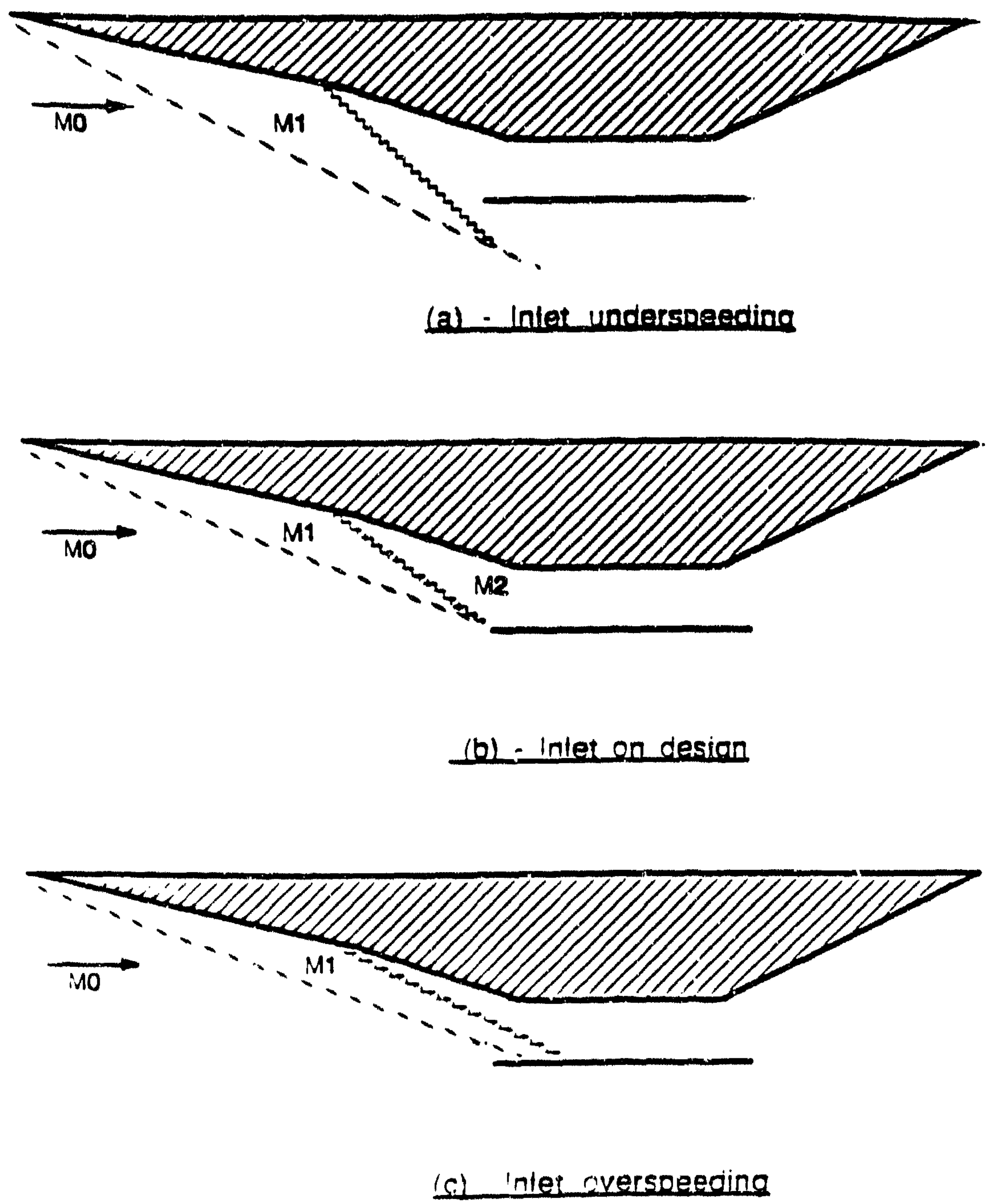


Figure 4 - Dual Forebody Wedge Shock Patterns (Walton. 1988)

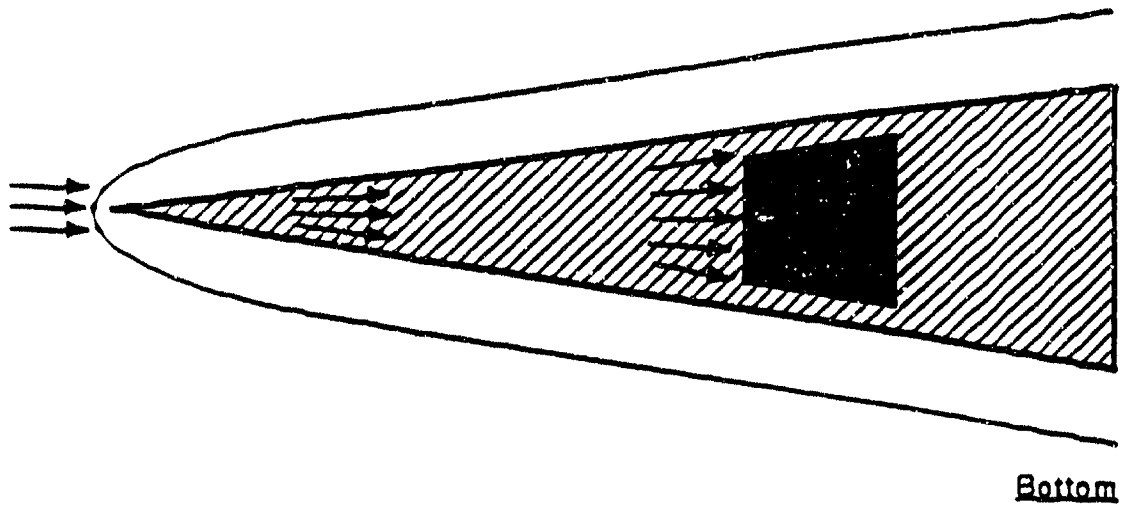


Figure 5 - Vehicle Horizontal Flow Gradients (Walton, 1988)

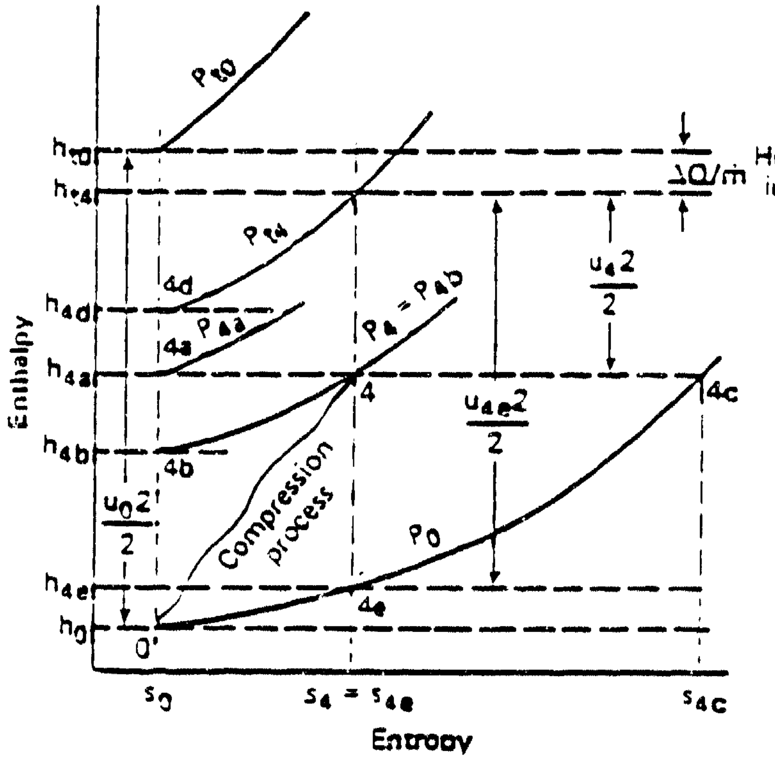


Figure 6 - Inlet Efficiency Parameters (Billig and Van Wie, 1987)

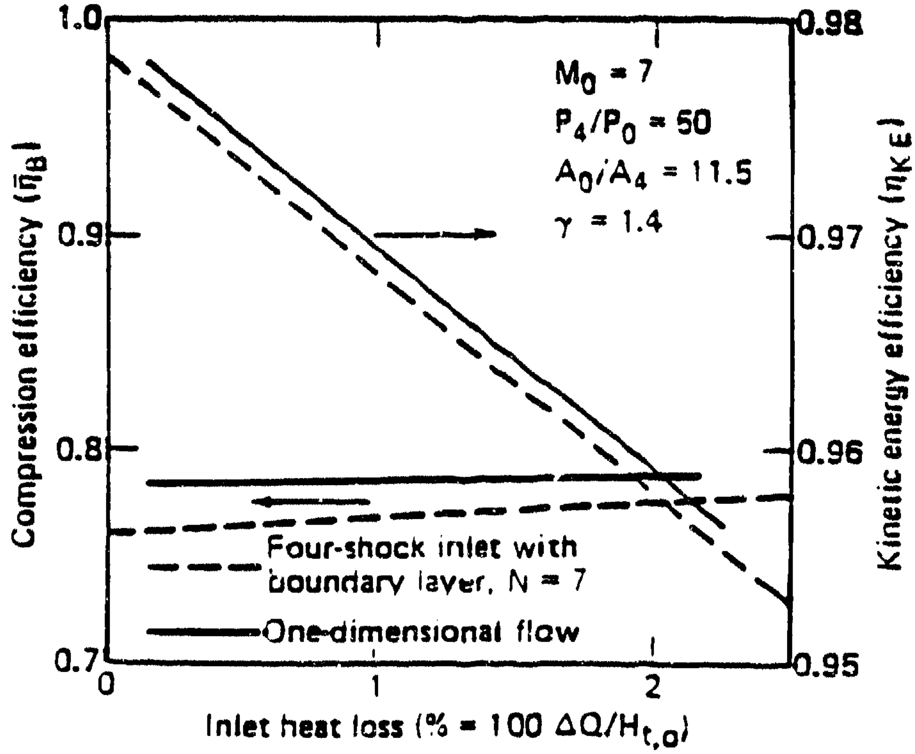
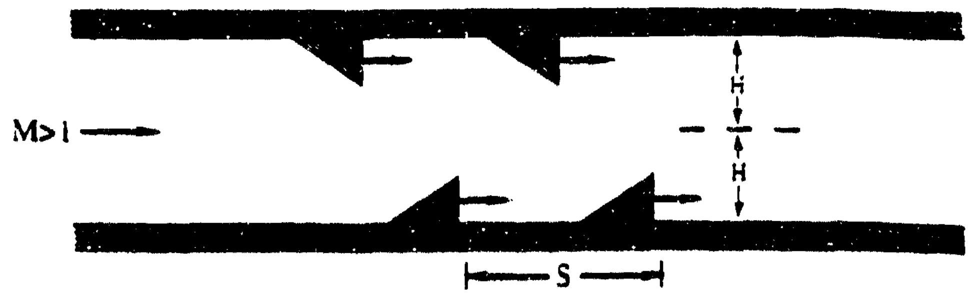
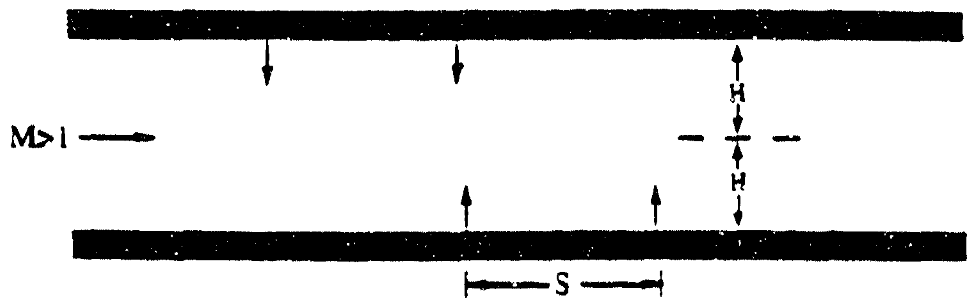


Figure 7 - Comparison of heat loss for η_{ke} and η_b (Billig and Van Wie, 1987)



(a) Parallel injection.



(b) Perpendicular injection.

Fuel injection from both sides of duct:

Mixing length, xl = 60 gaps

1 gap = S = 2H = duct height

$\therefore$ xl = 60 * S = 120 * H

Figure 8 - Schematic of Northam/Anderson Mixing Model (Houck et al., 1990)

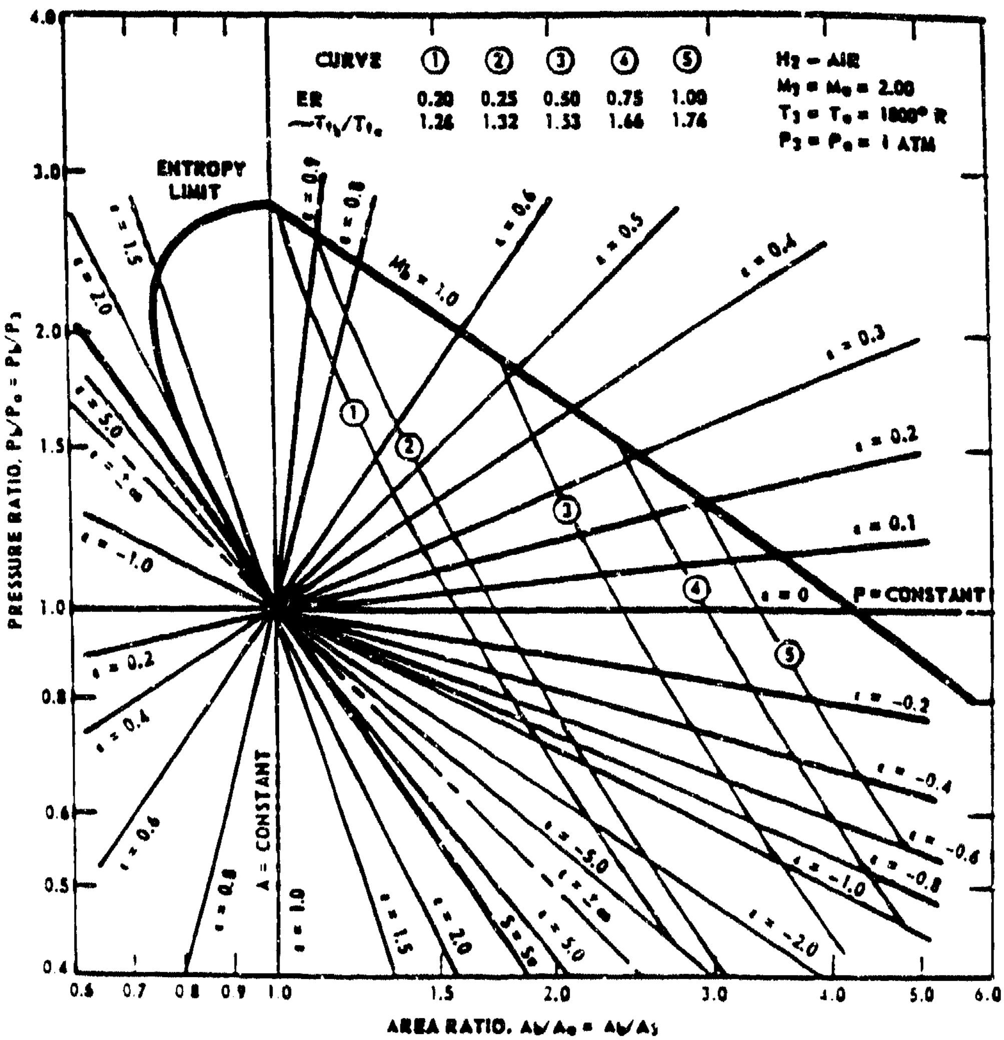


Figure 9 - Pressure-Area Distribution for Supersonic Combustion with constant ε (Billig, 1967)

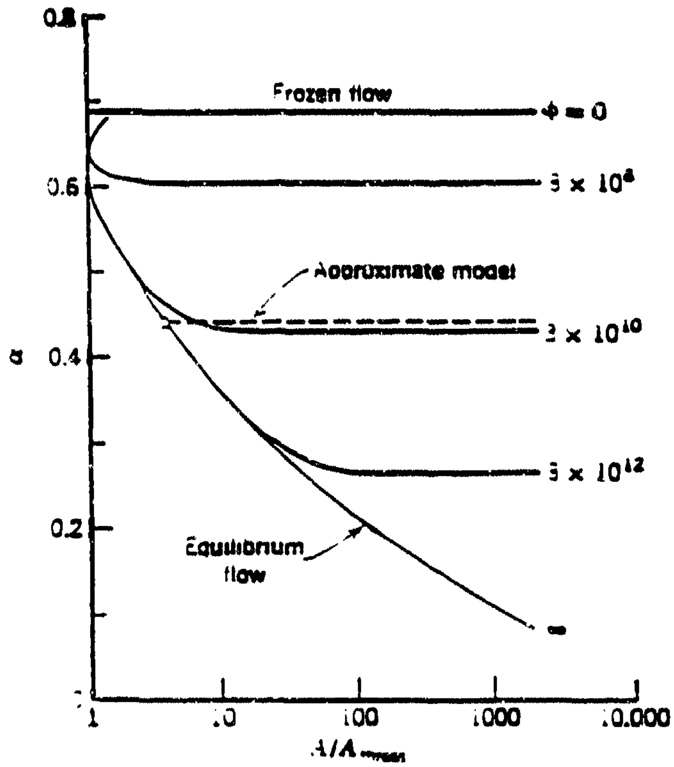


Figure 10 - Flow Variables in a Hypersonic Nozzle (Vincenti and Kruger, 1965:297)

Chapter 3 - Methodology

3.1. - Introduction

This chapter gives a brief description of the three codes, RJPA, 3STREAM and H2SCRAM. RJPA and 3STREAM are used to develop a one-dimensional integrated PC-based Scramjet analysis code capable of modeling a Scramjet engine, while providing the individual engineer access to the realism of the FRC-combustion-model. The code, H2SCRAM, is used to generate the on-design geometry configuration at Mach 15. The final product, henceforth referred to as RJPA-FRC, and the logic behind the selection of the code RJPA as the shell program and 3STREAM as the FRC combustor are also discussed in this chapter.

The final sections of this chapter discuss the interface requirements between RJPA and 3STREAM, the initial conditions used in the parametric study, the ranges investigated during the case studies, and the resources used to perform the study.

3.2. - Code Description

3.2.1. - H2SCRAM

H2SCRAM is an interactive input, equilibrium-combustion-model, FORTRAN code developed at the Wright Laboratories, Wright-Patterson AFB (Smith, 1987). This program uses the foot-pound-second (FPS) system of units for input and output and is written in a contiguous format. In other words, the subroutines modeling any one engine component cannot be distinguished from the other engine component subroutines.

H2SCRAM performs a one-dimensional cycle analysis of a hydrogen fueled Scramjet at a given flight altitude and Mach number, with a specified velocity or

area ratio, and a specified inlet efficiency parameter, η_{ke} or η_{kd}. Input selections also include variables to determine if an equilibrium-combustion-model, or a frozen flow model for the nozzle is to be used. There are also inputs to determine if a constant pressure combustion, constant area combustion, or a specified Crocco index, "ε" combustion process is to be modeled. Recall, the Crocco index is a measure of the type of combustion process being modeled, with "1" being a constant area process and "0" being a constant pressure process. The last geometric input available is the area ratio between the inlet and nozzle exit. One final input that needs to be addressed is the combustion efficiency. This parameter accounts for the inefficiencies associated with mixing schedules, heat transfer, particle collision inefficiencies, and other mechanical losses.

H2SCRAM uses the closed integral forms of the energy, momentum, and continuity equations to determine values for the thermodynamic and physical properties at the inlet, the combustor entrance and exit, and the nozzle exit. Recall from Section 1.1 that only information about the engine station points is obtained when an engine component is modeled with the closed integral forms of the governing equations for gaseous flows. All information between the two stations is lost.

H2SCRAM's output values for the area ratio, velocity ratio, and pressure at the combustor entrance are of particular interest for this study. These values will be used as the on-design conditions for the Mach 15 Scramjet. Therefore, this program will be used to obtain a typical Scramjet geometry for a given flight condition.

3.2.2. - RJPA

RJPA was developed at the Johns Hopkins University-Applied Physics Laboratory (Pandolfini, 1986). RJPA, like H2SCRAM, uses the FPS system of

units. However, unlike H2SCRAM, RJPA is written in a modular format. The modular approach allows easy identification of the subroutines associated with each component. The modular approach also allows each component of the Scramjet to be "turned on" or "turned off". In other words, RJPA can model an engine with all of the traditional components, or it can model an engine with only a combustor and nozzle, or only an inlet and combustor, or any other combination of the components.

Like H2SCRAM, RJPA is a one-dimensional Scramjet cycle analysis code that uses the closed integral form of the governing equations for gas flow. However, RJPA has much greater input flexibility than does H2SCRAM. A sample RJPA input file, Validation Input File 2, is listed in Appendix B.

RJPA's input file is divided into five sections. One for the fuel/air specifications, and one for each of the components. The first section defines the fuel/air composition. RJPA allows up to 12 different compounds be used at any one time as fuel and oxidizer inputs. Additionally, 70 species may be considered in the combustion process.

The next section of the input file defines the free stream conditions. RJPA uses a combination of free stream Mach number, velocity, pressure, altitude, and temperature, and species mass fractions to define the Scramjet flight conditions.

The third section of the input file defines the inlet configuration. The inlet configuration is defined by specifying a required diffuser exit area, a required diffuser exit pressure, or a required exit Mach number, and one of four efficiency parameters: the kinetic energy efficiency η_{ke}, the process efficiency η_{kd}, the total pressure recovery efficiency η_{pt}, or the Billig compression efficiency η_b.

The fourth section of the input file defines the combustor. RJPA uses the equilibrium-combustion-model as its combustor. RJPA has options to allow for a combustor with a specified exit area, with the exit pressure to be found; or for a

combustor with a specified exit pressure, with the exit area to be found. Unlike H2SCRAM, the Crocco index is merely an output and the combustor exit area or the combustor exit pressure must be iterated upon to achieve a desired Crocco combustion process. The fuel or gas generator properties of temperature, density, velocity, and exit area must also be specified .

RJPA simulates combustion inefficiencies by having a specified portion of the fuel and/or air frozen in the flow. This method of inefficiency simulation only accounts for chemical inefficiencies. RJPA accounts for all of the mechanical inefficiencies with the wall shearing coefficient.

The final input section is for the nozzle. RJPA has nozzle inputs that allow for expansion to a specified exit area or to a specified exit pressure.

RJPA provides a very extensive output data file. At each of the engine locations defined in Figure 1, RJPA provides a summary of the input conditions and the exit conditions. This output data includes all thermodynamic properties and species composition of the gas. Finally, thrust and I_{sp} calculations for frozen and equilibrium flows are summarized at the end of the data output report.

3.2.3. - 3STREAM

3STREAM was developed at Purdue in support of the NASP program by Sharon Houck (Houck et al., 1990). 3STREAM is a one-dimensional combustion code utilizing FRC combustion to model three gaseous streams of fluid. Referring to Figure 11, Stream 1 models the incoming air/oxidizer from an upstream source, stream 2 models the incoming fuel from the gas generator or injectors, and stream 3 models the combustion products (Houck et al., 1990). This program uses the centimeter-gram-second (CGS) system of units internally, but allows some of the input variables to be entered in the FPS or standard international (SI) systems of units.

A predetermined mixing schedule determines the rate at which the fuel and oxidizer streams are mixed into the products stream. Figure 11 depicts a mixing schedule for an equivalence ratio greater than 1. Note that stream 1 is depleted faster than stream 2. Once mixed, the streams are allowed to react with finite rate reactions. "Each of the three streams retains its own unique flow area, temperature, velocity, and species concentrations, while it is assumed that the pressure is the same for all streams at each axial location." (Houck et al., 1990:3) Gear's numerical integration method is used to solve the governing differential equations for a reacting gas flow.

3STREAM provides mechanisms to account for several additional important physical and thermodynamic phenomenon that allow the program to provide realistic trend information. Subroutines are provided to account for skin friction between the streams and the combustor wall, shearing losses between the streams, and turbulent mixing loses. Subroutines are also provided to account for heat transfer between the streams and the surrounding environment and for heat transfer between the individual streams.

3STREAM has a much more extensive input file than either H2SCRAM or RJPA. A sample input file for 3STREAM, Validation Input File 4, is listed in Appendix B. 3STREAM's input file uses a namelist directed format and is divided into 4 sections to control the pressure iteration process, mixing parameters, geometry, the heat transfer and skin friction processes, the integration process of the governing flow equations, and the initial values of the flow variables.

Variables to determine the area schedule and mixing schedule are contained in the first section of 3STREAM's input list. 3STREAM can use one of three formats for the area schedule and one of three different formats for the mixing schedules. The formats for the area schedules consist of a tabular input schedule, a cubic spline fit for the tabular data, or polynomial fit to the tabular data. Of

particular interest is the variable ARTOL. This variable is the error tolerance for the difference between the specified total area at any given location and the calculated total area of the three streams at the same location. The value selected for this variable can have a significant impact on the solution as will be seen in the sensitivity analysis in Chapter 4.

The first of the possible mixing schedules available in 3STREAM is the Northam/Anderson mixing schedule discussed in Section 2.3.2. Recall that the equations used in the Northam/Anderson model to define the mixing efficiency are based on experimental data. The second mixing schedule uses the same mixing efficiency equations as the Northam/Anderson schedule, but uses different coefficients to determine the mixing efficiencies. The third mixing schedule is simply a tabular schedule of mixing efficiencies at specified locations.

Variables defining the values of the heat transfer coefficients and the skin friction coefficients are located in the second section of the input file. These values are also defined in a tabular manner based on axial location along the combustor wall.

Variables that control the integration process of the governing equation for the gas flow are contained in the third section of the input file. Of particular interest are the variables EMAX and ATOLSP. EMAX is the relative error for the integration subroutine and ATOLSP is the absolute error for the integration subroutine. Houck et al., 1990 recommends that EMAX should be 10^9 times greater that ATOLSP. These variables can have a significant impact on the outcome of the solution. This will be verified during the sensitivity analysis in Chapter 4. The initial pressure of each of the three streams is also specified in this section.

Variable that determine the initial conditions for each of the streams and the elementary chemical reactions for each stream are in the fourth and final section of

the input file. Also, in this section are the initial values of the species composition of each stream.

3.3. - Code Selection Requirements

Several criteria were established for the selection of the equilibrium shell program and the FRC combustor program. First and foremost, the shell had to be written a modular format. Modularity was required to allow easy integration of new features into the program. Second, the shell program should have a versatile array of input features to allow for a variety of analyses. Finally, the shell program should be able to model a variety of fuels. PC compatibility was the primary criteria for the FRC combustor program. However, it should also have a versatile input array for geometry control and be able to model a variety of fuels.

Table 1 summarizes many of the important features of each of the three codes discussed in Section 3.2. The second column of the table highlights the features of H2SCRAM. H2SCRAM's advantages are its simple input file and the ability to directly input the type of combustion process used in terms of Crocco index. However, the input is limited to flight conditions and there is very limited control of vehicle geometry. The contiguous structure of the code further limits efforts to adapt it to other applications.

The third column of Table 1 highlights the features of RJPA. RJPA is a much more versatile program. Its modular structure easily permits modifications to continually enhance its performance. Furthermore, its input structure allows for a great deal of control over the vehicle geometry and combustion processes. The primary drawbacks to RJPA is the inability to directly enter a Crocco index and its limitation to the FPS system of units.

The fourth and final column of Table 1 highlights the features of 3STREAM. 3STREAM is a very powerful program that incorporates the desired

capabilities of modeling FRC combustion on a PC. 3STREAM has a very versatile input file and is capable of modeling combustion with numerous different fuels.

Based on the above criteria and the descriptions of the codes in Section 3.2, RJPA was selected as the shell that the final product (RJPA-FRC) would be built around and 3STREAM selected as the FRC combustor model inserted into RJPA. Finally, H2SCRAM was selected as the means to obtain the initial geometric configuration of the engines studied.

3.4. - Interface Requirements

Recall from Figure 1b that in the integrated program, RJPA-FRC, the equilibrium combustion module can be bypassed and the gas properties at station 4 can be used as the initial conditions for the oxidizer stream in the FRC combustor. Upon leaving the combustor, the gaseous mixture is sent to the equilibrium nozzle at station 5. Integrating RJPA and 3STREAM proved to be a formidable task. During the integration process a number of interface requirements were identified resulting in five interface modules. Referring to Figure 12, the five interfaces are the "Units and Input Interface 1", the "3STREAM Input Interface 2", the "Adiabatic Mixer Interface 3", the "3STREAM Output Interface 4", and the "Units and Output Interface 5".

3.4.1. - Interface 1

Interface 1 has two primary functions, maintaining unit consistency for the data input and providing a means for RJPA-FRC to accept the additional combustor data required for 3STREAM operation. RJPA only accepts FPS units (Pandolfini, 1986). However, the inevitable switch from the FPS system to the SI system dictates that any new engineering tool have the capability to work with

both sets of units. Therefore, while the original RJPA modules still use FPS units internally, Interface 1 allows RJPA-FRC to accept FPS, CGS, and SI units.

Recall from Section 3.2.3 that 3STREAM requires a significant amount of initial information to describe the combustion process and combustor geometry. Rather than have RJPA-FRC read in an input file containing only RJPA specific data and a second file containing only 3STREAM specific data, this author chose to develop an interface that would allow all of the flow properties and geometric data to be located in one single input file. A second data file contains the elementary chemical reaction processes for each of the three streams and the initial mass fractions for the fuel stream and the reaction products stream.

RJPA uses a formatted, list-directed input scheme. This system requires an input value for every variable possible whether or not it is required for the particular engine configuration be examined. This input scheme would be very cumbersome to use when one considers the 63 variables required for RJPA operation and the additional 98 variables required for 3STREAM operation. Therefore, a namelist directed input format was adopted. This system only requires that the variables required for the particular engine configuration be present in the data file. All other variables have predetermined default values. A detailed description of the variables and their required field location along with a description of the chemistry file is given in Appendix A.

3.4.2. - Interface 2

Referring to Figure 12, at station 4 the air from the diffuser enters the combustor and 3STREAM takes control of the program, if the FRC combustor model is specified. However, before 3STREAM is initiated, a data file must be constructed in a format suitable for 3STREAM to use. Interface 2's primary function is to construct this file. Numerous steps are required by the interface to

construct the file. First, all of the data is converted from RJPA internal FPS units to 3STREAM internal CGS units. Second, the interface performs various checks to insure the geometric dimensions, pressure, and velocity values entering the combustor are consistent with the values specified for the combustor area schedule. Third, the interface determines the initial mass fractions of the air exiting the diffuser. Next, the interface ensures the correct chemical symbology is used for the species coming from the diffuser (RJPA uses non-standard symbols for Argon and Hydroxyl that 3STREAM does not recognize). Finally, the variables defining the properties of the gas generator, the product stream, and the chemical reactions are then assembled into the data file. A sample of a data file assembled by this interface is given as Validation File 4 in Appendix B.

3.4.3. - Interface 3

Referring to Figure 12, at station 4, the fuel and air enter the combustor as two separate streams. However, the equilibrium-combustion-model equations do not allow for more than one flow stream. Therefore, the incoming streams must be instantly and adiabatically mixed. RJPA accomplishes this by calculating an area averaged pressure and a mass averaged velocity.

A similar situation arises at the exit of the FRC combustor, Station 5, if the fuel and air in the combustor are not completely mixed. Recall from Section 3.2.3, that 3STREAM models the fuel, air, and combustion products as three separate streams. The rate of depletion of the fuel and air streams is dependent on the mixing schedule and the combustor length. If the air and fuel are not completely mixed at the combustor exit, more than one stream will still be present at the nozzle entrance, station 5. Although incomplete mixing is a realistic situation, the equilibrium nozzle module, like the equilibrium combustion module, can only model flow as a single stream. Therefore, an adiabatic mixer, similar to the process

used in the equilibrium combustor, is used to obtain average flow properties after combustion.

The adiabatic, no work mixer used in RJPA-FRC, interface 3, operates as follows under the following assumptions; the control volume is an infinitely thin strip at the FRC combustor exit. Referring to Figure 13, streams 1, 2, and 3 enter the mixer on the left and stream 4, the mean properties, exits on the right. The flow entering and exiting the control volume is steady, without any heat losses or frictional losses. Furthermore, it is assumed that there are no body forces acting on the fluid within the control volume and the gravitational forces are considered negligible.

Therefore from the above assumptions, the continuity equation reduces to (Hill and Peterson, 1992:25):

$$\dot{m}_{cv} = \int_{cs} \rho \, \mathbf{u} \cdot \mathbf{n} \, dA \qquad (30)$$

or for this system

$$\dot{m}_4 = \dot{m}_1 + \dot{m}_2 + \dot{m}_3 \qquad (31)$$

where:

$\dot{m}_1$ = mass flow rate of stream 1

$\dot{m}_2$ = mass flow rate of stream 2

$\dot{m}_3$ = mass flow rate of stream 3

$\dot{m}_4$ = total mass flow rate

All quantities on the right hand side of Eq. 31 are known, therefore, the mass flow rate out of the control volume is known.

From the previously stated assumptions the momentum equation reduces to (Hill and Peterson, 1992:26):

$$\sum \mathbf{F} = \int_{cs} \rho \, \mathbf{u}(\mathbf{u} \cdot \mathbf{n}) dA \qquad (32)$$

or for this system

$$\dot{m}_1 U_1 + \dot{m}_2 U_2 + \dot{m}_3 U_3 - \dot{m}_4 U_4 = p_4 A_4 - p_1 A_1 - p_2 A_2 - p_3 A_3 \tag{33}$$

where:

$A_{1,2,3,4}$ = area of streams 1,2,3 or 4, respectively

$p_{1,2,3,4}$ = pressure of streams 1,2,3 or 4, respectively

$U_{1,2,3,4}$ = velocity of streams 1,2,3 or 4, respectively

However, recall from Section 3.2.3, that the pressure is the same for all of the streams at any axial location. Therefore,

$$p_4 = p_1 = p_2 = p_3$$

and

$$A_4 - A_1 - A_2 - A_3 = 0 \tag{34}$$

where A_4 is the sum of the areas of the three streams. Therefore, Eq. 33 can be written as:

$$U_4 = \frac{\dot{m}_1 U_1 + \dot{m}_2 U_2 + \dot{m}_3 U_3}{\dot{m}_4} \tag{35}$$

All quantities on the right hand side of Eq. 35 are known, therefore, the mean velocity out of the control volume is known.

From the definition of mass flow rate (Hill and Peterson, 1992:24) the mean density exiting the control volume can be found as:

$$\rho_4 = \frac{\dot{m}_4}{U_4 A_4} \tag{36}$$

where ρ_4 is the mean density of the flow leaving the control volume.

Once again using the earlier assumptions for the control volume, the energy equation can be written as (Hill and Peterson, 1992:28):

$$\int_{cs}\left(h+\frac{u^2}{2}\right)\rho\ (\mathbf{u}\cdot\mathbf{n})dA=0 \tag{37}$$

where h is the static enthalpy of any flow. The first term in parenthesis of Eq. 37 is often grouped together to define another term referred to as the total enthalpy and is written as (Hill and Peterson, 1992:36)

$$h_t=h+\frac{u^2}{2} \tag{38}$$

Applying the definition of total enthalpy and the assumptions made for this system, the energy equation can be written as:

$$\dot{m}_1h_{t,1}+\dot{m}_2h_{t,2}+\dot{m}_3h_{t,3}=\dot{m}_4h_{t,4} \tag{39}$$

or solving for $h_{t,4}$

$$h_{t,4}=\frac{\dot{m}_1h_{t,1}+\dot{m}_2h_{t,2}+\dot{m}_3h_{t,3}}{\dot{m}_4} \tag{40}$$

where $h_{t,4}$ is the total enthalpy for the flow leaving the system. Since all of the values on the right hand side of Eq. 40 are known, the mean total enthalpy is known. Now that $h_{t,4}$ is known, Eq. 38 can be solved for h and the mean static enthalpy found for the flow leaving the control volume.

A calorically perfect gaseous mixture can be assumed if the temperature of all three streams entering the control volume are near the same temperature. This

is likely to be the condition if a sufficient amount of mixing and combustion has occurred. Therefore, assuming a calorically perfect gas, the static enthalpy can be written as (Anderson, 1989:388):

$$h = C_p T \tag{41}$$

where:

C_p = specific heat at constant pressure

T = temperature

Therefore, for a calorically perfect gaseous mixture (Hill and Peterson, 1992:38):

$$C_{p,4} = \frac{\dot{m}_1 C_{p,1} + \dot{m}_2 C_{p,2} + \dot{m}_3 C_{p,3}}{\dot{m}_4} \tag{42}$$

Since all values on the right hand side of Eq. 42 are known, the mean value of $C_{p,4}$ can be found. Substituting the values for h_4 and $C_{p,4}$ into Eq. 41, the mean temperature leaving the control volume T_4, can be found.

For a steady, adiabatic flow, the second law of thermodynamics is given as (Hill and Peterson, 1992:32):

$$\int_{cs} s\rho\ (\mathbf{u} \cdot \mathbf{n}) dA = 0 \tag{43}$$

or for this system

$$s_4 = \frac{\dot{m}_1 s_1 + \dot{m}_2 s_2 + \dot{m}_3 s_3}{\dot{m}_4} \tag{44}$$

where s is the entropy change from a common reference state for each of the streams entering or leaving the control volume. Since all values on the right hand side of Eq. 44 are known, the mean entropy is known.

The mole-mass ratio σ, is the number of moles per unit mass (Anderson, 1989:381). The mole-mass ratio for a gaseous mixture is given as (Vincenti and Kruger, 1965:167)

$$\sigma_{i,4} = \frac{\sigma_{i,1}\dot{m}_1 + \sigma_{i,2}\dot{m}_2 + \sigma_{i,3}\dot{m}_3}{\dot{m}_4} \tag{45}$$

where σ_i is mole-mass ratio for each species in the system and $\sigma_{i,4}$ is the mole-mass ratio for the species in the flow exiting the control volume. Since all of the values on the right hand side of Eq. 45 are known, the mean mole-mass ratio for each species is known.

Finally, the mean values for mass-flow-rate $\dot{m}_4$, velocity U, density ρ_4, total enthalpy h_t, static enthalpy h, specific heat at constant pressure C_p, temperature T, entropy s, and the mole-mass ratio of each species σ_i, are passed to interface 4.

3.4.4. - Interface 4

Interface 4 performs many of the same functions as Interface 2, but in reverse. Interface 4 converts the data from 3STREAM internal CGS units to RJPA internal FPS units. The interface also insures the correct chemical symbology is used for the species being sent to the nozzle. Recall from Section 3.4.2 that RJPA uses non-standard symbols for some of the elements and compounds.

3.4.5. - Interface 5

The final interface is Interface 5, the Units and Output Interface. Its primary function is to maintain unit consistency for the output data. Recall from Section 3.2.2, RJPA only accepts input in the FPS system, therefore it only produces output in the FPS system (Pandolfini, 1986). However, as discussed in

Section 3.4.1, any new engineering tool should have the capability to work with the FPS system of units, the CGS system of units, and the SI system of units.

Interface 5 also calculates the axial impulse thrust for each component of the Scramjet and the pressure thrust brought about by the area difference of the inlet capture area and the nozzle exit area. The axial stream thrust for any engine station is given by (Zucrow and Hoffman, 1976:116):

$$F = pA + \dot{m}U \tag{46}$$

where:

A	= area
F	= stream thrust
$\dot{m}$	= mass flow rate
p	= pressure
U	= velocity

and the axial impulse thrust is found by taking the difference of the axial stream thrust between any two engine stations. For example, referring to Figure 12, the axial impulse thrust of the combustor is found by subtracting the axial stream thrust at the combustor exit F_5, from the axial stream thrust at the combustor entrance F_4 (Mattingly, 1987:230). The axial pressure thrust is given as (Mattingly, 1987:226):

$$\text{Pressure Thrust} = p_0(A_6 - A_0) \tag{47}$$

where:

A_0	= inlet capture area
A_6	= nozzle exit area
p_0	= free stream pressure

The overall axial engine thrust is found by summing the axial impulse thrust of each component and subtracting from that sum the pressure thrust resulting from the area difference of the inlet and nozzle exit. The overall axial thrust equation for an air-breathing engine is given as (Mattingly, 1987:226):

$$\mathbf{T} = F_6 - F_0 - p_0(A_6 - A_0) \tag{48}$$

where:

T	= overall engine thrust
F_6	= nozzle exit stream thrust
F_0	= free-stream stream thrust

3.5. - Initial Conditions

Flight conditions for a Scramjet are often defined in terms of a constant dynamic pressure (Leingang, 1993). Dynamic pressure is the pressure exerted on the vehicle by a moving air flow and is defined as (Anderson, 1989:36):

$$q = \frac{\gamma p_o M_o^2}{2} \tag{49}$$

where:

q	= dynamic pressure
γ	= ratio of the specific heats
p_o	= free stream pressure
M_o	= free stream Mach number

Once the dynamic pressure is specified, the entire flight trajectory is determined since for any Mach number there is only one value of free stream pressure that will satisfy Eq. 49. Using this free stream pressure, the corresponding

altitude is readily available from the atmospheric tables in Zucrow and Hoffman, 1976 or Anderson, 1985.

Typically, a combination of flight Mach number and altitude is used to maintain a constant dynamic pressure on the exterior of the hypersonic vehicle. A commonly accepted value for dynamic pressure is 50,000 Pa and a typical flight Mach number is Mach 15 (Leingang, 1993). Using Eq. 49 with $\gamma = 1.4$, the required free stream pressure is 317.5 Pa. The corresponding altitude for this pressure is 39,272 m (Anderson, 1985: 520). This flight condition was considered the baseline flight condition of the Scramjet during this study.

As the hypersonic vehicle changes altitude and flight Mach number, the free stream conditions will change and therefore, so will the operating characteristics of the inlet. However, over the range of Mach numbers between Mach 12 and Mach 18 the inlet kinetic energy efficiency η_{ke} remains relatively constant (Leingang, 1993) and typical state-of-the-art Scramjet inlets can achieve kinetic energy efficiencies, η_{ke}, of 0.976 over this range (Curran et al., 1992). Therefore, for this study the value used for η_{ke} was 0.976.

Since η_{ke} is assumed constant for this study over the range of flight Mach numbers between Mach 12 and Mach 18, the two extremes of Mach 12 and Mach 18 were selected as the off-design flight speeds to be investigated. Using Eq. 49 and keeping the dynamic pressure constant at 50,000 Pa, the altitude for flight at Mach 12 is found to be 36,038 m and for flight at Mach 18 the altitude is found to be 42,400 m.

Typical Scramjet combustors are designed to have a static pressure at the combustor entrance between 40,000 Pa and 80.000 Pa (Leingang, 1993). However, if the Scramjet will be required to operate over a range of Mach numbers the on-design entrance pressure should be such that the pressure at the off-design conditions is still at a reasonable value. In other words, if the off-

design pressure becomes too low the fuel and air may not combust. On the other hand, the combustor structure may fail if the pressure is too high. Therefore, a static pressure between 50,000 Pa and 55,000 Pa was selected as a reasonable on-design value to try to achieve at the combustor entrance (Leingang, 1993).

The program H2SCRAM was used to find an inlet area contraction ratio that produces the desired combustor entrance pressure for flight speed of Mach 15 at an altitude of 39,272 m and a kinetic energy efficiency of 0.976. From this program a contraction ratio of 20 was found to produce a static pressure of 51,674.6 Pa at the combustor entrance. The output file from H2SCRAM is located in Appendix C.

A summary of the conditions the Scramjet will encounter as it flies along a constant dynamic pressure trajectory of 50,000 Pa with an inlet area contraction ratio of 20 is provided in Table 2. Notice that as the Mach number and altitude increase the free stream pressure decreases. This decrease in free stream pressure is translated into a decrease in static pressure at the combustor entrance. This drop in combustor pressure would be cause for concern except that as the Scramjet flies faster, the temperature at the combustor entrance increases. Recall from Section 2.2.3, that as pressure drops, so does the rate-of-combustion. However, recall from the same section, that the decrease in combustion due to the decrease in pressure is counteracted by the more significant increase in temperature.

It is generally accepted that an equivalence ratio of 1 and complete mixing of the fuel and air in the combustor will produce the largest amount of energy release, hence, the largest amount of thrust for a given flight condition (Leingang, 1993). Therefore, using the above assumptions of ER equal to 1 and complete mixing at the combustor exit, the combustor geometry was calculated using the Northam/Anderson mixing equations, Eqs. 20 - 22, typical Scramjet engine dimensions, and test facility requirements.

Recall from Section 2.3.2.2.1 and referring to Figure 8, that the combustor length for complete mixing is approximately 60 injector gaps for an equivalence ratio equal to 1.0. Also recall that the combustor duct height is defined as 2H, which is one injector gap space. Therefore, if a typical Scramjet combustor length of 3 m (Leingang, 1993) is used as the baseline combustor length and the recommended 60 injector gaps from Northam and Anderson's paper mixing model is used, a combustor duct height of 0.05 m is required to achieve complete mixing. These are in fact the values that will be used during this study as the baseline dimensions for the combustor length and duct height.

Typical Scramjet engines have of a depth of 0.30 - 0.90 m (Leingang, 1993). Furthermore, most of the current wind tunnel test facilities have wind tunnel test section diameters ranging from 0.45 m to 1.00 m (Wittliff, 1987). Therefore, to allow for potential wind tunnel testing of the engine, 0.60 m was selected as the initial value for the combustor depth.

Recall from Figure 12, that the cross sectional area of the diffuser exit at station 4 is the same as the cross sectional area of the air entering the combustor. Therefore, using the combustor dimensions listed above, the diffuser exit area or the combustor cross sectional area for the incoming air from the diffuser is calculated as the duct height (0.05 m) multiplied by the duct width (0.60 m) or 0.030 m^2. Using the value for the cross sectional area of the diffuser exit, and the inlet area contraction ratio of 20, the inlet capture area is found to be 0.60 m^2.

At the high altitudes encountered during typical hypersonic flight, the free stream pressure is very low. As seen in Table 2, pressures are typically less than 400 Pa. However, to achieve these pressures at the nozzle exit, the nozzle exit area would have to be several times larger than the inlet capture area. From the thrust equation, Eq. 48, one can see that if the nozzle exit area is larger than the inlet capture area the pressure thrust term will be positive resulting in a reduction of the

overall thrust. Therefore, hypersonic vehicles usually have inlet area to nozzle exit area ratios of 1-1.5 (Leingang, 1993). For this study a ratio of one was selected.

Recall from Figure 11, that stream 2 represents the fuel flow. Typically the gas generator or fuel injectors will comprise about 5% of the incoming flow cross sectional area (Leingang, 1993). Therefore, the area of the gas generator and the initial area of stream 2 is 0.0015 m^2.

In Section 3.2.3, stream 3 was introduced as the products stream, Figure 11. In the description of stream 3 it was pointed out that 3STREAM requires stream 3 to have a non-zero initial area. Since this area can not exist in a vacuum, it must also have non-zero initial values for the chemical and thermodynamic properties. Of course, one can not assign arbitrary values to these properties, they must be consistent with the physics of the flow surrounding the area. Houck (Houck et al., 1990) suggests that this area, and the properties associated with it, be used to simulate a flame holding region. However, a different approach was used in this study.

RJPA does not have a product stream, but it does have an area called the base area (ABASE) and this region is required to have a pressure associated with it, see Figure 12. One of the objectives of this study is to compare the results of the equilibrium combustion module to the results of the FRC combustion module. Therefore, one would want to match as many of the flow conditions as possible. With this philosophy in mind, when the FRC option was selected, the initial conditions for the product stream was set to the incoming conditions of the air exiting the diffuser. When the equilibrium option was selected the pressure for ABASE was set to the same pressure as the incoming air exiting the diffuser.

A sensitivity analysis was performed to determine the influence of ABASE on the flow solution. A summary of the areas investigated and the results of the analysis is given in Table 3. During the analysis, values for ABASE were varied

from 0.000005 m^2 to 0.00005 m^2. These values represent the lowest value for ABASE that the program would still run at and the point at which an inflection in the results was detected. The sensitivity analysis results indicate that ABASE should be set to 0.00004 m^2 or 0.133% of the incoming flow area.

At this point all of the values required to describe the baseline Scramjet geometry are available. The dimensions of the Scramjet are summarized in Table 4. The first column of the table lists the parameter of interest and the station location of the parameter as defined in Figure 12. The second column lists the physical dimensions of each parameter.

When the FRC combustor option is selected a chemical reaction model must also be supplied. For this study the elementary chemical reactions used to model the incoming air is a reduced set of the Dunn/Kang high-temperature air model without the ionic reactions (Dunn and Kang, 1973). The elementary chemical reactions used to model the combustion products is the kinetic mechanism for H_2-air of Jachimowski (Jachimowski, 1988). A listing of the chemical reaction equations is given in Appendix A in the sample chemical input file.

3.6. - Ranges Examined

The Scramjet performance was examined over a range of velocities, combustor lengths, and combustor exit areas. The flight Mach numbers examined were Mach 12, 15, and 18. The combustor lengths examined were 1,2,3,4, and 5 meters. Finally, the combustor exit area at station 5 was varied to provide Crocco index numbers of 0.0, 0.25, 0.50, 0.75, and 1.0 for the on-design geometry. The areas corresponding to the aforementioned Crocco index numbers are listed in Table 5. The first column of Table 5 lists the Crocco index to be investigated. Recall from Section 2.3.2.2.2 that a Crocco index of "1" corresponds to a constant

area combustion process, while a Crocco index of "0" corresponds to a constant pressure combustion process. The second column of Table 5 lists the combustor exit areas that result in the Crocco indexes in column 1 for an equilibrium-combustion-model.

3.7. - Equipment Used

RJPA-FRC was compiled and executed on a FAST DATA PC. This particular PC used a 486DX 33 MHz microprocessor as its central processing unit. Furthermore the PC was equipped with 4 Megabytes of RAM, 128K of cache memory storage, and a 170 Megabyte hard drive for data storage. The compiler used to compile RJPA-FRC was the Lahey FORTRAN Compiler, Version 5.01.

The time required to execute the input files used for the parametric study varied with the combustion model selected and the length of the combustor being modeled. When the equilibrium combustion option was selected, the execution time was 5 to 10 seconds. On the other hand, when the FRC combustion option was selected, the execution time ranged from 5 to 20 minutes. The time required for execution was largely determined by the length of the combustor and the error tolerances used.

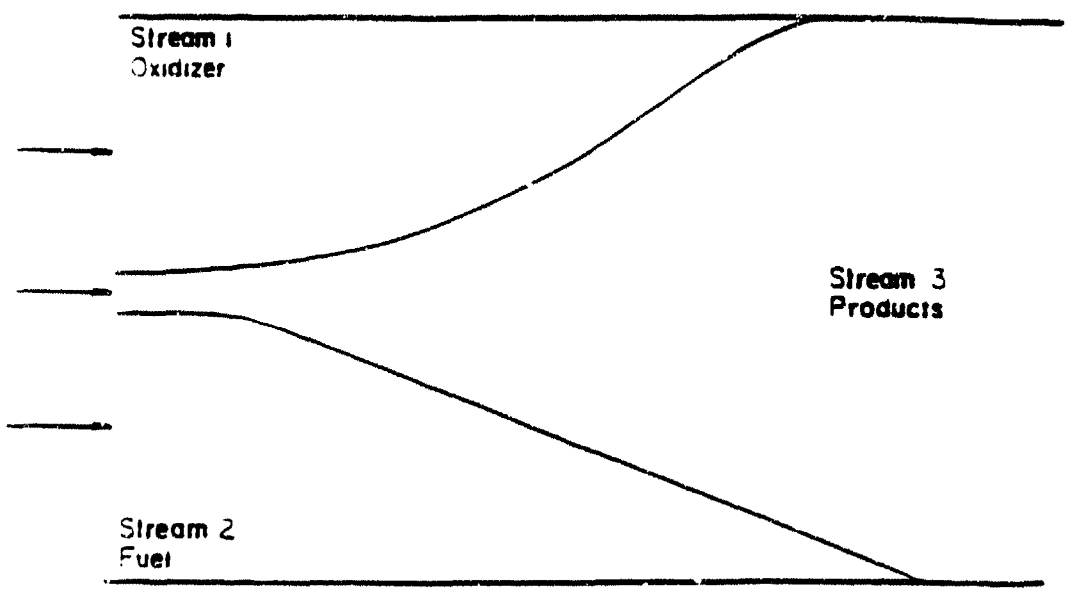


Figure 11 - Oxidizer, Fuel, and Products Streams, as Modeled by 3STREAM (Houck et al., 1990)

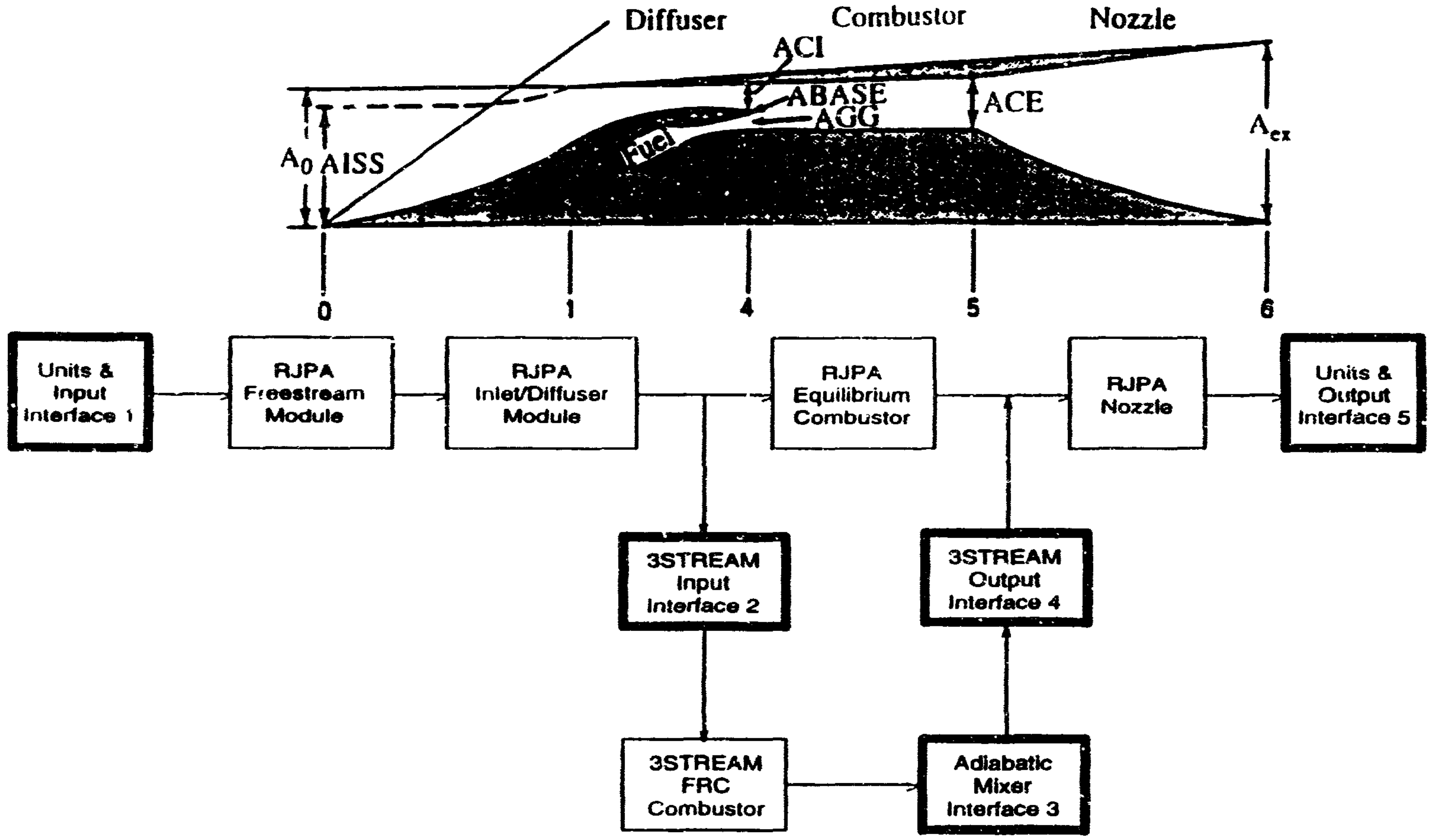


Figure 12 - Block Diagram of RJPA-FRC

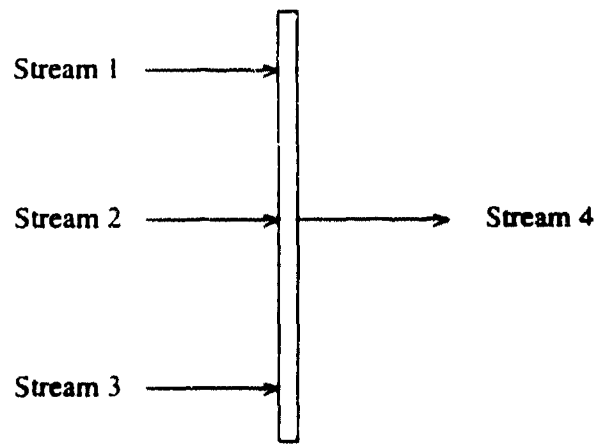


Figure 13 - Adiabatic Mixer

Table 1 - Summary of Codes Used

	H2SCRAM	RJPA	3STREAM
Inputs	Flight conditions and area ratios only at station "0" and "6"	Flight conditions and flow properties at station "0" and areas or pressures at all other stations	Stream areas and flow properties at combustor entrance, combustor area schedule and fuel/air mixing schedule
Combustor model	Direct input of constant area constant pressure Crocco index	Indirect input of constant area constant pressure Crocco index	Indirect input of constant area constant pressure
Combustor Geometry Input	None	Area or pressure values at station 1 and 4	Area schedule
Type of Combustion	Equilibrium (combustion efficiency)	Equilibrium (% frozen, % equilibrium)	Finite-Rate-Chemistry
Fuel used	Hydrogen	Numerous types	Numerous types
Type of Flow	Supersonic	Supersonic & Subsonic	Supersonic
Structure of Code	Contiguous	Modular	Combustor only
Length scale	None	None	Combustor length
Units	FPS	FPS	Mixed combination of CGS, FPS, and SI

Table 2 - Flight Condition for a Constant Dynamic Pressure Trajectory of 50,000 Pa and an Inlet Contraction Ratio of 20

Flight Mach Number	12	15	18
Altitude (m)	36038	39272	42400
Free Stream Velocity (m/s)	3721.2	4740.0	5796.0
Free Stream Pressure (Pa)	495.86	316.87	208.7
Free Stream Temperature (K)	239.4	248.34	208.7
Pressure at Combustor Entrance (Pa)	67455.7	51674.6	40186.7
Temperature at Combustor Entrance (K)	1462.2	1853.3	2285.2

Table 3 - Sensitivity Analysis of ABASE

ABASE (m^2)	% Difference in Thrust
0.000005	-4.489
0.000010	-4.153
0.000020	-3.956
0.000030	-3.495
0.000040	-2.986
0.000050	-3.263

Table 4 - On-Design Scramjet Geometry

Parameter/Station	
Inlet Capture Area /0	0.60000 (m^2)
Diffuser Exit Area/4	0.03000 (m^2)
Gas Generator Exit Area/4	0.00150 (m^2)
Base Area/4	0.00004 (m^2)
Total Combustor Entrance Area/4	0.03154 (m^2)
Combustor Duct Height/4	0.05 (m)
Combustor Width/4	0.6308 (m)
Length/4-5	3.0 (m)
Combustor Exit Area/5	0.03154 (m^2)
Nozzle Exit Area/6	0.60000 (m^2)

Table 5 - Areas Corresponding to Specified Crocco Index Numbers

Crocco Index Number	Area (m^2)
0.0	0.0534030
0.25	0.0474740
0.50	0.0418487
0.75	0.0365319
1.00	0.0315400

Chapter 4 - Validation of RJPA-FRC

4.1. - Introduction

Before the parametric study was conducted, RJPA-FRC had to be validated. Both RJPA and 3STREAM are considered industry standards and have individually been extensively validated. Therefore, rather than repeat previous validation efforts, RJPA-FRC was validated by performing three tests to verify proper operation of the interfaces. These tests were designed to verify that the original functions of RJPA and 3STREAM are still operating as intended within the integrated program.

Two additional, tests were developed to verify that the overall program operates as intended. The first of these additional test was designed to verify that the FRC option achieves the same fully-reacted conditions as calculated by RJPA if instantaneously mixed fuel and air enter the combustor. The second of the additional tests was designed to verify that the FRC code is stable for very long combustors.

4.2. - Test 1 - Verification of RJPA

4.2.1. - Test Description

The first test had two objectives. The first objective was to verify that RJPA still operates correctly within RJPA-FRC when the equilibrium-combustion-model is selected. The second objective was to verify the operation of Interface 1 and Interface 5. Recall from Section 3.4.1 and referring to Figure 12, that Interface 1 controls the input data and unit conversion operations of RJPA-FRC. Also, recall from Section 3.4.5 and referring to Figure 12, that Interface 5 controls the output data and unit conversion operations of RJPA-FRC.

This test was performed by using a sample input file provided with the original RJPA program disks. The data from this file was converted from the original RJPA input format to the namelist format used by RJPA-FRC. The converted input file was then run on RJPA-FRC and its output was compared to the original sample file output, also provided with the original RJPA program. Finally, the data of the sample input file was converted from the FPS system of units to the CGS and SI systems of units. These files were then run on RJPA-FRC and the output files were then compared to insure output consistency in the different unit systems. A listing of the input file "Example 1" is given in Appendix B along with a listing for the input files "FPS", "CGS", and "SI". The latter input files were used as the input for RJPA-FRC.

4.2.2. - Case Description

As stated above, the sample input file used was "Example 1". Example 1 is an input data file describing a Scramjet operating at an altitude of 155,700 ft. (39272 m) with a flight Mach number of 25. The inlet for this test case had a capture area specified as 11909.52 in^2 (7.6835 m^2), an exit pressure specified as 4.761 psia (32825.6 Pa), and an inlet kinetic energy efficiency of 0.9773. The combustor of this sample case used H_2 as its fuel. For this case the fuel is injected parallel to the incoming air stream at Mach 2.42 with an equivalence ratio of 0.9447. Furthermore, the combustor used a constant area configuration with a cross sectional area of 398.894 in^2 (0.26305 m^2). For this case the nozzle exit pressure was specified to be 0.1245 psia (858.3973 Pa). Finally, for the combustor and exit nozzle 5% of the H_2 was specified to be frozen. This is to simulate combustion inefficiencies.

4.2.3. - Test Results

Comparison of the output of "Example 1" and "FPS", term for term, reveals complete agreement. The only differences arise from the number of significant digits printed. The original RJPA only printed six digits, RJPA-FRC prints eight digits. Furthermore, comparing the output files for "FPS", "SI", and "CGS" to each other reveals very close agreement to each other. The differences between the output files is simply a result of conversion from one system of units to another. It is likely the results would have better agreement if more digits were used in the input files.

Based on the results of this test, one can conclude that the original RJPA modules are still functioning in RJPA-FRC as originally intended and that Interfaces 1 and 5 are functioning as designed.

4.3. - Test 2 - Verification of 3STREAM

4.3.1. - Test Description

The second test also had two objectives. The first objective was to verify that the 3STREAM module still operates correctly within RJPA-FRC when the FRC-combustion-model is selected. The second objective of this test was to verify the correct operation of Interface 2.

This test was performed by using a modified version of the "SI" test file used as the input for Test 1, henceforth referred to as "SI-FRC". For this test, the FRC combustion module was selected, rather than the equilibrium combustion module. Recall from Section 3.4.2 and referring to Figure 12, that Interface 2 constructs a data file that is used as the input to the 3STREAM module. Therefore, once the file "SI-FRC" was run on RJPA-FRC, the data file constructed by Interface 2, henceforth referred to as "SI-3STREAM", was used as the input file to the original 3STREAM program. Once "SI-3STREAM" had been executed by

the original 3STREAM program, its output was compared to the output of RJPA-FRC for "SI-FRC" prior to the data being sent to the adiabatic mixer, Interface 3.

4.3.2. - Case Description

A number of changes were made to the "SI" file to accommodate the FRC combustor module. Changes were made to the diffuser exit conditions, initial fuel conditions, and the base region of the combustor. A mixing schedule was also added to the input file.

The first change to the input file modified the diffuser exit conditions. The diffuser exit condition was redefined to meet a specified exit area of 0.2573504 m^2 rather than a specified pressure. This was done to allow greater control over the combustor entrance area dimensions.

The second modification to the input file changed the base region properties. Recall from Section 3.2.3 that the base region in Figure 12 corresponds to stream 3 in Figure 11. Also recall from Section 3.2.3 that stream 3 must have an initial area and thermodynamic properties associated with it. Therefore, a pressure, temperature, Mach number, and base area must be added to the input file used for this test. The properties used for the base region in this test are the same ones used in "Sample Case 1" from the original 3STREAM code. These are the properties of combusted fuel and air that have achieved fully-reacted conditions at a pressure of 303475 Pa, a temperature of 1200 K, and a Mach number of 1.5. The initial conditions for the fuel-air mixture that produced these results was a pressure equal to 1.0 atm, temperature equal to 1600 K, and Mach number equal to 1.7 (Houck et al., 1990).

The final modification to the "SI" input file added a linear mixing model to the combustor and turned off the nozzle module. For this model the mixing schedule required that the fuel and air be completely mixed 1 cm after entering the

combustor. This short mixing length was selected to minimize computer run time. The nozzle module was turned off because it was not needed for this test.

In addition to the extra input need for the base region and the mixing schedule, a file defining the chemical reactions is needed. This test used a file called "Test 6" and it contains the chemical reactions describing the combustion process for streams 1,2 and 3. The reactions in this file are described in Section 3.5.

The actual input and output files for this test are located in Appendix B as Test 2 input and output files "SI-FRC", "SI-3STREAM", and "Chemistry Input File - Test 6".

4.3.3. - Test Results

A term-by-term comparison of the output from 3STREAM using the "SI-3STREAM" input file and the combustor output from RJPA-FRC using the "SI-FRC" input file shows that each term is identical. Therefore, based on the results of this test, one can conclude that 3STREAM does still function correctly within RJPA-FRC and that Interface 2 correctly constructs an input file for use by the FRC combustion module.

4.4. - Test 3 - Validation of RJPA-FRC

4.4.1. - Test Description

Like the first two tests, Test 3 had two objectives. The first objective was to verify that the remaining untested interfaces, Interface 3 and 4, operate properly. The second objective of this test was to verify that for a very long combustor with almost instantaneous mixing of the fuel and air, that the FRC combustion module achieves the same exit flow conditions as the equilibrium module.

This test compared the output of two input files that describe the same flight condition. The input file "T3-FRC", used the FRC combustion option, while the input file "T3-EQ", used the equilibrium combustion option. The flight conditions and engine configuration used for this test are those set forth in Section 3.5 as the baseline configuration and outlined in Table 2. Recall that the flight Mach number for the baseline Scramjet configuration is Mach 15 with an altitude of 39,272 m.

After the two files were run on RJPA-FRC, the thermodynamic and mechanical flow properties at the combustor exit were compared to each other. Referring to Figure 12, the combustor output data for the equilibrium combustion case, "T3-EQ", was taken directly from the equilibrium combustor module. On the other hand, the combustor output data for the FRC combustion case, "T3-FRC", was taken from the output of Interface 4.

As in the previous tests, the actual input and output files for this test are located in Appendix B. They are labeled Test 3 input and output files "T3-FRC" and "T3-EQ".

4.4.2. - Case Description

The only modifications to the baseline configuration required for this test were to the combustor. For this test the fuel and air mixing schedule was changed such that complete mixing was achieved in 1 mm and the combustor length was extended to 100 m. These completely unrealistic conditions were selected so that the FRC-combustion-model could simulate the equilibrium-combustion-model as closely as possible. Recall from Section 3.4.3 that the equilibrium-combustion-model assumes that the fuel and air are instantly and completely mixed upon entering the combustor. Furthermore, recall from Section 2.2.2 that the equilibrium-combustion-model does not have a combustor length associated with

it. Therefore, when the equilibrium-combustion-model is used, the combustor could be any conceivable length possible, even 100 m.

4.4.3. - Test Results

Table 6 is a summary of the results from Test 3. The first column of data is the results of the equilibrium-combustion-model at station 5 as defined in Figure 12. The second column of data is the results of the FRC-combustion-model at station 5. The third and final column of data is the percent difference of the FRC-combustion-model results from the equilibrium-combustion-model results. With the exception of the enthalpy and the density, all of the thermodynamic properties at the combustor exits agreed to within 0.03138% of each other.

Although the densities of the two cases examined in this test only have a difference of 0.11262 %, this is still an order of magnitude greater than the percent differences seen in most of the other properties listed in Table 6. This rather large percent difference is likely the result of the different methods of calculation of the initial fuel properties used by 3STREAM and RJPA and the additional mass added to the mixture from stream 3.

RJPA and 3STREAM use different methods to establish the initial conditions for the fuel. When the equilibrium combustor module of RJPA is selected the fuel density is a direct input to the program. However, when the FRC combustion module of 3STREAM is selected the density is calculated from stream 2's initial pressure and temperature. Although one should be able to calculate the exact same value for the density, input rounding and computer truncation can give different results.

Another significant contributor to the density difference is that the FRC module, 3STREAM, starts with a slightly larger mass flow rate due to the non-zero conditions of stream 3. Recall from Section 3.2.3 and referring to Figure 11, that

3STREAM requires the product stream to have a non-zero initial area and that an initial mass flow rate must be specified as an initial pressure, temperature, and velocity. Although the initial area may be very, very small, 0.0004 m^2 for this case, it still adds some additional mass to the system.

The enthalpies listed in Table 6 also had a significantly larger percent difference than the other properties. Once again this is likely the result of the two programs calculating the enthalpy of each species in a different manner. The enthalpy per mole of a substance is defined as (Vincenti and Kruger, 1965:78):

$$h = \sum_s N_s \left(\int_{T_o}^{T} \hat{C}_{p,s}\, dT + \hat{h}_{o,s} \right) \tag{50}$$

where:

$\hat{C}_p$ = molar specific heat at constant pressure

h = enthalpy of the system

$\hat{h}_{o,s}$ = molar reference enthalpy of each species

N = number of moles of each species in the system

s = species

T = temperature of the system

T_o = reference temperature of the system

Each species in a reacting gas will have a different value for $\hat{C}_p$. Not only is this value different for each species, it changes with temperature. The value for $\hat{C}_p$ at different temperatures for many substances is tabulated in the JANNAF table. However for a computer program to use these values, they must be entered into the program as large blocks of data, which requires vast amounts of data storage capability, or the data can be curve fit such that a polynomial equation can be used to approximate the behavior of $\hat{C}_p$ as a function of temperature. Both

RJPA and 3STREAM used the latter approach. However, even though both programs use the same data, there are numerous methods of curve fits available, cubic splines and least squares to name a few. Even if the same method of curve fit is used, different weighting to different regions of the data will yield a different curve fit equation. Therefore, the numerous different methods to approximate $\hat{C}_p$ is the most likely reason the enthalpy values are different between the two programs. As a point of fact RJPA uses the Naval Ordnance Testing Station (NOTS) equilibrium thermodynamic package as the equation of state solver to find enthalpy (Cruise, 1964), and 3STREAM uses the NASA Langley Research Center thermodynamic data to solve for enthalpy.

The mixing schedule of 1 mm was intended to minimize the effects of mixing on the solution of the flow properties. Therefore, the percent differences in the entropy, pressure, temperature, and velocity are most likely from the entropy rise brought about by the continued chemical reactions of the species after complete mixing. Of course, if any one of the properties of entropy, pressure, temperature or velocity change, all of the others are effected when the energy, momentum, and continuity equations are solved. Therefore, if the entropy increases, all of the other properties will change accordingly.

The phenomenon of entropy rise can be explained by a reexamination of the definition of the equilibrium assumption and the processes that occur in the FRC-combustion-model. Recall from Section 1.1 that the equilibrium assumption states that "all molecular processes take place within the gas infinitely rapidly, that is, that the gas can adjust instantaneously to changes in its environment" (Vincenti & Kruger, 1965:178). Implied in this definition is the assumption that the fuel and air are completely mixed at the beginning of the combustion process and that the combustion products at the end of the combustion process are also completely mixed and fully-reacted. Therefore, no further reactions take place in the gases.

However, as explained in Section 2.2.3, reactions continue to occur for a finite-rate of time in the FRC-combustion-model. Therefore, as seen in Eq. 23, the entropy will continue to increase as long as reactions continue to occur. Hence, as will be discussed in Section 5.2, in a constant area duct, an increase in entropy results in an increase in pressure and a decrease in temperature and velocity.

Based on the results of this test, one can conclude that under the appropriate conditions, the FRC combustion module does achieve the same fully-reacted conditions as those calculated by the equilibrium-combustion-model and that all of the interfaces in RJPA-FRC are functioning as intended.

4.5. - Test 4 - Sensitivity Analysis

4.5.1. - Test Description

Before the program can be declared ready to use, a sensitivity analysis of how the integration tolerance variables effect the exit thrust must be completed. Therefore, this test has only one objective, determine the best values for the flow integration tolerances and the combustor area tolerance.

The need for this test arose from the inconsistent results from the program for different mixing lengths. For example, as seen in the second column of Table 7, 5983.3 N of thrust is achieved when the input file "T3-FRC" is used with a mixing length of 0.01 m. This value is only -1.06% different from the 6047.5 N of thrust calculated when using the input file "T3-EQ". However, if the mixing length in "T3-FRC" is increased to 0.1 m, the difference in thrust is -11.31% and for a mixing length of 1.5 m the difference is -5.766%. As can be seen from the other values in the third column of Table 7, the % difference in thrust varies quite dramatically with mixing length. A physical cause for this difference could not be explained, therefore, a numerical cause was investigated.

The objective of this test was to determine which values of the variables, ARTOL, EMAX, and ATOLSP produce consistent output results for thrust when the FRC option is selected. Recall from Section 3.2.3 that ARTOL determines the error tolerance for the difference between the specified total area of the combustor at any axial location and the calculated total area of the combustor at the same location. Also, recall from Section 3.2.3 that EMAX is the relative error permitted for the integration of the flow equations and ATOLSP is the absolute error permitted for the same equations and that EMAX should be 10^9 times greater than ATOLSP.

4.5.2. - Case Description

The determination of the proper values of ARTOL, EMAX, and ATOLSP was carried out by running the input file "T3-FRC" on RJPA-FRC for various values of ARTOL, EMAX, and ATOLSP with a mixing length of 0.1 m. This mixing length was selected because it was the first mixing length in Table 7 that produced inconsistent results. The default values of ARTOL, EMAX, and ATOLSP provided with the original version of 3STREAM (Houck et al., 1990) were used as the initial values for this test. These values correspond to case 1 listed in Table 8.

4.5.3. - Test Results

The results of this test are summarized in Table 8. Columns 2, 3, and 4 of Table 8 is a matrix of the values used for ARTOL, EMAX, and ATOLSP during this test. Column 5 is the percent difference in thrust from the equilibrium-combustion-model and FRC-combustion-model for each case examined.

The trends for the thrust percent difference seen in Table 8 indicate two courses of action should be taken. First, ARTOL should be set to as strict a

tolerance as possible. This seems reasonable since ARTOL determines how close the total cross sectional area of the three streams approximates the specified total cross sectional area of the combustor. However, if the value of ARTOL is too stringent, the program will get stuck in an infinite loop trying to meet a tolerance it cannot reach. This was the situation with Case 3 in Table 8. When ARTOL was set to 10^{-9} the tolerance for the area could not converge to the value specified. Therefore, 10^{-8} was the most stringent value of ARTOL that the program still could operate at. Second, EMAX and ATOLSP should be set to looser tolerances than those suggested by the default values. Initially this seems contradictory to what one might expect. However, the governing equations for reacting flows are stiff differential equations that require large amounts of iterations to solve (Houck et al., 1990). Hence, it is reasonable that making the tolerances tighter for the governing equations is causing the program to perform excessive iterations resulting in a significant amount of computer machine error. Therefore, based on the results of this test, the values that should be used for ARTOL, EMAX, and ATOLSP during this study are those for case 9 in Table 8.

Using the values for ARTOL, EMAX, and ATOLSP from case 9 in Table 8 as the new tolerances, "T3-FRC" was run again for the mixing lengths shown in the first column of Table 6. Once again comparing the thrust output of "T3-FRC" to the thrust output of "T3-EQ", one can see from column 5 of Table 7 that the results for all of the cases are consistently between -1.06% and -1.28%. Therefore, based on the results of this test one can conclude that RJPA-FRC does provide consistent results.

The lower thrust value calculated by RJPA-FRC when the FRC option is used is primarily a result of the percent differences of the enthalpy, pressure, and velocity at the combustor exit. Recall from Section 4.4.3 that RJPA uses the NOTS subroutine as the equation of state to calculate the flow properties when the

equilibrium combustion module is used. This same subroutine is used as the equation of state when the flow properties in the nozzle are calculated.

When the NOTS subroutine is used as the equation of state in the nozzle, NOTS evaluates the properties as a function of pressure and enthalpy with the other property values as initial conditions for the flow. Recall from Table 6 that the enthalpy at the combustor exit for the FRC case was 0.20696 % greater than the enthalpy at the combustor exit for the equilibrium case and that the pressure at the combustor exit for the FRC case was 0.03138 % greater than the pressure at the combustor exit for the equilibrium case. Also, the velocity at the combustor exit for the FRC case was 0.01217 % lower than the velocity at the combustor exit for the equilibrium case. Therefore, once after the flow has gone through the nozzle, the percent difference in the properties at the combustor exit is amplified. In fact the percent difference for the velocity is -0.1335 % and the pressure is 0.5574 %.

The effect these changes have on the overall thrust can be evaluated with stream thrust equation, Eq. 46, and the overall thrust equation, Eq. 48, by comparing the influence each term in the stream thrust equation has on the overall thrust of the engine. The output data from the input files used in Test 3 was used for this comparison and is summarized in Table 9. The first column of data is from the equilibrium case and the second column of data is from the FRC case. The final column of data is the difference in the values of the equilibrium case and the FRC case. Clearly the $\dot{m}U$ term dominates the stream thrust equations and losses in velocity are much more significant than increases in pressure. Therefore, even though the pressure of the FRC case has an increase over the equilibrium pressure, when the pressure is multiplied by the nozzle exit area of 0.6 m^2, the resulting thrust is quite small when compared to the resulting thrust of the $\dot{m}U$ term.

4.6. - Test 5 - Stability Analysis

4.6.1. - Test Description

The final test performed for the validation of RJPA-FRC was the stability test. The objective of this test is to demonstrate that the values determined for ARTOL, EMAX, and ATOLSP, in Test 4, result in stable operation of the program over a wide range of combustor lengths.

4.6.2. - Case Description

The objective of this test was carried out by once again using the input file "T3-FRC". For this test the mixing length was set to the baseline mixing length of 3m and the combustor length was varied from 3 m to 20 m in 1 m increments and 10 m increments from 20 m up to 100 m. Past 100 m the combustor length was increased in 50 m increments up to 750 m.

4.6.3. - Test Results

The results of this are illustrated in Figures 14 and 15. In Figure 14, combustor length is plotted on the ordinate, while the thrust is plotted on the abscissa. To allow for improved resolution of the data from the program, only the first 100 m of data is plotted on Figure 14. In Figure 14 the curve marked by the "crosses" is a third degree polynomial curve fit of the data from the FRC case "T3-FRC" with a 3 m mixing length, while the curve marked by the circles represents the equilibrium case "T3-EQ". Although the equilibrium-combustion-model data is plotted for all of the lengths shown in Figure 14, as pointed out in Section 2.2.2, the length of the combustor is irrelevant to equilibrium flow assumption calculations. The curve marked by the "diamonds" is also a third degree polynomial curve fit, but it represents the "T3-FRC" case with a 1 mm mixing length. This case is included as an additional reference point.

As can be seen in Figure 14, after 30 m the 3 m mixing length case has essentially achieved a fully-reacted state relative to the conditions prior to the first 30 m. However, by the time the flow reaches the 50 m point the thrust begins to decrease and then increase again after reaching 80 m. Close examination of the curve for the 1 mm mixing length case reveals a similar trend of reaching a fully-reacted state around 30 m and then the thrust output starting to increase again.

These oscillations are likely the result of computer machine error. Computer machine error is introduced to the solution because once the reacting flow has achieved a fully-reacted state, the differences between one iteration solution and the next is very small. However, since the flow is required to continue down the combustor length, calculations to determine the state of the flow along the axial distance must continue. With each step down the combustor, additional error is introduced to the solution. However, if the solution algorithm to the equations of motion for a reacting gas is stable, the solution will oscillate around a point.

The assumption that the FRC combustion code is stable is verified by Figure 15. Figure 15 illustrates the changes in the thrust as the combustor length is increased. Although it appears that the solution is fluctuating wildly as the combustor length increases, the thrust is really only changing 2 % from a peak value of 4600 N to a minimum value of 4550 N. Therefore, based on the results of this test, one can conclude that RJPA-FRC is stable over the range of combustor lengths examined.

4.7. - Summary

In this chapter the tests performed to validate the modifications made to RJPA and 3STREAM has been described and discussed. These tests have demonstrated that the program RJPA-FRC is ready to use.

Table 6 - Equilibrium and FRC Combustor Validation Results

Property	Equilibrium	FRC	% DIFFERENCE
Pressure (Pa)	0.105163e6	0.105196e6	0.03138
Temperature (K)	0.297515e4	0.297507e4	-0.00269
Velocity (m/s)	0.427335e4	0.427283e4	-0.01217
Density (Kg/m^3)	0.967838e-1	0.968928e-1	0.11262
Enthalpy (J/Kg)	0.256089e7	0.256619e7	0.20696
Entropy (J/Kg/K)	0.119524e5	0.119538e5	0.01171
Mass Flow (Kg/S)	0.130447e2	0.130453e2	0.00460

Table 7 - Thrust Variations with Mixing Length for Input File "T3-FRC"

Equilibrium Thrust = 6047.5 (N)				
Mixing Length (m)	Original Thrust (N)	Original Thrust % Difference	Calibrated Thrust (N)	Calibrated Thrust % Difference
0.001	5983.6	-1.06	5984.3	-1.06
0.010	597.34	-1.23	5986.1	-1.23
0.100	5366.3	-11.26	5974.0	-1.23
1.000	5257.9	-13.05	5971.2	-1.26
1.500	5699.4	-5.76	5969.9	-1.28
2.000	5278.9	-12.71	5980.0	-1.11

Table 8 - Sensitivity Analysis of Tolerance Variables

Case	ARTOL	EMAX	ATOLSP	% Difference
1	10^{-7}	10^{-4}	10^{-13}	-11.50
2	10^{-8}	10^{-4}	10^{-13}	-11.17
3	10^{-9}	10^{-4}	10^{-13}	program hung
4	10^{-7}	10^{-3}	10^{-12}	-10.74
5	10^{-8}	10^{-3}	10^{-12}	-8.18
6	10^{-7}	10^{-2}	10^{-11}	-6.03
7	10^{-8}	10^{-2}	10^{-11}	-1.64
8	10^{-7}	10^{-1}	10^{-10}	-1.63
9	10^{-8}	10^{-1}	10^{-10}	1.27

Table 9 - Influence of Stream Thrust Terms on Overall Thrust

	Equilibrium	FRC	Difference
pA (N)	1859.11	1869.48	10.37
$\dot{m}U$ (N)	64607.4	64524.14	-83.26
Stream Thrust at Nozzle Exit (N)	66466.51	66393.63	-72.88

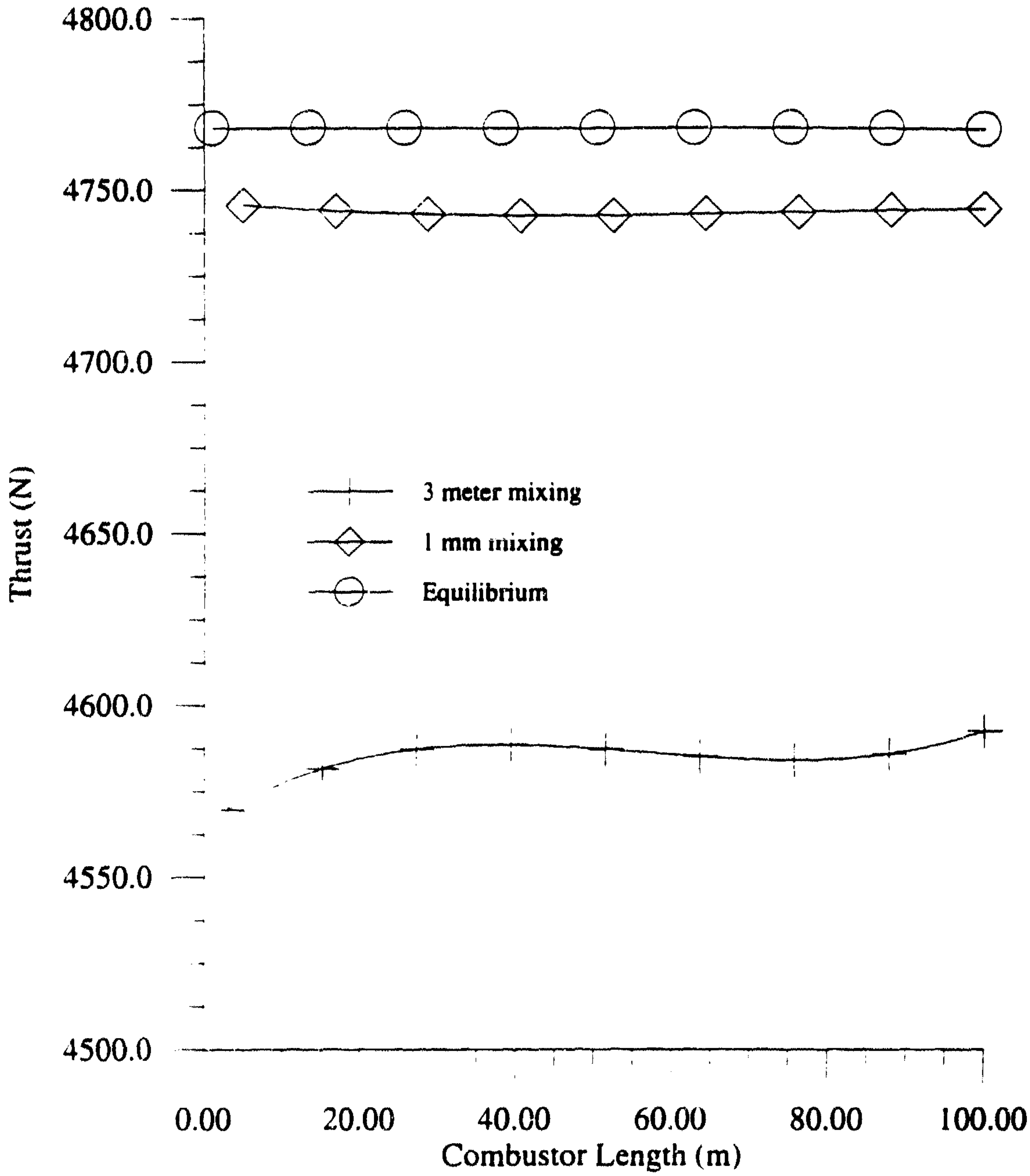


Figure 14 -Thrust vs. Combustor Length up to 100 m
Reacting Flow in Inlet and Combustor, Frozen Flow in Nozzle

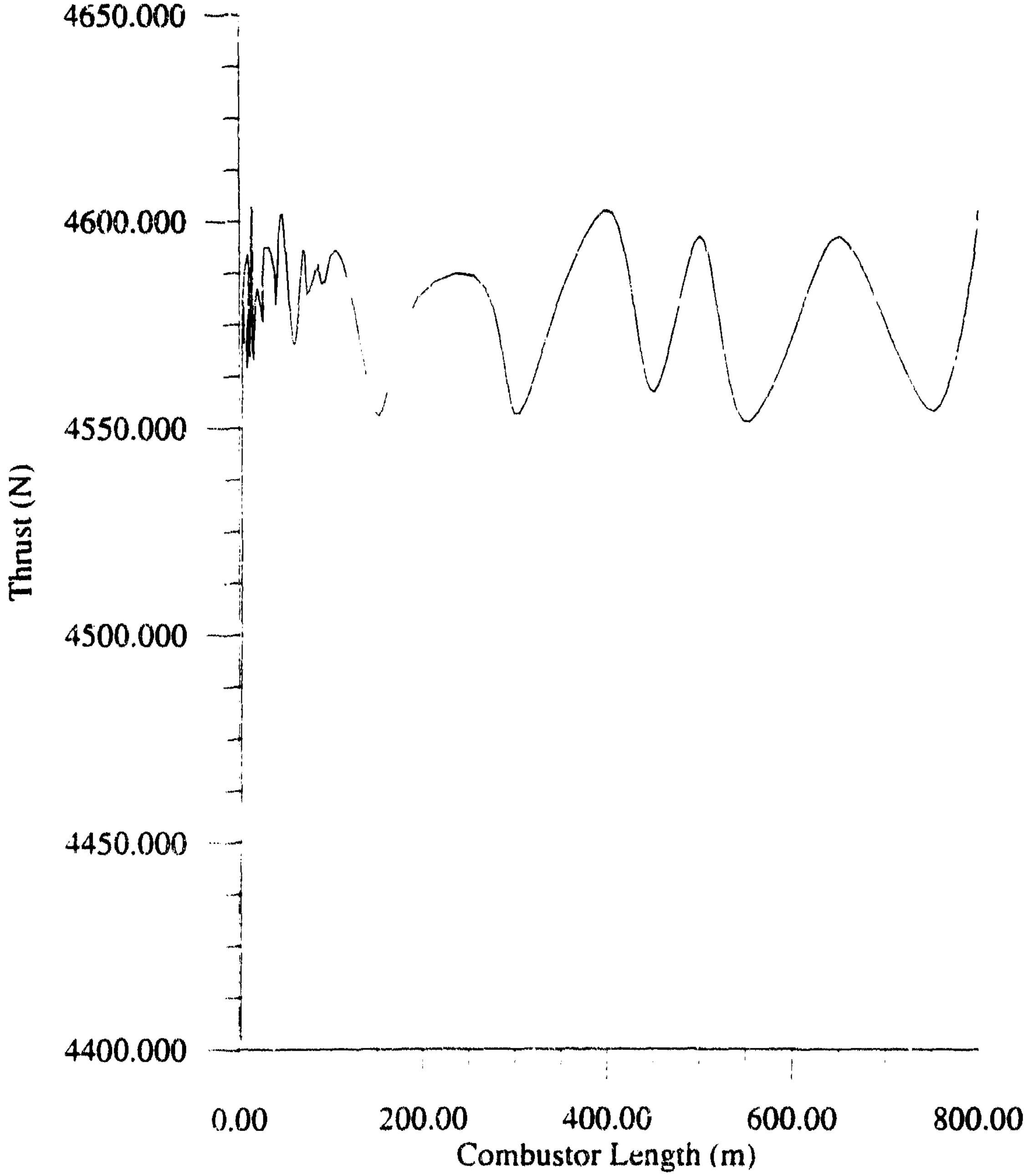


Figure 15 - Thrust vs Combustor Length up to 800 m
Reacting Flow in Inlet and Combustor, Frozen Flow in Nozzle

Chapter 5 - Case Studies

5.1. - Introduction

In this chapter, the results of the parametric study are presented. Initially, the results of the Mach 15 baseline flight condition are examined. These results are followed by the results of the Mach 12 off-design flight condition and the discussion will conclude with the results of the Mach 18 off-design flight condition. Recall from Section 1.3, that for this study the geometry of the inlet, the combustor entrance, and the nozzle exit were held constant for all flight conditions. Therefore, only the combustor length and the combustor exit area were varied.

As pointed out in Section 3.5, a linear mixing schedule with an equivalence ratio of 1 was used for all of the flight conditions examined in this study. Furthermore, the mixing schedule selected for the fuel and air produced a completely mixed product stream 3 m down from the combustor entrance. As a result of this mixing schedule, the cases with a 1 m long combustor only have 33.3% of the fuel and air mixed at the combustor exit. Likewise, the 2 m long combustors only have 66.6% of the fuel and air mixed at the combustor exit, and in the 3 m long combustors, the fuel and air has just completed the mixing process at the combustor ext. By the time the gases reach the combustor exit of the 4 m and 5 m long combustors, the gases have completed the mixing process, but they have had additional time in the combustor to allow the mixture to react and possibly achieve a fully-reacted state.

Table 10 is a summary of the combustor lengths and exit areas examined for each of the three flight Mach numbers considered. The third and fifth columns of the table list the combustor exit areas examined, while the second and fourth

columns of the table list the combustor lengths examined for each exit area. Recall from Table 5 that each of the combustor exit areas examined results in a Crocco index of either 0.0, 0.25, 0.5, 0.75, or 1.0 for fully-reacted conditions at the combustor exit at Mach 15 flight conditions, when the equilibrium-combustion-model is selected. As explained in Section 2.3.2.2.2, a Crocco index of "1" indicates a constant area combustion process has occurred and a Crocco index of "0" indicates a constant pressure combustion process has taken place.

A Crocco index of "0" based on the pressure and area at the entrance and exit of the combustor does not insure a constant pressure combustion process is really occurring. For the combustion process to be truly a constant pressure combustion process, the pressure in the *pdA* integral of Eq. 24 must be constant along the entire length of the combustor. For this situation to occur the combustor walls would have to expand very quickly near the combustor entrance and taper off to nearly a constant area near the combustor exit (Leingang, 1993). This is not the combustor geometry used during this study. The combustors used in this study had straight walls which expand at a constant angle.

5.2. - Mach 15

The first flight condition examined is the baseline flight condition, Mach 15. As stated in Section 3.5, the inlet geometry, combustor entrance geometry, and nozzle exit geometry are fixed for this flight condition and all subsequent flight conditions. The Scramjet geometry used for this study is given in Table 4.

Although a range of combustor exit areas was examined for this study, the characteristics of the two extreme exit areas , 0.03154 m^2 and 0.053403 m^2, warrant closer examination at this point than the three intermediate combustor exit areas. Using Eq. 27 and the data for an exit area of 0.3154 m^2, a Crocco index of "1" is the result for all flight conditions and mixing lengths examined when the

constant area combustor is used. However, when an exit area of 0.053403 m^2 is used, a Crocco index of "0", is produced only when the equilibrium combustion module is selected for Mach 15 flight conditions and when the FRC combustion module is selected for the 4 m and 5 m long combustor at Mach 15 flight conditions. All other flight conditions and combustor lengths examined using this exit area resulted in a non-zero Crocco index.

An exit area of 0.053403 m^2 was expected to result in a constant pressure combustion process when the FRC combustion option was selected for Mach 15 flight conditions. Although this exit area does result in a Crocco index of "0" for a limited number of configurations, it does not result in a constant pressure combustion process for any configuration investigated. In fact, when this exit area does result in a Crocco index of "0", it is only because the combustor exit has the same pressure as the combustor entrance. This phenomenon is caused by the shape of the combustor walls used for this study. As pointed out in Section 5.1, the walls of the combustor would have to be shaped such that a quick expansion of the area would relieve the initial pressure rise from combustion and then taper off to a near constant area to maintain a constant pressure once the reactions slowed. Figure 16 verifies the need for this predicted shape.

Plotted in Figure 16 is the axial internal pressure and velocity of a 5 m long constant area and expanding area combustor at Mach 15 flight conditions. The internal velocity is represented by the dashed lines and the internal pressure by the solid lines. The diamonds represent the calculated data for a constant area combustor with a cross sectional area of 0.03154 m^2, while the crosses represent the calculated data for an expanding area combustor with an exit area of 0.053404 m^2. As stated above, the expanding area combustor with an exit area of 0.053404 m^2 was intended to represent a constant pressure combustion process, however as seen in this figure, constant pressure is far from what was achieved.

Clearly illustrated in Figure 16 is the behavior of the internal pressure and the internal velocity of a constant area combustor and an expanding area combustor as the flow moves down the length of the combustor. Initially the pressure steadily increases, while the velocity steadily decreases for both exit area configurations. However, after the flow has proceeded 3 m down the length of the combustor, the fuel and air has been completely mixed and the combustion process slows. Once the combustion process slows, the pressure begins to decrease in the expanding area combustor, while the pressure remains steady in the constant area combustor. The decrease in pressure in the expanding area combustor is the result of the continued expansion of the gases as the flow moves down the length of the combustor. Also, as the cross sectional area of the duct increases, the gases will accelerate to fill the void created by the increased volume, thereby increasing the flow velocity. On the other hand, the pressure in the constant area combustor remains elevated and the velocity depressed because the gases cannot expand to relieve the pressure.

Once again, as shown in Figure 16, the constant pressure combustion process simulated in this study is really one where the pressure at the combustor entrance and exit is the same. Therefore, for this study, combustors with a combustor exit area of 0.053403 m^2 will be referred to as the "greatest-expanded-exit-area" combustor.

The effects of the mixing schedule, the combustor length, and the combustor exit area on the overall engine thrust are examined with the aid of Figure 17. In Figure 17, the thrust is plotted against the combustor length for a flight speed of Mach 15. Recall from Section 3.5 that this is a study to determine how FRC combustion and combustor geometry changes effect Scramjet performance. Therefore, non-reacting or frozen flow was used in the nozzle to minimize the effects of the nozzle on the overall thrust of the Scramjet.

Plotted in Figure 17 are two families of curves. The curves with the dark symbols represent the equilibrium-combustion-model results, while the curves with the lighter symbols represent the FRC-combustion-model results. Each curve on Figure 17 was produced for a given combustor exit area. However, each point on the curve represents a combustor with a different length. Therefore, the walls of each combustor have different expansion angles. For example, the thin crosses correspond to an FRC combustor with an exit area of 0.053403 m^2. A 1 m long combustor with the aforementioned exit area has an expansion angle of 1.985° for the upper and lower walls. However, a 5 m long combustor with the same exit area has an expansion angle of only 0.397°. Therefore, the thrust plotted in Figure 17 and any subsequent figures should not be misconstrued as the thrust that would be produced if the 5 m long combustor was truncated at the various lengths shown.

The first family of curves on Figure 17 to be discussed are the curves representing the equilibrium-combustion-model. These curves are represented by the thicker symbols. The thick diamonds on the lower curve represents the thrust produced by the constant area combustor and the thick crosses on the upper curve represents the thrust produced by the greatest-expanded-exit area combustor. These two lines bracket the range of thrust available from the equilibrium combustion module for the combustor exit areas listed in Table 4 and for the initial thermodynamic conditions at the combustor entrance listed in Table 2. Notice that each of these lines has a marker corresponding to a different combustor length. These markers were added to clarify the location of the line on the plot. These additional points should not be misconstrued as different combustor lengths investigated with an equilibrium-combustion-model. As indicated previously in Section 2.2.2, the length of the combustor is irrelevant for equilibrium-combustion-model calculations.

The second family of curves plotted on Figure 17 represents the thrust available when the FRC combustion module is selected. The thin diamonds on the bottom curve represents the thrust available from the constant area combustor when evaluated with the FRC combustion module, while the thin crosses on the top curve represents the thrust available from the greatest-expanded-exit-area combustor when evaluated with the FRC combustion module. The triangles, circles and squares represents the thrust of several intermediate combustor exit areas when evaluated with the FRC combustion module.

The first of several trends identified in Figure 17 is that the thrust increases as the combustor exit area increases. As a point of reference, consider the overall thrust increase when the exit area of a 3 m long combustor is increased from 0.03154 m^2 to 0.053403 m^2. For the Mach 15 flight condition, the overall thrust increases from 4545 N for the constant area combustor to 4979.4 N for the greatest-expanded-exit-area combustor. The net result of increasing the exit area is a 9.56% increase in overall thrust. Although the specific values will differ, this trend will be seen regardless of the combustor length.

Increases in thrust with increases of the combustor exit area is explicable with the aid of Figure 18 and the overall thrust equation, Eq. 48. Equation 48 is given in Chapter 3 as $T = F_6 - F_0 - p_0(A_6 - A_0)$, where the stream thrust F is defined in Eq. 46 as $F = pA + \dot{m}U$. Recall from the initial conditions given in Section 3.5, the inlet capture area A_0, and nozzle exit area A_6, are the same. Therefore, Eq. 48 reduces to $T = F_6 - F_0$. Furthermore, since F_0 is constant for all of the combustor configurations plotted on Figure 17, the only term that can vary is the stream thrust at the nozzle exit F_6. However, the stream thrust at the nozzle exit is a function of the stream thrust at the combustor exit F_5. Since the values of pA and $\dot{m}U$ for F_5 serve as the initial conditions for the flow entering the nozzle, any increase in F_5 will result in an increase of F_6.

Figure 18 is a plot of the stream thrust components produced by the pA term and the $\dot{m}U$ term at the combustor exit as a function of the combustor length for the Mach 15 flight conditions. In this figure the dashed lines represent the $\dot{m}U$ term and the solid lines represent the pA term. It can be seen from Figure 18 that as the combustor exit area increases, the pA term decreases. This is a result of the exit pressure decreasing faster than the exit area is increasing. Undoubtedly, the overall thrust would decrease as a result of the decrease in the pA term if the reduced exit pressure did not allow the exit velocity to increase. Of course, increasing the exit velocity increases the magnitude of the $\dot{m}U$ term, thereby, compensating for the thrust lost from the decrease of the pA term. In fact when the exit area of the 3 m long combustor increases from 0.03154 m^2 to 0.053403 m^2, the thrust from the $\dot{m}U$ term increases by 2087 N as compared to the decrease in the thrust of only 374 N from pA term. Therefore, when the $\dot{m}U$ term and the pA term is added together, the net result is an increase in the stream thrust of 1713 N.

Based on the calculated data presented in Figure 17, it is reasonable to conclude that a combustor with an exit area greater than the combustor inlet area can more effectively convert the internal energy of the fuel into thrust producing kinetic energy. Recall, this analysis is based on an inviscid flow without heat transfer between the individual streams or the surrounding environment. If these loss mechanisms were accounted for, the overall thrust output would be less than the thrust calculated here. However, the particular trend identified in Figure 17 will not change and the conclusions made based on different combustor exit areas will not change.

The second trend identified in Figure 17 is that the thrust increases as the degree of mixing increases. The degree of mixing represents the amount of fuel and air available for combustion. Recall that after the flow has proceeded 1 m down the length of the combustor, only 33.3% of the fuel and air has been mixed.

Yet, for this relatively small degree of mixing, 77.24% of the equilibrium-combustion-model thrust has been achieved by the constant area combustor when the FRC module is selected. Furthermore, 78.21% of the equilibrium-combustion-model thrust has been achieved by the greatest-expanded-exit-area combustor when the FRC combustion module is selected. After the flow has proceeded 2 m down the length of the combustors shown in Figure 17, 66.6% of the fuel and air has been mixed. With this degree of mixing the constant area combustor achieves 91.95% of the equilibrium-combustion-model thrust and the greatest-expanded-exit-area combustor has achieved 96.86% of the equilibrium-combustion-model thrust. Finally, after the flow has proceeded 3 m down the length of the combustors shown in Figure 17, the fuel and air has been completely mixed. At this point the constant area combustor achieves 95.32% of the equilibrium-combustion-model thrust and the greatest-expanded-exit-area combustor achieves 101.14% of the equilibrium-combustion-model thrust.

Based on the results shown in Figure 17, for an inviscid flow without heat transfer, complete mixing is not necessary to achieve significant amounts of the equilibrium-combustion-model thrust. In fact, more than 91% of the equilibrium-combustion-model thrust is achieved with only 66.6% of the fuel and air mixed for all of the cases examined at the Mach 15 flight condition.

After the mixing process has been completed, the fuel and air will continue to react until a fully-reacted condition is achieved or until the flow leaves the combustor. In Figure 17, one can see that the thrust continues to increase as the combustor length increases from 3 m to 4m. This is the result of the continued energy release from the reactions in the fuel-air mixture. Although the thrust continues to increase if the reactions are allowed to continue, the increase in thrust with respect to the increase in combustor length is very small in comparison to the gains made earlier when additional fuel and air was being added to the flow. In

fact, when the combustor length is increased from 3 m to 4 m, the constant area combustor only gains 0.78% more thrust and the greatest-expanded-exit-area combustor thrust only increases by 0.99%. Therefore, one could surmise that for an inviscid flow without heat transfer, increasing the combustor length past the point of complete mixing produces little or no benefit to the overall thrust of the vehicle. However, in a viscous flow, where skin friction, boundary layer effects, and thermal losses occur, a 1% gain in gross thrust brought about by a longer combustor may outweigh the additional weight added to the vehicle by the additional combustor length. In fact, a 1% increase in the gross thrust may be the difference between a net positive thrust and no thrust at all (Leingang, 1993).

Another trend identified in Figure 17 is the appearance of a critical combustor length for a given combustor exit area. Combustor lengths longer than this critical length experience a thrust decrease rather than a thrust increase. For the flight conditions investigated in Figure 17, the thrust from the constant area combustor decreases by 0.23% when the combustor length is increased from 4 m to 5 m and by 0.13% for the greatest-expanded-exit-area combustor. Since this is an inviscid flow without heat transfer, the decrease in thrust can only be attributed to the losses brought about by an entropy increase from continued chemical reactions. The mechanism for this entropy increase is seen in Eq. 23; this phenomenon will be discussed in greater detail in Section 5.3. Once again, based solely on an inviscid flow without heat transfer, one can conclude that increasing the combustor length past the point where mixing is complete is of little or no benefit to the overall thrust of the vehicle.

The most important trend observed in Figure 17 is that once the fuel and air have been completely mixed, the thrust of the constant area combustor is less than the equilibrium-combustion-model thrust, whereas the thrust of the greatest-expanded-exit-area combustor is greater than the equilibrium-combustion-model

thrust. Both of these combustor configurations attain their greatest thrust output for the 4 m long combustor. For this combustor length, the constant area combustor thrust is 3.93% less than the equilibrium-combustion-model thrust and the greatest-expanded-exit-area combustor thrust is 2.14% more than the equilibrium-combustion-model thrust. This phenomenon can be explained by a reexamination of the definition of the equilibrium assumption and the processes that occur during FRC combustion.

Recall that the definition of the equilibrium assumption was given in Section 1.1 as a flow which assumes that "all molecular processes take place within the gas infinitely rapidly, that is, that the gas can adjust instantaneously to changes in its environment" (Vincenti & Kruger, 1965:178). Implied in this definition is the assumption that the fuel and air are completely mixed at the beginning of the combustion process and that the combustion products at the end of the combustion process are also completely mixed and fully-reacted. In the equilibrium-combustion-model, the initial conditions at the beginning of the flow are also assumed to be appropriate to model the entire combustion process.

The assumptions made about the mixing process and the instantaneous release of energy means that the equilibrium-combustion-model is path independent. In other words, even if a mixing schedule is simulated for the equilibrium-combustion-model by dividing the combustor into a large number of discreet sections and incrementally adding small portions of fuel and air to the system, the end result would be the same as if all of the fuel and air were added at the same time. Needless to say, when the above process is applied to the FRC-combustion-model, very different results are obtained. In other words, the FRC-combustion-model is path dependent.

This path dependence is a fundamental difference between the equilibrium-combustion-model and the FRC-combustion-model. The equilibrium-combustion-

model is path independent because it does not have a length dependence built into it (Vincenti and Kruger, 1965:178). Therefore, even though each discrete section of the combustor is evaluated on an individual basis, the results of each section are still equilibrium assumption results based on instantaneous mixing and energy release. On the other hand, FRC combustion processes are path dependent (Vincenti and Kruger, 1965:229). In other words, when each section of the combustor is evaluated using the FRC-combustion-model, the flow in each combustor element is reacting at a finite rate and will not achieve its maximum energy release until a finite length of time has passed. Therefore, the fuel and air may not have achieved its maximum energy release in the time allowed for the flow to pass through a particular section of the combustor. However, even if the species in a particular flow element was allowed an infinite length of time to achieve the fully-reacted conditions and no more fuel and air were added to this element, the fully-reacted conditions achieved by this element would not match the fully-reacted conditions achieved by the element that underwent instantaneous mixing and energy release of the equilibrium-combustion-model.

The reason two identical elements, with identical initial conditions, converge to different fully-reacted end states, when the FRC combustion is used for one of the elements and the equilibrium-combustion-model is used for the other element, is found in Eq. 23. Equation 23 represents the entropy change for a chemically reacting flow, where $[X_i]$ is the molar concentration of each species in the overall system. In the equilibrium-combustion-model, the changes to the molar concentrations occur instantly and remain fixed from that point on. Therefore, the entropy of a system undergoing combustion modeled by the equilibrium assumptions will remain fixed once the constituent species are mixed. On the other hand, in the FRC-combustion-model, the changes to the molar

concentrations and the mixing of the species occur over a finite-length of time. Therefore, the entropy change in the FRC-combustion-model is time dependent.

The time dependent nature of the mixing process used in the FRC-combustion-model promotes a higher entropy rise than the instantaneous mixing process. Examination of the entropy values for the equilibrium-combustion-model and the FRC-combustion-model with the fuel and air just after the mixing process is completed, shows that the FRC-combustion-model entropy is 0.32% greater than the equilibrium-combustion-model. It is unlikely this percent difference is caused by machine error, since further increases in the entropy occur after complete mixing has occurred in the FRC-combustion-model. The continued entropy increase is the result of continued reactions in the flow after mixing is completed. These continued reactions of the flow as the combustor length is increase to 5 m, acts to further increase the overall entropy of the system by 0.012%.

Based on the above discussion on the effects of entropy rise in a finite-rate reacting system, one can conclude that the reason the constant area combustor does not achieve the equilibrium-combustion-model thrust when the FRC option is selected. is because the FRC-combustion-model accounts for the entropy rise produced by the gradual mixing process and the continued reactions of the system that occur after mixing has been completed. Furthermore, one can conclude that the entropy increase from time dependent mixing is the dominate phenomenon causing the entropy rise when the FRC-combustion-model is used.

An explanation of why the FRC-combustion-model thrust is greater than the equilibrium-combustion-model thrust for the greatest-expanded-exit-area combustor can also be attributed to the path dependent nature of FRC combustion. As explained in the previous discussion, any two elements with the same initial conditions will achieve different fully-reacted end states depending on the combustion model used. Once again this is because of the different entropy rise

process that the flow experiences. Recall from Section 2.2.2 that when the equation of state and the continuity, momentum, and energy equations are solved for the equilibrium-combustion-model, all of the thermodynamic properties are fixed from that point on. However, when these equations are solved for a finite-rate reacting system, the properties are constantly changing. Recall from the previous discussion that the entropy of any element in the FRC-combustion-model will be greater than the entropy of an element with the identical initial conditions in the equilibrium-combustion-model. Therefore, all of the other thermodynamic properties will be different.

After examination of Eq. 23, it is conceivable that the pressure of the element in the FRC-combustion-model is less than the pressure of the element in the equilibrium-combustion-model. Therefore, as shown in Figure 18, when the pressure in the combustor drops, the velocity increases, thereby, increasing the overall thrust above the equilibrium-combustion-model thrust. This analysis opens the possibility that the equilibrium-combustion-model does not necessarily yield the maximum possible thrust for a given combustor configuration.

Based on the results of the data presented in Figure 17 and the implications the FRC-combustion-model has on entropy rise, one can conclude that an equilibrium-combustion-model is not sufficient to predict the thrust produced by a combustor with a scheduled mixture of fuel and air.

Plotted on Figure 19 is a family of curves representing the thrust as a function of the combustor exit area for a flight condition of Mach 15. Each line on this figure was produced for a given combustor length. Illustrated in this figure are many of the same trends seen in Figure 17; however, some of the variables that influence the results are shown more effectively in this figure. In addition to the previous trends noted is the indication of a critical combustor exit area for a given combustor length.

The most important of the previous trends noted in Figure 17 that are more clearly illustrated in Figure 19 is the effect mixing has on thrust. The line marked by the crosses in Figure 19 represents a 1 m long combustor. Recall that only 33.3% of the fuel and air has been mixed after the flow has proceeded 1 m down the length of the combustor. As in Figure 17, one can see that when the exit area of the 1 m long combustor is 0.047474 m^2, 79.51% of the equilibrium-combustion-model thrust has been achieved. However, the subsequent increases in thrust achieved by additional mixing and continued reaction for the longer combustor lengths is much more dramatically illustrated in Figure 19 than in Figure 17. The line marked by the circles represent the thrust available after 66.6% of the fuel and air have been mixed. This calculated data clearly indicates that significant gains in thrust can be achieved by continued mixing of the fuel and air past 33.3%. As a matter of fact, for a combustor exit area of 0.047474 m^2, the thrust is increased by an additional 17.44% or 96.95% of the equilibrium-combustion-model thrust. On the other hand, the line marked by the thin diamonds and representing 100% mixing of the fuel and air, indicates that the additional thrust gained by continued mixing past 66.6% may not be worth the additional weight added to the vehicle when the combustor length is increased to achieve a higher degree of mixing. Once again, using the data for the combustor with an exit area of 0.047474 m^2, one can see that the additional mixing only results in a thrust increase of 2.8%.

Even more significant are the implications of the lines marked by the boxes and the triangles. These lines respectively represent the 4 m and 5 m combustors and clearly indicate that the additional combustor length added to allow the flow additional time to fully react does not produce a significant increase in thrust. Therefore, as indicated in Figure 17 and reinforced in Figure 19, increasing the combustor length past the point of 100% mixing does not result in a significant increase in thrust and the gains in thrust achieved from mixing past 66.6% are

marginal at best. However, one must remember that this analysis is based on an inviscid flow without heat transfer between the flow streams or the surrounding environment and that once these factors are considered, the marginal gains in thrust achieved by increasing the combustor length may be the difference between a net positive thrust and no thrust at all.

A trend not identified in Figure 17, but seen very clearly in Figure 19, is that for a given combustor length, there is a critical exit area past which the thrust begins to fall. This phenomenon is most pronounced for the 1 m long combustor, but it is also seen in the 2 m long combustor. In this figure, the 1 m long combustor is represented by the crosses and the 2 m long combustor by the circles. As one can see from Figure 19, when the exit area of the 1 m long combustor is increased from 0.047474 m^2 to 0.053403 m^2, the thrust decreases by 1.13%. This phenomenon can be explained if one considers the expanding area combustor as a nozzle containing a reacting flow.

Implied in the definition of the equilibrium assumption is the assumption that in addition to the flow being in chemical equilibrium, it is also in thermal and mechanical equilibrium. That is, none of the macroscopic thermal and mechanical properties are changing (Vincenti and Kruger, 1965:60). However, as long as a flow is moving into an expanding cross sectional area, the pressure of the flow will decrease. Therefore, a flow that is moving into a continuously expanding cross sectional area can never achieve chemical and mechanical equilibrium. It was also stated that for the flow to be in chemical equilibrium, the flow must continuously and instantly adjust to its surrounding conditions (Vincenti and Kruger, 1965:178) However, Bray pointed out that if the flow is moving into an expanding cross sectional area, the pressure of the flow will eventually become so low that the flow will not be able to react fast enough to maintain fully-reacted chemical conditions.

In fact, if the area is increasing too fast, the chemical reaction rates will become so slow that the system will essentially behave as a frozen flow (Bray, 1959).

It is reasonable to conclude that the walls of the 1 m long combustor with an exit area of 0.053403 m^2 have an expansion angle large enough to cause the reaction rates to slow to the point where parts of the flow are beginning to behave as a frozen flow. The results shown in Figure 19 indicate that the expansion angle does not have to be very large for this phenomenon to occur. In fact, only an increase in the expansion angle of 0.877° caused the flow characteristics to change. Although this phenomenon is only seen in Figure 19 for the 1 m and 2 m combustor lengths, it is reasonable to expect that the same phenomenon would be seen for the longer combustor lengths if their expansion angles were increased.

Therefore, based on the trends seen in Figure 19, one can conclude that if a Scramjet design is limited to short combustor lengths, rapid expansion of the gases provide the largest amounts of thrust. However, caution must be used so that the expansion angle of the combustor wall is not so large that the rate of expansion causes the flow to stop reacting, thereby reducing the overall thrust produced.

5.3. - Mach 12

The second case examined is the undersped inlet at a flight condition of Mach 12. Recall from Section 2.3.1.1 that the undersped inlet does not capture all of the compressed air. Therefore, the spilled air results in an additive drag component to the thrust equation, resulting in reduced overall thrust (Mattingly, 1987:185). However, this program does not evaluate the external drag forces. Therefore, one should be aware that this program's analysis for off-design conditions does not include the effects of additive drag.

Recall from Section 3.5 that the Scramjet geometry used for this flight condition is the same as the geometry used for the Mach 15 flight condition.

Therefore, as with the Mach 15 flight condition, the inlet geometry, the combustor entrance geometry, and the nozzle exit geometry are fixed.

As in Figure 17, the thrust in Figure 20 is plotted against the combustor length. However, in this figure the data is for a flight condition of Mach 12. As in the previous case, two families of curves are plotted on Figure 20. Once again, the curves with the thick symbols represent the equilibrium-combustion-model results, while the curves with the thin symbols represent the FRC-combustion-model results. As in Figure 17, each curve on this figure was produced for a given combustor exit area.

Many of the same trends identified in Figure 17 are also seen to varying degrees in Figure 20. As before, the larger the combustor exit area for a given combustor length, the larger the overall thrust. Also, as seen in the previous case, the majority of the equilibrium-combustion-model thrust has been achieved after only 33.3% of the fuel and air is mixed (1 m down from the combustor entrance). When the FRC-combustion-model is selected, the constant area combustor achieves 73.22% of the equilibrium-combustion-model thrust and the greatest-expanded-exit area combustor achieves 76.66% of the equilibrium-combustion-model thrust. These configurations are respectively marked by the thin diamonds and the thin crosses.

Once again, as the degree of mixing proceeds to 66.6% of the available fuel and air (2 m down from the combustor entrance), a significant amount of additional thrust is realized. The thrust of the constant area combustor increases to 90.36% of the equilibrium-combustion-model thrust and the greatest-expanded-exit-area combustor thrust increases to 96.33% of the equilibrium-combustion-model thrust.

Finally as before, when the fuel and air are completely mixed, there is a moderate improvement in the overall thrust. The constant area combustor thrust

increases to 96.04% of the equilibrium-combustion-model thrust and the greatest-expanded-exit-area combustor thrust improves to 99.82% of the equilibrium-combustion-model thrust.

Recall from Figure 17 that a critical length for a given combustor exit area was identified. This phenomenon is even more evident in for the constant area combustor under these flight conditions. In Figure 20, the thrust sharply drops off for the constant area combustors longer than 3 m. This phenomenon is caused by a combination of continued entropy rise after the mixing process is complete, an initial velocity and temperature at the combustor entrance lower than the initial velocity and temperature of the Mach 15 case, and an initial pressure at the combustor entrance higher than the initial pressure of the Mach 15 case.

The initial conditions at the combustor entrance for the Mach 12 flight conditions form a more severe adverse pressure gradient in the combustor than to the initial conditions of the Mach 15 case. As can be seen from Table 2, at the Mach 12 flight condition, the pressure at the combustor entrance is 30.5% greater than the pressure at the combustor entrance at the Mach 15 flight condition. Also, at the Mach 12 flight condition, the temperature of the air at the combustor entrance is 21.1% lower than the temperature of the air at the Mach 15 flight condition. As pointed out in Section 2.2.2, the energy release for most fuels is more efficient at higher temperatures than at lower temperatures. Couple less efficient energy release with an initial incoming air velocity that is 21.1% lower than the incoming air at the Mach 15 flight conditions, and the momentum of the flow is severely reduced. Of course, as seen from the momentum equation, the lower the momentum of the flow, the harder it will be for the flow to overcome the adverse pressure gradient in the combustor.

Although the initial conditions at the combustor entrance contribute to the reduced energy of the flow, for an inviscid flow, without any heat transfer, the

thrust should not decrease with increased combustor lengths. However, as was pointed out in Section 5.2, the entropy continues to increase in the FRC-combustion-model as long as reactions continue to take place. In fact, the entropy at the exit of the 5 m long combustor is 0.02% greater than the entropy of the 3 m combustor. Therefore, as long as the entropy of the flow continues to change, so will the pressure, temperature, and velocity in the combustor. As pointed out in Section 5.2, an entropy rise generally results in a pressure rise for a constant area combustor. Furthermore, as seen in Figure 16, when the pressure in the combustor increases, the velocity in the combustor decreases. This increase in combustor exit pressure and decrease in combustor exit velocity reduces the magnitude of the stream thrust at the combustor exit, which causes a reduction of the overall Scramjet thrust.

Therefore, one can conclude that even when skin friction and heat transfer are ignored, the thrust of a constant area combustor will decrease after the mixing process is complete. This is brought about by the entropy rise from the continued reactions in the flow. Furthermore, this phenomenon is more apparent at the Mach 12 flight condition than at the Mach 15 flight condition because the combustor for the Mach 12 flight condition has a larger initial pressure-to-velocity ratio and a lower initial temperature at the combustor entrance than the Mach 15 flight condition.

In general, the Mach 12 and Mach 15 flight conditions exhibit the same characteristics. Both flight conditions exhibit increased thrust when the combustor exit area is increased and when the degree of mixing is increased. However, there are two notable differences between the Mach 12 and Mach 15 flight conditions. The first difference is the sharp decrease in thrust for the constant area combustor at Mach 12 flight conditions when the combustor length is longer than 3 m. The second noteworthy difference is that the overall thrust of the Mach 12 flight

condition is 1.75 times greater than the overall thrust of the Mach 15 flight condition.

The difference in thrust between the Mach 12 flight conditions and the Mach 15 flight condition is easily explained with the stream thrust equation (Eq. 46), the overall thrust equation (Eq. 48), and the initial flight velocities given in Table 2.

Recall, the overall thrust for this Scramjet configuration is simply the difference of the stream thrust at the nozzle exit and the stream thrust of the inlet capture area. Also, as shown in Section 5.2, the dominant term in the stream thrust equation is the $\dot{m}U$ term. Therefore, subtracting the velocity at the nozzle exit (4033 m/s) from the velocity of the free stream (3733 m/s), one finds an overall flow velocity increase of 300 m/s for the Mach 12 flight conditions. Using a nozzle exit velocity of 4904 m/s and a free stream velocity of 4751 m/s for Mach 15 flight conditions, one can find the overall flow velocity increase for the Mach 15 flight conditions to be 152 m/s. The ratio of these two velocities is 1.97. Therefore, the majority of the thrust decrease between the Mach 12 and Mach 15 flight conditions is from the reduced ability of the combustor to increase the incoming flow velocity when the vehicle is operating at Mach 15 flight conditions. The remaining thrust difference is the result of the different free stream pressures and the different pressures at the nozzle exit.

5.4. - Mach 18

The final flight condition examined is the oversped inlet at a flight speed of Mach 18. Recall from Section 2.3.1.1 that the oversped inlet captures excess uncompressed air and that the ingestion of this uncompressed air contributes to the formation of a shock train at the inlet entrance that enters into the diffuser and the combustor. This shock train results in a two dimensional flow pattern that this

code is incapable of analyzing. Therefore, one should be aware that this program's analysis for off-design conditions does not include the effects of the shock train seen in an oversped inlet.

Recall from Section 3.5 that the Scramjet geometry used for this flight condition is the same as the geometry used for the Mach 15 flight condition and the Mach 12 flight condition. Therefore, as with the two previous cases, the inlet geometry, the combustor entrance geometry, and the nozzle exit geometry remain fixed.

Figure 21 is a plot of the thrust as a function of the combustor length for the Mach 18 flight condition. As before, there are two families of curves plotted on this figure. The curves with the thick symbols represent the equilibrium-combustion-model results, while the curves with the thin symbols represent the FRC-combustion-model results. Once again, each curve on this figure was produced for a given combustor exit area.

All of the trends noted in the previous two cases are seen to varying degrees in Figure 21 for the Mach 18 flight condition. As in the previous cases examined, the larger the combustor exit area for a given combustor length, the larger the overall thrust. The expanded exit area combustors still achieve more thrust than the equilibrium-combustion-model thrust and the presence of a critical combustor length is still seen for the constant area combustor. The only significant difference between the Mach 18 flight condition and the previous flight conditions examined is the amount of thrust produced with the degree of mixing.

As in the previous cases, the majority of the equilibrium-combustion-model thrust is achieved with only 33.3% of the fuel and air mixed. However, 83.65% of the equilibrium-combustion-model thrust is achieved by the constant area combustor for this flight speed as compared to 77.24% for the Mach 15 flight speed and 73.22% for the Mach 12 flight speed. Similar results are seen for the

greatest-expanded-exit-area combustor. With only 33.3% of the fuel and air mixed, 84.78% of the equilibrium-combustion-model thrust is achieved as compared to 78.21% at Mach 15 and 76.66% at Mach 12.

The accelerated rates of combustion for the Mach 18 flight condition are the result of a higher initial temperature of the incoming air at the combustor entrance. As can be seen from Table 2, the initial temperature of the Mach 18 flight condition air is 23.3% greater than the temperature of the incoming air for the Mach 15 flight condition. Although, the pressure of the incoming air for the Mach 18 flight conditions is 22.23% lower than the incoming air pressure for the Mach 15 case, it was shown by Eq. 9 and Eq. 13 that temperature has a much greater influence on the rate of combustion than pressure.

As in the previous two cases, marked increases in thrust are also achieved as the degree of mixing reaches 66.6% of the available fuel and air. However, unlike the previous cases, almost all of the equilibrium-combustion-model thrust is realized at this point. For the constant area combustor, the FRC thrust increases to 95.27% of the equilibrium-combustion-model thrust as compared to 90.33% for the Mach 15 case. The FRC thrust of the greatest-expanded-exit-area combustor is significantly higher than the Mach 15 case, 101.58%, as compared to 96.36%. Notice that the greatest-expanded-exit-area combustor thrust is already greater than the equilibrium-combustion-model thrust.

The reason that the combustion rate is so much greater after only 66.6% of the fuel and air is mixed for the Mach 18 flight condition ties in with the same reasons for the accelerated rates of combustion after only 33.3% mixing, higher temperatures. At the Mach 18 flight condition, the temperature in the constant area combustor is already 2689K by the time the flow has proceeded 2 m down the length of the combustor. Of course, this length corresponds to 66.6% mixing of the fuel and air. Compare this temperature to the temperature in the constant area

combustor operating at Mach 15 flight conditions and one will see that the combustor operating at the Mach 18 flight conditions has a temperature 4% greater than the temperature of the combustor operating at Mach 15 flight conditions.

Finally, as before, when the fuel and air are completely mixed, there is a slight improvement in the overall thrust. For this flight condition, the constant area combustor thrust increases to 96.67% of the equilibrium-combustion-model thrust and the greatest-expanded-exit-area combustor thrust increases to 102.79% of the equilibrium-combustion-model thrust. Based on the analysis of the results for this flight speed, one can conclude that because of the higher initial temperatures of the incoming air, a large degree of mixing is not necessary to achieve a significant amount of thrust for the Mach 18 flight condition.

As with the Mach 12 flight conditions, the Mach 18 flight condition exhibits the same characteristics as the Mach 15 flight condition. Again, both Mach 15 and Mach 18 flight conditions have thrust increases when the combustor exit area is increased. However, for the same degree of mixing, the Mach 18 flight conditions cause the fuel and air to react more quickly than the Mach 15 flight conditions. As with the Mach 12 and Mach 15 flight conditions, the overall thrust between the Mach 15 and Mach 18 flight conditions is different. However, for the Mach 15 and Mach 18 flight conditions, the overall thrust of the Mach 15 flight condition is 56% greater than the Mach 18 flight condition thrust.

As with the Mach 12 flight condition, the difference in thrust between the Mach 18 flight condition and the Mach 15 flight condition is easily explained with the stream thrust equation (Eq. 46), the overall thrust equation (Eq. 48), and the initial flight velocities given in Table 2. For the Mach 18 flight condition, the velocity at the nozzle exit is 5830 m/s and the free stream velocity is 5796 m/s. Therefore, the overall flow velocity increase for the Mach 18 flight condition is 34 m/s. As shown previously, the overall velocity increase for the Mach 15 flight

condition is 152 m/s. The ratio of these two velocities is 0.22. Therefore, only 40% of the thrust difference between the Mach 18 and Mach 15 flight conditions is from the reduced ability of the combustor to increase the incoming flow's velocity when the vehicle is operating at Mach 18 flight conditions. The remaining 60% is from the pressure difference between the nozzle the free stream flow.

Table 10 - Combustor Dimensions Examined

Case	Combustor Length (m)	Combustor Exit Area (m^2)	Case	Combustor Length (m)	Combustor Exit Area (m^2)
1	1	0.031540	16	1	0.047474
2	2	0.031540	17	2	0.047474
3	3	0.031540	18	3	0.047474
4	4	0.031540	19	4	0.047474
5	5	0.031540	20	5	0.047474
6	1	0.0365319	21	1	0.053403
7	2	0.0365319	22	2	0.053403
8	3	0.0365319	23	3	0.053403
9	4	0.0365319	24	4	0.053403
10	5	0.0365319	25	5	0.053403
11	1	0.0418487			
12	2	0.0418487			
13	3	0.0418487			
14	4	0.0418487			
15	5	0.0418487			

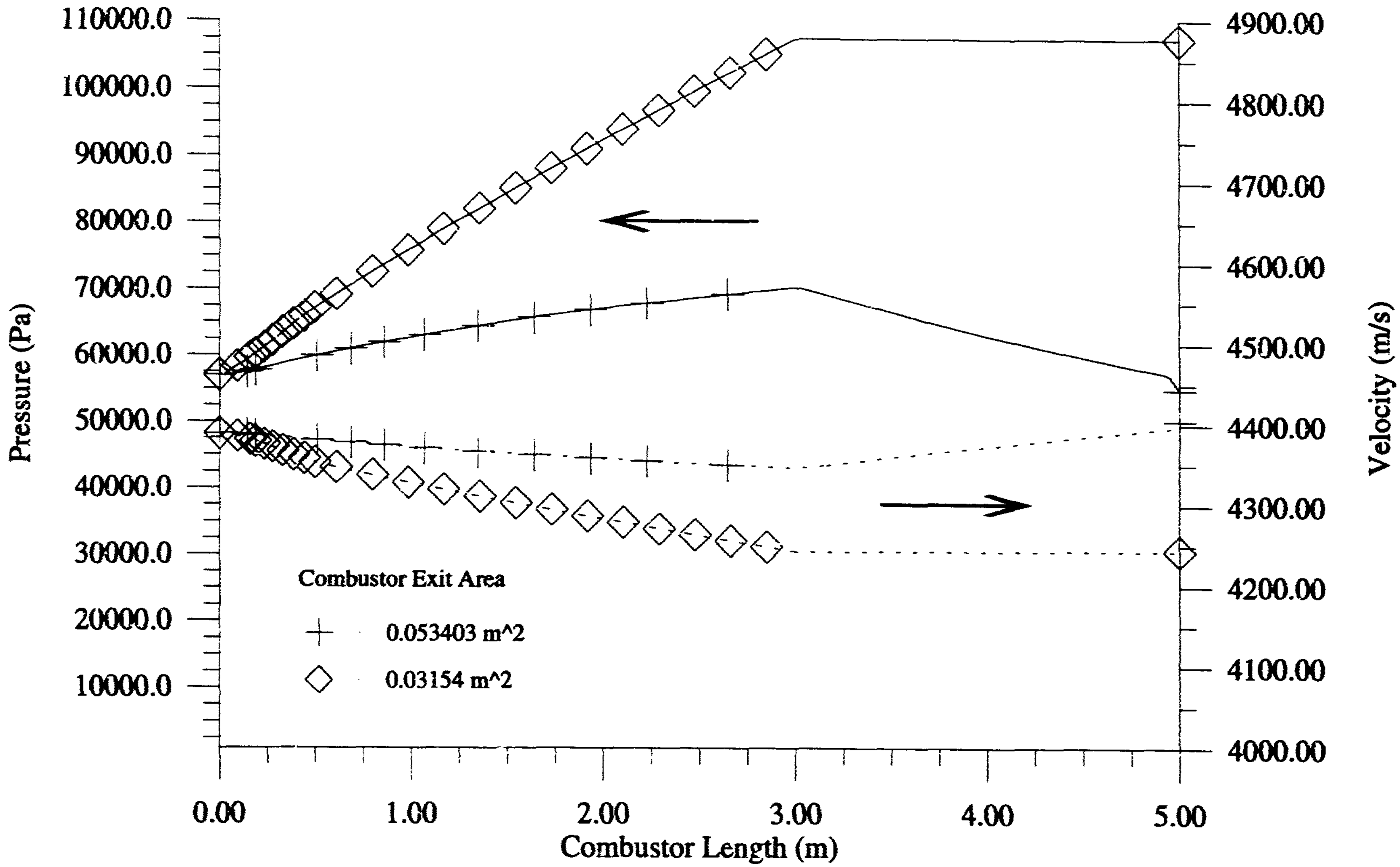


Figure 16 Internal Combustor Pressure and Velocity vs. Combustor Length
Mach 15 Flight Conditions

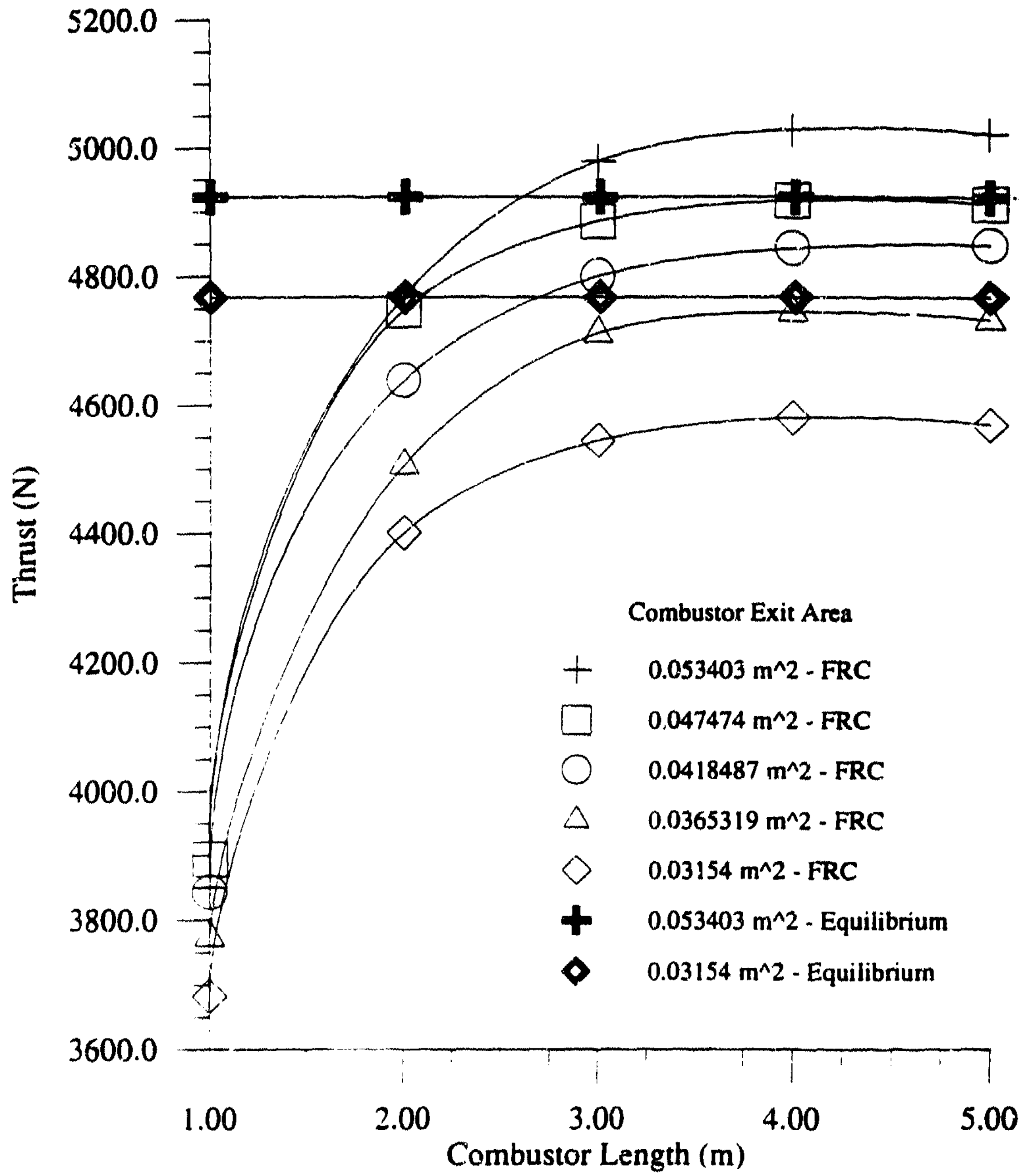


Figure 17 - Thrust vs. Combustor Length
Reacting Flow in Inlet and Combustor, Frozen Flow in Nozzle
Mach 15 Flight Conditions

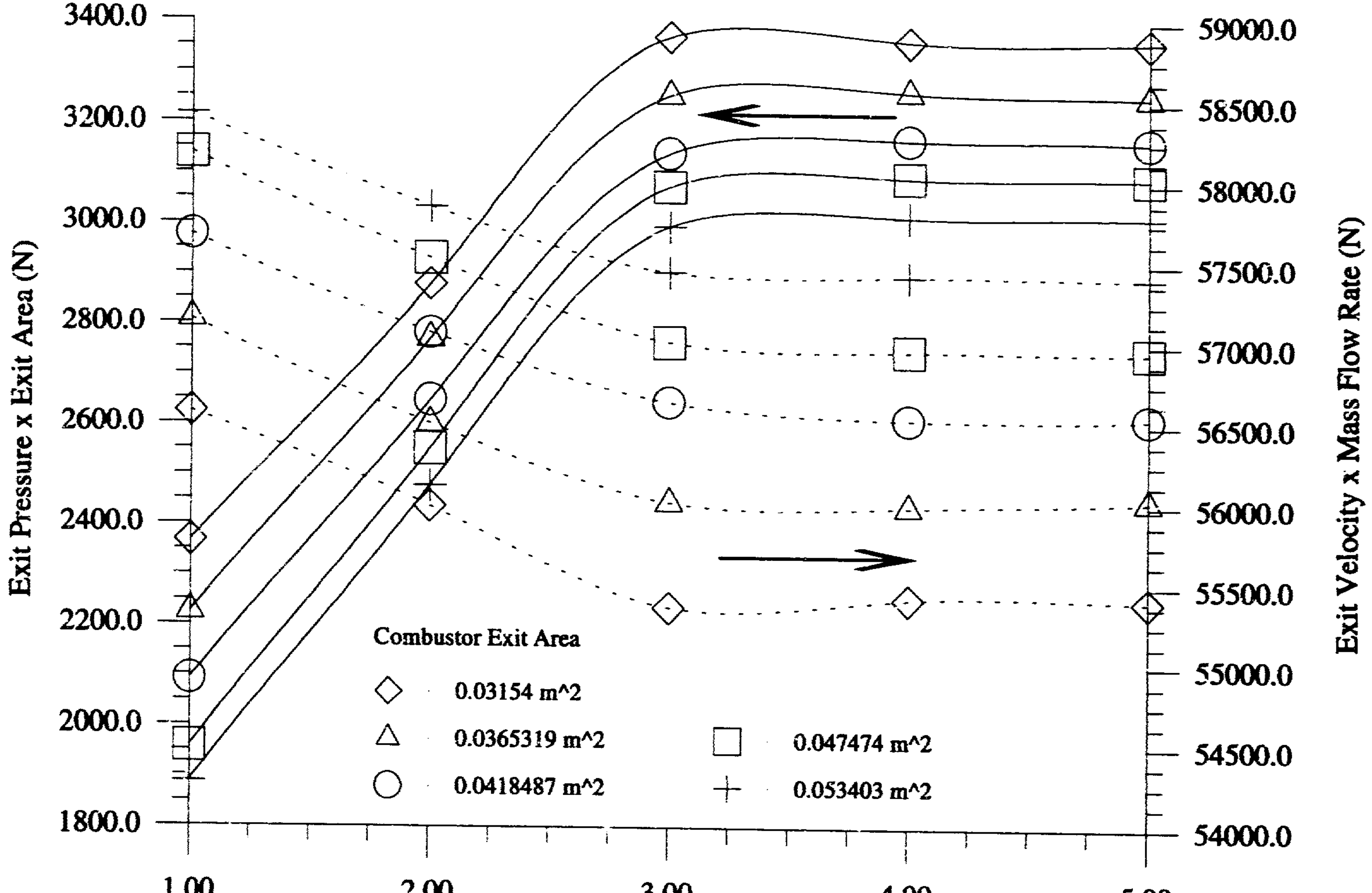


Figure 18 - Combustor Exit Stream Thrust Components vs. Combustor Length
Mach 15 Flight Conditions

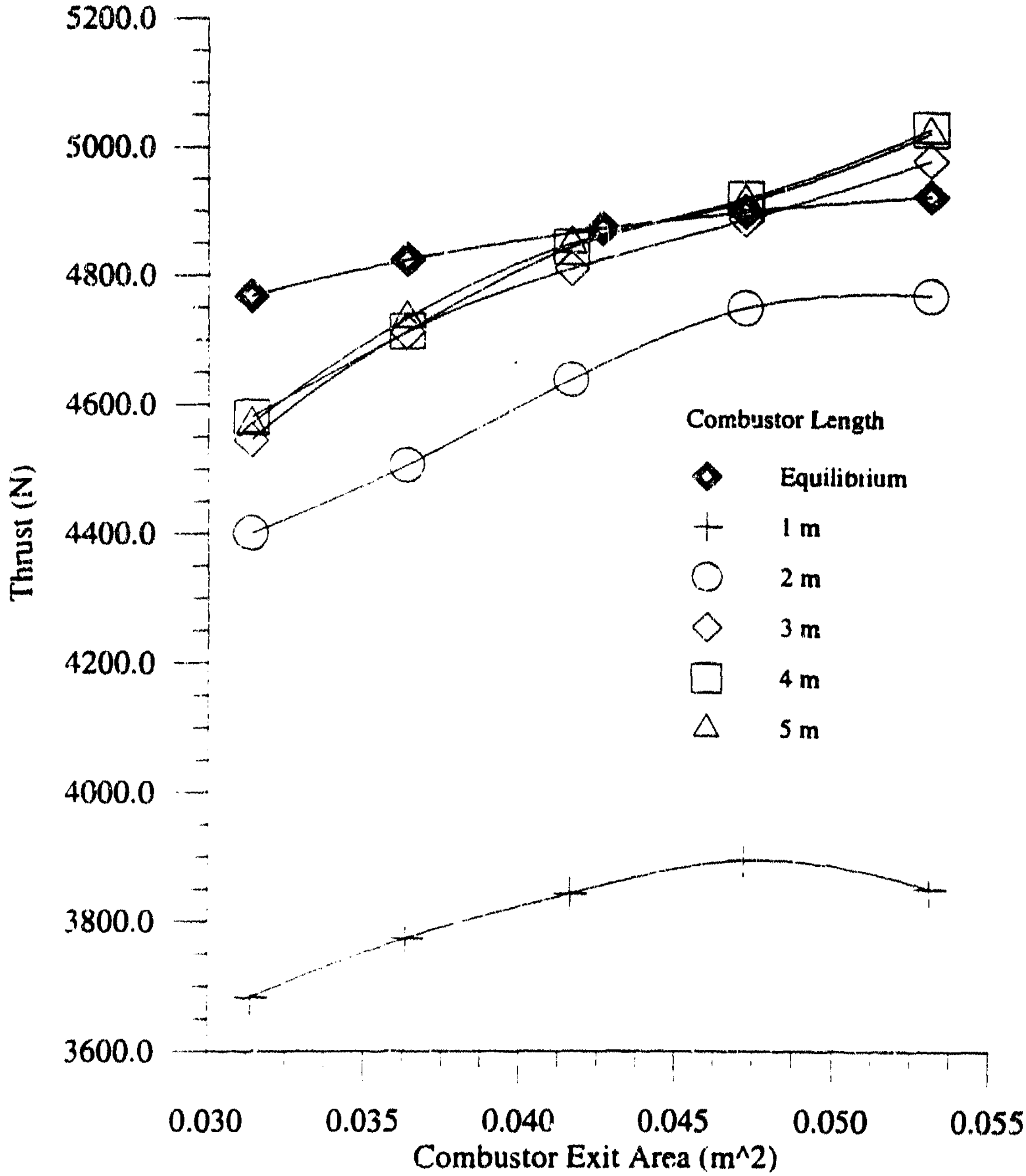


Figure 19 - Thrust vs. Combustor Exit Area
Reacting Flow in Inlet and Combustor, Frozen Flow in Nozzle
Mach 15 Flight Conditions

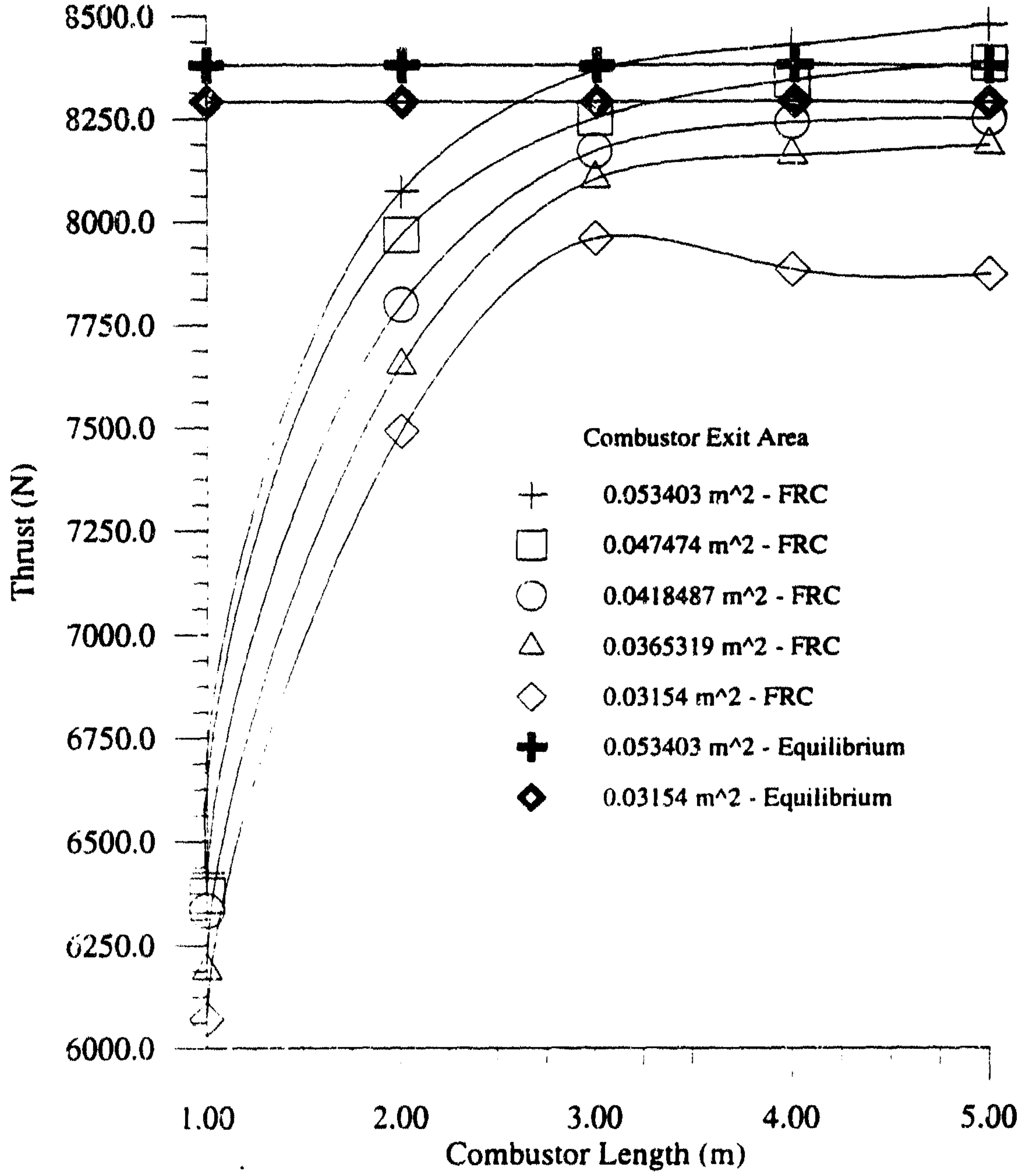


Figure 20 - Thrust vs. Combustor Length
Reacting Flow in Inlet and Combustor, Frozen Flow in Nozzle
Mach 12 Flight Conditions

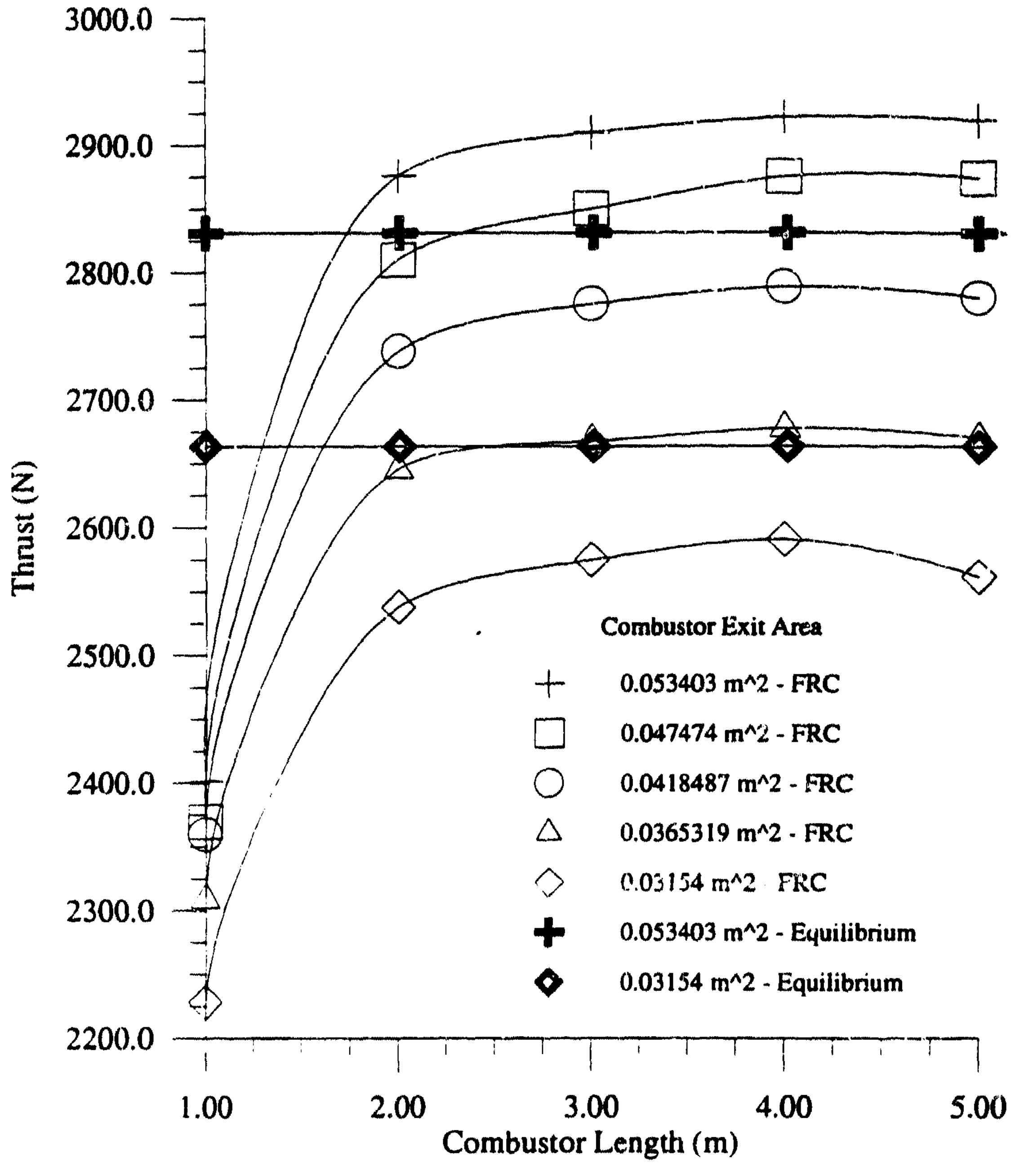


Figure 21 - Thrust vs. Combustor Length
Reacting Flow in Inlet and Combustor, Frozen Flow in Nozzle
Mach 18 Flight Conditions

Chapter 6 - Conclusions/Recommendations

6.1. - Conclusions

The overall comparison of the results for the FRC-combustion-model to the equilibrium-combustion-model has revealed a number of short comings in the equilibrium-combustion-model results. The equilibrium-combustion-model ignores the effects a mixing schedule has on the amount of thrust a Scramjet engine can produce. However, the FRC-combustion-model results from this study indicate that for an inviscid flow, without heat transfer between the individual streams or the surroundings, a significant amount of thrust can be achieved without large degrees of mixing. The results of this study indicate that the additional combustor length required to achieve 100 % mixing produces only marginal thrust increases. However, one must be careful not to overlook the fact that this study only considered an adiabatic, inviscid flow. Once the losses from friction and heat transfer are considered, the additional length required for complete mixing may be the difference between a net positive thrust and no thrust at all.

The equilibrium-combustion-model also ignores the effects of entropy rise brought about by the mixing of the fuel and air and the continued reaction of the gases once the fuel and air are completely mixed. The entropy rise from mixing and the continued reactions manifests itself in three ways. First, it allows the expanding area combustor to achieve a thrust greater than the equilibrium-combustion-model thrust for the same combustor area ratio. This implies that the equilibrium-combustion-model underestimates the thrust for an expanding area combustor in which complete mixing has occurred. Second, regardless of how long a flow element modeled by the FRC-combustion-model is allowed to react, the entropy from mixing and the continuous reactions, prevent the flow element

from ever achieving the same fully-reacted values as an element modeled by the equilibrium-combustion-model. This implies that the constant area combustor will never be able to achieve the equilibrium-combustion-model thrust. Finally, the entropy rise from continued reactions causes the thrust to decrease for increasingly longer combustors once complete mixing has been achieved. This implies that there is a critical length for a given combustor exit area, past which the thrust decreases rather than increases. Therefore, there is a loss mechanism present in a finite-rate reacting flow even though the flow is adiabatic and inviscid. This manifestation is particularly evident in the constant area combustors investigated at the Mach 12 flight condition.

The equilibrium-combustion-model also ignores the effects rapid expansion of the gases in the combustor has on the rate of combustion. Although the results of this study indicate that a combustor with an exit area greater than its entrance area produces larger amounts of thrust than a constant area combustor, excessively rapid expansion of the gases in the combustor causes the reaction rates to slow down, thereby reducing the overall thrust. This implies that there is a critical exit area for a given combustor length past which, the thrust decreases rather than increases. This manifestation is particularly evident in the short combustors with incomplete mixing and large exit areas relative to their entrance areas.

6.2. - Recommendations

With the completion of this project a tool has been developed which provides a complete one-dimensional cycle analysis of the Scramjet engine. This program is one of the first computer codes to offer the realism of finite-rate-chemistry combustion without the overhead of mainframe computers. In other words, this program fills the gap between the simple one-dimensional equilibrium-

combustion-models and the very complex multi-dimensional Navier-Stokes models.

The full capabilities of RJPA-FRC have barely been tapped by this study. Investigations to include heat transfer, skin friction, complex area schedules, non-linear mixing schedules, and other fuels are all possibilities for future study.

Currently the FRC combustor can only accept an area schedule for geometric input. Future versions of the program may allow a pressure schedule to be used as the input and the program will determine the required area schedule to produce the desired pressure schedule. Another future option may be that the program will produce an area or pressure schedule for a specified Crocco index.

List of References

Anderson, J.D. Jr. Introduction to Flight. New York: McGraw - Hill, 1985.

Anderson, J.D. Hypersonic and High Temperature Gas Dynamics. New York: McGraw-Hill, 1989.

Angelucci, E. Rand McNally Encyclopedia of Military Aircraft. New York: Crescent Books, 1990.

Askeland, D.R. The Science and Engineering of Materials. Boston, MA.: PWS-Kent Publishing Company, 1984.

Barthelemy, Robert R. "The National Aerospace Plane Program: A Revolutionary Concept" APL Technical Review, Vol. 2, No. 1, 1990.

Billig, F.S. "Design of Supersonic Combustors Based on Pressure-Area Fields", Proceedings of the Eleventh Symposium on Combustion, The Combustion Institute, Pittsburgh, PA., pp. 755-769, 1967.

Billig, F.S., Orth, R.C., and Lasky, M. "Effects of Thermal Compression on the Performance Estimates of Hypersonic Ramjets", Journal of Spacecraft and Rockets, Vol. 5, No. 9, pp. 1076-1081, 1968.

Billig, F.S. and Van Wie, D.M. "Efficiency Parameters for Inlets Operating at Hypersonic Speeds", 1987 International Society of Air-Breathing Engines Meeting, Cincinnati, OH.

Billig, F.S., Corda, S., Stockbridge, R.D. "Combustor-Inlet Interaction in Scramjet Engines" APL Technical Review, Vol. 2, No. 1, 1990.

Bray, K.N.C. "Atomic Recombination in a Hypersonic Wind-Tunnel Nozzle", Journal of Fluid Mechanics, Vol. 6, Part 1, p.1, 1959.

Bricker, A., Numbers, K., and Hoover, R. "Optimization of Geometrically Limited Hypersonic Air-Breathing Cruise Missiles" AIAA-89-2353, July 1989.

Byron, S.N. "Measurement of the Rate of Dissociation of Oxygen", Journal of Chemistry and Physics, Vol. 30, No. 6, p. 1380, 1959.

Crocco, L. One Dimensional Treatment of Steady Gas Dynamics", Fundamentals of Gas Dynamics, Volume 3 of High Speed Aerodynamics and Jet Propulsion, Princeton, NJ: Princeton University Press, 1958.

Cruise, D.R., "Notes on Rapid Computation of Chemical Equilibria," Journal of Physics and Chemistry, Vol. 68, No. 12, pp. 3797-3802, 1964.

Curran, E.T. and Bergsten, M.B. "Inlet Efficiency Parameters for Supersonic Combustion Ramjet Engines", Air Force Aero-propulsion Laboratory, Air Force Systems Command, Wright-Patterson AFB. OH, TDR64-61, 1964.

Curran, E.T., Leingang, J.L., Carreiro, L.R., and Petters, D.P. "Further Studies of Kinetic Methods in High Speed Ramjet Cycle Analysis", AIAA 92-3805, 28th Joint Propulsion Conference and Exhibit, 1992.

Dreil, I.L. and Belles F.E. "Survey of Hydrocarbon Combustion Properties", NACA Report No. 1383.

Dunn, M.G. and Kang, S.W. "Theoretical and Experimental Studies of Reentry Plasmas", NASA CR-2232, 1973.

Evans, P.J., Jr. "Analytical Investigation of Ramjet Engine Performance in Flight Mach Number Range From 3 to 7", NACA RM E51H02, 1951.

Hill, P.G. and Peterson, C.B. Mechanics and Thermodynamics of Propulsion, Second Edition. Reading, MA.: Addison-Wessley Publishing, 1992.

Houck, S.W., Hoffman, J.D., Thompson, H.D. "3STREAM: An Engineering Tool for Modeling Complex Combustion Processes; Volume I and II " NASP Contractor Report 1093, 1990.

Jachimowski, C.J. "An Analytical Study of the Hydrogen-Air Reaction Mechanism With Application to Scramjet Combustion", NASA Technical Paper 2791, 1988.

Jane's All of the World's Aircraft 1989-90. London: Paulton House, 1990.

Leingang, J. Former Chief of Analysis and Applications Branch, Wright Laboratory-Aero Propulsion and Power Directorate, Wright-Patterson AFB, OH. Personal Interview, 18 September 1993.

Lee, C.C. and Boedicker, C. "Subsonic Diffuser Design and Performance for Advanced Fighter Aircraft", AIAA 83-0175, 1983.

Mattingly, J.D., Heiser, W.H., and Daley, D.H. Aircraft Engine Design, AIAA Education Series, Washington, DC, 1987.

McClinton, C.R., Torrence, M.G., Gooderum, P.B., and Young, I.G. "Non reactive Mixing Study of Scramjet Swept-Strut Fuel Injectors", NASA Technical Note D-8069, 1975.

Molder, S. "Intakes for Hypersonic Ramjets" McGill University Report 62-6, McGill University, Montreal, Quebec, Canada, 1962.

NASA Ames Research Center. "Equations, Tables, and Charts for Compressible Flow - NACA Report 1135" AMTEC Engineering INC. Bellevue, WA.

Northam, G.B. and Anderson, G.Y. "Supersonic Combustion Ramjet Research at Langley", AIAA Paper 86-0159, 1986.

Pandolfini, P. "Instructions for Using Ramjet Performance Analysis (RJPA)" - IBM-PC Version 1.0, JHU/APL NASP 86-2, Johns Hopkins University-Applied Physics Laboratory, 1986.

Raymer, D.P. Aircraft Design: A Conceptual Approach, AIAA Education Series, Washington, DC, 1989.

Segal, Bernice G. Chemistry: Experiment and Theory, New York: Wiley and Sons, 1985.

Seddon, J. and Goldsmith, E.L. Intake Aerodynamics, AIAA Education Series. Washington, D.C., 1985.

Smith, J. "H2SCRAM User's Manual" Advanced Propulsion Division-Wright Laboratory, Wright-Patterson AFB, OH. 1987.

Vincenti, W.G. and Kruger, C.H., Jr. Introduction to Physical Gas Dynamics. Malabar, FL: Robert E. Kreiger Publishing Company, 1965.

Walton, J.T. "An Overview of Airframe Integrated Scramjet Cycle Components and Flow Features" NASP Technical Memorandum 1029, 1988.

Waltup, P.J. "Engine Sizing and Integration Requirements for Hypersonic Air-breathing Missile Applications", Applied Physics Lab, Johns Hopkins University, Laurel, MD, 1981.

White, F.M. Viscous Fluid Flow - Second Edition. New York: McGraw - Hill, 1991.

Wittliff, C.E. "A Survey of Hypersonic Ground Test Facilities-North America", Aerodynamics of Hypersonic Lifting Vehicles Conference Proceedings, AD-A198-665, pp. 1-1 through 1-17, 1987.

Wray, K.L. and Teare, J.D. "Shock Tube Study of the Kinetics of Nitric Oxide at High Temperatures", Journal of Chemistry and Physics, Vol. 36, No. 10, p. 2582, 1962.

Zucrow, M. J. and Hoffman, J.D. Gas Dynamics Volume 1. New York: Wiley and Sons, 1976.

Appendix A - Input Variable Description

A.1 - Introduction

The following is a list of the variables used in the program RJPA-FRC. Many of the variables used in RJPA-FRC retain their original function from the programs RJPA and 3STREAM. Therefore, only the new, or redefined variables in RJPA-FRC are described below.

Each of the variables is followed by several pieces of descriptive information. The label (RJPA), (3STREAM), or (NEW) following each of the listed variables indicates the location of the variable's description. For example, the description of a variable followed by the label (RJPA) is found in Pandolfini, 1986. Likewise, the description of a variable followed by the label (3STREAM) is found in Houck et al., 1990. The description of a variables followed by the label (NEW) is contained in this text. Several variables used in RJPA are also used in 3STREAM, but have different names. The RJPA name for these variables has been retained in RJPA-FRC. The original 3STREAM name of these variables is listed along with the new RJPA-FRC name. Each variable is also followed by a label indicating the units associated with it. The units for each variable is listed in the following order: FPS, CGS, and SI.

Three sample input files are provided on the following pages. These sample files illustrate input configurations for an equilibrium combustor, a Northam/ Anderson mixing schedule, and a tabular mixing schedule. On the pages following the sample input files is a description of the input protocol for each namelist field and the variables associated with the namelist.

One final sample input file is provided after the namelist description to illustrate the use of the chemical reaction input file. Following the sample chemical reaction input file is a description of the input protocol for the reactions.

A.2 - Sample Input Files

SAMPLE INPUT FILE FOR EQUILIBRIUM COMBUSTION

```
SCRAMJET CASE EQ6-8, MACH 15.0, Z= 39272 M, NO FROZEN H2,
CROCCO =1.0
 EJANAF.DAT
 5,1, 1, 1, 1, 1 /
 3, 1.000000,    0.0,  2.0, 'H  ' /
 0, 0.013250,    0.0,  1.0, 'A  ' /
 0, 0.231460,    0.0,  2.0, 'O  ' /
 0, 0.755290     0.0,  2.0, 'N  ' /
 2.016 /
 14, 1,288,300,304,310,350,351,352,381,767,810,1271,1272,1273 /

 &FRSTR
  UNITS=SI, INIT=1, PAR=15, Z=39272.0, TEMP=249.05,
  PITI=0,AREF=0.6, AISS=0.6, AIGG=0.0, WOFIN0=1.E11  &END

 &DIFFUSER
  DIFF=1, PAR1=0.030, EFF=0.976, HEAT=1, QDIFF=342829.14,
  PITD=0, GAMG1=1.2, GAMG2=1.3, SWT=0.5 &END

 &SHCK SHK=0, BET=90.0, DEL=0.0, PITS=0 &END

 &COMBUSTOR
  COMB=1, ICOMB=0, ACE=0.03154, AWALL=0.64516
  PCEG1=0.00, PCEG2=0.C0, PITC=0, PSPCI=1.0000 &END

 &HEATFRICTION CF=0.0, QWALL=0.0 &END

 &MIXER FSR=0.029164, WOFIN=34.288849,XI=1.0 &END

 &OXIDIZER ACI= 0.030, BETA=0.0 &END

 &FUEL  AGG=0.0015, ALPHA=0.0, HGG=1.039599187E7, MWGG=2.016,
  NCFIN=1, RHOGG=0.422572E-1, TGG=935, UGG=5.79221924E3 &END

 &PRODUCTS ABASE=0.00004, PBASE=.516746E5 &END

 &NOZZLE EXP=1, EFFN=0.9740, J22=2, PEX=0.6, PITN=0,
  RATIOFE=0.6667  &END
```

SAMPLE INPUT FILE FOR NORTHAM/ANDERSON MIXING SCHED

```
Scramjet Case FRC15na, Mach 15.0, Z= 39272, No Frozen H2, Crocco =1.0
EJANAF.DAT
5, 1, 1, 1, 1, 1 /
3, 1.000000,   0.0,  2.0, 'H  ' /
0, 0.013250,   0.0,  1.0, 'A  ' /
0, 0.231460,   0.0,  2.0, 'O  ' /
0, 0.755290    0.0,  2.0, 'N  ' /
2.016 /
14, 1,288,300,304,310,350,351,352,381,767,810,1271,1272,1273 /

&FRSTR
 INIT=1, UNITS=SI, PAR=15, Z=39272,TEMP=249.05, PITI=0,
 AREF=0.6, AISS=0.6, AIGG=0.0, WOFIN0=1.E11, &END

&DIFFUSER
 DIFF=1, PAR1=0.03, EFF=0.976, HEAT=1, QDIFF=342829.1400, PITD=0,
 GAMG1=1.2, GAMG2=1.3, SWT=0.5 &END

&SHCK   SHK=0, BET=90.0, DEL=0.0, PITS=0 &END

&COMBUSTOR   COMB=6, iCOMB=0, FRC= 'CHEM15',
 ISPLINE=2, NOUT=1, ARTOL=1E-6, EMAX=1.0E-3,ATOLSP=1.0E-12,
 XATB=0.0,   0.001,  40.0,   800.00,  AATB=0.03151, 0.03151, 0.03151,
 0.03151, NATB=4,  MAXSTP=32000, PRINT=100.00, NPRNTS=1, &END

&HEATFRICTION  &END

&MIXER  MX=1, IWOFER=1, WOFIN=34.288849, FSR=0.029164, DHI=0.05,
GAPSI=60, &END

&OXIDIZER  BETA=0.0, DPODX=-4.053E5, INERTO='ar' &END

&FUEL    AGG=0.0015, TGG=935.0, MACHF=2.5, PGG=0.164066E6,
 DPFDX=-4.053E5, alpha=0.0 &END

&PRODUCTS   ALLM1P=F, ABASE=0.00001, TPP=1853.33,
 MACHP=5.22732, INERTP='ar',  PBASE=.516746e5, DPPDX=-4.053E5 &END

&NOZZLE
 EXP=1, EFFN=0.9740, J22=2, PEX=0.6, PITN=0, RATIOFE=0.6667 &END
```

SAMPLE INPUT FILE FOR TABULAR MIXING SCHEDULE

```
SCRAMJET CASE FRC15L33, MACH 15.0, Z= 39272, NO FROZEN H2
EJANAF.DAT
5, 1, 1, 1, 1, 1 /
3, 1.000000,    0.0,  2.0, 'H  ' /
0, 0.013250,    0.0,  1.0, 'A  ' /
0, 0.231460,    0.0,  2.0, 'O  ' /
0, 0.755290     0.0,  2.0, 'N  ' /
2.016 /
14, 1,288,300,304,310,350,351,352,381,767,810,1271,1272,1273 /
&FRSTR
 INIT=1, UNITS=SI, PAR=15, Z=39272,TEMP=249.05, PITI=0,
 AREF=0.6, AISS=0.6, AIGG=0.0, WOFIN0=1.E11, &END

&DIFFUSER  DIFF=1, PAR1=0.03, EFF=0.976, HEAT=1, QDIFF=342829.14,
PITD=0,  GAMG1=1.2, GAMG2=1.3, SWT=0.5 &END

&SHCK SHK=0, BET=90.0, DEL=0.0, PITS=0 &END

&COMBUSTOR  COMB=6, ICOMB=0, FRC= 'CHEM15',
 ISPLINE=2, NOUT=1, ARTOL=1E-8,EMAX=1.0E-1,ATOLSP=1.0E-10,
 XATB=0.0,    0.001,  40.0,    800.00,  AATB=0.03154, 0.03154, 0.03154,
 0.03154, NATB=4,  MAXSTP=32000, PRINT=3.00,  NPRNTS=1, &END

&HEATFRICTION  &END

&MIXER  MX=3,IWOFER=1, FSR=0.029164,
 NAA=4,  XDA= 0.0, 3.0, 100.0, 800.0, DAA=0.0, 1.0, 1.0, 1.0,
 NFF=4,  XDF= 0.0, 3.0, 100.0, 800.0, DFF=0.0, 1.0, 1.0, 1.0,  &END

&OXIDIZER  BETA=0.0, DPODX=-4.053E5, INERTO='AR' &END

&FUEL  AGG=0.0015, TGG=935.0, MACHF=2.5, PGG=0.164066E6,
 DPFDX=-4.053E5, ALPHA=0.0 &END

&PRODUCTS  ALLM1P=F, ABASE=0.00004, TPP=1853.33,
MACHP=5.22732, INERTP='AR',  PBASE=.516746E5, DPPDX=-4.053E5
&END

&NOZZLE  EXP=1, EFFN=0.9740, J22=2, PEX=0.6, PITN=0,
RATIOFE=0.6667 &END
```

A.3 - RJPA-FRC Input File Description

This first section is in a list directed read format. Examples of how to use the variables located in the following two sections are provided in the three sample input files located at the front of this appendix.

Section 1

Two heading lines

HEAD 1 (RJPA)

HEAD 2 (RJPA)

Location of the Thermochemical Data File

FILE13 (RJPA)

Fuel/Air Specification I.

L2 (RJPA)

JJ (RJPA)

Fuel/Air Specification II.

KFUEL (RJPA)

WT(L) (RJPA)

ENTH(L) (RJPA) same units for all systems (cal/gm-mole)

X(J) (RJPA)

D(J) (RJPA)

Fuel/Air Specification III.

ATW(34+I) (RJPA)

Product Species

N (RJPA)

KEY (RJPA)

Section II

This section is in a namelist directed format. To use the namelist format place the namelist symbol "&" in column 2, followed by the name of the namelist. On the next line enter the namelist variables that need to be initialized. End the namelist with namelist symbol "&" followed by the word "END"

Namelist FRST

Namelist FRST contains the variables describing the free stream conditions. Examples of how to use the variables located in this namelist are provided in the three sample input files located at the front of this appendix.

INIT	(RJPA)	
PAR	(RJPA)	(ft/s), (cm/s), (m/s)
Z	(RJPA)	(ft), (cm), (m) or (psia), (atm), (Pa) or Mach number
TEMP	(RJPA)	(R), (K), (K)
PITI	(RJPA)	
AREF	(RJPA)	(in^2), (cm^2), (m^2)
AIGG	(RJPA)	(in^2), (cm^2), (m^2)
AISS	(RJPA)	(in^2), (cm^2), (m^2)
WOFINO	(RJPA)	
UNITS	(NEW)	determines the units system used, input is 'FPS', 'CGS', or 'SI'

Namelist DIFFUSER

Namelist DIFFUSER contains the variables describing the diffuser. Examples of how to use the variables located in this namelist are provided in the three sample input files located at the front of this appendix.

DIFF	(RJPA)	
PAR1	(RJPA)	(in^2), (cm^2), (m^2) or (psia), (atm), (Pa) or Mach number
EFF	(RJPA)	
HEAT	(RJPA)	
QDIFF	(RJPA)	(Btu/lbm), (Cal/gm), (J/Kg)
PITD	(RJPA)	
GAMG1	(RJPA)	
GAMG2	(RJPA)	
SWT	(RJPA)	

Namelist SHCK

Namelist SHCK contains the variables describing the shock at the end of the diffuser. Examples of how to use the variables located in this namelist are provided in the three sample input files located at the front of this appendix.

SHK (RJPA)

BET (RJPA)

DEL (RJPA)

PITS (RJPA)

Namelist COMBUSTOR

Namelist COMBUSTOR contains the variables describing the combustor geometry.

The following variables are used for all cases. Examples of how to use these variables are provided in the three sample input files located at the front of this appendix.

COMB	(RJPA)	option 6 selects the FRC combustion model
ICOMB	(RJPA)	must be set to 0 when COMB = 6

The following variables are used exclusively if COMB = 1-5. An example of how to use these variables is provided in the sample input file for equilibrium combustion located at the front of this appendix.

ACE	(RJPA)	(in^2), (cm^2), (m^2)
AWALL	(RJPA)	(in^2), (cm^2), (m^2)
NCFIN	(RJPA)	formerly NCF
PCEG1	(RJPA)	(psia), (atm), (Pa)
PCEG2	(RJPA)	(psia), (atm), (Pa)
PITC	(RJPA)	
PSPCI	(RJPA)	

The following variables are used exclusively if COMB =6. Examples of how to use these variables are provided in the sample input file for the Northam/Anderson mixing schedule and the tabular mixing schedule located at the front of this appendix.

FRC	(NEW)	a character string which names the chemical reaction file to be used.
ISTREAM	(3STREAM)	
ARTOL	(3STREAM)	
ISPLINE	(3STREAM)	
AX0	(3STREAM)	(in^2), (cm^2), (m^2)
AX1	(3STREAM)	(in), (cm), (m)
AX2	(3STREAM)	
AX3	(3STREAM)	(in^{-1}), (cm^{-1}), (m^{-1})
NATB	(3STREAM)	
XATB	(3STREAM)	(in), (cm), (m)
AATB	(3STREAM)	(in^2), (cm^2), (m^2)
EMAX	(3STREAM)	
EXCHR	(3STREAM)	
MAXSTP	(3STREAM)	
ATOLSP	(3STREAM)	
NPRINTS	(3STREAM)	
PRINT	(3STREAM)	(in), (cm), (m)
MF	(3STREAM)	
PNORM	(3STREAM)	(psia), (atm), (Pa)

DJ	(3STREAM)
NOUT	(3STREAM)

Namelist HEATFRICTION

Namelist HEATFRICTION contains the variables describing the heat transfer and friction processes.

The following variables are used exclusively if COMB = 1-5. An example of how to use these variables is provided in the sample input file for equilibrium combustion located at the front of this appendix.

CF	(RJPA)
QWALL	(RJPA) (Btu/s), (erg/s), (W)

The following variables are used exclusively if COMB = 6. Examples of how to use these variables are provided in the sample input file for the Northam/Anderson mixing schedule and the tabular mixing schedule located at the front of this appendix.

IENV1, IENV2, IENV3	(3STREAM)
IQST1, IQST2	(3STREAM)
NHC1, NHC2, NHC3, NHC4, NHC5	(3STREAM)
XH1, XH2, XH3, XH4, XH5	(3STREAM) (R), (K), (K)
HC1, HC2, HC3, HC4, HC5	(3STREAM) {Btu/(in^2 s R)}, {erg/(cm^2 s K)}, {W/(m^2 K)}
ISKIN1, ISKIN2, ISKIN3	(3STREAM)
NCF1, NCF2, NCF3	(3STREAM)

XCF1, XCF2, XCF3	(3STREAM) (in), (cm),(m)
CF1, CF2, CF3	(3STREAM)
TWALL	(3STREAM) (R), (K), (K)

Namelist MIXER

Namelist MIXER describes the mixing process used.

The following variables are used for all cases. Examples of how to use the these variables are provided in the three sample input files located at the front of this appendix.

FSR	(RJPA) formerly STRATI in (3STREAM), use this variable when the equilibrium combustion model is selected and when MX = 1 in the FRC combustion model

The following variables are used exclusively if COMB = 1-5. An example of how to use the following variables is provided in the sample input file for equilibrium combustion located at the front of this appendix.

WOFIN	(RJPA)
XI	(RJPA)

The following variables are used exclusively if COMB = 6. Examples of how to use these variables are provided in the sample input files for the Northam/Anderson mixing schedule and the tabular mixing schedule located at the front of this appendix.

MX	(3STREAM)
PTOLI	(3STREAM) (psi-in^2), (atm-cm^2), (Pa-m^2)
ERRI	(3STREAM)

If MX = 1 the following variables are used. An example of how to use these variables is provided in the sample input file for the Northam/Anderson mixing schedule located at the front of this appendix.

IWOFIN	(NEW)	1 use WOFIN to specify equivalence ratio 0 use ER to specify equivalence ratio
ER	formerly STRATI (3STREAM)	
GAPSI	(3STREAM)	
DHI	(3STREAM) (in), (cm), (m)	

If MX = 2 the following variables are used. An example of how to use these variables is provided in the sample input file for the tabular mixing schedule located at the front of this appendix.

AAI	(3STREAM)
AFI	(3STREAM)
XLAI	(3STREAM) (in), (cm), (m)
XLAF	(3STREAM) (in), (cm), (m)

If MX = 3 the following variables are used.

NAA	(3STREAM)
NFF	(3STREAM)
XDA	(3STREAM) (in), (cm), (m)
XDF	(3STREAM) (in), (cm), (m)
DAA	(3STREAM)
DFF	(3STREAM)

Namelist OXIDIZER

Namelist OXIDIZER contains variables describing the conditions of the incoming oxidizer stream.

The following variables are used for all cases. Examples of how to use these variables are provided in the three sample input files located at the front of this appendix.

ACI	(RJPA)	(in^2), (cm^2), (m^2)
BETA	(RJPA)	formerly BETAAI (3STREAM)

The following variables are used exclusively if COMB =6. Examples of how to use these variables are provided in the sample input files for the Northam/Anderson mixing schedule and the tabular mixing schedule located at the front of this appendix.

ALLMIO	formerly ALLM1 (3STREAM)
DPODX	formerly CX1Z (3STREAM) (psia/in), (atm/cm), (Pa/m)
INERTO	(NEW) specifies the inert gases in the oxidizer stream. Lower case characters must be used.

Namelist FUEL

Namelist FUEL describes the incoming conditions of the fuel.

The following variables are used for all cases. Examples of how to use the these variables are provided in the three sample input files located at the front of this appendix.

AGG	(RJPA) formerly AREAZ (3STREAM) (in^2), (cm^2),(m^2)
ALPHA	(RJPA) formerly BETA1I if MX =1 (3STREAM) (Degrees) formerly BETAFI if MX =2 (3STREAM) (Degrees)
TGG	(RJPA) formerly TZ (3STREAM) (R), (K), (K)
UGG	(RJPA) formerly VZ (3STREAM) (ft/s), (cm/s), (m/s)

The following variables are used exclusively if COMB = 1 - 5. An example of how to use these variables is provided in the sample input file for equilibrium combustion located at the front of this appendix.

RHOGG	(RJPA) (lbm/ft^3), (gm/cm^3), (Kg/m^3)
MWGG	(RJPA)
HGG	(RJPA) (Btu/lbm), (Cal/gm), (J/Kg)

The following variables are used exclusively if COMB = 6. Examples of how to use these variables are provided in the sample input file for the Northam/Anderson mixing schedule and the tabular mixing schedule located at the front of this appendix.

PGG	formerly CX0Z (3STREAM) (psia), (atm), (Pa)
DPFDX	formerly CX1Z (3STREAM) (psia/in), (atm/cm), (Pa/m)
MACHF	formerly MACH (3STREAM) can be used in place of UGG
ALLM1F	formerly ALLM1 (3STREAM)
INERTF	(NEW) specifies the inert gases in the fuel stream. Lower case characters must be used.

Namelist PRODUCTS

These variables describe the initial conditions for the reaction products stream.

The following variables are used for all cases. Examples of how to use the these variables are provided in the three sample input files located at the front of this appendix.

ABASE	(RJPA)	(in^2), (cm^2), (m^2)
PBASE	(RJPA)	(psia), (atm), (Pa)

The following variables are used exclusively if COMB = 6. Examples of how to use these variables are provided in the sample input files for the Northam/Anderson mixing schedule and the tabular mixing schedule located at the front of this appendix.

TPP	formerly TZ (3STREAM) (R), (K), (K)
UGG	formerly VZ (3STREAM) (ft/s), (cm/s), (m/s)
MACHP	formerly MACH (3STREAM) can be used in place of UGG
DPPDX	formerly CX1Z (3STREAM) (psia/in), (atm/cm), (Pa/m)
ALM1P	(NEW) specifies the inert gases in the fuel stream. Lower case characters must be used.

Namelist NOZZLE

The following variables describe the exit nozzle. Examples of how to use these variables are provided in the three sample input files located at the front of this appendix.

EXP	(RJPA)	
EFFN	(RJPA)	
J22	(RJPA)	
PEX	(RJPA)	(in²), (cm²), (m²) or (psia), (atm), (Pa)
PITN	(RJPA)	
RATIOFE	(RJPA)	

A.4 - Sample Chemical Reaction File

```
  Stream 1 - air
   o       +  o       =  o2     +  m          6.0e+17   0.        -1800.
   o       +  no2     =  no     +  o2         1.0e+13   0.        600.
   m       +  no2     =  no     +  o          1.16e+16  0.        66000.
   n       +  o2      =  no     +  o          6.4e+9    1.        6300.
   n       +  n       =  n2     +  m          2.8e+17   -.75      0.
   n       +  no      =  n2     +  o          1.6e+13   0.        0.
END     ENTER THIRD BODY EFFICIENCIES FOR STREAM 1 BELOW THIS LINE
END     ENTER STREAM 2 REACTIONS BELOW THIS LINE
  Stream 2 - hydrogen
   h       +  h       =  h2     +  m          8.3e+17   -1.        0.
END     ENTER THIRD BODY EFFICIENCIES FOR STREAM 2 BELOW THIS LINE
END     ENTER INITIAL MOLE FRACTIONS OF STREAM 2 BELOW THIS LINE
h2        .99
h         .01
END     ENTER STREAM 3 REACTIONS BELOW THIS LINE
  Stream 3 hydrogen - air reaction
   h       +  o2      =  oh     +  o          2.6e+14   0.        16800.
   o       +  h2      =  oh     +  h          1.8e+10   1.        8900.
   h2      +  oh      =  h2o    +  h          2.2e+13   0.        5150.
   oh      +  oh      =  o      +  h2o        6.3e+12   0.        1090.
   h       +  o2      =  ho2    +  m          2.1e+15   0.        -1000.
   o       +  o       =  o2     +  m          6.0e+17   0.        -1800.
   h       +  h       =  h2     +  m          6.4e+17   -1.        0.
   h       +  oh      =  h2o    +  m          2.2e+22   -2.       0.
   m       +  h2o2    =2.0oh                  1.2e+17  0.         45500.
   h2      +  o2      =2.0oh                  1.70e+13 0.         48000.
   h       +  ho2     =  oh     +  oh         1.4e+14   0.        1080.
   o       +  ho2     =  oh     +  o2         1.5e+13   0.        950.
   oh      +  ho2     =  h2o    +  o2         8.0e+12   0.        0.
            2.0ho2    =  h2o2   +  o2         2.00e+12 0.         0.
   ho2     +  no      =  no2    +  oh         3.4e+12   0.        -260.
   o       +  no2     =  no     +  o2         1.0e+13    0.       600.
```

```
  m      +   no2    =   no     +   o           1.16e+16   0.      66000.
  no2    +   h      =   no     +   oh          3.5e+14    0.      1500.
  n      +   o2     =   no     +   o             6.4e+9   1.      6300.
  h      +   o      =   oh     +   m           6.0e+15   -.6      0.
  n      +   oh     =   no     +   h           6.3e+11    0.5     0.
  ho2    +   h      =   h2     +   o2          1.30e+13   0.      0.
  ho2    +   h      =   h2o    +   o           1.0e+13    0.      1080.
  h      +   h2o2   =   h2     +   ho2         1.4e+12    0.      3690.
  o      +   h2o2   =   oh     +   ho2         1.4e+13    0.      6400.
  oh     +   h2o2   =   h2o    +   ho2         6.1e+12    0.      1430.
  n      +   n      =   n2     +   m           2.8e+17   -.75     0.
  n      +   no     =   n2     +   o           1.6e+13    0.      0.
  h      +   no     =   hno    +   m           5.4e+15    0.      -600.
  h      +   hno    =   no     +   h2          4.8e+12    0.      0.
  o      +   hno    =   no     +   oh          5.0e+11     .50    0.
  oh     +   hno    =   no     +   h2o         3.6e+13    0.      0.
  ho2    +   hno    =   no     +   h2o2        2.0e+12    0.      0.
END      ENTER THIRD BODY EFFICIENCIES FOR STREAM 3 BELOW THIS LINE
  h      +   o2     =   ho2    +   m      h2         2.0
  same                                    h2o       16.0
  h          h      =   h2     +   m      h2         2.0
  same                                    h2o        6.0
  m      +   h2o2   =2.0oh                h2o       15.0
  h      +   oh     =   h2o    +   m      h2o        6.0
  h      +   o      =   oh     +   m      h2o        5.0
END      ENTER INITIAL MOLE FRACTIONS FOR STREAM 3 BELOW THIS LINE
ar         .009608
h          .0000001
no         .005233
no2        .000008
o          .000126
n2         .778215
o2         .206810
END      ENTER THE WORD "FINAL" BELOW THIS LINE
FINAL
```

A.5 - Detailed Input Description for the Chemical Reaction File

The following list is a detailed description of the chemical reaction file used by RJPA-FRC when COMB = 6. A sample file is given following the description.

1. The first line is the title or description of stream one - beginning in column 2, the input may be up to 80 characters long

2. After the title, the reaction mechanism is specified. It is suggested that an existing file be edited, rather than building one from scratch. However, if a file is to be created from scratch, the following format must be used:

column 1-3, the first reactant stoichiometric coefficient. If different from 1, it must be written in a fixed point format, not as an integer.

column 4-11, the first reactant symbol. All substance symbols must be in lower case letters.

column 12, a plus "+" sign.

column 13-15, the second reactant stoichiometric coefficient.

column 16-24, the second reactant symbol.

column 25, the equals "=" sign.

column 26-28, the first product stoichiometric coefficient.

column 29-36, the first product symbol.

column 37, the plus "+" sign.

column 38-40, the second product stoichiometric coefficient.

column 41-49, the second product symbol.

column 50-52, place the letter "S" here if the second of the following equations is used.

column 53-62, 63-72, 73-80, the value of the constants A, n, and E in the Arrhenius equation of the form

$$k_r = A_r T^{n_r} e^{-\frac{E_r}{RT}}$$

or the values of the constants A, n, and c in the Arrhenius equation of the form

$$k_r = A_r T^{n_r} e^{c_r T}$$

Up to 150 reaction mechanism may be specified, of which, up to 35 may be third body reactions. As many as 50 species may be used.

3. The word "END" is placed in column 1 on the line below the last reaction.

4. Any third body efficiencies are placed on next the line. The third body efficiencies are entered using the same format as the chemical reactions except that in column 52-57, the third body symbol is entered and in column 58-62, the efficiency is entered.

5. The word "END" is placed in column 1 on the line below the last reaction.

6. The next line is the title or description of stream 2.

7. Repeat steps 2-5 for stream 2

8. The initial mole fractions for the stream is entered on the next line after the word "END". The symbol for each species is placed in column 1-10, and the mole fraction is placed in column 11-20.

9. The next line is the title or description of stream 3

10. Repeat steps 7-9 for stream 3.

11. Starting in column 1, place the word "FINAL" on the last line of the file.

Appendix B - Validation Results

B.1.1 - Test 1 Input Data File - Example 1

```
FC RJPA Test *** CODE VALIDATION RUN ***
Scramjet Case, Mach 25.0, Z= 155,700, Some Frozen H2 For Inefficiency
EJANAF.DAT
 5, 1, 1, 1, 1, 1 /
 0, 0.050000,     0.0    1.0, 'FRZ1' /
 3, 0.950000,     0.0,   2.0, 'H    ' /
 0, 0.013250,     0.0,   1.0, 'A    ' /
 0, 0.231460      0.0    2.0. 'O    ' /
 0, 0.755290      0.0,   2.0, 'N    ' /
 2.016 /
 14, 1,288,300,304,-304,310,350,351,352,381,402,1271,1272,1273 /
 3,
   27060.39, 0.0160, 487.17,
   0,
   11909.52, 11909.52, 0.0 , 1.E11 /
 4,
   4.7671, 0.9773, 0, 147.39,
   0,
   1.2, 1.3, 0.5 /
 0, 90 , 0., 0 /
 1, 0,
    0.0, 398.894, 396.909, 18.452, 0., 1000., 0., 0.000, 0.029164,
    3968.42, 2.016, 1, 0.,  0.00,  0.00, 0, 1.0000,
    0.0, 0.00592847, 1682.26, 7575.25, 34.482759, 1.0 /
 1, 0.9740,
    1, 0.1245, 0, 0.6667 /
```

B.1.2 - Test 1 Output File - Example 1

```
                         RAMJET PERFORMANCE ANALYSIS, VERSION 1.24
 PC RJPA Test    *** CODE VALIDATION RUN ***
 Scramjet Case, Mach 25.0, Z= 155.700, Some Frozen H2 For Inefficiency
EJANAF.DAT

FOLLOWING DATA READ FROM JANAF Thermochemical File:
  KEY          NAME                                    FORMULA       DATE    HF-298
     1   ARGON                                (G)   A(G)         A0672  0.00000E+00
   288   HYDROGEN, MONATOMIC                  (G)   H(G)         J 674  0.52103E+02
   300   HYDROXYL                             (G)   HO(G)        J1270  0.94920E+01
   304   HYDROGEN, DIATOMIC                   (R)   H2(R)        J 361  0.00000E+00
Frozen Species ===> H2(R)    FRZ1
   310   HYDROGEN PEROXIDE                    (G)   H2O2(G)      J1260 -0.32530E+02
   350   NITROGEN, MONATOMIC                  (G)   N(G)         J 361  0.11297E+03
   351   NITRIC OXIDE                         (G)   NO(G)        J 663  0.21580E+02
   352   NITROGEN DIOXIDE                     (G)   NO2(G)       J 964  0.79100E+01
   381   OXYGEN, MONATOMIC                    (G)   O(G)         J 674  0.59553E+02
   402   OZONE                                (G)   O3(G)        J 661  0.34100E+02
  1271 WATER-LOW TEMP. FITS                   (G)   H2O(G)       A 368 -0.57798E+02
  1272 NITROGEN-LOW TEMP. FITS                (G)   N2(G)        A 368  0.00000E+00
  1273 OXYGEN-LOW TEMP. FITS                  (G)   O2(G)        A 368  0.00000E+00
 INIT =  3
     PAR   =     0.270604E+05
     Z     =     0.160000E-01
     TEMP  =     0.487170E+03
     PITI  =   0
     AREF  =     0.119095E+05
     AISS  =     0.119095E+05
     AIGG  =     0.000000E+00
     WOFINO=      0.100000E+12

 DIFF =  4
     PAR1  =     0.476710E+01
     EFF   =     0.977300E+00
     HEAT  =   0
     QDIFF  =     0.147390E+03
     PITD  =   0
     GAMG1  =     0.120000E+01
     GAMG2  =     0.130000E+01
     SWT    =     0.500000E+00

 SHK   =  0
     BET   =     0.900000E+02
     DEL   =     0.000000E+00
     PITS  =   0
```

```
COMB =  1        ICOMB =  0
    ABASE =    0.000000E+00      ACE   =     0.398894E+03
    ACI   =    0.396909E+03      AGG   =     0.184520E+02
    ALPHA =    0.000000E+00      AWALL =     0.100000E+04
    BETA  =    0.000000E+00      CF    =     0.000000E+00
    FSR   =    0.291640E-01      HGG   =     0.396842E+04
    MWGG  =    0.201600E+01      NCF   =  2
    PBASE =    0.000000E+00      PCEG1 =     0.000000E+00
    PCEG2 =    0.000000E+00      PITC  =  0
    PSPCI =    0.100000E+01      QWALL =     0.000000E+00
    RHOGG =    0.592847E-02      TGG   =     0.168226E+04
    UGG   =    0.757525E+04      WOFIN =     0.344828E+02
    XI    =    0.100000E+01

EXP =  1
    EFFN  =   0.974000E+00
    J22   =  1
    PEX   =   0.124500E+00
    PITN  =  0
    RATIOFE =      0.667

 RJPA of September 12, 1988

INPUT MIXTURE
WT. %     HF(C/MOLE)     M.W.     MOLECULAR FORMULA
0.050000       0.0    2.016  1.0000    FRZ1
0.950000       0.0    2.016  2.0000    H
0.013250       0.0   39.941  1.0000    A
0.231460       0.0   32.000  2.0000    O
0.755290       0.0   28.016  2.0000    N

               RESULTING GRAM ATOMS,  5 ELEMENTS
    ELEMENT     AT. NO.      AT. WT.      VAL    GRAM ATOMS
      H            1          1.008       1.0     0.000000
      N            7         14.008       0.0     5.391847
      O            8         16.000      -2.0     1.446625
      A           18         39.941       0.0     0.033174
      FRZ1       111          2.016       0.0     0.000000

EQUIVALENCE RATIO        =       0.0000
STOIC FUEL/OX RATIO      =       0.0307
FUEL/OX RATIO(WF/WO)     =       0.0000
OX/FUEL RATIO(WO/WF)     =************
MIXTURE WT (GRAMS)       =     100.0000
MIXTURE ENTH (BTU/LB)    =       0.0000
ROC. EQ. FRAC.           =       0.0000
```

DIF of Jan. 17, 1989

INPUT MIXTURE

WT. %	HF(C/MOLE)	M.W.	MOLECULAR FORMULA	
0.050000	0.0	2.016	1.0000	FRZ1
0.950000	0.0	2.016	2.0000	H
0.013250	0.0	39.941	1.0000	A
0.231460	0.0	32.000	2.0000	O
0.755290	0.0	28.016	2.0000	N

RESULTING GRAM ATOMS, 5 ELEMENTS

ELEMENT	AT. NO.	AT. WT.	VAL	GRAM ATOMS
H	1	1.008	1.0	2.656108
N	7	14.008	0.0	5.239891
O	8	16.000	-2.0	1.405855
A	18	39.941	0.0	0.032239
FRZ1	111	2.016	0.0	0.069898

EQUIVALENCE RATIO = 0.9447
STOIC FUEL/OX RATIO = 0.0307
FUEL/OX RATIO(WF/WO) = 0.0290
OX/FUEL RATIO(WO/WF) = 34.4828
MIXTURE WT (GRAMS) = 100.0000
MIXTURE ENTH (BTU/LB) = 0.0000
ROC. EQ. FRAC. = 0.4858

CROC of Dec 20, 1990
EXPAN of November 3, 1986

******** RAMJET PERFORMANCE ANALYSIS ********

APR 4, 1991

CASE: PC RJPA Test
Scramjet Case, Mach 25.0, Z= 155,700, Some Frozen H2 For Inefficiency
INLET CONDITIONS

INIT = 3 PAR = 0.270604E+05
Z = 0.160000E-01 TEMP = 0.487170E+03

PRESSURE (psia) = 0.160000E-01
TEMPERATURE (R) = 0.487170E+03
DENSITY (lbm/ft3) = 0.886673E-04
ENTHALPY (Btu/lbm) = -.122214E+02
ENTROPY (Btu/lbm-R) = 0.208198E+01
Pitot PRESSURE (psia) = 0.000000E+00
Total Pressure (psia) = 0.000000E+00
Total TEMPERATURE (R) = 0.000000E+00
W/A (lbm/s-ft2) = 0.239937E+01
SENSIBLE ENTHALPY = -.122214E+02
TOTAL ENTH. (Btu/lbm) = 0.146166E+05
Eq.Sound Speed (ft/s) = 0.108443E+04
Eq.Gamma = 0.140663E+01
Eq.Compress. (1/psia) = 0.625001E+02

Frozen MACH NUMBER = 0.249558E+02
VELOCITY (ft/s) = 0.270604E+05
Frz SOUND SPEED (ft/s) = 0.108433E+04
Frozen GAMMA = 0.140637E+01
MOL.WT. (lbm/mole) = 0.289653E+02
A/W (ft2-s/lbm) = 0.416776E+00
F/W (lbf-s/lbm) = 0.842024E+03
F/A (lbf/ft2) = 0.202033E+04
WT.FRCT.COND.PROD. = 0.000000E+00
Eq.Mach Number = 0.249536E+02
Eq.Cp (BTU/lbm-R) = 0.237269E+00

GAS COMPOSITION

TOTAL GAS MOLES= 3.452410 P/FN = 0.000315

	PRODUCTS GAS		MOLE-PCT OF GAS	PARTIAL PRESSURE	WEIGHT PCT	MOLE /100-GM	MOLECULAR WEIGHT	
1	A(G)		0.9609	0.15374E-03	1.3250	0.033174	39.941	1
2	H(G)		0.0000	0.46344E-32	0.0000	0.000000	1.008	2
3	HO(G)		0.0000	0.46344E-32	0.0000	0.000000	17.008	3
4	H2(R)		0.0000	0.46344E-32	0.0000	0.000000	2.016	4
5	H2(R)	FRZ1	0.0000	0.11494E-12	0.0000	0.000000	2.016	5
6	H2O2(G)		0.0000	0.46344E-32	0.0000	0.000000	34.016	6
7	N(G)		0.0000	0.46344E-32	0.0000	0.000000	14.008	7
8	NO(G)		0.0000	0.93360E-19	0.0000	0.000000	30.008	8
9	NO2(G)		0.0000	0.21007E-13	0.0000	0.000000	46.008	9
10	O(G)		0.0000	0.46344E-32	0.0000	0.000000	16.000	10
11	O3(G)		0.0000	0.46344E-32	0.0000	0.000000	48.000	11
12	H2O(G)		0.0000	0.21839E-11	0.0000	0.000000	18.016	12
13	N2(G)		78.0882	0.12494E-01	75.5290	2.695924	28.016	13
14	O2(G)		20.9509	0.33522E-02	23.1460	0.723313	32.000	14

******** RAMJET PERFORMANCE ANALYSIS ********

APR 4, 1991

CASE: PC RJPA Test

Scramjet Case, Mach 25.0, Z= 155,700, Some Frozen H2 For Inefficiency

DIFFUSER EXIT CONDITIONS

DIFF = 4 PAR1 = 0.476710E+01

EFF = 0.977300E+00 AOI = 0.119095E+05 in2

ADICAL = 0.396932E+03 in2

PRESSURE (psia)	= 0.476710E+01	Frozen MACH NUMBER	= 0.806573E+01
TEMPERATURE (R)	= 0.457365E+04	VELOCITY (ft/s)	= 0.257557E+05
DENSITY (lbm/ft3)	= 0.279513E-02	Frz SOUND SPEED (ft/s)	= 0.319323E+04
ENTHALPY (Btu/lbm)	= 0.121699E+04	Frozen GAMMA	= 0.129045E+01
ENTROPY (Btu/lbm-R)	= 0.231030E+01	MOL.WT. (lbm/mole)	= 0.287716E+02
Pitot PRESSURE (psia)	= 0.000000E+00	A/W (ft2-s/lbm)	= 0.138907E-01
Total Pressure (psia)	= 0.000000E+00	F/W (lbf-s/lbm)	= 0.810049E+03
Total TEMPERATURE (R)	= 0.000000E+00	F/A (lbf/ft2)	= 0.583159E+05
W/A (lbm/s-ft2)	= 0.719906E+02		
SENSIBLE ENTHALPY	= 0.113418E+04	WT.FRCT.COND.PROD.	= 0.000000E+00
Eq.Sound Speed (ft/s)	= 0.308329E+04	Eq.Mach Number	= 0.835334E+01
Eq.Gamma	= 0.120312E+01	Eq.Cp (BTU/lbm-R)	= 0.467194E+00
Eq.Compress. (1/psia)	= 0.210464E+00		

GAS COMPOSITION

TOTAL GAS MOLES= 3.475737 P/FN = 0.093327

	PRODUCTS GAS		MOLE-PCT OF GAS	PARTIAL PRESSURE	WEIGHT PCT	MOLE /100-GM	MOLECULAR WEIGHT	
1	A(G)		0.9544	0.45499E-01	1.3250	0.033174	39.941	1
2	H(G)		0.0000	0.15582E-09	0.0000	0.000000	1.008	2
3	HO(G)		0.0000	0.11368E-08	0.0000	0.000000	17.008	3
4	H2(R)		0.0000	0.18378E-17	0.0000	0.000000	2.016	4
5	H2(R)	FRZ1	0.0000	0.34016E-10	0.0000	0.000000	2.016	5
6	H2O2(G)		0.0000	0.12133E-21	0.0000	0.000000	34.016	6
7	N(G)		0.0001	0.31148E-05	0.0000	0.000002	14.008	7
8	NO(G)		2.4302	0.11585E+00	2.5347	0.084467	30.008	8
9	NO2(G)		0.0010	0.48283E-04	0.0016	0.000035	46.008	9
10	O(G)		1.3431	0.64028E-01	0.7459	0.046684	16.000	10
11	O3(G)		0.0000	0.74381E-07	0.0000	0.000000	48.000	11
12	H2O(G)		0.0000	0.62190E-16	0.0000	0.000000	18.016	12
13	N2(G)		76.3485	0.36396E+01	74.3453	2.653672	28.016	13
14	O2(G)		18.9227	0.90206E+00	21.0465	0.657702	32.000	14

******** RAMJET PERFORMANCE ANALYSIS ********

APR 1, 1991

CASE: PC RJPA Test

Scramjet Case, Mach 25.0, Z= 155,700, Some Frozen H2 For Inefficiency

COMBUSTOR RESULTS

WOF	= 0.344828E+02	XI	= 0.100000E+01
ERGG	= 0.999999E+06	WASS	= 0.198429E+03 lbm/s
ERS	= 0.994377E+00	WAGG	= 0.000000E+00 lbm/s
ERO	= 0.994377E+00	WF	= 0.575443E+01 lbm/s
FSR	= 0.291640E-01	WCE	= 0.204183E+03 lbm/s
CEFF	= 95.000122%	CF	= 0.000000E+00

CROCCO EPS	= 0.150476E+01	ACE	= 0.298894E+03 in2
PSPCI	= 0.100000E+01	ACI	= 0.396909E+03 in2
MCE	= 0.635553E+01	AGG	= 0.184520E+02 in2
MCE @ S.L.	= 0.132068E+01	ABASE	= 0.000000E+00 in2
PBASE (psia)	= 0.476710E+01	ATOTAL	= 0.415361E+03 in2
PGG (psia)	= 0.530845E+02	RHOGG	= 0.592822E-02 lbm/ft3

PRESSURE (psia)	= 0.779911E+01	Frozen MACH NUMBER	= 0.635553E+01
TEMPERATURE (R)	= 0.543363E+04	VELOCITY (ft/s)	= 0.251865E+05
DENSITY (lbm/ft3)	= 0.292655E-02	Frz SOUND SPEED (ft/s)	= 0.396293E+04
ENTHALPY (Btu/lbm)	= 0.153262E+04	Frozen GAMMA	= 0.127197E+01
ENTROPY (Btu/lbm-R)	= 0.299452E+01	MOL.WT. (lbm/mole)	= 0.218318E+02
Pitot PRESSURE (psia)	= 0.000000E+00	A/W (ft2-s/lbm)	= 0.135667E-01
Total Pressure (psia)	= 0.000000E+00	F/W (lbf-s/lbm)	= 0.798059E+03
Total TEMPERATURE (R)	= 0.000000E+00	F/A (lbf/ft2)	= 0.588247E+05
W/A (lbm/s-ft2)	= 0.737097E+02		
SENSIBLE ENTHALPY	= 0.186955E+04	WT.FRCT.COND.PROD.	= 0.000000E+00
Eq.Sound Speed (ft/s)	= 0.372988E+04	Eq.Mach Number	= 0.675263E+01
Eq.Gamma	= 0.112677E+01	Eq.Cp (BTU/lbm-R)	= 0.208624E+01
Eq.Compress. (1/psia)	= 0.134104E+00		

GAS COMPOSITION

TOTAL GAS MOLES= 4.571586 P/FN = 0.116086

	PRODUCTS GAS	MOLE-PCT OF GAS	PARTIAL PRESSURE	WEIGHT PCT	MOLE /100-GM	MOLECULAR WEIGHT	
1	A(G)	0.7052	0.55000E-01	1.2877	0.032239	39.941	1
2	H(G)	6.0489	0.47176E+00	0.2787	0.276533	1.008	2
3	HO(G)	4.8821	0.38076E+00	3.7960	0.223189	17.008	3
4	H2(R)	6.9621	0.54298E+00	0.6416	0.318277	2.016	4
5	H2(R) FRZ1	1.5290	0.11924E+00	0.1409	0.069898	2.016	5
6	H2O2(G)	0.0000	0.27632E-05	0.0001	0.000002	34.016	6
7	N(G)	0.0016	0.12687E-03	0.0010	0.000074	14.008	7
8	NO(G)	1.5081	0.11761E+00	2.0688	0.068942	30.008	8
9	NO2(G)	0.0002	0.15021E-04	0.0004	0.000009	46.008	9
10	O(G)	2.6329	0.20534E+00	1.9259	0.120366	16.000	10
11	O3(G)	0.0000	0.23046E-07	0.0000	0.000000	48.000	11
12	H2O(G)	16.6226	0.12964E+01	13.6906	0.759914	18.016	12
13	N2(G)	56.5544	0.44107E+01	72.4335	2.585433	28.016	13
14	O2(G)	2.5530	0.19911E+00	3.7348	0.116712	32.000	14

******** RAMJET PERFORMANCE ANALYSIS ********

APR 4, 1991

CASE: PC RJPA Test

Scramjet Case, Mach 25.0, Z= 155,700, Some Frozen H2 For Inefficiency

EQUILIBRIUM NOZZLE EXPANSION TO REQUIRED PRESSURE

EXP = 1 J22 = 1

PEX = 0.124500E+00

PRESSURE (psia)	= 0.124500E+00	Frozen MACH NUMBER	= 0.856422E+01
TEMPERATURE (R)	= 0.376567E+04	VELOCITY (ft/s)	= 0.267655E+05
DENSITY (lbm/ft3)	= 0.743230E-04	Frz SOUND SPEED (ft/s)	= 0.312527E+04
ENTHALPY (Btu/lbm)	= -.106108E+03	Frozen GAMMA	= 0.125852E+01
ENTROPY (Btu/lbm-R)	= 0.299452E+01	MOL.WT. (lbm/mole)	= 0.241184E+02
Pitot PRESSURE (psia)	= 0.000000E+00	A/W (ft2-s/lbm)	= 0.502692E+00
Total Pressure (psia)	= 0.000000E+00	F/W (lbf-s/lbm)	= 0.840909E+03
Total TEMPERATURE (R)	= 0.000000E+00	F/A (lbf/ft2)	= 0.167281E+04
W/A (lbm/s-ft2)	= 0.198929E+01		
SENSIBLE ENTHALPY	= 0.114711E+04	WT.FRCT.COND.PROD.	= 0.000000E+00
Eq.Sound Speed (ft/s)	= 0.298533E+04	Eq.Mach Number	= 0.896567E+01
Eq.Gamma	= 0.114834E+01	Eq.Cp (BTU/lbm-R)	= 0.850187E+00
Eq.Compress. (1/psia)	= 0.808184E+01		

GAS COMPOSITION

TOTAL GAS MOLES= 4.146205 P/FN = 0.002043

	PRODUCTS GAS	MOLE-PCT OF GAS	PARTIAL PRESSURE	WEIGHT PCT	MOLE /100-GM	MOLECULAR WEIGHT	
1	A(G)	0.7776	0.96806E-03	1.2877	0.032239	39.941	1
2	H(G)	0.3989	0.49661E-03	0.0167	0.016538	1.008	2
3	HO(G)	0.8887	0.11064E-02	0.6267	0.036847	17.008	3
4	H2(R)	1.5481	0.19274E-02	0.1294	0.064189	2.016	4

5	H2(R)	FRZ1	1.685[illegible]	0.20988E-02	0.1409	0.069898	2.016	5
6	H2O2(G)		0.0000	0.10246E-08	0.0000	0.000000	34.016	6
7	N(G)		0.0000	0.34500E-08	0.0000	0.000000	14.008	7
8	NO(G)		0.2387	0.29717E-03	0.2970	0.009896	30.008	8
9	NO2(G)		0.0000	0.97222E-08	0.0000	0.000000	46.008	9
10	O(G)		0.1668	0.20770E-03	0.1107	0.006917	16.000	10
11	O3(G)		0.0000	0.14183E-11	0.0000	0.000000	48.000	11
12	H2O(G)		29.8387	0.37149E-01	22.2889	1.237172	18.016	12
13	N2(G)		63.0696	0.78522E-01	73.2618	2.614997	28.016	13
14	O2(G)		1.3871	0.17269E-02	1.8404	0.057511	32.000	14

******** RAMJET PERFORMANCE ANALYSIS ********

APR 4, 1991

CASE: PC RJPA Test
Scramjet Case, Mach 25.0, Z= 155,700, Some Frozen H2 For Inefficiency

FROZEN NOZZLE EXPANSION TO REQUIRED PRESSURE

EXP = 1 J22 = 1
PEX = 0.124500E+00

PRESSURE (psia)	= 0.124500E+00	Frozen MACH NUMBER	= 0.104937E+02
TEMPERATURE (R)	= 0.210990E+04	VELOCITY (ft/s)	= 0.264785E+05
DENSITY (lbm/ft3)	= 0.120306E-03	Frz SOUND SPEED (ft/s)	= 0.252329E+04
ENTHALPY (Btu/lbm)	= 0.199112E+03	Frozen GAMMA	= 0.132795E+01
ENTROPY (Btu/lbm-R)	= 0.299452E+01	MOL.WT. (lbm/mole)	= 0.218742E+02
Pitot PRESSURE (psia)	= 0.000000E+00	A/W (ft2-s/lbm)	= 0.313921E+00
Total Pressure (psia)	= 0.000000E+00	F/W (lbf-s/lbm)	= 0.828607E+03
Total TEMPERATURE (R)	= 0.000000E+00	F/A (lbf/ft2)	= 0.263954E+04
W/A (lbm/s-ft2)	= 0.318552E+01		
Eq.Sound Speed (ft/s)	= ------------	Eq.Mach Number	= ------------
Eq.Gamma	= ------------	Eq.Cp (BTU/lbm-R)	= ------------
Eq.Compress. (1/psia)	= ------------		

GAS COMPOSITION
TOTAL GAS MOLES= 4.571586 P/FN = 0.001853

	PRODUCTS GAS		MOLE-PCT OF GAS	PARTIAL PRESSURE	WEIGHT PCT	MOLE /100-GM	MOLECULAR WEIGHT	
1	A(G)		0.7052	0.87798E-03	1.2877	0.032239	39.941	1
2	H(G)		6.0489	0.75309E-02	0.2787	0.276533	1.008	2
3	HO(G)		4.8821	0.60782E-02	3.7960	0.223189	17.008	3
4	H2(R)		6.9621	0.86678E-02	0.6416	0.318277	2.016	4
5	H2(R)	FRZ1	1.5290	0.19036E-02	0.1409	0.069898	2.016	5
6	H2O2(G)		0.0000	0.44429E-07	0.0001	0.000002	34.015	6
7	N(G)		0.0016	0.20253E-05	0.0010	0.000074	14.008	7
8	NO(G)		1.5081	0.18775E-02	2.0688	0.068942	30.008	8
9	NO2(G)		0.0002	0.23973E-06	0.0004	0.000009	46.008	9
10	O(G)		2.6329	0.32780E-02	1.9259	0.120366	16.000	10
11	O3(G)		0.0000	0.36790E-09	0.0000	0.000000	48.000	11
12	H2O(G)		16.6226	0.20695E-01	13.6906	0.759914	18.016	12
13	N2(G)		56.5544	0.70410E-01	72.4335	2.585433	28.016	13
14	O2(G)		2.5530	0.31785E-02	3.7346	0.116712	32.000	14

******** RAMJET PERFORMANCE ANALYSIS ********

APR 4, 1991

CASE: PC RJPA Test
Scramjet Case, Mach 25.0, Z= 155,700, Some Frozen H2 For Inefficiency

Q0 (lbf/ft2) = 0.100901E+04

COMBINED-- 0.667

NOZZ EFF (%)	THRUST(lbf)	CT	ISP(lbf-s/lbm)
97.40	-.146437E+04	-0.017548	-254.48
97.66	-.102230E+04	-0.012250	-177.65
97.92	-.580233E+03	-0.006953	-100.83
98.18	-.138166E+03	-0.001656	-24.01
98.44	0.303901E+03	0.003642	52.81
98.70	0.745968E+03	0.008939	129.63
98.96	0.118803E+04	0.014236	206.46
99.22	0.163010E+04	0.019534	283.28
99.48	0.207217E+04	0.024831	360.10
99.74	0.251424E+04	0.030128	436.92
100.00	0.295630E+04	0.035426	513.74

FROZEN Only

NOZZ EFF (%)	THRUST(lbf)	CT	ISP(lbf-s/lbm)
97.40	-.225026E+04	-0.026965	-391.05
97.66	-.181037E+04	-0.021694	-314.60
97.92	-.137048E+04	-0.016423	-238.16
98.18	-.930593E+03	-0.011151	-161.72
98.44	-.490703E+03	-0.005880	-85.27
98.70	-.508133E+02	-0.000609	-8.83
98.96	0.389077E+03	0.004662	67.61
99.22	0.828967E+03	0.009934	144.06
99.48	0.126886E+04	0.015205	220.50
99.74	0.170875E+04	0.020476	296.94
100.00	0.214864E+04	0.025747	373.39

EQUILIBRIUM Only

NOZZ EFF (%)	THRUST(lbf)	CT	ISP(lbf-s/lbm)
97.40	0.107663E+03	0.001290	18.71
97.66	0.554084E+03	0.006640	96.29
97.92	0.100051E+04	0.011989	173.87
98.18	0.144693E+04	0.017339	251.45
98.44	0.189335E+04	0.022688	329.02
98.70	0.233977E+04	0.028038	406.60
98.96	0.278619E+04	0.033387	484.18
99.22	0.323261E+04	0.038737	561.76
99.48	0.367903E+04	0.044086	639.34
99.74	0.412546E+04	0.049436	716.92
100.00	0.457188E+04	0.054786	794.50

End Of Simulation

B.1.3 - Test 1 Input Data File - FPS

```
 PC RJPA Test *** CODE VALIDATION RUN ***
 Scramjet Case, Mach 25.0, Z= 155,700, Some Frozen H2 For Inefficiency
EJANAF.DAT
 5, 1, 1, 1, 1, 1 /
 0, 0.050000,      0.0     1.0, 'FRZ1' /
 3, 0.950000,      0.0,    2.0, 'H    ' /
 0, 0.013250,      0.0.    1.0, 'A    ' /
 0, 0.231460,      0.0,    2.0, 'O    ' /
 0, 0.755290       0.0,    2.0, 'N    ' /
 2.016 /
 14, 1,288,300,304,-304,310,350,351,352,381,402,1271,1272,1273 /

 &FRSTR
  UNITS= fps, INIT=3, PAR=27060.39, Z=0.0160, TEMP=487.17,
  PITI=0, AREF=11909.52, AISS=11909.52, AIGG=0.0, WOFINO=1.E11
 &END

 &DIFFUSER
  DIFF=4, PAR1=4.7671, EFF=0.9773, HEAT=0, QDIFF=147.39, PITD=0,
  GAMG1=1.2, GAMG2=1.3, SWT=0.5 &END

 &SHCK  SHK=0, BET=90., DEL=0., PITS=0  &END

 &COMBUSTOR
  COMB=1, ICOMB=0, FRC='NONE', ACE=398.894, AWALL=1000.0, PCEG1=0.0,
  PCEG2=0.0, PITC=0, PSPCI=1.0 &END

 &HEATFRICTION  CF=0.0, QWALL=0.0 &END

 &MIXER  FSR=0.029164, WOFIN=34.482759, XI=1.0 &END

 &OXIDIZER  ACI=396.909, BETA=0.0 &END

 &FUEL  AGG=18.452, ALPHA=0.0, HGG=3968.42, MWGG=2.016, NCFIN=1,
  RHOGG=0.00592847, TGG=1682.26, UGG=7575.25 &END

 &PRODUCTS  ABASE=0.0, PBASE=0.0 &END

 &NOZZLE  EXP=1, EFFN=0.9740, J22=1, PEX=0.1245, PITN=0, RATIOFE=0.6667
 &END
```

B.1.4 - Test 1 Output File - FPS

```
                         RAMJET PERFORMANCE ANALYSIS, VERSION 1.24
 PC RJPA Test    *** CODE VALIDATION RUN ***
 Scramjet Case, Mach 25.0, Z= 155,700, Some Frozen H2 For Inefficiency
EJANAF.DAT

FOLLOWING DATA READ FROM JANAF THERMOCHEMICAL FILE:
  KEY           NAME                              FORMULA        DATE     HF-298
     1   ARGON                            (G)   A(G)           A0672   0.00000E+00
   288   HYDROGEN, MONATOMIC              (G)   H(G)           J 674   0.52103E+02
   300   HYDROXYL                         (G)   HO(G)          J1270   0.94920E+01
   304   HYDROGEN, DIATOMIC               (R)   H2(R)          J 361   0.00000E+00
FROZEN SPECIES ===> H2(R)    FRZ1
   310   HYDROGEN PEROXIDE                (G)   H2O2(G)        J1260  -0.32530E+02
   350   NITROGEN, MONATOMIC              (G)   N(G)           J 361   0.11297E+03
   351   NITRIC OXIDE                     (G)   NO(G)          J 663   0.21580E+02
   352   NITROGEN DIOXIDE                 (G)   NO2(G)         J 964   0.79100E+01
   381   OXYGEN, MONATOMIC                (G)   O(G)           J 674   0.59553E+02
   402   OZONE                            (G)   O3(G)          J 661   0.34100E+02
  1271 WATER-LOW TEMP. FITS               (G)   H2O(G)         A 368  -0.57798E+02
  1272 NITROGEN-LOW TEMP. FITS            (G)   N2(G)          A 368   0.00000E+00
  1273 OXYGEN-LOW TEMP. FITS              (G)   O2(G)          A 368   0.00000E+00

 UNITS = fps
 INIT  =  3
     PAR    =  0.27060391E+05
     Z      =  0.16000001E-01
     TEMP   =  0.48717001E+03
     PITI   =  0
     AREF   =  0.11909520E+05
     AISS   =  0.11909520E+05
     AIGG   =  0.00000000E+00
     WOFINO=   0.99999998E+11

 DIFF =  4
     PAR1   =  0.47670999E+01
     EFF    =  0.97729999E+00
     HEAT   =  0
     QDIFF  =  0.14739000E+03
     PITD   =  0
     GAMG1  =  0.12000000E+01
     GAMG2  =  0.13000000E+01
     SWT    =  0.50000000E+00

 SHK   =  0
     BET   =  0.90000000E+02
     DEL   =  0.00000000E+00
     PITS  =  0
```

COMB = 1 ICOMB = 0 FRC = NONE

ABASE	=	0.00000000E+00	ACE	=	0.39889401E+03
ACI	=	0.39690900E+03	AGG	=	0.18452000E+02
ALPHA	=	0.00000000E+00	AWALL	=	0.10000000E+04
BETA	=	0.00000000E+00	CF	=	0.00000000E+00
FSR	=	0.29163999E-01	HGG	=	0.39684199E+04
MWGG	=	0.20160000E+01	NCF	=	2
PBASE	=	0.00000000E+00	PCEG1	=	0.00000000E+00
PCEG2	=	0.00000000E+00	PITC	=	0
PSPCI	=	0.10000000E+01	QWALL	=	0.00000000E+00
RHOGG	=	0.59284698E-02	TGG	=	0.16822600E+04
UGG	=	0.75752500E+04	WOFIN	=	0.34482758E+02
XI	=	0.10000000E+01			

EXP = 1

EFFN	=	0.97399998E+00
J22	=	1
PEX	=	0.12450000E+00
PITN	=	0
RATIOFE	=	0.66670001E+00

RJPA OF SEPTEMBER 12, 1988

INPUT MIXTURE

WT. %	HF(C/MOLE)	M.W.	MOLECULAR FORMULA	
0.050000	0.0	2.016	1.0000	FRZ1
0.950000	0.0	2.016	2.0000	H
0.013250	0.0	39.941	1.0000	A
0.231460	0.0	32.000	2.0000	O
0.755290	0.0	28.016	2.0000	N

RESULTING GRAM ATOMS, 5 ELEMENTS

ELEMENT	AT. NO.	AT. WT.	VAL	GRAM ATOMS
H	1	1.008	1.0	0.000000
N	7	14.008	0.0	5.391847
O	8	16.000	-2.0	1.446625
A	18	39.941	0.0	0.033174
FRZ1	111	2.016	0.0	0.000000

EQUIVALENCE RATIO	=	0.00000000
STOIC FUEL/OX RATIO	=	0.03069891
FUEL/OX RATIO(WF/WO)	=	0.00000000
OX/FUEL RATIO(WO/WF)	=	***************
MIXTURE WT (GRAMS)	=	100.00000000
MIXTURE ENTH (BTU/LB)	=	0.00000000
ROC. EQ. FRAC.	=	0.00000000

DIF OF JAN. 17, 1989

******** RAMJET PERFORMANCE ANALYSIS ********

08/24/93

CASE: PC RJPA Test

Scramjet Case, Mach 25.0, Z= 155,700, Some Frozen H2 For Inefficiency

INLET CONDITIONS

INIT =	3	PAR =	0.27060391E+05
Z =	0.16000001E-01	TEMP =	0.48717001E+03

PRESSURE (PSIA) =	0.16000001E-01	FROZEN MACH NUMBER =	0.24955839E+02
TEMPERATURE (R) =	0.48717004E+03	VELOCITY (FT/S) =	0.27060391E+05
DENSITY (LBM/FT3) =	0.88667330E-04	FRZ SOUND SPEED(FT/S) =	0.10843311E+04
ENTHALPY (BTU/LBM) =	-0.12221440E+02	FROZEN GAMMA =	0.14063709E+01
ENTROPY (BTU/LBM-R) =	0.20819807E+01	MOL.WT. (LBM/MOLE) =	0.28965271E+02
PITOT PRESSURE (PSIA) =	0.00000000E+00	A/W (FT2-S/LBM) =	0.41677561E+00
TOTAL PRESSURE (PSIA) =	0.00000000E+00	F/W (LBF-S/LBM) =	0.84202417E+03
TOTAL TEMPERATURE (R) =	0.00000000E+00	F/A (LBF/FT2) =	0.20203297E+04
W/A (LBM/S-FT2) =	0.23993726E+01		
SENSIBLE ENTHALPY =	-0.12221439E+02	WT.FRCT.COND.PROD. =	0.00000000E+00
TOTAL ENTH. (BTU/LBM) =	0.14616599E+05		
EQ.SOUND SPEED (FT/S) =	0.10844304E+04	EQ.MACH NUMBER =	0.24953552E+02
EQ.GAMMA =	0.14066286E+01	EQ.CP (BTU/LBM-R) =	0.23726857E+00
EQ.COMPRESS. (1/PSIA) =	0.62500149E+02		

GAS COMPOSITION

TOTAL GAS MOLES = 0.34524102E+01 P/FN = 0.31535520E-03

PRODUCTS GAS		MOLE-PCT OF GAS	PARTIAL PRESSURE	WEIGHT PCT	MOLE /100-GM	MOLECULAR WEIGHT	
1 A(G)		0.9609	0.15374E-03	1.3250	0.331739E-01	39.941	1
2 H(G)		0.0000	0.22157E-26	0.0000	0.478089E-24	1.008	2
3 HO(G)		0.0000	0.22157E-26	0.0000	0.478031E-24	17.008	3
4 H2(R)		0.0000	0.22157E-26	0.0000	0.478089E-24	2.016	4
5 H2(R)	FRZ1	0.0000	0.11494E-12	0.0000	0.248016E-10	2.016	5
6 H2O2(G)		0.0000	0.22157E-26	0.0000	0.478089E-24	34.016	6
7 N(G)		0.0000	0.22157E-26	0.0000	0.478089E-24	14.008	7
8 NO(G)		0.0000	0.93360E-19	0.0000	0.201448E-16	30.008	8
9 NO2(G)		0.0000	0.21007E-13	0.0000	0.453274E-11	46.008	9
10 O(G)		0.0000	0.22157E-26	0.0000	0.478089E-24	16.000	10
11 O3(G)		0.0000	0.22157E-26	0.0000	0.478089E-24	48.000	11
12 H2O(G)		0.0000	0.21839E-11	0.0000	0.471230E-09	18.016	12
13 N2(G)		78.0882	0.12494E-01	75.5290	0.269592E+01	28.016	13
14 O2(G)		20.9509	0.33522E-02	23.1460	0.723313E+00	32.000	14

******** RAMJET PERFORMANCE ANALYSIS ********

08/24/93

CASE: PC RJPA Test

Scramjet Case, Mach 25.0, Z= 155,700, Some Frozen H2 For Inefficiency

DIFFUSER EXIT CONDITIONS

DIFF =	4	PAR1 =	0.47670999E+01
EFF =	0.97729999E+00	AOI =	0.11909520E+05 IN2
ADICAL =	0.39693134E+03 IN2		

PRESSURE (PSIA) =	0.47670999E+01	FROZEN MACH NUMBER =	0.80657339E+01
TEMPERATURE (R) =	0.45736416E+04	VELOCITY (FT/S) =	0.25755719E+05
DENSITY (LBM/FT3) =	0.27951356E-02	FRZ SOUND SPEED(FT/S) =	0.31932271E+04
ENTHALPY (BTU/LBM) =	0.12169916E+04	FROZEN GAMMA =	0.12904484E+01
ENTROPY (BTU/LBM-R) =	0.23102965E+01	MOL.WT. (LBM/MOLE) =	0.28771608E+02
PITOT PRESSURE (PSIA) =	0.00000000E+00	A/W (FT2-S/LBM) =	0.13890678E-01
TOTAL PRESSURE (PSIA) =	0.00000000E+00	F/W (LBF-S/LBM) =	0.81004883E+03
TOTAL TEMPERATURE (R) =	0.00000000E+00	F/A (LBF/FT2) =	0.58316004E+05
W/A (LBM/S-FT2) =	0.71990723E+02		
SENSIBLE ENTHALPY =	0.11341837E+04	WT.FRCT.COND.PROD. =	0.00000000E+00
EQ.SOUND SPEED (FT/S) =	0.30832888E+04	EQ.MACH NUMBER =	0.83533268E+01
EQ.GAMMA =	0.12031214E+01	EQ.CP (BTU/LBM-R) =	0.46719265E+00
EQ.COMPRESS. (1/PSIA) =	0.21046399E+00		

GAS COMPOSITION

TOTAL GAS MOLES = 0.34757376E+01 P/FN = 0.93327500E-01

PRODUCTS GAS		MOLE-PCT OF GAS	PARTIAL PRESSURE	WEIGHT PCT	MOLE /100-GM	MOLECULAR WEIGHT	
1 A(G)		0.9544	0.45499E-01	1.3250	0.331739E-01	39.941	1
2 H(G)		0.0000	0.15582E-09	0.0000	0.113607E-09	1.008	2
3 HO(G)		0.0000	0.11368E-08	0.0000	0.828853E-09	17.008	3
4 H2(R)		0.0000	0.18378E-17	0.0000	0.133998E-17	2.016	4
5 H2(R)	FRZ1	0.0000	0.34016E-10	0.0000	0.248016E-10	2.016	5
6 H2O2(G)		0.0000	0.12134E-21	0.0000	0.884675E-22	34.016	6
7 N(G)		0.0001	0.31148E-05	0.0000	0.227100E-05	14.008	7
8 NO(G)		2.4302	0.11585E+00	2.5347	0.844671E-01	30.008	8
9 NO2(G)		0.0010	0.48283E-04	0.0016	0.352038E-04	46.008	9
10 O(G)		1.3431	0.64027E-01	0.7469	0.466830E-01	16.000	10
11 O3(G)		0.0000	0.74380E-07	0.0000	0.542314E-07	48.000	11
12 H2O(G)		0.0000	0.62191E-16	0.0000	0.453437E-16	18.016	12
13 N2(G)		76.3485	0.36396E+01	74.3453	0.265367E+01	28.016	13
14 O2(G)		18.9227	0.90206E+00	21.0465	0.657702E+00	32.000	14

INPUT MIXTURE

WT. %	HF(C/MOLE)	M.W.	MOLECULAR FORMULA	
0.050000	0.0	2.016	1.0000	FRZ1
0.950000	0.0	2.016	2.0000	H
0.013250	0.0	39.941	1.0000	A
0.231460	0.0	32.000	2.0000	O
0.755290	0.0	28.016	2.0000	N

RESULTING GRAM ATOMS, 5 ELEMENTS

ELEMENT	AT. NO.	AT. WT.	VAL	GRAM ATOMS
H	1	1.008	1.0	2.656108
N	7	14.008	0.0	5.239891
O	8	16.000	-2.0	1.405855
A	18	39.941	0.0	0.032239
FRZ1	111	2.016	0.0	0.069898

EQUIVALENCE RATIO	=	0.94465905
STOIC FUEL/OX RATIO	=	0.03069091
FUEL/OX RATIO(WF/WO)	=	0.02900000
OX/FUEL RATIO(WO/WF)	=	34.48275760
MIXTURE WT (GRAMS)	=	100.00000000
MIXTURE ENTH (BTU/LB)	=	0.00000000
ROC. EQ. FRAC.	=	0.48577103

CROC OF APR 9, 1991
EXPAN OF NOVEMBER 3, 1986

******** RAMJET PERFORMANCE ANALYSIS ********

08/24/93

CASE: PC RJPA Test
Scramjet Case, Mach 25.0, Z= 153,700, Some Frozen H2 For Inefficiency

COMBUSTOR RESULTS

WOF =	0.34482758E+02	XI =	0.10000000E+01
ERGG =	0.99999900E+06	WASS =	0.19842894E+03 LBM/S
ERS =	0.99437666E+00	WAGG =	0.00000000E+00 LBM/S
ERO =	0.99437666E+00	WF =	0.57544394E+01 LBM/S
FSR =	0.29163999E-01	WCE =	0.20418338E+03 LBM/S
CEFF =	95.000122%	CF =	0.00000000E+00

CROCCO EPS =	0.15047547E+01	ACE =	0.39889401E+03 IN2
PSPCI =	0.10000000E+01	ACI =	0.39690900E+03 IN2
MCE =	0.63555255E+01	AGG =	0.18452000E+02 IN2
MCE @ E.L. =	0.13206807E+01	ABASE =	0.00000000E+00 IN2
PBASE (PSIA) =	0.47670999E+01	ATOTAL =	0.41536099E+03 IN2
PGG (PSIA) =	0.53087685E+02	RHOGG =	0.59282309E-02 LBM/FT3

PRESSURE (PSIA) =	0.77991142E+01	FROZEN MACH NUMBER =	0.63555255E+01
TEMPERATURE (R) =	0.54336504E+04	VELOCITY (FT/S) =	0.25186533E+05
DENSITY (LBM/FT3) =	0.29255569E-02	FRZ SOUND SPEED(FT/S) =	0.39629348E+04
ENTHALPY (BTU/LBM) =	0.15326188E+04	FROZEN GAMMA =	0.12719733E+01
ENTROPY (BTU/LBM-R) =	0.29945240E+01	MOL.WT. (LBM/MOLE) =	0.21881756E+02
PITOT PRESSURE (PSIA) =	0.00000000E+00	A/W (FT2-S/LBM) =	0.13566713E-01
TOTAL PRESSURE (PSIA) =	0.00000000E+00	F/W (LBF-S/LBM) =	0.79805890E+03
TOTAL TEMPERATURE (R) =	0.00000000E+00	F/A (LBF/FT2) =	0.58824781E+05
W/A (LBM/S-FT2) =	0.73709824E+02		
SENSIBLE ENTHALPY =	0.18695474E+04	WT.FRCT.COND.PROD. =	0.00000000E+00
EQ.SOUND SPEED (FT/S) =	0.37298752E+04	EQ.MACH NUMBER =	0.67526474E+01
EQ.GAMMA =	0.11267633E+01	EQ.CP (BTU/LBM-R) =	0.20863218E+01
EQ.COMPRESS. (1/PSIA) =	0.13410476E+00		

GAS COMPOSITION

TOTAL GAS MOLES = 0.45715866E+01   P/FN = 0.11608623E+00

PRODUCTS GAS		MOLE-PCT OF GAS	PARTIAL PRESSURE	WEIGHT PCT	MOLE /100-GM	MOLECULAR WEIGHT	
1 A(G)		0.7052	0.55000E-01	1.2877	0.322390E-01	39.941	1
2 H(G)		6.0489	0.47176E+00	0.2787	0.276533E+00	1.008	2
3 HO(G)		4.8821	0.38076E+00	3.7960	0.223189E+00	17.008	3
4 H2(R)		6.9621	0.54298E+00	0.6416	0.318277E+00	2.016	4
5 H2(R)	FRZ1	1.5290	0.11925E+00	0.1409	0.698976E-01	2.016	5
6 H2O2(G)		0.0000	0.27832E-05	0.0001	0.163143E-05	34.016	6
7 N(G)		0.0016	0.12687E-03	0.0010	0.743672E-04	14.008	7
8 NO(G)		1.5081	0.11761E+00	2.0688	0.689420E-01	30.008	8
9 NO2(G)		0.0002	0.15021E-04	0.0004	0.880473E-05	46.008	9
10 O(G)		2.6329	0.20534E+00	1.9259	0.120366E+00	16.000	10
11 O3(G)		0.0000	0.23046E-07	0.0000	0.135090E-07	48.000	11
12 H2O(G)		16.6226	0.12964E+01	13.6906	0.759915E+00	18.016	12
13 N2(G)		56.5544	0.44107E+01	72.4335	0.258543E+01	28.016	13
14 O2(G)		2.5530	0.19911E+00	3.7348	0.116712E+00	32.000	14

******** RAMJET PERFORMANCE ANALYSIS ********

08/24/93

CASE: PC RJPA Test

Scramjet Case, Mach 25.0, Z= 155,700, Some Frozen H2 For Inefficiency

EQUILIBRIUM NOZZLE EXPANSION TO REQUIRED PRESSURE

EXP = 1   J22 = 1

PEX = 0.12450000E+00

PRESSURE (PSIA) =	0.12450000E+00	FROZEN MACH NUMBER =	0.85642204E+01
TEMPERATURE (R) =	0.37656680E+04	VELOCITY (FT/S) =	0.26765465E+05
DENSITY (LBM/FT3) =	0.74322983E-04	FRZ SOUND SPEED(FT/S) =	0.31252656E+04
ENTHALPY (BTU/LBM) =	-0.10610816E+03	FROZEN GAMMA =	0.12585199E+01
ENTROPY (BTU/LBM-R) =	0.29945240E+01	MOL.WT. (LBM/MOLE) =	0.24118439E+02
PITOT PRESSURE (PSIA) =	0.00000000E+00	A/W (FT2-S/LBM) =	0.50269210E+00
TOTAL PRESSURE (PSIA) =	0.00000000E+00	F/W (LBF-S/LBM) =	0.84090948E+03
TOTAL TEMPERATURE (R) =	0.00000000E+00	F/A (LBF/FT2) =	0.16728123E+04
W/A (LBM/S-FT2) =	0.19892893E+01		
SENSIBLE ENTHALPY =	0.11471149E+04	WT.FRCT.COND.PROD. =	0.00000000E+00
EQ.SOUND SPEED (FT/S) =	0.29853066E+04	EQ.MACH NUMBER =	0.89657335E+01
EQ.GAMMA =	0.11483232E+01	EQ.CP (BTU/LBM-R) =	0.85019350E+00
EQ.COMPRESS. (1 PSIA) =	0.80819435E+01		
EXIT AREA (IN**2) =	0.14780357E+05		

GAS COMPOSITION

TOTAL GAS MOLES = 0.41462049E+01   P/FN = 0.20432475E-02

PRODUCTS GAS	MOLE-PCT OF GAS	PARTIAL PRESSURE	WEIGHT PCT	MOLE /100-GM	MOLECULAR WEIGHT	
1 A(G)	0.7776	0.96806E-03	1.2877	0.322390E-01	39.941	1
2 H(G)	0.3989	0.49661E-03	0.0167	0.165384E-01	1.008	2
3 HO(G)	0.8887	0.11064E-02	0.6267	0.368474E-01	17.008	3
4 H2(R)	1.5481	0.19274E-02	0.1294	0.641899E-01	2.016	4

5	H2(R)	FRZ1	1.6858	0.20988E-02	0.1409	0.698976E-01	2.016	5
6	H2O2(G)		0.0000	0.10246E-08	0.0000	0.341235E-07	34.016	6
7	N(G)		0.0000	0.34500E-08	0.0000	0.114896E-06	14.008	7
8	NO(G)		0.2387	0.29716E-03	0.2970	0.989644E-02	30.008	8
9	NO2(G)		0.0000	0.97222E-08	0.0000	0.322777E-06	46.008	9
10	O(G)		0.1668	0.20770E-03	0.1107	0.691695E-02	16.000	10
11	O3(G)		0.0000	0.14183E-11	0.0000	0.472337E-10	48.000	11
12	H2O(G)		29.8387	0.37149E-01	22.2889	0.123717E+01	18.016	12
13	N2(G)		63.0696	0.78522E-01	73.2617	0.261500E+01	28.016	13
14	O2(G)		1.3871	0.17269E-02	1.8403	0.575108E-01	32.000	14

******** RAMJET PERFORMANCE ANALYSIS ********

08/24/93

CASE: PC RJPA Test

Scramjet Case, Mach 25.0, Z= 155,700, Some Frozen H2 For Inefficiency

FROZEN NOZZLE EXPANSION TO REQUIRED PRESSURE

EXP = 1 J22 = 1

PEX = 0.12450000E+00

PRESSURE (PSIA) =	0.12450000E+00	FROZEN MACH NUMBER =	0.10403657E+02
TEMPERATURE (R) =	0.21099043E+04	VELOCITY (FT/S) =	0.26478520E+05
DENSITY (LBM/FT3) =	0.12030571E-03	FRZ SOUND SPEED(FT/S) =	0.25232881E+04
ENTHALPY (BTU/LBM) =	0.19911075E+03	FROZEN GAMMA =	0.13279539E+01
ENTROPY (BTU/LBM-R) =	0.29945240E+01	MOL.WT. (LBM/MOLE) =	0.21874243E+02
PITOT PRESSURE (PSIA) =	0.00000000E+00	A/W (FT2-S/LBM) =	0.31392077E+00
TOTAL PRESSURE (PSIA) =	0.00000000E+00	F/W (LBF-S/LBM) =	0.82660675E+03
TOTAL TEMPERATURE (R) =	0.00000000E+00	F/A (LBF/FT2) =	0.26395410E+04
W/A (LBM/S-FT2) =	0.31855173E+01		
EQ.SOUND SPEED (FT/S) =	0.00000000E+00	EQ.MACH NUMBER =	0.00000000E+00
EQ.GAMMA =	0.00000000E+00	EQ.CP (BTU/LBM-R) =	0.00000000E+00
EQ.COMPRESS. (1/PSIA) =	0.00000000E+00		
EXIT AREA (IN**2) =	0.92300264E+04		

GAS COMPOSITION

TOTAL GAS MOLES = 0.45715866E+01 P/FN = 0.18531253E-02

	PRODUCTS GAS		MOLE-PCT OF GAS	PARTIAL PRESSURE	WEIGHT PCT	MOLE 100-GM	MOLECULAR WEIGHT	
1	A(G)		0.7052	0.87798E-03	1.2877	0.322390E-01	39.941	1
2	H(G)		6.0489	0.75309E-02	0.2787	0.276533E+00	1.008	2
3	HO(G)		4.8821	0.60782E-02	3.7960	0.223189E+00	17.008	3
4	H2(R)		6.9621	0.86678E-02	0.6416	0.318277E+00	2.016	4
5	H2(R)	FRZ1	1.5290	0.19036E-02	0.1409	0.698976E-01	2.016	5
6	H2O2(G)		0.0000	0.44429E-07	0.0001	0.163143E-05	34.016	6
7	N(G)		0.0016	0.20253E-05	0.0010	0.743672E-04	14.008	7
8	NO(G)		1.5081	0.18775E-02	2.0688	0.689420E-01	30.008	8
9	NO2(G)		0.0002	0.23978E-06	0.0004	0.880473E-05	46.008	9
10	O(G)		2.6329	0.32780E-02	1.9259	0.120366E+00	16.000	10
11	O3(G)		0.0000	0.36790E-09	0.0000	0.135090E-07	48.000	11
12	H2O(G)		16.6226	0.20695E-01	13.6906	0.759915E+00	18.016	12
13	N2(G)		56.5544	0.70410E-01	72.4335	0.258543E+01	28.016	13
14	O2(G)		2.5530	0.31785E-02	3.7348	0.116712E+00	32.000	14

******** RAMJET PERFORMANCE ANALYSIS ********

08/24/93

CASE: PC RJPA Test
Scramjet Case, Mach 25.0, Z= 155,700, Some Frozen H2 For Inefficiency

Q0 (LBF/FT2) = 0.10090129E+04

COMBINED-- 0.667

NOZZ EFF (%)	THRUST(LBF)	CT	ISP(LBF-S/LBM)
97.40	-0.14643649E+04	-0.017548	-0.25447568E+03
97.66	-0.10222975E+04	-0.012250	-0.17765372E+03
97.92	-0.58023016E+03	-0.006953	-0.10083175E+03
98.18	-0.13816273E+03	-0.001656	-0.24009766E+02
98.44	0.30390466E+03	0.003642	0.52812210E+02
98.70	0.74597205E+03	0.008939	0.12963419E+03
98.96	0.11880394E+04	0.014236	0.20645616E+03
99.22	0.16301068E+04	0.019534	0.28327814E+03
99.48	0.20721743E+04	0.024831	0.36010013E+03
99.74	0.25142417E+04	0.030129	0.43692209E+03
100.00	0.29563091E+04	0.035426	0.51374408E+03

FROZEN ONLY

NOZZ EFF (%)	THRUST(LBF)	CT	ISP(LBF-S/LBM)
97.40	-0.22502585E+04	-0.026905	-0.39104739E+03
97.66	-0.18103682E+04	-0.021694	-0.31460373E+03
97.92	-0.13704777E+04	-0.016423	-0.23816006E+03
98.18	-0.93058710E+03	-0.011151	-0.16171638E+03
98.44	-0.49069659E+03	-0.005880	-0.85272705E+02
98.70	-0.50806099E+02	-0.000609	-0.88290272E+01
98.96	0.38908441E+03	0.004662	0.67614655E+02
99.22	0.82897491E+03	0.009934	0.14405833E+03
99.48	0.12688654E+04	0.015205	0.22050200E+03
99.74	0.17087559E+04	0.020476	0.29694568E+03
100.00	0.21486465E+04	0.025748	0.37338937E+03

EQUILIBRIUM ONLY

NOZZ EFF (%)	THRUST(LBF)	CT	ISP(LBF-S/LBM)
97.40	0.10765829E+03	0.001290	0.18708738E+02
97.66	0.55408014E+03	0.006640	0.96287422E+02
97.92	0.10005020E+04	0.011989	0.17386610E+03
98.18	0.14469238E+04	0.017339	0.25144479E+03
98.44	0.18933456E+04	0.022688	0.32902347E+03
98.70	0.23397673E+04	0.028038	0.40660214E+03
98.96	0.27861892E+04	0.033387	0.48418082E+03
99.22	0.32326111E+04	0.038737	0.56175952E+03
99.48	0.36790330E+04	0.044086	0.63933820E+03
99.74	0.41254546E+04	0.049436	0.71691687E+03
100.00	0.45718765E+04	0.054786	0.79449554E+03

```
COMPONENT IMPULSE SUMMARY
 DIFFUSER (LBF)             = -0.63451875E+04
 COMBUSTOR (LBF)            =  0.22042031E+04
 FROZEN NOZZLE (LBF)        =  0.62373594E+04
 EQUILIBRIUM NOZZLE (LBF) =  0.87493906E+04
 END OF SIMULATION
```

B.1.5 - Test 1 Input Data File - CGS

```
PC RJPA Test
Scramjet Case F6, Mach 25.0, Z= 155,700. Some Frozen H2 For Inefficiency
EJANAF.DAT
5, 1, 1, 1, 1, 1 /
0, 0.050000,     0.0     1.0, 'FRZ1' /
3, 0.950000,     0.0,    2.0, 'H    ' /
0, 0.013250,     0.0,    1.0, 'A    ' /
0, 0.231460,     0.0,    2.0, 'O    ' /
0, 0.755290      0.0,    2.0, 'N    ' /
2.016 /
15, 1,288,300,304,-304,310,350,351,352,391,767,810,1271,1272,1273 /

&FRSTR
 units=cgs,init=3,
 par=824800.6872, z=0.001088735, temp=270.65,piti=0,
 aref=76835.459232, aias=76835.459232, aigg=0.0, WOFINO=1.E11
 &END

&DIFFUSER
  DIFF=4, PAR1=0.324281915, EFF=0.9773, HEAT=0, QDIFF=3428291400.,
  PITD=0, GAMG1=1.2, GAMG2=1.3, SWT=0.5 &END

&SHCK
 SHF=0, BET=90.0, DEL=0.0, PITS=0 &END

&COMBUSTOR
 COMB=1, ICOMB=0, FRC= 'NONE'  ACE=2573.50453, AWALL=6451.0
 PCEG1=0.00, PCEG2=0.00, PITC=0, PSPCI=1.0000  &END

&HEATFRICTION
 CF=0.0, QWALL=0.0 &END

&MIXER FSR=0.029164,WOFIN=34.482759,XI=1.0  &END

&OXIDIZER
 ACI= 2560.6981, BETA=0.0 &END

&FUEL
 AGG=119.0449232, ALPHA=0.0, HGG=2.483038889E3, MWGG=2.016, NCFIN=1,
 RHOGG=.000094965, TGG=934.5889, UGG=230896.62 &END

&PRODUCTS
 ABASE=0.0, PBASE=0.0 &END

&NOZZLE
 EXP=1, EFFN=0.9740, J22=1, PEX=0.008471723, PITN=0, RATIOFE=0.6667
 &END
```

B.1.6 - Test 1 Output File - CGS

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                        RAMJET PERFORMANCE ANALYSIS, VERSION 1.24
 PC RJPA Test
 Scramjet Case F6, Mach 25.0, Z= 155,700, Some Frozen H2 For Ineffícienc
EJANAF.DAT

FOLLOWING DATA READ FROM JANAF THERMOCHEMICAL FILE:
  KEY              NAME                                FORMULA          DATE      HF-298
     1   ARGON                                (G)  A(G)              A0672   0.00000E+00
   288   HYDROGEN, MONATOMIC                  (G)  H(G)              J 674   0.52103E+02
   300   HYDROXYL                             (G)  HO(G)             J1270   0.94920E+01
   304   HYDROGEN, DIATOMIC                   (R)  H2(R)             J 361   0.00000E+00
FROZEN SPECIES ===> H2(R)    FRZ1
   310   HYDROGEN PEROXIDE                    (G)  H2O2(G)           J1260  -0.32530E+02
   350   NITROGEN, MONATOMIC                  (G)  N(G)              J 361   0.11297E+03
   351   NITRIC OXIDE                         (G)  NO(G)             J 663   0.21580E+02
   352   NITROGEN DIOXIDE                     (G)  NO2(G)            J 964   0.79100E+01
   381   OXYGEN, MONATOMIC                    (G)  O(G)              J 674   0.59553E+02
   767   NITROXYL                             (G)  HNO(G)            J 363   0.23800E+02
   810   HYDROPEROXYL                         (G)  HO2(G)            J 364   0.50000E+01
  1271 WATER-LOW TEMP. FITS                   (G)  H2O(G)            A 368  -0.57798E+02
  1272 NITROGEN-LOW TEMP. FITS                (G)  N2(G)             A 368   0.00000E+00
  1273 OXYGEN-LOW TEMP. FITS                  (G)  O2(G)             A 368   0.00000E+00

 UNITS = cgs
 INIT  =  3
     PAR    =  0.82460069E+06
     Z      =  0.10887349E-02
     TEMP   =  0.27064999E+03
     PITI   =  0
     APEF   =  0.76835461E+05
     AISS   =  0.76835461E+05
     AIGG   =  0.00000000E+00
     WOFINO=   0.99999998E+11

 DIFF =  4
     PAR1   =  0.32438192E+00
     EFF    =  0.97729999E+00
     HEAT   =  0
     QDIFF  =  0.34282913E+10
     PITD   =  0
     GAMG1  =  0.12000000E+01
     GAMG2  =  0.13000000E+01
     SWT    =  0.50000000E+00

 SHK   =  1
     BET   =  0.90000000E+02
     DEL   =  0.00000000E+00
     PITS  =  0
```

```
COMB =  1       ICOMB =  0       FRC = NONE
    ABASE =  0.00000000E+00      ACE    =  0.25735046E+04
    ACI   =  0.25606980E+04      AGG    =  0.11904492E+03
    ALPHA =  0.00000000E+00      AWALL  =  0.34515001E+04
    BETA  =  0.00000000E+00      CF     =  0.00000000E+00
    FSR   =  0.29163999E-01      HGG    =  0.24830308E+04
    MWGG  =  0.20160000E+01      NCF    =  2
    PBASE =  0.00000000E+00      PCEG1  =  0.00000000E+00
    PCEG2 =  0.00000000E+00      PITC   =  0
    PSPCI =  0.10000000E+01      QWALL  =  0.00000000E+00
    RHOGG =  0.94964998E-04      TGG    =  0.93458893E+03
    UGG   =  0.230??663E+06      WOFIN  =  0.34482758E+02
    XI    =  0.10000000E+01

EXP =  1
    EFFN     =  0.97399998E+00
    J22      =  1
    PEX      =  0.84717227E-02
    PITN     =  0
    RATIOFE  =  0.66670001E+00

RJPA OF SEPTEMBER 12, 1988

INPUT MIXTURE
WT. %     HF(C/MOLE)    M.W.     MOLECULAR FORMULA
0.050000        0.0    2.016   1.0000    FRZ1
0.950000        0.0    2.016   2.0000    H
0.013250        0.0   39.941   1.0000    A
0.231460        0.0   32.000   2.0000    O
0.755290        0.0   28.016   2.0000    N

               RESULTING GRAM ATOMS,  5 ELEMENTS
    ELEMENT     AT. NO.     AT. WT.     VAL    GRAM ATOMS
      H            1         1.008      1.0     0.000000
      N            7        14.008      0.0     5.391847
      O            8        16.000     -2.0     1.146625
      A           18        39.941      0.0     0.033174
      FRZ1       111         2.016      0.0     0.000000

EQUIVALENCE RATIO        =      0.00000000
STOIC FUEL/OX RATIO      =      0.03069891
FUEL/OX RATIO(WF/WO)     =      0.00000000
OX/FUEL RATIO(WO/WF)     =***************
MIXTURE WT (GRAMS)       =    100.00000000
MIXTURE ENTH (CAL/G)     =      0.00000000
ROC. EQ. FRAC.           =      0.00000000

DIF OF JAN. 17, 1989
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******** RAMJET PERFORMANCE ANALYSIS ********

10/24/93

CASE: PC RJPA Test
Scramjet Case F6, Mach 25.0, Z= 155,700, Some Frozen H2 For Inefficienc

INLET CONDITIONS

INIT = 3 PAR = 0.824801E+06
Z = 0.108873E-02 TEMP = 0.270650E+03

PRESSURE (ATM)	= 0.108873E-02	FROZEN MACH NUMBER	= 0.249558E+02
TEMPERATURE (K)	= 0.270650E+03	VELOCITY (CM/S)	= 0.824801E+06
DENSITY (G/CM3)	= 0.142031E-05	FRZ SOUND SPD(CM/S)	= 0.330504E+05
ENTHALPY (CAL/G)	= -.678970E+01	FROZEN GAMMA	= 0.140637E+01
ENTROPY (CAL/G-K)	= 0.208198E+01	MOL.WT. (G/GMOLE)	= 0.289653E+02
PITOT PRESSR (ATM)	= 0.000000E+00	A/W (CM2-S/G)	= 0.853624E+00
TOTAL PRESSR (ATM)	= 0.000000E+00	F/W (DYN-S/G)	= 0.825744E+06
TOTAL TEMP (K)	= 0.000000E+00	F/A (DYN/CM2)	= 0.967339E+06
W/A (G/S-CM2)	= 0.117148E+01		
SENSIBLE ENTHALPY	= -.678970E+01	WT.FRCT.COND.PROD.	= 0.000000E+00
TOTAL ENTH. (CAL/G)	= 0.812033E+04		
EQ.SOUND SPD (CM/S)	= 0.330535E+05	EQ.MACH NUMBER	= 0.249535E+02
EQ.GAMMA	= 0.140663E+01	EQ.CP (ERG/G-K)	= 0.993395E+07
EQ.COMPRSS. (1/ATM)	= 0.918498E+03		

GAS COMPOSITION
TOTAL GAS MOLES = 0.34524102E+01 P/FN = 0.31535505E-03

	PRODUCTS GAS		MOLE-PCT OF GAS	PARTIAL PRESSURE	WEIGHT PCT	MOLE /100-GM	MOLECULAR WEIGHT	
1	A(G)		0.9609	0.10462E-04	1.3250	0.331739E-01	39.941	1
2	H(G)		0.0000	0.15077E-27	0.0000	0.478089E-24	1.008	2
3	HO(G)		0.0000	0.15077E-27	0.0000	0.478091E-24	17.008	3
4	H2(R)		0.0000	0.15077E-27	0.0000	0.478089E-24	2.016	4
5	H2(R)	FRZ1	0.0000	0.78213E-14	0.0000	0.248016E-10	2.016	5
6	H2O2(G)		0.0000	0.15077E-27	0.0000	0.478089E-24	34.016	6
7	N(G)		0.0000	0.15077E-27	0.0000	0.478089E-24	14.008	7
8	NO(G)		0.0000	0.63527E-20	0.0000	0.201447E-16	30.008	8
9	NO2(G)		0.0000	0.14294E-14	0.0000	0.453273E-11	46.008	9
10	O(G)		0.0000	0.15077E-27	0.0000	0.478089E-24	16.000	10
11	HNO(G)		0.0000	0.15077E-27	0.0000	0.478089E-24	31.016	11
12	HO2(G)		0.0000	0.15077E-27	0.0000	0.478089E-24	33.008	12
13	H2O(G)		0.0000	0.14860E-12	0.0000	0.471230E-09	18.016	13
14	N2(G)		78.0882	0.85017E-03	75.5290	0.269592E+01	28.016	14
15	O2(G)		20.9509	0.22810E-03	23.1460	0.723313E+00	32.000	15

******** RAMJET PERFORMANCE ANALYSIS ********

10/24/93

CASE: PC RJPA Test
Scramjet Case F6, Mach 25.0, Z= 155,700, Some Frozen H2 For Inefficienc

DIFFUSER EXIT CONDITIONS

DIFF	= 4	PAR1	= 0.700571E+02
EFF	= 0.977300E+00	AOI	= 0.768355E+05 CM2
ADICAL	= 0.256084E+04 CM2		

PRESSURE (ATM)	= 0.324382E+00	FROZEN MACH NUMBER	= 0.806573E+01
TEMPERATURE (K)	= 0.254091E+04	VELOCITY (CM/S)	= 0.785034E+06
DENSITY (G/CM3)	= 0.447738E-04	FRZ SOUND SPD(CM/S)	= 0.973296E+05
ENTHALPY (CAL/G)	= 0.676107E+03	FROZEN GAMMA	= 0.129045E+01
ENTROPY (CAL/G-K)	= 0.231030E+01	MOL.WT. (G/GMOLE)	= 0.287716E+02
PITOT PRESSR (ATM)	= 0.000000E+00	A/W (CM2-S/G)	= 0.284503E-01
TOTAL PRESSR (ATM)	= 0.000000E+00	F/W (DYN-S/G)	= 0.794386E+06
TOTAL TEMP (K)	= 0.000000E+00	F/A (DYN/CM2)	= 0.279219E+08
W/A (G/S-CM2)	= 0.351490E+02		
SENSIBLE ENTHALPY	= 0.263811E+11	WT.FRCT.COND.PROD.	= 0.000000E+00
EQ.SOUND SPD (CM/S)	= 0.939784E+05	EQ.MACH NUMBER	= 0.835335E+01
EQ.GAMMA	= 0.120312E+01	EQ.CP (ERG/G-K)	= 0.195605E+08
EQ.COMPRSS. (1/ATM)	= 0.143212E-01		

GAS COMPOSITION
TOTAL GAS MOLES = 0.34757373E+01 P/FN = 0.93327507E-01

PRODUCTS GAS		MOLE-PCT OF GAS	PARTIAL PRESSURE	WEIGHT PCT	MOLE /100-GM	MOLECULAR WEIGHT	
1 A(G)		0.9544	0.30960E-02	1.3250	0.331739E-01	39.941	1
2 H(G)		0.0000	0.10600E-10	0.0000	0.113575E-09	1.008	2
3 HO(G)		0.0000	0.77334E-10	0.0000	0.828627E-09	17.008	3
4 H2(R)		0.0000	0.12499E-18	0.0000	0.133925E-17	2.016	4
5 H2(R)	FRZ1	0.0000	0.23147E-11	0.0000	0.248016E-10	2.016	5
6 H2O2(G)		0.0000	0.82519E-23	0.0000	0.884192E-22	34.016	6
7 N(G)		0.0001	0.21195E-06	0.0000	0.227099E-05	14.008	7
8 NO(G)		2.4302	0.78831E-02	2.5347	0.844671E-01	30.008	8
9 NO2(G)		0.0010	0.32855E-05	0.0016	0.352038E-04	46.008	9
10 O(G)		1.3431	0.43568E-02	0.7469	0.466829E-01	16.000	10
11 HNO(G)		0.0000	0.12243E-14	0.0000	0.131178E-13	31.016	11
12 HO2(G)		0.0000	0.22907E-13	0.0000	0.245452E-12	33.008	12
13 H2O(G)		0.0000	0.42295E-17	0.0000	0.453190E-16	18.016	13
14 N2(G)		76.3485	0.24766E+00	74.3453	0.265367E+01	28.016	14
15 O2(G)		18.9227	0.61382E-01	21.0465	0.657702E+00	32.000	15

INPUT MIXTURE

WT. %	HF(C/MOLE)	M.W.	MOLECULAR FORMULA	
0.050000	0.0	2.016	1.0000	FRZ1
0.950000	0.0	2.016	2.0000	H
0.013250	0.0	39.941	1.0000	A
0.231460	0.0	32.000	2.0000	O
0.755290	0.0	28.016	2.0000	N

RESULTING GRAM ATOMS, 5 ELEMENTS

ELEMENT	AT. NO.	AT. WT.	VAL	GRAM ATOMS
H	1	1.008	1.0	2.656108
N	7	14.008	0.0	5.239891
O	8	16.000	-2.0	1.405855
A	18	39.941	0.0	0.032239
FRZ1	111	2.016	0.0	0.069898

```
EQUIVALENCE RATIO       =     0.94465905
STOIC FUEL/OX RATIO     =     0.03069891
FUEL/OX RATIO(WF/WO)    =     0.02900000
OX/FUEL RATIO(WO/WF)    =    34.48275760
MIXTURE WT (GRAMS)      =   100.00000000
MIXTURE ENTH (CAL/G)    =     0.00000000
LOC. EQ. FRAC.          =     0.48577103

CROC OF APR 9, 1991
EXPAN OF NOVEMBER 3, 1986


******** RAMJET PERFORMANCE ANALYSIS ********
---------------------------------------------
                 10/24/93

CASE:  PC RJPA Test
     Scramjet Case F6, Mach 25.0, Z= 155,700, Some Frozen H2 For Inefficienc

COMBUSTOR RESULTS

 WOF  = 0.344828E+02    XI   = 0.100000E+01
 ERGG = 0.999999E+06    WASS = 0.900059E+05 G/S
 ERS  = 0.994377E+00    WAGG = 0.000000E+00 G/S
 ERO  = 0.994377E+00    WF   = 0.261017E+04 G/S
 FSR  = 0.291640E-01    WCE  = 0.926160E+05 G/S
 CEFF =    95.000122%     CF   = 0.000000E+00

 CROCCO EPS      = 0.148927E+01          ACE    = 0.257350E+04 CM2
 PSPCI           = 0.100000E+01          ACI    = 0.256070E+04 CM2
 MCE             = 0.634584E+01          AGG    = 0.119045E+03 CM2
 MCE @ E.L.      = 0.131089E+01          ABASE  = 0.000000E+00 CM2
 PBASE (ATM)     = 0.324382E+00          ATOTAL = 0.267974E+04 CM2
 PGG (ATM)       = 0.361236E+01          RHOGG  = 0.949599E-04 G/CM3
 PMODEL (ATM)    = 0.470405E+00

PRESSURE (ATM)       = 0.532044E+00  FROZEN MACH NUMBER = 0.634584E+01
TEMPERATURE (K)      = 0.302311E+04  VELOCITY (CM/S)    = 0.767647E+06
DENSITY (G/CM3)      = 0.468813E-04  FRZ SOUND SPD(CM/S)= 0.120969E+06
ENTHALPY (CAL/G)     = 0.860008E+03  FROZEN GAMMA       = 0.127257E+01
ENTROPY (CAL/G-K)    = 0.299712E+01  MOL.WT. (G/GMOLE)  = 0.218552E+02
PITOT PRESSR (ATM)   = 0.000000E+00  A/W (CM2-S/G)      = 0.277868E-01
TOTAL PRESSR (ATM)   = 0.000000E+00  F/W (DYN-S/G)      = 0.782628E+06
TOTAL TEMP (K)       = 0.000000E+00  F/A (DYN/CM2)      = 0.281654E+08
W/A (G/S-CM2)        = 0.359883E+02
```

SENSIBLE ENTHALPY = 0.435719E+11 WT.FRCT.COND.PROD. = 0.000000E+00
EQ.SOUND SPD (CM/S)= 0.113835E+06 EQ.MACH NUMBER = 0.674349E+01
EQ.GAMMA = 0.112691E+01 EQ.CP (ERG/G-K) = 0.878737E+08
EQ.COMPRSS. (1/ATM)= 0.910442E-02

GAS COMPOSITION
TOTAL GAS MOLES = 0.45771570E+01 P/FN = 0.11623891E+00

	PRODUCTS GAS		MOLE-PCT OF GAS	PARTIAL PRESSURE	WEIGHT PCT	MOLE /100-GM	MOLECULAR WEIGHT	
1	A(G)		0.7043	0.37474E-02	1.2877	0.322390E-01	39.941	1
2	H(G)		6.1371	0.32652E-01	0.2832	0.280905E+00	1.008	2
3	HO(G)		4.9095	0.26121E-01	3.8220	0.224716E+00	17.008	3
4	H2(R)		6.9948	0.37216E-01	0.6455	0.320165E+00	2.016	4
5	H2(R)	FRZ1	1.5271	0.81248E-02	0.1409	0.698976E-01	2.016	5
6	H2O2(G)		0.0000	0.19015E-06	0.0001	0.163590E-05	34.016	6
7	N(G)		0.0017	0.88845E-05	0.0011	0.764332E-04	14.008	7
8	NO(G)		1.5167	0.80697E-02	2.0833	0.694234E-01	30.008	8
9	NO2(G)		0.0002	0.10295E-05	0.0004	0.885660E-05	46.008	9
10	O(G)		2.6723	0.14218E-01	1.9570	0.122313E+00	16.000	10
11	HNO(G)		0.0001	0.72022E-06	0.0002	0.619601E-05	31.016	11
12	HO2(G)		0.0006	0.31031E-05	0.0009	0.266958E-04	33.008	12
13	H2O(G)		16.4963	0.87768E-01	13.6032	0.755062E+00	18.016	13
14	N2(G)		56.4802	0.30050E+00	72.4266	0.258519E+01	28.016	14
15	O2(G)		2.5590	0.13615E-01	3.7482	0.117131E+00	32.000	15

******** RAMJET PERFORMANCE ANALYSIS ********

10/24/93

CASE: PC RJPA Test
Scramjet Case F6, Mach 25.0, Z= 155,700, Some Frozen H2 For Inefficienc

EQUILIBRIUM NOZZLE EXPANSION TO REQUIRED PRESSURE

EXP = 1 J22 = 1
PEX = 0.182965E+01

PRESSURE (ATM) = 0.847172E-02 FROZEN MACH NUMBER = 0.854971E+01
TEMPERATURE (K) = 0.209857E+04 VELOCITY (CM/S) = 0.815934E+06
DENSITY (G/CM3) = 0.118615E-05 FRZ SOUND SPD(CM/S)= 0.954341E+05
ENTHALPY (CAL/G) = -.534980E+02 FROZEN GAMMA = 0.125851E+01
ENTROPY (CAL/G-K) = 0.299712E+01 MOL.WT. (G/GMOLE) = 0.241045E+02
PITOT PRESSR (ATM) = 0.000000E+00 A/W (CM2-S/G) = 0.103325E+01
TOTAL PRESSR (ATM) = 0.000000E+00 F/W (DYN-S/G) = 0.824805E+06
TOTAL TEMP (K) = 0.000000E+00 F/A (DYN/CM2) = 0.798261E+06
W/A (G/S-CM2) = 0.967818E+00
SENSIBLE ENTHALPY = 0.267895E+11 WT.FRCT.COND.PROD. = 0.000000E+00
EQ.SOUND SPD (CM/S)= 0.911051E+05 EQ.MACH NUMBER = 0.895597E+01
EQ.GAMMA = 0.114693E+01 EQ.CP (ERG/G-K) = 0.362496E+08
EQ.COMPRSS. (1/ATM)= 0.557364E-05
EXIT AREA (CM**2) = 0.956957E+05

GAS COMPOSITION

TOTAL GAS MOLES = 0.41486011E+01 P/FN = 0.20420672E-02

PRODUCTS GAS		MOLE-PCT OF GAS	PARTIAL PRESSURE	WEIGHT PCT	MOLE /100-GM	MOLECULAR WEIGHT	
1 A(G)		0.7771	0.65834E-04	1.2877	0.322390E-01	39.941	1
2 H(G)		0.4228	0.35817E-04	0.0177	0.175396E-01	1.008	2
3 HO(G)		0.9166	0.77654E-04	0.6468	0.380271E-01	17.008	3
4 H2(R)		1.6033	0.13583E-03	0.1341	0.665140E-01	2.016	4
5 H2(R)	FRZ1	1.6848	0.14274E-03	0.1409	0.698976E-01	2.016	5
6 H2O2(C)		0.0000	0.71363E-10	0.0000	0.349467E-07	34.016	6
7 N(G)		0.0000	0.25575E-09	0.0000	0.125240E-06	14.008	7
8 NO(G)		0.2442	0.20684E-04	0.3040	0.101290E-01	30.008	8
9 NO2(G)		0.0000	0.67434E-09	0.0000	0.330223E-06	46.008	9
10 O(G)		0.1758	0.14895E-04	0.1157	0.729410E-02	16.000	10
11 HNO(G)		0.0000	0.99549E-10	0.0000	0.487492E-07	31.016	11
12 HO2(G)		0.0000	0.12562E-08	0.0000	0.615146E-06	33.008	12
13 H2O(G)		29.7391	0.25194E-02	22.2274	0.123376E+01	18.016	13
14 N2(G)		63.0304	0.53398E-02	73.2584	0.261488E+01	28.016	14
15 O2(G)		1.4059	0.11910E-03	1.8664	0.583234E-01	32.000	15

******** RAMJET PERFORMANCE ANALYSIS ********

10/24/93

CASE: PC RJPA Test

Scramjet Case F6, Mach 25.0, Z= 155,700, Some Frozen H2 For Inefficienc

FROZEN NOZZLE EXPANSION TO REQUIRED PRESSURE

```
 EXP   =  1          J22  =  1
 PEX   = 0 180572E-04

PRESSURE (ATM)        = 0.847172E-02  FROZEN MACH NUMBER  = 0.104869E+02
TEMPERATURE (K)       = 0.117209E+04  VELOCITY (CM/S)     = 0.807129E+06
DENSITY (G/CM3)       = 0.192490E-05  FRZ SOUND SPD(CM/S) = 0.769653E+05
ENTHALPY (CAL/G)      = 0.117230E+03  FROZEN GAMMA        = 0.132634E+01
ENTROPY (CAL/G-K)     = 0.299712E+01  MOL.WT. (G/GMOLE)   = 0.218476E+02
PITOT PRESSR (ATM)    = 0.000000E+00  A/W (CM2-S/G)       = 0.643650E+00
TOTAL PRESSR (ATM)    = 0.000000E+00  F/W (DYN-S/G)       = 0.812656E+06
TOTAL TEMP (K)        = 0.000000E+00  F/A (DYN/CM2)       = 0.126257E+07
W/A (G/S-CM2)         = 0.155364E+01
EQ.SOUND SPD (CM/S)   = 0.000000E+00  EQ.MACH NUMBER      = 0.000000E+00
EQ.GAMMA              = 0.000000E+00  EQ.CP (ERG/G-K)     = 0.000000E+00
EQ.COMPRSS. (1/ATM)   = 0.000000E+00
EXIT AREA (CM**2)     = 0.596123E+05
```

GAS COMPOSITION

TOTAL GAS MOLES = 0.45771570E+01 P/FN = 0.18508700E-02

PRODUCTS GAS	MOLE-PCT OF GAS	PARTIAL PRESSURE	WEIGHT PCT	MOLE 100-GM	MOLECULAR WEIGHT	
1 A(G)	0.7043	0.59570E-04	1.2377	0.322390E-01	39.941	1
2 H(G)	6.1371	0.51992E-03	0.2832	0.280905E+00	1.008	2

3	HO(G)		4.9095	0.41592E-03	3.8220	0.224716E+00	17.008	3
4	H2(R)		6.9948	0.59258E-03	0.6455	0.320165E+00	2.016	4
5	H2(R)	FRZ1	1.5271	0.12937E-03	0.1409	0.698976E-01	2.016	5
6	H2O2(G)		0.0000	0.30278E-08	0.0001	0.163590E-05	34.016	6
7	N(G)		0.0017	0.14147E-06	0.0011	0.764332E-04	14.008	7
8	NO(G)		1.5167	0.12849E-03	2.0833	0.694234E-01	30.008	8
9	NO2(G)		0.0002	0.16392E-07	0.0004	0.885660E-05	46.008	9
10	O(G)		2.6723	0.22639E-03	1.9570	0.122313E+00	16.000	10
11	HNO(G)		0.0001	0.11468E-07	0.0002	0.619601E-05	31.016	11
12	HO2(G)		0.0006	0.49411E-07	0.0009	0.266958E-04	33.008	12
13	H2O(G)		16.4963	0.13975E-02	13.6032	0.755062E+00	18.016	13
14	N2(G)		56.4802	0.47848E-02	72.4266	0.258519E+01	28.016	14
15	O2(G)		2.5590	0.21679E-03	3.7482	0.117131E+00	32.000	15

******** RAMJET PERFORMANCE ANALYSIS ********

10/24/93

CASE: PC RJPA Test

Scramjet Case F6, Mach 25.0, Z= 155,700, Some Frozen H2 For Inefficienc

Q0 (DYN/CM2) = 0.483118E+06

COMBINED-- 0.667

NOZZ EFF (%)	THRUST(DYN)	CT	ISP(DYN-S/G)
97.40	-0.64271610E+09	-0.017314	-0.24623534E+06
97.66	-0.44605110E+09	-0.012016	-0.17088969E+06
97.92	-0.24938613E+09	-0.006718	-0.95544016E+05
98.18	-0.52721164E+08	-0.001420	-0.20198363E+05
98.44	0.14396381E+09	0.003878	0.55147297E+05
98.70	0.34060880E+09	0.009176	0.13049295E+06
98.96	0.53727379E+09	0.014474	0.20583861E+06
99.22	0.73393875E+09	0.019772	0.28118425E+06
99.48	0.93060365E+09	0.025070	0.35652991E+06
99.74	0.11272687E+10	0.030368	0.43187559E+06
100.00	0.13239337E+10	0.035666	0.50722125E+06

FROZEN ONLY

NOZZ EFF (%)	THRUST(DYN)	CT	ISP(DYN-S/G)
97.40	-0.99473434E+09	-0.026797	-0.38109944E+06
97.66	-0.79904435E+09	-0.021526	-0.30612731E+06
97.92	-0.60335450E+09	-0.016254	-0.23115523E+06
98.18	-0.40766464E+09	-0.010982	-0.15618319E+06
98.44	-0.21197477E+09	-0.005710	-0.81211094E+05
98.70	0.16284892E+08	0.000439	-0.62390156E+04
98.96	0.17940498E+09	0.004833	0.68733063E+05
99.22	0.37509488E+09	0.010105	0.14370514E+06
99.48	0.57078477E+09	0.015377	0.21867723E+06
99.74	0.76647462E+09	0.020648	0.29364931E+06
100.00	0.96216442E+09	0.025920	0.36862138E+06

EQUILIBRIUM ONLY

NOZZ EFF (%)	THRUST(DYN)	CT	ISP(DYN-S/G)
97.40	0.61425912E+08	0.001655	0.23533297E+05
97.66	0.26004136E+09	0.007005	0.99626219E+05
97.92	0.45865683E+09	0.012356	0.17571914E+06
98.18	0.65727232E+09	0.017706	0.25181206E+06
98.44	0.85588781E+09	0.023057	0.32790500E+06
98.70	0.10545033E+10	0.028408	0.40399791E+06
98.96	0.12531187E+10	0.033758	0.48009084E+06
99.22	0.14517343E+10	0.039109	0.55618381E+06
99.48	0.16503497E+10	0.044459	0.63227669E+06
99.74	0.18489652E+10	0.049810	0.70836963E+06
100.00	0.20475807E+10	0.055160	0.78446256E+06

COMPONENT IMPULSE SUMMARY

DIFFUSER (DYN) = -.282248E+10

COMBUSTOR (DYN) = 0.980444E+09

FROZEN NOZZLE (DYN) = 0.278104E+10

EQUILIBRIUM NOZZLE (DYN) = 0.390627E+10

B.1.7 - Test 1 Input Data File - SI

```
PC FJPA Test
Scramjet Case F10, Mach 25.0, Z= 155,700, Some Frozen H2 For Inefficiency
EJANAF.DAT
5, 1, 1, 1, 1, 1 /
0, 0.050000,      0.0     1.0, 'FRZ1' /
3, 0.950000,      0.0,    2.0, 'H    ' /
0. 0.013250,      0.0.    1.0, 'A    ' /
0, 0.231460.      0.0,    2.0, 'O    ' /
0, 0.755290       0.0,    2.0, 'N    ' /
2.016 /
15, 1,288,300,304,-304,310,330,351,352,381,767,810,1271,1272,1273 /

&FRSTR
 UNITS=SI,INIT=3, PAR=8248.006872, Z=1.103161167E2, TEMP=270.65,
 PITI=0,AREF=7.6835459232, AISS=7.6835459232, AIGG=0.0, WOFINO=1.E11
 &END

&DIFFUSER
  DIFF=4, PAR1=32864.9975, EFF=0.9773, HEAT=0, QDIFF=342829.14,
  PITD=0. GAMG1=1.2, GAMG2=1.3, SWT=0.5 &END

&SHCK
 SHK=0, BET=90.0, DEL=0.0, PITS=0 &END

&COMBUSTOR
 COMB=1, ICOMB=0. FRC= 'NONE', ACE=0.257350453, AWALL=0.64516
 PCEG1=0 00, PCEG2=0.00, PITC=0, PSPCI=1.0000 &END

&HEATFRICTION
 CF=0.0, QWALL=0.0 &END

&MIXER FSR=0.029164, WOFIN=34 482759,XI=1.0 &END

&OXIDIZER
 ACI= 0.25606981, BETA=0.0 &END

&FUEL
 AGG=0.011904492, ALPHA=0.0, HGG=1.039599187E7, MWGG=2.016, NCFIN=1,
 RHOGG=0.09496498, TGG=934.5889, UGG=2308.9362 &END

&PRODUCTS
 ABASE=0.0. PBASE=0 0 &END

&NOZZLE
 EXP=1, EFFN=0.9740, J22=1, PEX=8.583972832E2, PITN=0, RATIOFE=0.6667
 &END
```

B.1.8 - Test 1 Output File - SI

```
                         RAMJET PERFORMANCE ANALYSIS, VERSION 1.24
 PC RJPA Test
 Scramjet Case F10, Mach 25.0, Z= 155,700, Some Frozen H2 For Inefficien
EJANAF.DAT

FOLLOWING DATA READ FROM JANAF THERMOCHEMICAL FILE:
  KEY          NAME                                FORMULA        DATE     HF-298
     1   ARGON                              (G)   A(G)          A0672   0.00000E+00
   288   HYDROGEN, MONATOMIC                (G)   H(G)          J 674   0.52103E+02
   300   HYDROXYL                           (G)   HO(G)         J1270   0.94920E+01
   304   HYDROGEN, DIATOMIC                 (R)   H2(R)         J 361   0.00000E+00
FROZEN SPECIES ===> H2(R)    FRZ1
   310   HYDROGEN PEROXIDE                  (G)   H2O2(G)       J1260  -0.32530E+02
   350   NITROGEN, MONATOMIC                (G)   N(G)          J 361   0.11297E+03
   351   NITRIC OXIDE                       (G)   NO(G)         J 663   0.21580E+02
   352   NITROGEN DIOXIDE                   (G)   NO2(G)        J 964   0.79100E+01
   381   OXYGEN, MONATOMIC                  (G)   O(G)          J 674   0.59553E+02
   767   NITROXYL                           (G)   HNO(G)        J 363   0.23800E+02
   810   HYDROPEROXYL                       (G)   HO2(G)        J 364   0.50000E+01
  1271  WATER-LOW TEMP. FITS                (G)   H2O(G)        A 368  -0.57798E+02
  1272  NITROGEN-LOW TEMP. FITS             (G)   N2(G)         A 368   0.00000E+00
  1273  OXYGEN-LOW TEMP. FITS               (G)   O2(G)         A 368   0.00000E+00

 UNITS = si
 INIT  =  3
     PAR    =  0.82480068E+04
     Z      =  0.11031612E+03
     TEMP   =  0.27064999E+03
     PITI   =  0
     AREF   =  0.76835461E+01
     AISS   =  0.76835461E+01
     AIGG   =  0.00000000E+00
     WOFINO=  0.99999998E+11

 DIFF =  4
     PAR1   =  0.32864996E+05
     EFF    =  0.97729999E+00
     HEAT   =  0
     QDIFF  =  0.34282913E+06
     PITD   =  0
     GAMG1  =  0.12000000E+01
     GAMG2  =  0.13000000E+01
     SWT    =  0.50000000E+00

 SHK   =  0
     BET   =  0.90000000E+02
     DEL   =  0.00000000E+00
     PITS  =  0
```

COMB = 1   ICOMB = 0   FRC = NONE

ABASE	=	0.00000000E+00	ACE	=	0.25735064E+00
ACI	=	0.25606981E+00	AGG	=	0.11904492E-01
ALPHA	=	0.00000000E+00	AWALL	=	0.64516002E+00
BETA	=	0.00000000E+00	CF	=	0.00000000E+00
FSR	=	0.29163999E-01	HGG	=	0.10395592E+08
MWGG	=	0.20160000E+01	NCF	=	2
PBASE	=	0.00000000E+00	PCEG1	=	0.00000000E+00
PCEG2	=	0.00000000E+00	PITC	=	0
PSPCI	=	0.10000000E+01	QWALL	=	0.00000000E+00
RHOGG	=	0.94964981E-01	TGG	=	0.93458893E+03
UGG	=	0.23089363E+04	WOFIN	=	0.34482738E+02
XI	=	0.10000000E+01			

EXP = 1

EFFN	=	0.97399998E+00
J22	=	1
PEX	=	0.85839728E+03
PITN	=	0
RATIOFE	=	0.66670001E+00

RJPA OF SEPTEMBER 12, 1988

INPUT MIXTURE

WT. %	HF(C/MOLE)	M.W.	MOLECULAR	FORMULA
0.050000	0.0	2.016	1.0000	FRZ1
0.950000	0.0	2.016	2.0000	H
0.013250	0.0	39.941	1.0000	A
0.231460	0.0	32.000	2.0000	O
0.755290	0.0	28.016	2.0000	N

RESULTING GRAM ATOMS, 5 ELEMENTS

ELEMENT	AT. NO.	AT. WT.	VAL	GRAM ATOMS
H	1	1.008	1.0	0.000000
N	7	14.008	0.0	5.391847
O	8	16.000	-2.0	1.446625
A	18	39.941	0.0	0.033174
FRZ1	111	2.016	0.0	0.000000

EQUIVALENCE RATIO	=	0.00000000
STOIC FUEL/OX RATIO	=	0.03069891
FUEL/OX RATIO(WF/WO)	=	0.00000000
OX/FUEL RATIO(WO/WF)	=	***************
MIXTURE WT (Kg)	=	0.10000000
MIXTURE ENTH (J/Kg)	=	0.00000000
ROC. EQ. FRAC.	=	0.00000000

DIF OF JAN. 17, 1989

******** RAMJET PERFORMANCE ANALYSIS ********

10/24/93

CASE: PC RJPA Test

Scramjet Case F10, Mach 25.0, Z= 155,700, Some Frozen H2 For Ineffícien

INLET CONDITIONS

INIT	= 3	PAR	= 0.824801E+04
Z	= 0.110316E+03	TEMP	= 0.270650E+03

PRESSURE (Pa)	= 0.110316E+03	FROZEN MACH NUMBER	= 0.249558E+02
TEMPERATURE (K)	= 0.270650E+03	VELOCITY (M/S)	= 0.824801E+04
DENSITY (Kg/M3)	= 0.142031E-02	FRZ SOUND SPD (M/S)	= 0.330504E+03
ENTHALPY (J/Kg)	= -.284271E+05	FROZEN GAMMA	= 0.140637E+01
ENTROPY (J/Kg-K)	= 0.871684E+04	MOL.WT. (Kg/KgMOLE)	= 0.289653E+02
PITOT PRESSURE (Pa)	= 0.000000E+00	A/W (M2-S/Kg)	= 0.853624E-01
TOTAL PRESSURE (Pa)	= 0.000000E+00	F/W (N-S/Kg)	= 0.825743E+04
TOTAL TEMP (K)	= 0.000000E+00	F/A (Pa)	= 0.967339E+05
W/A (Kg/S-M2)	= 0.117148E+02		
SENSIBLE ENTHALPY	= -.284271E+05	WT.FRCT.COND.PROD.	= 0.000000E+00
TOTAL ENTH. (J/KG)	= 0.339982E+08		
EQ.SOUND SPD (M/S)	= 0.330534E+03	EQ.MACH NUMBER	= 0.249535E+02
EQ.GAMMA	= 0.140663E+01	EQ.CP (J/KG-K)	= 0.993395E+03
EQ.COMPRESS. (1/Pa)	= 0.906488E-02		

GAS COMPOSITION

TOTAL GAS MOLES = 0.34524102E+01 P/FN = 0.31535517E-03

	PRODUCTS GAS		MOLE-PCT OF GAS	PARTIAL PRESSURE	WEIGHT PCT	MOLE /100-GM	MOLECULAR WEIGHT	
1	A(G)		0.9609	0.10600E+01	1.3250	0.331739E-01	39.941	1
2	H(G)		0.0000	0.15277E-22	0.0000	0.478089E-24	1.008	2
3	HO(G)		0.0000	0.15277E-22	0.0000	0.478091E-24	17.008	3
4	H2(R)		0.0000	0.15277E-22	0.0000	0.478089E-24	2.016	4
5	H2(R)	FRZ1	0.0000	0.79249E-09	0.0000	0.248016E-10	2.016	5
6	H2O2(G)		0.0000	0.15277E-22	0.0000	0.478089E-24	34.016	6
7	N(G)		0.0000	0.15277E-22	0.0000	0.478089E-24	14.008	7
8	NO(G)		0.0000	0.64369E-15	0.0000	0.201447E-16	30.008	8
9	NO2(G)		0.0000	0.14484E-09	0.0000	0.453274E-11	46.008	9
10	O(G)		0.0000	0.15277E-22	0.0000	0.478089E-24	16.000	10
11	HNO(G)		0.0000	0.15277E-22	0.0000	0.478089E-24	31.016	11
12	HO2(G)		0.0000	0.15277E-22	0.0000	0.478089E-24	33.008	12
13	H2O(G)		0.0000	0.15057E-07	0.0000	0.471230E-09	18.016	13
14	N2(G)		78.0882	0.86144E+02	75.5290	0.269592E+01	28.016	14
15	O2(G)		20.9509	0.23112E+02	23.1460	0.723313E+00	32.000	15

******** RAMJET PERFORMANCE ANALYSIS ********

10/24/93

CASE: PC RJPA Test
Scramjet Case F10, Mach 25.0, Z= 155,700, Some Frozen H2 For Inefficien

DIFFUSER EXIT CONDITIONS

DIFF	= 4	PAR1	= 0.691346E-03
EFF	= 0.977300E+00	AOI	= 0.768355E+01 M2
ADICAL	= 0.256103E+00 M2		

PRESSURE (Pa)	= 0.328650E+05	FROZEN MACH NUMBER	= 0.806580E+01
TEMPERATURE (K)	= 0.254088E+04	VELOCITY (M/S)	= 0.785035E+04
DENSITY (Kg/M3)	= 0.447704E-01	FRZ SOUND SPD (M/S)	= 0.973288E+03
ENTHALPY (J/Kg)	= 0.283065E+07	FROZEN GAMMA	= 0.129045E+01
ENTROPY (J/Kg-K)	= 0.967275E+04	MOL.WT. (Kg/KgMOLE)	= 0.287716E+02
PITOT PRESSURE (Pa)	= 0.000000E+00	A/W (M2-S/Kg)	= 0.284525E-02
TOTAL PRESSURE (Pa)	= 0.000000E+00	F/W (N-S/Kg)	= 0.794387E+04
TOTAL TEMP (K)	= 0.000000E+00	F/A (Pa)	- 0.279198E+07
W/A (Kg/S-M2)	= 0.351463E+03		
SENSIBLE ENTHALPY	= 0.263806E+07	WT.FRCT.COND.PROD.	= 0.000000E+00
EQ.SOUND SPD (M/S)	= 0.939780E+03	EQ.MACH NUMBER	= 0.835340E+01
EQ.GAMMA	= 0.120312E+01	EQ.CP (J/KG-K)	= 0.195600E+04
EQ.COMPRESS. (1/Pa)	= 0.145123E+04		

GAS COMPOSITION

TOTAL GAS MOLES = 0.34757335E+01 P/FN = 0.93319088E-01

	PRODUCTS GAS		MOLE-PCT OF GAS	PARTIAL PRESSURE	WEIGHT PCT	MOLE /100-GM	MOLECULAR WEIGHT	
1	A(G)		0.9544	0.31368E+03	1.3250	0.331739E-01	39.941	1
2	H(G)		0.0000	0.10738E-05	0.0000	0.113567E-09	1.008	2
3	HO(G)		0.0000	0.78352E-05	0.0000	0.828634E-09	17.008	3
4	H2(R)		0.0000	0.12664E-13	0.0000	0.133933E-17	2.016	4
5	H2(R)	FRZ1	0.0000	0.23451E-06	0.0000	0.248016E-10	2.016	5
6	H2O2(G)		0.0000	0.83610E-18	0.0000	0.884246E-22	34.016	6
7	N(G)		0.0001	0.21468E-01	0.0000	0.227037E-05	14.008	7
8	NO(G)		2.4301	0.79864E+03	2.5346	0.844625E-01	30.008	8
9	NO2(G)		0.0010	0.332885E+00	0.0016	0.352016E-04	46.008	9
10	O(G)		1.3429	0.44136E+03	0.7468	0.466773E-01	16.000	10
11	HNO(G)		0.0000	0.12403E-09	0.0000	0.131169E-13	31.016	11
12	HO2(G)		0.0000	0.23208E-08	0.0000	0.245447E-12	33.008	12
13	H2O(G)		0.0000	0.42860E-12	0.0000	0.453277E-16	18.016	13
14	N2(G)		76.3486	0.25092E+05	74.3454	0.265367E+01	28.016	14
15	O2(G)		18.9228	0.62190E+04	21.0466	0.657708E+00	32.000	15

INPUT MIXTURE

WT. %	HF(C/MOLE)	M.W.	MOLECULAR FORMULA	
0.050000	0.0	2.016	1.0000	FRZ1
0.950000	0.0	2.016	2.0000	H
0.013250	0.0	39.941	1.0000	A
0.231460	0.0	32.000	2.0000	O
0.755290	0.0	28.016	2.0000	N

RESULTING GRAM ATOMS, 5 ELEMENTS

ELEMENT	AT. NO.	AT. WT.	VAL	GRAM ATOMS
H	1	1.008	1.0	2.656108
N	7	14.008	0.0	5.239891
O	8	16.000	-2.0	1.405855
A	18	39.941	0.0	0.032239
FRZ1	111	2.016	0.0	0.069898

EQUIVALENCE RATIO	=	0.94465905
STOIC FUEL/OX RATIO	=	0.03069891
FUEL/OX RATIO(WF/WO)	=	0.02900000
OX/FUEL RATIO(WO/WF)	=	34.48275760
MIXTURE WT (Kg)	=	0.10000000
MIXTURE ENTH (J/Kg)	=	0.00000000
ROC. EQ. FRAC.	=	0.48577103

CROC OF APR 9, 1991
EXPAN OF NOVEMBER 3, 1986

******** RAMJET PERFORMANCE ANALYSIS ********

10/24/93

CASE: PC RJPA Test
Scramjet Case F10, Mach 25.0, Z= 155,700, Some Frozen H2 For Inefficien

COMBUSTOR RESULTS

WOF	= 0.344828E+02	XI	= 0.100000E+01
ERGG	= 0.999999E+06	WASS	= 0.899991E+02 KG/S
ERS	= 0.994377E+00	WAGG	= 0.000000E+00 KG/S
ERO	= 0.994377E+00	WF	= 0.260997E+01 KG/S
FSR	= 0.291640E-01	WCE	= 0.926091E+02 KG/S
CEFF	= 95.000130%	CF	= 0.000000E+00

CROCCO EPS	= 0.148928E+01	ACE	= 0.257350E+00 M2
PSPCI	= 0.100000E+01	ACI	= 0.256070E+00 M2
MCE	= 0.634587E+01	AGG	= 0.119045E-01 M2
MCE @ E.L.	= 0.131090E+01	ABASE	= 0.000000E+00 M2
PBASE (Pa)	= 0.328650E+05	ATOTAL	= 0.267974E+00 M2
PGG (Pa)	= 0.365999E+06	RHOGG	= 0.949540E-01 KG/M3
PMODEL (Pa)	= 0.476599E+05		

PRESSURE (Pa)	= 0.539048E+05	FROZEN MACH NUMBER	= 0.634587E+01
TEMPERATURE (K)	= 0.302310E+04	VELOCITY (M/S)	= 0.767648E+04
DENSITY (Kg/M3)	= 0.468777E-01	FRZ SOUND SPD (M/S)	= 0.120968E+04
ENTHALPY (J/Kg)	= 0.360062E+07	FROZEN GAMMA	= 0.127257E+01
ENTROPY (J/Kg-K)	= 0.125484E+05	MOL.WT. (Kg/KgMOLE)	= 0.218552E+02
PITOT PRESSURE (Pa)	= 0.000000E+00	A/W (M2-S/Kg)	= 0.277889E-02
TOTAL PRESSURE (Pa)	= 0.000000E+00	F/W (N-S/Kg)	= 0.782628E+04
TOTAL TEMP (K)	= 0.000000E+00	F/A (Pa)	= 0.281633E+07

W/A (Kg/S-M2)	= 0.359856E+03		
SENSIBLE ENTHALPY	= 0.435716E+07	WT.FRCT.COND.PROD.	= 0.000000E+00
EQ.SOUND SPD (M/S)	= 0.113835E+04	EQ.MACH NUMBER	= 0.674352E+01
EQ.GAMMA	= 0.112691E+01	EQ.CP (J/KG-K)	= 0.878736E+04
EQ.COMPRESS. (1/Pa)	= 0.922582E+03		

GAS COMPOSITION

TOTAL GAS MOLES = 0.45771523E+01 P/FN = 0.11622931E+00

PRODUCTS GAS		MOLE-PCT OF GAS	PARTIAL PRESSURE	WEIGHT PCT	MOLE /100-GM	MOLECULAR WEIGHT	
1 A(G)		0.7043	0.37968E+03	1.2877	0.322390E-01	39.941	1
2 H(G)		6.1370	0.33082E+04	0.2831	0.280901E+00	1.008	2
3 HO(G)		4.9095	0.26464E+04	3.8219	0.224713E+00	17.008	3
4 H2(R)		6.9948	0.37705E+04	0.6454	0.320162E+00	2.016	4
5 H2(R)	FRZ1	1.5271	0.82318E+03	0.1409	0.698976E-01	2.016	5
6 H2O2(G)		0.0000	0.19265E-01	0.0001	0.163580E-05	34.016	6
7 N(G)		0.0017	0.90009E+00	0.0011	0.764282E-04	14.008	7
8 NO(G)		1.5167	0.81758E+03	2.0832	0.694222E-01	30.008	8
9 NO2(G)		0.0002	0.10430E+00	0.0004	0.885624E-05	46.008	9
10 O(G)		2.6722	0.14405E+04	1.9570	0.122311E+00	16.000	10
11 HNO(G)		0.0001	0.72965E-01	0.0002	0.619559E-05	31.016	11
12 HO2(G)		0.0006	0.31438E+00	0.0009	0.266946E-04	33.008	12
13 H2O(G)		16.4964	0.88924E+04	13.6033	0.755067E+00	18.016	13
14 N2(G)		56.4803	0.30446E+05	72.4266	0.258519E+01	28.016	14
15 O2(G)		2.5590	0.13794E+04	3.7482	0.117131E+00	32.000	15

******** RAMJET PERFORMANCE ANALYSIS ********

10/24/93

CASE: PC RJPA Test

Scramjet Case F10, Mach 25.0, Z= 155,700, Some Frozen H2 For Inefficien

EQUILIBRIUM NOZZLE EXPANSION TO REQUIRED PRESSURE

EXP = 1 J22 = 1

PEX = 0.180572E-04

PRESSURE (Pa)	= 0.858397E+03	FROZEN MACH NUMBER	= 0.854969E+01
TEMPERATURE (K)	= 0.209858E+04	VELOCITY (M/S)	= 0.815934E+04
DENSITY (Kg/M3)	= 0.118614E-02	FRZ SOUND SPD (M/S)	= 0.954343E+03
ENTHALPY (J/Kg)	= -.223957E+06	FROZEN GAMMA	= 0.125851E+01
ENTROPY (J/Kg-K)	= 0.125484E+05	MOL.WT. (Kg/KgMOLE)	= 0.241045E+02
PITOT PRESSURE (Pa)	= 0.000000E+00	A/W (M2-S/Kg)	= 0.103326E+00
TOTAL PRESSURE (Pa)	= 0.000000E+00	F/W (N-S/Kg)	= 0.824804E+04
TOTAL TEMP (K)	= 0.000000E+00	F/A (Pa)	= 0.798257E+05
W/A (Kg/S-M2)	= 0.967814E+01		
SENSIBLE ENTHALPY	= 0.267896E+07	WT.FRCT.COND.PROD.	= 0.000000E+00
EQ.SOUND SPD (M/S)	= 0.911055E+03	EQ.MACH NUMBER	= 0.895592E+01
EQ.GAMMA	= 0.114694E+01	EQ.CP (J/KG-K)	= 0.362488E+04
EQ.COMPRESS. (1/Pa)	= 0.557361E+05		
EXIT AREA (M**2)	= 0.956889E+01		

GAS COMPOSITION

TOTAL GAS MOLES = 0.41486049E+01 P/FN = 0.20420651E-02

	PRODUCTS GAS		MOLE-PCT OF GAS	PARTIAL PRESSURE	WEIGHT PCT	MOLE /100-GM	MOLECULAR WEIGHT	
1	A(G)		0.7771	0.66706E+01	1.2877	0.322390E-01	39.941	1
2	H(G)		0.4228	0.36294E+01	0.0177	0.175406E-01	1.008	2
3	HO(G)		0.9167	0.78685E+01	0.6468	0.380282E-01	17.008	3
4	H2(R)		1.6033	0.13763E+02	0.1341	0.665162E-01	2.016	4
5	H2(R)	FRZ1	1.6848	0.14463E+02	0.1409	0.698976E-01	2.016	5
6	H2O2(G)		0.0000	0.72310E-05	0.0000	0.349474E-07	34.016	6
7	N(G)		0.0000	0.25916E-04	0.0000	0.125251E-06	14.008	7
8	NO(G)		0.2442	0.20959E+01	0.3040	0.101293E-01	30.008	8
9	NO2(G)		0.0000	0.68328E-04	0.0000	0.330228E-06	46.008	9
10	O(G)		0.1758	0.15093E+01	0.1167	0.729449E-02	16.000	10
11	HNO(G)		0.0000	0.10087E-04	0.0000	0.487512E-07	31.016	11
12	HO2(G)		0.0000	0.12729E-03	0.0000	0.615168E-06	33.008	12
13	H2O(G)		29.7390	0.25528E+03	22.2273	0.123375E+01	18.016	13
14	N2(G)		63.0304	0.54105E+03	73.2585	0.261488E+01	28.016	14
15	O2(G)		1.4059	0.12068E+02	1.8664	0.583245E-01	32.000	15

******** RAMJET PERFORMANCE ANALYSIS ********

10/24/93

CASE: PC RJPA Test

Scramjet Case F10, Mach 25.0, Z= 155,700, Some Frozen H2 For Inefficien

FROZEN NOZZLE EXPANSION TO REQUIRED PRESSURE

EXP = 1 J22 = 1

PEX = 0.180572E-04

PRESSURE (Pa)	= 0.858397E+03	FROZEN MACH NUMBER	= 0.104868E+02
TEMPERATURE (K)	= 0.117211E+04	VELOCITY (M/S)	= 0.807129E+04
DENSITY (Kg/M3)	= 0.192487E-02	FRZ SOUND SPD (M/S)	= 0.769658E+03
ENTHALPY (J/Kg)	= 0.490820E+06	FROZEN GAMMA	= 0.132834E+01
ENTROPY (J/Kg-K)	= 0.125484E+05	MOL.WT. (Kg/KgMOLE)	= 0.218476E+02
PITOT PRESSURE (Pa)	= 0.000000E+00	A/W (M2-S/Kg)	= 0.643660E-01
TOTAL PRESSURE (Pa)	= 0.000000E+00	F/W (N-S/Kg)	= 0.812656E+04
TOTAL TEMP (K)	= 0.000000E+00	F/A (Pa)	= 0.126255E+06
W/A (Kg/S-M2)	= 0.155362E+02		
EQ.SOUND SPD (M/S)	= 0.000000E+00	EQ.MACH NUMBER	= 0.000000E+00
EQ.GAMMA	= 0.000000E+00	EQ.CP (J/KG-K)	= 0.000000E+00
EQ.COMPRESS. (1/Pa)	= 0.000000E+00		
EXIT AREA (M**2)	= 0.596087E+01		

GAS COMPOSITION

TOTAL GAS MOLES = 0.45771523E+01 P/FN = 0.18508717E-02

	PRODUCTS GAS	MOLE-PCT OF GAS	PARTIAL PRESSURE	WEIGHT PCT	MOLE /100-GM	MOLECULAR WEIGHT	
1	A(G)	0.7043	0.60461E+01	1.2877	0.322390E-01	39.941	1

2	H(G)		6.1370	0.52680E+02	0.2831	0.280901E+00	1.008	2
3	HO(G)		4.9095	0.42143E+02	3.8219	0.224713E+00	17.008	3
4	H2(R)		6.9948	0.60043E+02	0.6454	0.320162E+00	2.016	4
5	H2(R)	FRZ1	1.5271	0.13109E+02	0.1409	0.698976E-01	2.016	5
6	H2O2(G)		0.0000	0.30678E-03	0.0001	0.163580E-05	34.016	6
7	N(G)		0.0017	0.14333E-01	0.0011	0.764282E-04	14.008	7
8	NO(G)		1.5167	0.13019E+02	2.0832	0.694222E-01	30.008	8
9	NO2(G)		0.0002	0.16609E-02	0.0004	0.885624E-05	46.008	9
10	O(G)		2.6722	0.22938E+02	1.9570	0.122311E+00	16.000	10
11	HNO(G)		0.0001	0.11619E-02	0.0002	0.619559E-05	31.016	11
12	HO2(G)		0.0006	0.50063E-02	0.0009	0.266946E-04	33.008	12
13	H2O(G)		16.4964	0.14160E+03	13.6033	0.755067E+00	18.016	13
14	N2(G)		56.4803	0.48483E+03	72.4266	0.258519E+01	28.016	14
15	O2(G)		2.5590	0.21967E+02	3.7482	0.117131E+00	32.000	15

******** RAMJET PERFORMANCE ANALYSIS ********

10/24/93

CASE: PC RJPA Test
Scramjet Case F10, Mach 25.0, Z= 155,700, Some Frozen H2 For Inefficien

Q0 (Pa) = 0.483118E+05

COMBINED-- 0.667

NOZZ EFF (%)	THRUST(N)	CT	ISP(N-S/KG)
97.40	-0.64267271E+04	-0.017313	-0.24623727E+03
97.66	-0.44602256E+04	-0.012016	-0.17089162E+03
97.92	-0.24937239E+04	-0.006718	-0.95545952E+02
98.18	-0.52722253E+03	-0.001420	-0.20200304E+02
98.44	0.14392789E+04	0.003877	0.55145348E+02
98.70	0.34057805E+04	0.009175	0.13049101E+03
98.96	0.53722822E+04	0.014473	0.20583665E+03
99.22	0.73387832E+04	0.019770	0.28118228E+03
99.48	0.93052852E+04	0.025068	0.35652802E+03
99.74	0.11271786E+05	0.030365	0.43187363E+03
100.00	0.13238287E+05	0.035663	0.50721930E+03

FROZEN ONLY

NOZZ EFF (%)	THRUST(N)	CT	ISP(N-S/KG)
97.40	-0.99465586E+04	-0.026795	-0.38109811E+03
97.66	-0.79898071E+04	-0.021524	-0.30612601E+03
97.92	-0.60330557E+04	-0.016253	-0.23115392E+03
98.18	-0.40763042E+04	-0.010981	-0.15618182E+03
98.44	-0.21195530E+04	-0.005710	-0.81209755E+02
98.70	-0.16280141E+03	-0.000439	-0.62376657E+01
98.96	0.17939501E+04	0.004833	0.68734421E+02
99.22	0.37507014E+04	0.010104	0.14370651E+03
99.48	0.57074526E+04	0.015375	0.21867859E+03
99.74	0.76642041E+04	0.020647	0.29365067E+03
100.00	0.96209561E+04	0.025918	0.36862277E+03

EQUILIBRIUM ONLY

NOZZ EFF (%)	THRUST(N)	CT	ISP(N-S/KG)
97.40	0.61399249E+03	0.001654	0.23524858E+02
97.66	0.25999968E+04	0.007004	0.99617760E+02
97.92	0.45860015E+04	0.012354	0.17571066E+03
98.18	0.65720059E+04	0.017704	0.25180356E+03
98.44	0.85580098E+04	0.023055	0.32789645E+03
98.70	0.10544015E+05	0.028405	0.40398941E+03
98.96	0.12530019E+05	0.033755	0.48008228E+03
99.22	0.14516023E+05	0.039105	0.55617523E+03
99.48	0.16502027E+05	0.044455	0.63226807E+03
99.74	0.18488031E+05	0.049805	0.70836096E+03
100.00	0.20474037E+05	0.055155	0.78445386E+03

COMPONENT IMPULSE SUMMARY

DIFFUSER (N) = -.282241E+05
COMBUSTOR (N) = 0.974960E+04
FROZEN NOZZLE (N) = 0.278078E+05
EQUILIBRIUM NOZZLE (N) = 0.390589E+05

B.2.1 - Test 2 File SI-FRC

```
 PC RJPA Test Calibration Run
 Scramjet Case F11, Mach 25.0, Z= 39272, No Frozen H2, Crocco =1.0
EJANAF.DAT
 5, 1, 1, 1, 1, 1 /
 3, 1.000000,     0.0,   2.0, 'H   ' /
 0, 0.013250,     0.0,   1.0, 'A   ' /
 0, 0.231460,     0.0,   2.0, 'O   ' /
 0, 0.755290      0.0,   2.0, 'N   ' /
 2.016 /
 14, 1,288,300,304,310,350,351,352,381,767,810,1271,1272,1273 /
 &FRSTR
  init=3, units=si,
  par=8248.006372,   z=1.103161167E2,temp=270.65, piti=0,
  aref=7.6835459232,  aiss=7.6835459232, aigg=0.0,
  WOFINO=1.E11, &END

 &DIFFUSER
   DIFF=1,    PAR1=0.257350453, EFF=0.9773,
   HEAT=0,    QDIFF=342829.1400, PITD=0,
   GAMG1=1.2, GAMG2=1.3,     SWT=0.5 &END

 &SHCK   SHK=0, BET=90.0, DEL=0.0, PITS=0 &END

 &COMBUSTOR
  COMB=6,       ICOMB=0,      FRC= 'TEST6',
  ISPLINE=2, NOUT=1, ARTOL=1E-6
  XATB=0.0,          0.001,       40.0,       800.00,
  AATB=0.26305143, 0.26305143, 0.26305143, 0.26305143, NATB=4,
  MAXSTP=8000, PRINT=40.00,
  NPRNTS=1, &END

 &HEATFRICTION  &END

 &MIXER MX=3,IWOFER=0, FSR=0.029164,
 naa=7, xda=0.0,0.01,0.05,0.5,1.0,40.0,800.0, daa=0.0,1.0,1.0,1.0,1.0,
    1.0,1.0,
 nff=7, xdf=0.0,0.01,0.05,0.5,1.0,40.0,800.0, dff=0.0,1.0,1.0,1.0,1.0,
    1.0,1.0,  &END

 &OXIDIZER  BETA=0.0, DPODX=-4.053E5, INERTO='ar' &END

 &FUEL  AGG=.570093E-2, TGG=934.5889, UGG=4.66084E3,
  PGG=3.8084e5, DPFDX=-4.053E5, alpha=0.0 &END

 &PRODUCTS  ALLMIP=F, ABASE=2.55e-5,   TPP=1200., MACHP=1.5, INERTP='ar',
  pbase=3.03475E5, DPPDX=-4.053E5 &END

 &NOZZLE
  EXP=0, EFFN=0.9740, J22=1,
  PEX=8.58397282E2, PITN=0, RATIOFE=0.6667 &END
```

B.2.2 - Chemistry Input File - Test 6

```
  Stream 1 - air
   o       +   o       =   o2      +   m          6.0e+17   0.        -1800.
   o       +   no2     =   no      +   o2         1.0e+13    0.       600.
   m       +   no2     =   no      +   o         1.16e+16   0.        66000.
   n       +   o2      =   no      +   o           6.4e+9   1.        6300.
   n       +   n       =   n2      +   m          2.8e+17   -.75      0.
   n       +   no      =   n2      +   o          1.6e+13   0.        0.
END     ENTER THIRD BODY EFFICIENCIES FOR STREAM 1 BELOW THIS LINE
END     ENTER STREAM 2 REACTIONS BELOW THIS LINE
  Stream 2 - hydrogen
   h       +   h       =   h2      +   m          8.3e+17   -1.        0.
END     ENTER THIRD BODY EFFICIENCIES FOR STREAM 2 BELOW THIS LINE
END     ENTER INITIAL MOLE FRACTIONS OF STREAM 2 BELOW THIS LINE
h2        .99
h         .01
END     ENTER STREAM 3 REACTIONS BELOW THIS LINE
  Stream 3 hydrogen - air reaction
   h       +   o2      =   oh      +   o          2.6e+14   0.        16800.
   o       +   h2      =   oh      +   h          1.8e+10   1.        8900.
   h2      +   oh      =   h2o     +   h          2.2e+13   0.        5150.
   oh      +   oh      =   o       +   h2o        6.3e+12   0.        1090.
   h       +   o2      =   ho2     +   m          2.1e+15    0.       -1000.
   o       +   o       =   o2      +   m          6.0e+17   0.        -1800.
   h       +   h       =   h2      +   m          6.4e+17   -1.        0.
   h       +   oh      =   h2o     +   m          2.2e+22   -2.       0.
   m       +   h2o2    =2.0oh                     1.2e+17  0.        45500.
   h2      +   o2      =2.0oh                    1.70e+13  0.        48000.
   h       +   ho2     =   oh      +   oh         1.4e+14   0.        1080.
   o       +   ho2     =   oh      +   o2         1.5e+13   0.        950.
   oh      +   ho2     =   h2o     +   o2         8.0e+12   0.        0.
              2.0ho2   =   h2o2    +   o2        2.00e+12  0.        0.
   ho2     +   no      =   no2     +   oh         3.4e+12    0.       -260.
   o       +   no2     =   no      +   o2         1.0e+13    0.       600.
   m       +   no2     =   no      +   o         1.16e+16   0.        66000.
   no2     +   h       =   no      +   oh         3.5e+14   0.        1500.
   n       +   o2      =   no      +   o           6.4e+9   1.        6300.
   h       +   o       =   oh      +   m          6.0e+16   -.6       0.
   n       +   oh      =   no      +   h         6.3e+11    0.5       0.
   ho2     +   h       =   h2      +   o2        1.30e+13   0.        0.
   ho2     +   h       =   h2o     +   o          1.0e+13   0.        1080.
   h       +   h2o2    =   h2      +   ho2        1.4e+12   0.        3690.
   o       +   h2o2    =   oh      +   ho2        1.4e+13   0.        6400.
   oh      +   h2o2    =   h2o     +   ho2        6.1e+12   0.        1430.
   n       +   n       =   n2      +   m          2.8e+17   -.75      0.
   n       +   no      =   n2      +   o          1.6e+13   0.        0.
   h       +   no      =   hno     +   m          5.4e+15   0.        -600.
   h       +   hno     =   no      +   h2         4.8e+12   0.        0.
   o       +   hno     =   no      +   oh         5.0e+11    .50      0.
   oh      +   hno     =   no      +   h2o        3.6e+13   0.        0.
   ho2     +   hno     =   no      +   h2o2       2.0e+12   0.        0.
```

```
END      ENTER THIRD BODY EFFICIENCIES FOR STREAM 3 BELOW THIS LINE
   h        +   o2      =   ho2     +   m       h2       2.0
   same                                         h2o     16.0
   h            h       =   h2      +   m       h2       2.0
   same                                         h2o      6.0
   m        +   h2o2    =2.0oh                  h2o     15.0
   h        +   oh      =   h2o     +   m       h2o      6.0
   h        +   o       =   oh      +   m       h2o      5.0
END      ENTER INTIAL MOLE FRACTIONS FOR STREAM 3 BELOW THIS LINE
ar        .00536
h2o       .33864
no        .00041
n2        .44843
oh        .00003
o2        .20713
END      ENTER THE WORD "FINAL" BELOW THIS LINE
FINAL
```

B.2.3 - Test 2 Output File - SI-FRC

```
                    RAMJET PERFORMANCE ANALYSIS, VERSION 1.24
 PC RJPA Test Calibration Run
 Scramjet Case F11, Mach 25.0, Z= 155,700, No Frozen H2, Crocco =1.0
EJANAF.DAT

FOLLOWING DATA READ FROM JANAF THERMOCHEMICAL FILE:
  KEY          NAME                              FORMULA       DATE     HF-298
     1   ARGON                            (G)   A(G)          A0672   0.00000E+00
   288   HYDROGEN, MONATOMIC              (G)   H(G)          J 674   0.52103E+02
   300   HYDROXYL                         (G)   HO(G)         J1270   0.94920E+01
   304   HYDROGEN, DIATOMIC               (R)   H2(R)         J 361   0.00000E+00
   310   HYDROGEN PEROXIDE                (G)   H2O2(G)       J1260  -0.32530E+02
   350   NITROGEN, MONATOMIC              (G)   N(G)          J 361   0.11297E+03
   351   NITRIC OXIDE                     (G)   NO(G)         J 663   0.21580E+02
   352   NITROGEN DIOXIDE                 (G)   NO2(G)        J 964   0.79100E+01
   381   OXYGEN, MONATOMIC                (G)   O(G)          J 674   0.59553E+02
   767   NITROXYL                         (G)   HNO(G)        J 363   0.23800E+02
   810   HYDROPEROXYL                     (G)   HO2(G)        J 364   0.50000E+01
  1271 WATER-LOW TEMP. FITS               (G)   H2O(G)        A 368  -0.57798E+02
  1272 NITROGEN-LOW TEMP. FITS            (G)   N2(G)         A 368   0.00000E+00
  1273 OXYGEN-LOW TEMP. FITS              (G)   O2(G)         A 368   0.00000E+00

 UNITS = si
 INIT  =  3
     PAR    =  0.82480068E+04
     Z      =  0.11031612E+03
     TEMP   =  0.27064999E+03
     PITI   =  0
     AREF   =  0.76835461E+01
     AISS   =  0.76835461E+01
     AIGG   =  0.00000000E+00
     WOFINO=   0.99999998E+11

 DIFF =  1
     PAR1   =  0.25735044E+00
     EFF    =  0.97729999E+00
     HEAT   =  0
     QDIFF  =  0.34282913E+06
     PITD   =  0
     GAMG1  =  0.12000000E+01
     GAMG2  =  0.13000000E+01
     SWT    =  0.50000000E+00

 SHK  =  0
     BET  =  0.90000000E+02
     DEL  =  0.00000000E+00
     PITS =  0

 COMB =  6      ICOMB =  0      FRC = TEST6
 ISTREAM =                 3      ARTOL =  0.10000000E-05
 DJ      =  0.10132500E+06      PNORM =  0.99999998E-02
```

```
ISPLINE = 2      NATB =   4
XATB =   0.00000000E+00   0.10000000E-02   0.40000000E+02   0.80000000E+03
AATB =   0.26305142E+00   0.26305142E+00   0.26305142E+00   0.26305142E+00


IENV1  = 0

IENV2  = 0

IENV3  = 0

IQST1  = 0

IQST2  = 0

MX   =    3      PTOLI   =   0.10132500E-02
NAA  =    7      NFF     =    7

XDA  =  0.00000000E+00   0.99999998E-02   0.50000001E-01   0.50000000E+00
DAA  =  0.00000000E+00   0.10000000E+01   0.10000000E+01   0.10000000E+01

XDA  =  0.10000000E+01   0.40000000E+02   0.80000000E+03
DAA  =  0.10000000E+01   0.10000000E+01   0.10000000E+01

XDF  =  0.00000000E+00   0.99999998E-02   0.50000001E-01   0.50000000E+00
DFF  =  0.00000000E+00   0.10000000E+01   0.10000000E+01   0.10000000E+01

XDF  =  0.10000000E+01   0.40000000E+02   0.80000000E+03
DFF  =  0.10000000E+01   0.10000000E+01   0.10000000E+01

BETA    =   0.00000000E+00      DPODX  = -0.40530000E+06
ALLM1O  = T       INERTO  = ar

AGG     =   0.57009300E-02      TGG     =   0.93458893E+03
UGG     =   0.46608398E+04      PGG     =   0.38084000E+06
ALPHA   =   0.00000000E+00      DPFDX  = -0.40530000E+06
ALLM1F  = T       INERTF  =

ABASE   =   0.25500000E-04      TPP      =   0.12000000E+04
MACHP   =   0.15000000E+01      PBASE    =   0.30347500E+06
DPFDX   =  -0.40530000E+06      ALLM1P  =  F
INERTP  =  ar

EXP  =   0
    EFFN      =   0.97399998E+00
    J22       =   1
    PEX       =   0.85839728E+03
    PITN      =   0
    RATIOFE  =   0.66670001E+00

RJPA OF SEPTEMBER 12, 1988
```

INPUT MIXTURE

WT. %	HF(C/MOLE)	M.W.	MOLECULAR FORMULA	
1.000000	0.0	2.016	2.0000	H
0.013250	0.0	39.941	1.0000	A
0.231460	0.0	32.000	2.0000	O
0.755290	0.0	28.016	2.0000	N
0.000000	0.0	28.016	2.0000	N

RESULTING GRAM ATOMS, 4 ELEMENTS

ELEMENT	AT. NO.	AT. WT.	VAL	GRAM ATOMS
H	1	1.008	1.0	0.000000
N	7	14.008	0.0	5.391847
O	8	16.000	-2.0	1.446625
A	18	39.941	0.0	0.033174

EQUIVALENCE RATIO = 0.00000000
STOIC FUEL/OX RATIO = 0.02916396
FUEL/OX RATIO(WF/WO) = 0.00000000
OX/FUEL RATIO(WO/WF) =***************
MIXTURE WT (Kg) = 0.10000000
MIXTURE ENTH (J/Kg) = 0.00000000
ROC. EQ. FRAC. = 0.00000000

DIF OF JAN. 17, 1989

******** RAMJET PERFORMANCE ANALYSIS ********

10/13/93

CASE: PC RJPA Test Calibration Run
Scramjet Case F11, Mach 25.0, Z= 155,700, No Frozen H2, Crocco =1.0

INLET CONDITIONS

INIT = 3 PAR = 0.824801E+04
Z = 0.110316E+03 TEMP = 0.270650E+03

PRESSURE (Pa)	= 0.110316E+03	FROZEN MACH NUMBER	= 0.249558E+02
TEMPERATURE (K)	= 0.270650E+03	VELOCITY (M/S)	= 0.824801E+04
DENSITY (Kg/M3)	= 0.142031E-02	FRZ SOUND SPD (M/S)	= 0.330504E+03
ENTHALPY (J/Kg)	= -.284271E+05	FROZEN GAMMA	= 0.140637E+01
ENTROPY (J/Kg-K)	= 0.871684E+04	MOL.WT. (Kg/KgMOLE)	= 0.289653E+02
PITOT PRESSURE (Pa)	= 0.000000E+00	A/W (M2-S/Kg)	= 0.853624E-01
TOTAL PRESSURE (Pa)	= 0.000000E+00	F/W (N-S/Kg)	= 0.825743E+04
TOTAL TEMP (K)	= 0.000000E+00	F/A (Pa)	= 0.967339E+05
W/A (Kg/S-M2)	= 0.117149E+02		
SENSIBLE ENTHALPY	= -.284271E+05	WT.FRCT.COND.PROD.	= 0.000000E+00
TOTAL ENTH. (J/KG)	= 0.339982E+08		
EQ.SOUND SPD (M/S)	= 0.330534E+03	EQ.MACH NUMBER	= 0.249535E+02
EQ.GAMMA	= 0.140663E+01	EQ.CP (J/KG-K)	= 0.993395E+03
EQ.COMPRESS. (1/Pa)	= 0.906488E-02		

GAS COMPOSITION

TOTAL GAS MOLES = 0.34524102E+01 P/FN = 0.31535517E-03

PRODUCTS GAS	MOLE-PCT OF GAS	PARTIAL PRESSURE	WEIGHT PCT	MOLE /100-GM	MOLECULAR WEIGHT	
1 A(G)	0.9609	0.10600E+01	1.3250	0.331739E-01	39.941	1
2 H(G)	0.0000	0.15277E-22	0.0000	0.478089E-24	1.008	2
3 HO(G)	0.0000	0.15277E-22	0.0000	0.478091E-24	17.008	3
4 H2(R)	0.0000	0.15277E-22	0.0000	0.478089E-24	2.016	4
5 H2O2(G)	0.0000	0.15277E-22	0.0000	0.478089E-24	34.016	5
6 N(G)	0.0000	0.15277E-22	0.0000	0.478089E-24	14.008	6
7 NO(G)	0.0000	0.64369E-15	0.0000	0.201447E-16	30.008	7
8 NO2(G)	0.0000	0.14484E-09	0.0000	0.453274E-11	46.008	8
9 O(G)	0.0000	0.15277E-22	0.0000	0.478089E-24	16.000	9
10 HNO(G)	0.0000	0.15277E-22	0.0000	0.478089E-24	31.016	10
11 HO2(G)	0.0000	0.15277E-22	0.0000	0.478089E-24	33.008	11
12 H2O(G)	0.0000	0.15850E-07	0.0000	0.496032E-09	18.016	12
13 N2(G)	78.0882	0.86144E+02	75.5290	0.269592E+01	28.016	13
14 O2(G)	20.9509	0.23112E+02	23.1460	0.723313E+00	32.000	14

******** RAMJET PERFORMANCE ANALYSIS ********

10/13/93

CASE: PC RJPA Test Calibration Run
Scramjet Case F11, Mach 25.0, Z= 155,700, No Frozen H2, Crocco =1.0

DIFFUSER EXIT CONDITIONS

DIFF = 1 PAR1 = 0.257350E+00
EFF = 0.977300E+00 AOI = 0.768355E+01 M2
ADICAL = 0.257325E+00 M2

PRESSURE (Pa)	= 0.326734E+05	FROZEN MACH NUMBER	= 0.807045E+01
TEMPERATURE (K)	= 0.253843E+04	VELOCITY (M/S)	= 0.785090E+04
DENSITY (Kg/M3)	= 0.445548E-01	FRZ SOUND SPD (M/S)	= 0.972796E+03
ENTHALPY (J/Kg)	= 0.282636E+07	FROZEN GAMMA	= 0.129046E+01
ENTROPY (J/Kg-K)	= 0.967275E+04	MOL.WT. (Kg/KgMOLE)	= 0.287733E+02
PITOT PRESSURE (Pa)	= 0.000000E+00	A/W (M2-S/Kg)	= 0.285882E-02
TOTAL PRESSURE (Pa)	= 0.000000E+00	F/W (N-S/Kg)	= 0.794432E+04
TOTAL TEMP (K)	= 0.000000E+00	F/A (Pa)	= 0.277888E+07
W/A (Kg/S-M2)	= 0.349795E+03		
SENSIBLE ENTHALPY	= 0.263505E+07	WT.FRCT.COND.PROD.	= 0.000000E+00
EQ.SOUND SPD (M/S)	= 0.939402E+03	EQ.MACH NUMBER	= 0.835734E+01
EQ.GAMMA	= 0.120338E+01	EQ.CP (J/KG-K)	= 0.195218E+04
EQ.COMPRESS. (1/Pa)	= 0.145969E+04		

GAS COMPOSITION

TOTAL GAS MOLES = 0.34755354E+01 P/FN = 0.92780322E-01

PRODUCTS GAS	MOLE-PCT OF GAS	PARTIAL PRESSURE	WEIGHT PCT	MOLE /100-GM	MOLECULAR WEIGHT	
1 A(G)	0.9545	0.31187E+03	1.3250	0.331739E-01	39.941	1
2 H(G)	0.0000	0.11178E-05	0.0000	0.118900E-09	1.008	2
3 HO(G)	0.0000	0.82060E-05	0.0000	0.872891E-09	17.008	3
4 H2(R)	0.0000	0.14011E-13	0.0000	0.149037E-17	2.016	4
5 H2O2(G)	0.0000	0.92609E-18	0.0000	0.985105E-22	34.016	5
6 N(G)	0.0001	0.20941E-01	0.0000	0.222756E-05	14.008	6
7 NO(G)	2.4209	0.79101E+03	2.5249	0.841409E-01	30.008	7
8 NO2(G)	0.0010	0.32966E+00	0.0016	0.350670E-04	46.008	8
9 O(G)	1.3316	0.43509E+03	0.7405	0.462815E-01	16.000	9
10 HNO(G)	0.0000	0.12917E-09	0.0000	0.137400E-13	31.016	10
11 HO2(G)	0.0000	0.24267E-08	0.0000	0.258128E-12	33.008	11
12 H2O(G)	0.0000	0.47842E-12	0.0000	0.508904E-16	18.016	12
13 N2(G)	76.3576	0.24949E+05	74.3499	0.265384E+01	28.016	13
14 O2(G)	18.9342	0.61865E+04	21.0581	0.658066E+00	32.000	14

STREAM NO. 3

time 0.00000E+00 sec area 2.54999995E-05 sq m

axial position 0.00000000E+00 m

flow properties		integration indicators	
pressure (n/m**2)	3.03475469E+05	steps from last print	0
velocity (m/sec)	1.06339453E+03	average step size	0.00000000E+00
density (kg/m**3)	7.76164949E-01	total number of steps	0
temperature (deg k)	1.20000000E+03		
mass flow rate (kg/sec)	2.10469272E-02		
entropy joule/kg/deg k)	9.37133105E+03	function evaluations	0
mach number	1.50000000E+00	jacobian evaluations	0
gamma	1.28540099E+00		
enthalpy (joule/kg)	-2.00965813E+06		

chemical properties

species	concentration (moles/m**3)	mole fraction	net species production rate rate (mole/m**3/sec) sec)
h	0.00000E+00	0.00000E+00	1.23772E-07
o2	6.30025E-03	2.07130E-01	-3.56361E-06
oh	9.12507E-07	3.00000E-05	-8.75875E-03

o	0.00000E+00	0.00000E+00	3.32182E-03
h2	0.00000E+00	0.00000E+00	1.54774E-09
h2o	1.03004E-02	3.38640E-01	3.31825E-03
ho2	0.00000E+00	0.00000E+00	2.99943E-06
h2o2	0.00000E+00	0.00000E+00	1.05956E-03
no	1.24709E-05	4.10000E-04	-6.89860E-07
no2	0.00000E+00	0.00000E+00	6.87919E-07
n	0.00000E+00	0.00000E+00	2.00509E-31
n2	1.36398E-02	4.48430E-01	-1.00255E-31
hno	0.00000E+00	0.00000E+00	1.94084E-09
ar	1.63035E-04	5.36000E-03	0.00000E+00

derivatives (si units):

t	3.85887E-01
rho	-2.24168E-04
v	0.00000E+00

mixture molecular weight	0.255176E+02
total energy exchange rate (joule-m**3/kg**2/sec)	-.764560E+06
mass fraction sum	0.100000E+01

** initial conditions **

STREAM NO. 2

time 0.00000E+00 sec area 5.70093002E-03 sq m

axial position 0.00000000E+00 m

flow properties		integration indicators	
pressure (n/m**2)	3.80840156E+05	steps from last print	0
velocity (m/sec)	4.66083984E+03	average step size	0.00000000E+00
density (kg/m**3)	9.83026549E-02	total number of steps	0
temperature (deg k)	9.34589000E+02		
mass flow rate (kg/sec)	2.61201215E+00		
entropy joule/kg/deg k)	7.64155469E+04	function evaluations	0
mach number	2.01210713E+00	jacobian evaluations	0
gamma	1.38500230E+00		
enthalpy (joule/kg)	1.03890430E+07		

chemical properties

species	concentration (moles/m**3)	mole fraction	net species production rate (mole/m**3/sec)
h	4.90111E-04	1.00000E-02	-2.09108E+01
h2	4.85210E-02	9.90000E-01	1.04554E+01

derivatives (si units):

t	6.79049E+02
rho	-6.69250E-02
v	0.00000E+00

mixture molecular weight	0.200572E+01
total energy exchange rate (joule-m**3/kg**2/sec)	-.471729E+12
mass fraction sum	0.100000E+01

** initial conditions **

STREAM NO. 1

time 0.00000E+00 sec area 2.57324994E-01 sq m

axial position 0.00000000E+00 m

flow properties		integration indicators	
pressure (n/m**2)	3.26733613E+04	steps from last print	0
velocity (m/sec)	7.85089990E+03	average step size	0.00000000E+00
density (kg/m**3)	4.45396006E-02	total number of steps	0
temperature (deg k)	2.53843000E+03		
mass flow rate (kg/sec)	8.99803696E+01		
entropy joule/kg/deg k)	9.67702344E+03	function evaluations	0
mach number	8.06370544E+00	jacobian evaluations	0
gamma	1.29218243E+00		
enthalpy (joule/kg)	2.82970575E+06		

chemical properties

species	concentration (moles/m**3)	mole fraction	net species production rate (mole/m**3/sec)
o	2.06152E-05	1.33164E-02	-2.39104E-03
o2	2.93122E-04	1.89342E-01	1.03278E-03
no2	1.56199E-08	1.00897E-05	4.18139E-04
no	3.74789E-05	2.42095E-02	-5.10806E-04
n	9.92222E-10	6.40926E-07	2.05070E-05
n2	1.18210E-03	7.63576E-01	3.60799E-05
ar	1.47767E-05	9.54498E-03	0.00000E+00

derivatives (si units):

t	1.41819E+00
rho	-1.97740E-05
v	0.00000E+00

mixture molecular weight	0.287704E+02
total energy exchange rate (joule-m**3/kg**2/sec)	-.311736E+09
mass fraction sum	0.100000E+01

cpu time for initialization of gksp = 0.000781 s

1

STREAM NO. 3

time 5.17812E-03 sec area 2.63051003E-01 sq m

axial position 4.00000000E+01 m

flow properties		integration indicators	
pressure (n/m**2)	5.19085039E+04	steps from last print	268
velocity (m/sec)	7.72608350E+03	average step size	1.74676476E+01
density (kg/m**3)	4.55695316E-02	total number of steps	268
temperature (deg k)	3.00977965E+03		
mass flow rate (kg/sec)	9.26134262E+01		
entropy joule/kg/deg k)	1.25033799E+04	function evaluations	346
mach number	6.41828632E+00	jacobian evaluations	47
gamma	1.27209188E+00		
enthalpy (joule/kg)	3.44421600E+06		

chemical properties

species	concentration (moles/m**3)	mole fraction	net species production rate (mole/m**3/sec)
h	1.29026E-04	6.22013E-02	-2.40982E-09
o2	4.72289E-05	2.27684E-02	-4.00566E-08
oh	1.02701E-04	4.95108E-02	-2.29958E-08
o	5.09019E-05	2.45391E-02	-3.39119E-08
h2	1.57189E-04	7.57786E-02	1.52142E-08
h2o	3.64639E-04	1.75787E-01	-2.48299E-09
ho2	2.90877E-08	1.40228E-05	-5.08128E-11
h2o2	6.60877E-10	3.18599E-07	-4.00899E-12
no	2.80632E-05	1.35289E-02	1.39300E-07
no2	3.85763E-09	1.85970E-06	1.55602E-10
n	3.21447E-08	1.54965E-05	2.76868E-10
n2	1.17981E-03	5.68771E-01	-6.98674E-08
hno	2.54379E-09	1.22632E-06	1.97921E-12
ar	1.46907E-05	7.08217E-03	0.00000E+00

derivatives (si units):

t	-7.79059E-06
rho	-3.22566E-12
v	5.46894E-07

mixture molecular weight	0.219684E+02
total energy exchange rate (joule-m**3/kg**2/sec)	0.172324E+04
mass fraction sum	0.100000E+01

---

computer time (cpu) required:
for this step - 1.708078E+01 s
up to this time - 1.708078E+01 s

1
0(gksp) end of this case

total cpu time (including i/o) required = 18.730625 s

0(gksp) read data for next case

******** RAMJET PERFORMANCE ANALYSIS ********

10/13/93

CASE: PC RJPA Test Calibration Run

Scramjet Case F11, Mach 25.0, Z= 155,700, No Frozen H2, Crocco =1.0

COMBUSTOR RESULTS

```
WOF  = 0.999999E+06     XI   = 0.100000E+01
ERGG = 0.999999E+06     WASS = 0.899804E+02 KG/S
ERS  = 0.342889E-04     WAGG = 0.000000E+00 KG/S
ERO  = 0.342889E-04     WF   = 0.261201E+01 KG/S
FSR  = 0.291640E-01     WCE  = 0.926134E+02 KG/S
CEFF =     0.0034458       CF   = 0.000000E+00

CROCCO EPS     = 0.100001E+01          ACE    = 0.263053E+00 M2
PSPCI          = 0.100000E+01          ACI    = 0.257325E+00 M2
MCE            = 0.641821E+01          AGG    = 0.570093E-02 M2
MCE @ E.L.     = 0.100000E+01          ABASE  = 0.255000E-04 M2
PBASE (Pa)     = 0.303475E+06          ATOTAL = 0.263051E+00 M2
PGG (Pa)       = 0.380848E+06          RHOGG  = 0.983027E-01 KG/M3
PMODEL (Pa)    = 0.000000E+00

PRESSURE (Pa)         = 0.519085E+05  FROZEN MACH NUMBER = 0.641821E+01
TEMPERATURE (K)       = 0.300978E+04  VELOCITY (M/S)     = 0.772608E+04
DENSITY (Kg/M3)       = 0.455695E-01  FRZ SOUND SPD (M/S)= 0.120378E+04
ENTHALPY (J/Kg)       = 0.344652E+07  FROZEN GAMMA       = 0.127209E+01
ENTROPY (J/Kg-K)      = 0.125117E+05  MOL.WT. (Kg/KgMOLE)= 0.219684E+02
PITOT PRESSURE (Pa)= 0.000000E+00     A/W (M2-S/Kg)      = 0.284031E-02
TOTAL PRESSURE (Pa)= 0.000000E+00     F/W (N-S/Kg)       = 0.787336E+04
TOTAL TEMP (K)        = 0.000000E+00  F/A (Pa)           = 0.277200E+07
W/A (Kg/S-M2)         = 0.352074E+03
SENSIBLE ENTHALPY     = 0.434055E+07  WT.FRCT.COND.PROD. = 0.000000E+00
EQ.SOUND SPD (M/S)    = 0.108263E+04  EQ.MACH NUMBER     = 0.713639E+01
EQ.GAMMA              = 0.102896E+01  EQ.CP (J/KG-K)     = 0.318171E+04
EQ.COMPRESS. (1/Pa)= 0.118680E+04
```

GAS COMPOSITION

TOTAL GAS MOLES = 0.45519953E+01   P/FN = 0.11254342E+00

PRODUCTS GAS	MOLE-PCT OF GAS	PARTIAL PRESSURE	WEIGHT PCT	MOLE /100-GM	MOLECULAR WEIGHT	
1 A(G)	0.7082	0.36762E+03	1.2876	0.322380E-01	39.941	1
2 H(G)	6.2201	0.32288E+04	0.2854	0.283140E+00	1.008	2
3 HO(G)	4.9511	0.25700E+04	3.8331	0.225373E+00	17.008	3
4 H2(R)	7.5779	0.39336E+04	0.6954	0.344944E+00	2.016	4
5 H2O2(G)	0.0000	0.16538E-01	0.0000	0.145026E-05	34.016	5
6 N(G)	0.0015	0.80440E+00	0.0010	0.705399E-04	14.008	6
7 NO(G)	1.3529	0.70226E+03	1.8480	0.615833E-01	30.008	7
8 NO2(G)	0.0002	0.96534E-01	0.0004	0.846536E-05	46.008	8
9 O(G)	2.4539	0.12738E+04	1.7872	0.111702E+00	16.000	9
10 HNO(G)	0.0001	0.63657E-01	0.0002	0.558221E-05	31.016	10
11 HO2(G)	0.0014	0.72790E+00	0.0021	0.638315E-04	33.008	11
12 H2O(G)	17.5787	0.91248E+04	14.4161	0.800181E+00	18.016	12
13 N2(G)	56.8771	0.29524E+05	72.5346	0.258904E+01	28.016	13
14 O2(G)	2.2768	0.11819E+04	3.3165	0.103641E+00	32.000	14

B.2.4 - Test 2 Input File - SI-3STREAM

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```

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finis
tape
  Stream 1 - air
   o      +   o      =   o2     +   m          6.0e+17   0.       -1800.
   o      +   no2    =   no     +   o2         1.0e+13    0.      600.
   m      +   no2    =   no     +   o          1.16e+16  0.       66000.
   n      +   o2     =   no     +   o           6.4e+9   1.       6300.
   n      +   n      =   n2     +   m          2.8e+17   -.75     0.
   n      +   no     =   n2     +   o          1.6e+13   0.       0.

ar
distance  pressure  cgs      si
 &PROB EMAX=0.100000E-02,ALLM1=T,CONC=T,EXCHR=F,TWALL=0.000000,
 ITPSZ=2,PRINT=4000.00,0.000000,0.000000,0.000000,0.000000,0.000000,
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 0.000000,0.000000,0.000000,0.000000,NPRNTS=1,CX3Z=0.000000,CX2Z=0.000000,
 CX1Z=-0.400000E-01,CX0Z=0.322461,PSTAT=T,COMBUS=F,PC=0.000000,
 ATHROT=0.000000,ROCKET=F,MF=21,HTRANZ=F,ATOLSP=0.100000E-11,
 MAXSTP=8000,RXNTST=F &END

 &START MACH=0.000000,MOLEF=T,AREAZ=2573.25,VZ=785090.,TZ=2538.43 &END
ar         0.0095449844400
n          0.0000006409258
no         0.0242094677000
no2        0.0000100896668
o          0.0133163668000
n2         0.7635760310000
```

```
o2         0.1893424090000
end
finis
tape
  Stream 2 - hydrogen
   h      +   h       =   h2     +   m             8.3e+17   -1.         0.

distance  pressure  cgs      si
 &PROB EMAX=0.100000E-02,ALLM1=T,CONC=T,EXCHR=F,TWALL=0.000000,
 ITPSZ=2,PRINT=4000.00,0.000000,0.000000,0.000000,0.000000,0.000000,
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 CX1Z=-0.400000E-01,CX0Z=3.75860,PSTAT=T,COMBUS=F,PC=0.000000,
 ATHROT=0.000000,ROCKET=F,MF=21,HTRANZ=F,ATOLSP=0.100000E-11,
 MAXSTP=8000,RXNTST=F &END

 &START MACH=0.000000,MOLEF=T,AREAZ=57.0093,VZ=466084.,TZ=934.589 &END
h2         .99
h          .01
end
finis
tape
  Stream 3 hydrogen - air reaction
   h      +   o2      =   oh     +   o             2.6e+14    0.       16800.
   o      +   h2      =   oh     +   h             1.8e+10    1.        8900.
   h2     +   oh      =   h2o    +   h             2.2e+13    0.        5150.
   oh     +   oh      =   o      +   h2o           6.3e+12    0.        1090.
   h      +   o2      =   ho2    +   m             2.1e+15    0.       -1000.
   o      +   o       =   o2     +   m             6.0e+17    0.       -1800.
   h      +   h       =   h2     +   m             6.4e+17   -1.          0.
   h      +   oh      =   h2o    +   m             2.2e+22   -2.          0.
   m      +   h2o2    =2.0oh                       1.2e+17    0.       45500.
   h2     +   o2      =2.0oh                       1.70e+13   0.       48000.
   h      +   ho2     =   oh     +   oh            1.4e+14    0.        1080.
   o      +   ho2     =   oh     +   o2            1.5e+13    0.         950.
   oh     +   ho2     =   h2o    +   o2            8.0e+12    0.           0.
           2.0ho2     =   h2o2   +   o2            2.00e+12   0.           0.
   ho2    +   no      =   no2    +   oh            3.4e+12    0.        -260.
   o      +   no2     =   no     +   o2            1.0e+13    0.         600.
   m      +   no2     =   no     +   o             1.16e+16   0.       66000.
   no2    +   h       =   no     +   oh            3.5e+14    0.        1500.
   n      +   o2      =   no     +   o             6.4e+9     1.        6300.
   h      +   o       =   oh     +   m             6.0e+16   -.6           0.
   n      +   oh      =   no     +   h             6.3e+11    0.5          0.
   ho2    +   h       =   h2     +   o2            1.30e+13   0.           0.
   ho2    +   h       =   h2o    +   o             1.0e+13    0.        1080.
   h      +   h2o2    =   h2     +   ho2           1.4e+12    0.        3690.
   o      +   h2o2    =   oh     +   ho2           1.4e+13    0.        6400.
   oh     +   h2o2    =   h2o    +   ho2           6.1e+12    0.        1430.
```

```
   n        +    n        =    n2       +    m              2.8e+17   -.75      0.
   n        +    no       =    n2       +    o              1.6e+13   0.        0.
   h        +    no       =    hno      +    m              5.4e+15   0.        -600.
   h        +    hno      =    no       +    h2             4.8e+12   0.        0.
   o        +    hno      =    no       +    oh             5.0e+11    .50      0.
   oh       +    hno      =    no       +    h2o            3.6e+13   0.        0.
   ho2      +    hno      =    no       +    h2o2           2.0e+12   0.        0.

ar
distance  pressure  cgs       si
 &PROB EMAX=0.100000E-02,ALLM1=F,CONC=T,EXCHR=F,TWALL=0.000000,
 ITPSZ=2,PRINT=4000.00,0.000000,0.000000,0.000000,0.000000,0.000000,
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 0.000000,0.000000,0.000000,0.000000,0.000000,0.000000,0.000000,0.000000,
 0.000000,0.000000,0.000000,0.000000,NPRNTS=1,CX3Z=0.000000,CX2Z=0.000000,
 CX1Z=-0.400000E-01,CX0Z=2.99507,PSTAT=T,COMBUS=F,PC=0.000000,
 ATHROT=0.000000,ROCKET=F,MF=21,HTRANZ=F,ATOLSP=0.100000E-11,
 MAXSTP=8000,RXNTST=F &END
   h        +    o2       =    ho2      +    m        h2        2.0
   same                                               h2o      16.0
   h             h        =    h2       +    m        h2       2.0
   same                                               h2o      6.0
   m        +    h2o2     =2.0oh                      h2o      15.0
   h        +    oh       =    h2o      +    m        h2o       6.0
   h        +    o        =    oh       +    m        h2o       5.0

 &START MACH=1.50000,MOLEF=T,AREAZ=0.255000,VZ=0.000000,TZ=1200.00 &END
ar          .00536
h2o         .33864
no          .00041
n2          .44843
oh          .00003
o2          .20713
end
finis
```

B.2.5 - Test 2 Output File - SI-3STREAM

```
                              **  data cards  **

          1         2         3         4         5         6         7
8

12345678901234567890123456789012345678901234567890123456789012345678901234567890


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0.000000,0.000000,0.000000,0.000000,0.000000,NCF1=0,NCF2=0,NCF3=0,
CF1=0.000000,0.000000,0.000000,0.000000,0.000000,0.000000,0.000000,
0.000000,0.000000,0.000000,0.000000,0.000000,0.000000,0.000000,0.000000,
0.000000,0.000000,0.000000,0.000000,0.000000,0.000000,0.000000,0.000000,
0.000000,0.000000,0.000000,0.000000,0.000000,0.000000,0.000000,0.000000,
0.000000,0.000000,0.000000,0.000000,0.000000,0.000000,0.000000,0.000000,
0.000000,0.000000,0.000000,0.000000,0.000000,0.000000,0.000000,0.000000,
0.000000,0.000000,0.000000,CF2=0.000000,0.000000,0.000000,0.000000,
0.000000,0.000000,0.000000,0.000000,0.000000,0.000000,0.000000,0.000000,

```
 0.000000,0.000000,0.000000,0.000000,0.000000,0.000000,0.000000,0.000000,
 0.000000,0.000000,0.000000,0.000000,0.000000,0.000000,0.000000,0.000000,
 0.000000,0.000000,0.000000,0.000000,0.000000,0.000000,0.000000,0.000000,
 0.000000,0.000000,0.000000,0.000000,0.000000,0.000000,0.000000,0.000000,
 0.000000,0.000000,0.000000,0.000000,0.000000,0.000000,CF3=0.000000,
 0.000000,0.000000,0.000000,0.000000,0.000000,0.000000,0.000000,0.000000,
 0.000000,0.000000,0.000000,0.000000,0.000000,0.000000,0.000000,0.000000,
 0.000000,0.000000,0.000000,0.000000,0.000000,0.000000,0.000000,0.000000,
 0.000000,0.000000,0.000000,0.000000.0.000000,0.000000,0.000000,0.000000,
 0.000000,0.000000,0.000000,0.000000,0.000000,0.000000,0.000000,0.000000,
 0.000000,0.000000,0.000000,0.000000,0.000000,0.000000,0.000000,0.000000,
 0.000000,XCF1=0.000000,0.000000,0.000000,0.000000,0.000000,0.000000,
 0.000000,0.000000,0.000000,0.000000,0.000000,0.000000,0.000000,0.000000,
 0.000000,0.000000,0.000000,0.000000,0.000000,0.000000,0.000000,0.000000,
 0.000000,0.000000,0.000000,0.000000,0.000000,0.000000,0.000000,0.000000,
 0.000000,0.000000,0.000000,0.000000,0.000000,0.000000,0.000000,0.000000,
 0.000000,0.000000,0.000000,0.000000,0.000000,0.000000,0.000000,0.000000,
 0.000000,0.000000,0.000000,0.000000,XCF2=0.000000,0.000000,0.000000,
 0.000000,0.000000,0.000000,0.000000,0.000000,0.000000,0.000000,0.000000,
 0.000000,0.000000,0.000000,0.000000,0.000000,0.000000,0.000000,0.000000,
 0.000000,0.000000,0.000000,0.000000,0.000000,0.000000,0.000000,0.000000,
 0.000000,0.000000,0.000000,0.000000,0.000000,0.000000,0.000000,0.000000,
 0.000000,0.000000,0.000000,0.000000,0.000000,0.000000,0.000000,0.000000,
 0.000000,0.000000,0.000000,0.000000,0.000000,0.000000,0.000000,
 XCF3=0.000000,0.000000,0.000000,0.000000,0.000000,0.000000,0.000000,
 0.000000,0.000000,0.000000,0.000000,0.000000,0.000000,0.000000,0.000000,
 0.000000,0.000000,0.000000,0.000000,0.000000,0.000000,0.000000,0.000000,
 0.000000,0.000000,0.000000,0.000000,0.000000,0.000000,0.000000,0.000000,
 0.000000,0.000000,0.000000,0.000000,0.000000,0.000000,0.000000,0.000000,
 0.000000,0.000000,0.000000,0.000000,0.000000,0.000000,0.000000,0.000000,
 0.000000,0.000000,0.000000,ISKIN1=F,ISKIN2=F,ISKIN3=F &END
finis
                              ** data cards **

         1         2         3         4         5         6         7
8

12345678901234567890123456789012345678901234567890123456789012345678901234567890


   Stream 1 - air
   o     + o     = o2    + m          6.0e+17  0.       -
1800.
   o     + no2   = no    + o2         1.0e+13   0.      600.
   m     + no2   = no    + o          1.16e+16 0.
66000.
   n     + o2    = no    + o          6.4e+9   1.       6300.
   n     + n     = n2    + m          2.8e+17  -.75     0.
   n     + no    = n2    + o          1.6e+13  0.       0.
                              - blank card -
 ar
 distance  pressure  cgs      si
  &PROB EMAX=0.100000E-02,ALLM1=T,CONC=T,EXCHR=F,TWALL=0.000000,
  ITPSZ=2,PRINT=4000.00,0.000000,0.000000,0.000000,0.000000,0.000000,
```

```
0.000000,0.000000,0.000000,0.000000,0.000000,0.000000,0.000000,0.000000,
0.000000,0.000000,0.000000,0.000000,0.000000,0.000000,0.000000,0.000000,
0.000000,0.000000,0.000000,0.000000,0.000000,0.000000,0.000000,0.000000,
0.000000,0.000000,0.000000,0.000000,0.000000,0.000000,0.000000,0.000000,
0.000000,0.000000,0.000000,0.000000,0.000000,0.000000,0.000000,0.000000,
0.000000,0.000000,0.000000,0.000000,NPRNTS=1,CX3Z=0.000000,CX2Z=0.000000,
CX1Z=-0.400000E-01,CX0Z=0.322461,PSTAT=T,COMBUS=F,PC=0.000000,
ATHROT=0.000000,ROCKET=F,MF=21,HTRANZ=F,ATOLSP=0.100000E-11,
MAXSTP=8000,RXNTST=F &END
                                 - blank card -
&START MACH=0.000000,MOLEF=T,AREAZ=2573.25,VZ=785090.,TZ=2538.43 &END
ar        0.0095449844400
n         0.0000006409258
no        0.0242094677000
no2       0.0000100896668
o         0.0133163668000
n2        0.7635760310000
o2        0.1893424090000
end
finis

                          ** data cards **

          1         2         3         4         5         6         7
8
12345678901234567890123456789012345678901234567890123456789012345678901234567890


Stream 2 - hydrogen
h       +  h       =  h2      +  m             8.3e+17   -1.        0.
                                 - blank card -
                                 - blank card -
distance  pressure  cgs      si
&PROB EMAX=0.100000E-02,ALLM1=T,CONC=T,EXCHR=F,TWALL=0.000000,
ITPSZ=2,PRINT=4000.00,0.000000,0.000000,0.000000,0.000000,0.000000,
0.000000,0.000000,0.000000,0.000000,0.000000,0.000000,0.000000,0.000000,
0.000000,0.000000,0.000000,0.000000,0.000000,0.000000,0.000000,0.000000,
0.000000,0.000000,0.000000,0.000000,0.000000,0.000000,0.000000,0.000000,
0.000000,0.000000,0.000000,0.000000,0.000000,0.000000,0.000000,0.000000,
0.000000,0.000000,0.000000,0.000000,0.000000,0.000000,0.000000,0.000000,
0.000000,0.000000,0.000000,0.000000,NPRNTS=1,CX3Z=0.000000,CX2Z=0.000000,
CX1Z=-0.400000E-01,CX0Z=3.75860,PSTAT=T,COMBUS=F,PC=0.000000,
ATHROT=0.000000,ROCKET=F,MF=21,HTRANZ=F,ATOLSP=0.100000E-11,
MAXSTP=8000,RXNTST=F &END
                          ** data cards **

          1         2         3         4         5         6         7
8
12345678901234567890123456789012345678901234567890123456789012345678901234567890


Stream 3 hydrogen - air reaction
```

```
  h      +  o2     =  oh     +  o       2.6e+14   0.
16800.
  o      +  h2     =  oh     +  h       1.8e+10   1.      8900.
  h2     +  oh     =  h2o    +  h       2.2e+13   0.      5150.
  oh     +  oh     =  o      +  h2o     6.3e+12   0.      1090.
  h      +  o2     =  ho2    +  m       2.1e+15    0.     -
1000.
  o      +  o      =  o2     +  m       6.0e+17   0.      -
1800.
  h      +  h      =  h2     +  m       6.4e+17   -1.      0.
  h      +  oh     =  h2o    +  m       2.2e+22   -2.     0.
  m      +  h2o2   =2.0oh               1.2e+17  0.      45500.
  h2     +  o2     =2.0oh               1.70e+13  0.      48000.
  h      +  ho2    =  oh     +  oh      1.4e+14   0.      1080.
  o      +  ho2    =  oh     +  o2      1.5e+13   0.      950.
  oh     +  ho2    =  h2o    +  o2      8.0e+12   0.      0.
          2.0ho2   =  h2o2   +  o2      2.00e+12  0.      0.
  ho2    +  no     =  no2    +  oh      3.4e+12    0.     -260.
  o      +  no2    =  no     +  o2      1.0e+13     0.    600.
  m      +  no2    =  no     +  o       1.16e+16  0.
66000.
  no2    +  h      =  no     +  oh      3.5e+14   0.      1500.
  n      +  o2     =  no     +  o        6.4e+9   1.      6300.
  h      +  o      =  oh     +  m       6.0e+16   -.6     0.
  n      +  oh     =  no     +  h       6.3e+11   0.5     0.
  ho2    +  h      =  h2     +  o2      1.30e+13  0.      0.
  ho2    +  h      =  h2o    +  o       1.0e+13   0.      1080.
  h      +  h2o2   =  h2     +  ho2     1.4e+12   0.      3690.
  o      +  h2o2   =  oh     +  ho2     1.4e+13   0.      6400.
  oh     +  h2o2   =  h2o    +  ho2     6.1e+12   0.      1430.
  n      +  n      =  n2     +  m       2.8e+17   -.75    0.
  n      +  no     =  n2     +  o       1.6e+13   0.      0.
  h      +  no     =  hno    +  m       5.4e+15   0.      -600.
  h      +  hno    =  no     +  h2      4.8e+12   0.      0.
  o      +  hno    =  no     +  oh      5.0e+11    .50    0.
  oh     +  hno    =  no     +  h2o     3.6e+13   0.      0.
  ho2    +  hno    =  no     +  h2o2    2.0e+12   0.      0.
                          -  blank card  -
 ar
 distance  pressure  cgs      si
  &PROB EMAX=0.100000E-02,ALLM1=F,CONC=T,EXCHR=F,TWALL=0.000000,
  ITPSZ=2,PRINT=4000.00,0.000000,0.000000,0.000000,0.000000,0.000000,
  0.000000,0.000000,0.000000,0.000000,0.000000,0.000000,0.000000,0.000000,
  0.000000,0.000000,0.000000,0.000000,0.000000,0.000000,0.000000,0.000000,
  0.000000,0.000000,0.000000,0.000000,0.000000,0.000000,0.000000,0.000000,
  0.000000,0.000000,0.000000,0.000000,0.000000,0.000000,0.000000,0.000000,
  0.000000,0.000000,0.000000,0.000000,0.000000,0.000000,0.000000,0.000000,
  0.000000,0.000000,0.000000,0.000000,NPRNTS=1,CX3Z=0.000000,CX2Z=0.000000,
  CX1Z=-0.400000E-01,CX0Z=2.99507,PSTAT=T,COMBUS=F,PC=0.000000,
  ATHROT=0.000000,ROCKET=F,MF=21,HTRANZ=F,ATOLSP=0.100000E-11,
  MAXSTP=8000,RXNTST=F &END
  h      +  o2     =  ho2    +  m     h2       2.0
  same                                h2o     16.0
  h         h      =  h2     +  m     h2       2.0
```

```
same                                                     h2o      6.0
m       +   h2o2     =2.0oh                              h2o     15.0
h       +   oh       =   h2o      +    m                 h2o      6.0
h       +   o        =   oh       +    m                 h2o      5.0
                                  -  blank card  -
&START MACH=1.50000,MOLEF=T,AREAZ=0.255000,VZ=0.000000,TZ=1200.00 &END
ar        .00536
h2o       .33864
no        .00041
n2        .44843
oh        .00003
o2        .20713
end
finis
```

** initial conditions **

STREAM NO. 3

time 0.00000E+00 sec area 2.55000E-05 sq m axial position 0.00000E+00 m

flow properties		integration indicators	
pressure (n/m**2)	3.03475E+05	steps from last print	0
velocity (m/sec)	1.06339E+03	average step size	0.00000E+00
density (kg/m**3)	7.76165E-01	total number of steps	0
temperature (deg k)	1.20000E+03		
mass flow rate (kg/sec)	2.10469E-02		
entropy joule/kg/deg k)	9.37133E+03	function evaluations	0
mach number	1.50000E+00	jacobian evaluations	0
gamma	1.28540E+00		
enthalpy (joule/kg)	-2.00966E+06		

chemical properties

species	concentration (moles/m**3)	mole fraction	net species production rate (mole/m**3/sec)
h	0.00000E+00	0.00000E+00	1.23772E-07
o2	6.3002[illegible]E-03	2.07130E-01	-3.56361E-06
oh	9.12507E-07	3.00000E-05	-8.75875E-03
o	0.00000E+00	0.00000E+00	3.32182E-03
h2	0.00000E+00	0.00000E+00	1.54774E-09

h2o	1.03004E-02	3.38640E-01	3.31825E-03
ho2	0.00000E+00	0.00000E+00	2.99943E-06
h2o2	0.00000E+00	0.00000E+00	1.05956E-03
no	1.24709E-05	4.10000E-04	-6.89860E-07
no2	0.00000E+00	0.00000E+00	6.87919E-07
n	0.00000E+00	0.00000E+00	2.00509E-31
n2	1.36398E-02	4.48430E-01	-1.00255E-31
hno	0.00000E+00	0.00000E+00	1.94084E-09
ar	1.63035E-04	5.36000E-03	0.00000E+00

derivatives (si units): t 3.85887E-01 rho -2.24168E-04
v 0.00000E+00

mixture molecular weight 25.51756
total energy exchange rate -7.64560E+05
mass fraction sum 1.00000000

** initial conditions **

STREAM NO. 2

time 0.00000E+00 sec
area 5.70093E-03 sq m
axial position 0.00000E+00 m

flow properties		integration indicators	
pressure (n/m**2)	3.80840E+05	steps from last print	0
velocity (m/sec)	4.66084E+03	average step size	0.00000E+00
density (kg/m**3)	9.83027E-02	total number of steps	0
temperature (deg k)	9.34589E+02		
mass flow rate (kg/sec)	2.61201E+00		
entropy joule/kg/deg k)	7.64155E+04	function evaluations	0
mach number	2.01211E+00	jacobian evaluations	0
gamma	1.38500E+00		
enthalpy (joule/kg)	1.03890E+07		

chemical properties

species	concentration (moles/m**3)	mole fraction	net species production rate (mole/m**3/sec)
h	4.90111E-04	1.00000E-02	-2.09108E+01
h2	4.85210E-02	9.90000E-01	1.04554E+01

derivatives (si units):

t	6.79049E+02
rho	-6.69250E-02
v	0.00000E+00

mixture molecular weight 2.00572
total energy exchange rate -4.71729E+11
mass fraction sum 1.00000000

** initial conditions **

STREAM NO. 1
time 0.00000E+00 sec
area 2.57325E-01 sq m
axial position 0.00000E+00 m

flow properties		integration indicators	
pressure (n/m**2)	3.26734E+04	steps from last print	0
velocity (m/sec)	7.85090E+03	average step size	0.00000E+00
density (kg/m**3)	4.45396E-02	total number of steps	0
temperature (deg k)	2.53843E+03		
mass flow rate (kg/sec)	8.99804E+01		
entropy joule/kg/deg k)	9.67702E+03	function evaluations	0
mach number	8.06371E+00	jacobian evaluations	0
gamma	1.29218E+00		
enthalpy (joule/kg)	2.82971E+06		

chemical properties

species	concentration (moles/m**3)	mole fraction	net species production rate (mole/m**3/sec)
o	2.06152E-05	1.33164E-02	-2.39104E-03
o2	2.93122E-04	1.89342E-01	1.03278E-03
no2	1.56199E-08	1.00897E-05	4.18139E-04
no	3.74789E-05	2.42095E-02	-5.10806E-04
n	9.92222E-10	6.40926E-07	2.05070E-05

n2	1.18210E-03	7.63576E-01	3.60799E-05
ar	1.47767E-05	9.54498E-03	0.00000E+00

derivatives (si units):

t	1.41819E+00
rho	-1.97740E-05
v	0.00000E+00

mixture molecular weight 28.77035
total energy exchange rate -3.11736E+08
mass fraction sum 1.00000000

cpu time for initialization of gksp = -
0.000781 s

STREAM NO. 3
time 5.17812E-03 sec
area 2.63051E-01 sq m
axial position 4.00000E+01 m

flow properties integration indicators

pressure (n/m**2)	5.19085E+04	steps from last print	268
velocity (m/sec)	7.72608E+03	average step size	0.17468E+02
density (kg/m**3)	4.55695E-02	total number of steps	268
temperature (deg k)	3.00978E+03		
mass flow rate (kg/sec)	9.26134E+01		
entropy joule/kg/deg k)	1.25034E+04	function evaluations	346
mach number	6.41829E+00	jacobian evaluations	47
gamma	1.27209E+00		
enthalpy (joule/kg)	3.44422E+06		

chemical properties

species	concentration (moles/m**3)	mole fraction	net species production rate (mole/m**3/sec)
h	1.29026E-04	6.22013E-02	-2.40982E-09
o2	4.72289E-05	2.27684E-02	-4.00566E-08
oh	1.02701E-04	4.95108E-02	-2.29958E-08
o	5.09019E-05	2.45391E-02	-3.39119E-08
h2	1.57189E-04	7.57786E-02	1.52142E-08

h2o	3.64639E-04	1.75787E-01	-2.48299E-09
ho2	2.90877E-08	1.40228E-05	-5.08128E-11
h2o2	6.60877E-10	3.18599E-07	-4.00899E-12
no	2.80632E-05	1.35289E-02	1.39300E-07
no2	3.85763E-09	1.85970E-06	1.55602E-10
n	3.21447E-08	1.54965E-05	2.76868E-10
n2	1.17981E-03	5.68771E-01	-6.98674E-08
hno	2.54379E-09	1.22632E-06	1.97921E-12
ar	1.46907E-05	7.08217E-03	0.00000E+00

derivatives (si units):

t	-7.79059E-06
rho	-3.22566E-12
v	5.46894E-07

mixture molecular weight 21.96839
total energy exchange rate 1.72324E+03
mass fraction sum 1.00000024

---

computer time (cpu) required: for this step - 1.745922E+01 s up to this time - 1.745922E+01 s

1
0(gksp) end of this case

total cpu time (including i/o) required = 19.609062 s

0(gksp) read data for next case

B.3.1 - Test 3 Input File - T3-EQ

```
PC RJPA Test Calibration run
Scramjet Case eq6-1, Mach 15.0, Z= 39272 m, No Frozen H2, Crocco =1.0
EJANAF.DAT
 5,1, 1, 1, 1, 1 /
 3, 1.000000,      0.0,    2.0, 'H    ' /
 0, 0.013250,      0.0,    1.0, 'A    ' /
 0, 0.231460,      0.0,    2.0, 'O    ' /
 0, 0.755290       0.0,    2.0, 'N    ' /
 2.016 /
 14, 1,288,300,304,310,350,351,352,381,767,810,1271,1272,1273 /

 &FRSTR
  units=si,
  init=1, par=15, z=39272.0, temp=249.05,
  piti=0,aref=0.6, aiss=0.6, aigg=0.0, WOFINO=1.E11
  &END

 &DIFFUSER
   DIFF=1, PAR1=0.030, EFF=0.976, HEAT=1, QDIFF=342829.14,
   PITD=0, GAMG1=1.2, GAMG2=1.3, SWT=0.5 &END

 &SHCK
  SHK=0, BET=90.0, DEL=0.0, PITS=0 &END

 &COMBUSTOR
  COMB=1, ICOMB=0, FRC= 'NONE', ACE=0.03151, AWALL=0.64516
  PCEG1=0.00, PCEG2=0.00, PITC=0, PSPCI=1.0000 &END

 &HEATFRICTION
  CF=0.0, QWALL=0.0 &END

 &MIXER FSR=0.029164, WOFIN=34.288849,XI=1.0 &END

 &OXIDIZER
  ACI= 0.030, BETA=0.0 &END

 &FUEL
  AGG=0.0015, ALPHA=0.0, HGG=1.039599187E7, MWGG=2.016, NCFIN=1,
  RHOGG=0.422572e-1, TGG=935, UGG=5.79221924e3 &END

 &PRODUCTS
  ABASE=0.00001, PBASE=.516746E5 &END

 &NOZZLE
  EXP=1, EFFN=0.9740, J22=2, PEX=0.6, PITN=0, RATIOFE=0.6667
  &END
```

B.3.2 - Test 3 Output File - T3-EQ

```
                    RAMJET PERFORMANCE ANALYSIS, VERSION 1.24
 PC RJPA Test Calibration run
 Scramjet Case eq6-1, Mach 15.0, Z= 39272 m, No Frozen H2, Crocco =1.0
EJANAF.DAT

FOLLOWING DATA READ FROM JANAF THERMOCHEMICAL FILE:
  KEY            NAME                               FORMULA       DATE    HF-298
     1  ARGON                              (G)   A(G)         A0672   0.00000E+00
   288  HYDROGEN, MONATOMIC                (G)   H(G)         J 674   0.52103E+02
   300  HYDROXYL                           (G)   HO(G)        J1270   0.94920E+01
   304  HYDROGEN, DIATOMIC                 (R)   H2(R)        J 361   0.00000E+00
   310  HYDROGEN PEROXIDE                  (G)   H2O2(G)      J1260  -0.32530E+02
   350  NITROGEN, MONATOMIC                (G)   N(G)         J 361   0.11297E+03
   351  NITRIC OXIDE                       (G)   NO(G)        J 663   0.21580E+02
   352  NITROGEN DIOXIDE                   (G)   NO2(G)       J 964   0.79100E+01
   381  OXYGEN, MONATOMIC                  (G)   O(G)         J 674   0.59553E+02
   767  NITROXYL                           (G)   HNO(G)       J 363   0.23800E+02
   810  HYDROPEROXYL                       (G)   HO2(G)       J 364   0.50000E+01
  1271 WATER-LOW TEMP. FITS                (G)   H2O(G)       A 368  -0.57798E+02
  1272 NITROGEN-LOW TEMP. FITS             (G)   N2(G)        A 368   0.00000E+00
  1273 OXYGEN-LOW TEMP. FITS               (G)   O2(G)        A 368   0.00000E+00

 UNITS = si
 UNITO = ****
 INIT  =  1
     PAR    =  0.15000000E+02
     Z      =  0.39272000E+05
     TEMP   =  0.24905000E+03
     PITI   =  0
     AREF   =  0.60000002E+00
     AISS   =  0.60000002E+00
     AIGG   =  0.00000000E+00
     WOFINO=  0.99999998E+11

 DIFF =  1
     PAR1   =  0.29999999E-01
     EFF    =  0.97600001E+00
     HEAT   =  1
     QDIFF  =  0.34282913E+06
     PITD   =  0
     GAMG1  =  0.12000000E+01
     GAMG2  =  0.13000000E+01
     SWT    =  0.50000000E+00

 SHK  =  0
     BET   =  0.90000000E+02
     DEL   =  0.00000000E+00
     PITS =  0

 COMB =  1       ICOMB =  0       FRC = NONE
     ABASE =  0.99999997E-05      ACE    =  0.31509999E-01
```

ACI	=	0.29999999E-01	AGG	=	0.15000000E-02
ALPHA	=	0.00000000E+00	AWALL	=	0.64516002E+00
BETA	=	0.00000000E+00	CF	=	0.00000000E+00
FSR	=	0.29163999E-01	HGG	=	0.10395992E+08
MWGG	=	0.20160000E+01	NCF	=	2
PBASE	=	0.51674602E+05	PCEG1	=	0.00000000E+00
PCEG2	=	0.00000000E+00	PITC	=	0
PSPCI	=	0.10000000E+01	QWALL	=	0.00000000E+00
RHOGG	=	0.42257201E-01	TGG	=	0.93500000E+03
UGG	=	0.57922192E+04	WOFIN	=	0.34288849E+02
XI	=	0.10000000E+01			

EXP = 1

EFFN	=	0.97399998E+00
J22	=	2
PEX	=	0.60000002E+00
PITN	=	0
RATIOFE	=	0.66670001E+00

RJPA OF SEPTEMBER 12, 1988

INPUT MIXTURE

WT. %	HF(C/MOLE)	M.W.	MOLECULAR FORMULA	
1.000000	0.0	2.016	2.0000	H
0.013250	0.0	39.941	1.0000	A
0.231460	0.0	32.000	2.0000	O
0.755290	0.0	28.016	2.0000	N
0.000000	0.0	28.016	2.0000	N

RESULTING GRAM ATOMS, 4 ELEMENTS

ELEMENT	AT. NO.	AT. WT.	VAL	GRAM ATOMS
H	1	1.008	1.0	0.000000
N	7	14.008	0.0	5.391847
O	8	16.000	-2.0	1.446625
A	18	39.941	0.0	0.033174

EQUIVALENCE RATIO	=	0.00000000
STOIC FUEL/OX RATIO	=	0.02916396
FUEL/OX RATIO(WF/WO)	=	0.00000000
OX/FUEL RATIO(WO/WF)	=	***************
MIXTURE WT (Kg)	=	0.10000000
MIXTURE ENTH (J/Kg)	=	0.00000000
ROC. EQ. FRAC.	=	0.00000000

DIF OF JAN. 17, 1989

******** RAMJET PERFORMANCE ANALYSIS ********

09/23/93

CASE: PC RJPA Test Calibration run
Scramjet Case eq6-1, Mach 15.0, Z= 39272 m, No Frozen H2, Crocco =1.0

INLET CONDITIONS

```
 INIT =  1                PAR  = 0.150000E+02
 Z    = 0.392720E+05    TEMP = 0.138361E+03

PRESSURE (Pa)        = 0.316877E+03  FROZEN MACH NUMBER = 0.150000E+02
TEMPERATURE (K)      = 0.248336E+03  VELOCITY (M/S)     = 0.475183E+04
DENSITY (Kg/M3)      = 0.444636E-02  FRZ SOUND SPD (M/S)= 0.316789E+03
ENTHALPY (J/Kg)      = -.505579E+05  FROZEN GAMMA       = 0.140817E+01
ENTROPY (J/Kg-K)     = 0.832862E+04  MOL.WT. (Kg/KgMOLE)= 0.289653E+02
PITOT PRESSURE (Pa)= 0.000000E+00    A/W (M2-S/Kg)      = 0.473297E-01
TOTAL PRESSURE (Pa)= 0.000000E+00    F/W (N-S/Kg)       = 0.476684E+04
TOTAL TEMP (K)       = 0.000000E+00  F/A (Pa)           = 0.100716E+06
W/A (Kg/S-M2)        = 0.211284E+02
SENSIBLE ENTHALPY    = -.505579E+05  WT.FRCT.COND.PROD. = 0.000000E+00
TOTAL ENTH. (J/KG)   = 0.112433E+08
EQ.SOUND SPD (M/S)   = 0.316817E+03  EQ.MACH NUMBER     = 0.149987E+02
EQ.GAMMA             = 0.140842E+01  EQ.CP (J/KG-K)     = 0.990281E+03
EQ.COMPRESS. (1/Pa)= 0.315581E-02
```

GAS COMPOSITION

TOTAL GAS MOLES = 0.34524100E+01   P/FN = 0.90584130E-03

	PRODUCTS GAS	MOLE-PCT OF GAS	PARTIAL PRESSURE	WEIGHT PCT	MOLE /100-GM	MOLECULAR WEIGHT	
1	A(G)	0.9609	0.30448E+01	1.3250	0.331739E-01	39.941	1
2	H(G)	0.0000	0.43881E-22	0.0000	0.478089E-24	1.008	2
3	HO(G)	0.0000	0.43881E-22	0.0000	0.478091E-24	17.008	3
4	H2(R)	0.0000	0.43881E-22	0.0000	0.478089E-24	2.016	4
5	H2O2(G)	0.0000	0.43881E-22	0.0000	0.478089E-24	34.016	5
6	N(G)	0.0000	0.43881E-22	0.0000	0.478089E-24	14.008	6
7	NO(G)	0.0000	0.46543E-16	0.0000	0.507090E-18	30.008	7
8	NO2(G)	0.0000	0.16332E-09	0.0000	0.177941E-11	46.008	8
9	O(G)	0.0000	0.43881E-22	0.0000	0.478089E-24	16.000	9
10	HNO(G)	0.0000	0.43881E-22	0.0000	0.478089E-24	31.016	10
11	HO2(G)	0.0000	0.43881E-22	0.0000	0.478089E-24	33.008	11
12	H2O(G)	0.0000	0.45528E-07	0.0000	0.496032E-09	18.016	12
13	N2(G)	78.0882	0.24744E+03	75.5290	0.269592E+01	28.016	13
14	O2(G)	20.9509	0.66389E+02	23.1460	0.723312E+00	32.000	14

******** RAMJET PERFORMANCE ANALYSIS ********

09/23/93

CASE: PC RJPA Test Calibration run
Scramjet Case eq6-1, Mach 15.0, Z= 39272 m, No Frozen H2, Crocco =1.0

DIFFUSER EXIT CONDITIONS

```
DIFF    =  1                  PAR1 = 0.300000E-01
EFF     = 0.976000E+00      AOI  = 0.600000E+00 M2
ADICAL = 0.300048E-01 M2
```

PRESSURE (Pa)	= 0.516746E+05	FROZEN MACH NUMBER	= 0.522732E+01
TEMPERATURE (K)	= 0.185333E+04	VELOCITY (M/S)	= 0.434886E+04
DENSITY (Kg/M3)	= 0.971521E-01	FRZ SOUND SPD (M/S)	= 0.831948E+03
ENTHALPY (J/Kg)	= 0.178375E+07	FROZEN GAMMA	= 0.130127E+01
ENTROPY (J/Kg-K)	= 0.906732E+04	MOL.WT. (Kg/KgMOLE)	= 0.289636E+02
PITOT PRESSURE (Pa)	= 0.000000E+00	A/W (M2-S/Kg)	= 0.236686E-02
TOTAL PRESSURE (Pa)	= 0.000000E+00	F/W (N-S/Kg)	= 0.447117E+04
TOTAL TEMP (K)	= 0.000000E+00	F/A (Pa)	= 0.188907E+07
W/A (Kg/S-M2)	= 0.422501E+03		
SENSIBLE ENTHALPY	= 0.176635E+07	WT.FRCT.COND.PROD.	= 0.000000E+00
EQ.SOUND SPD (M/S)	= 0.826369E+03	EQ.MACH NUMBER	= 0.526261E+01
EQ.GAMMA	= 0.128388E+01	EQ.CP (J/KG-K)	= 0.130132E+04
EQ.COMPRESS. (1/Pa)	= 0.919975E+03		

GAS COMPOSITION

TOTAL GAS MOLES = 0.34526138E+01 P/FN = 0.14771095E+00

PRODUCTS GAS	MOLE-PCT OF GAS	PARTIAL PRESSURE	WEIGHT PCT	MOLE /100-GM	MOLECULAR WEIGHT	
1 A(G)	0.9608	0.49651E+03	1.3250	0.331739E-01	39.941	1
2 H(G)	0.0000	0.54749E-07	0.0000	0.365801E-11	1.008	2
3 HO(G)	0.0000	0.14784E-04	0.0000	0.987794E-09	17.008	3
4 H2(R)	0.0000	0.96913E-13	0.0000	0.647522E-17	2.016	4
5 H2O2(G)	0.0000	0.13038E-15	0.0000	0.871136E-20	34.016	5
6 N(G)	0.0000	0.58871E-05	0.0000	0.393341E-09	14.008	6
7 NO(G)	0.5233	0.27043E+03	0.5422	0.180686E-01	30.008	7
8 NO2(G)	0.0008	0.40388E+00	0.0012	0.269854E-04	46.008	8
9 O(G)	0.0126	0.65045E+01	0.0070	0.434594E-03	16.000	9
10 HNO(G)	0.0000	0.10370E-09	0.0000	0.692892E-14	31.016	10
11 HO2(G)	0.0000	0.83256E-08	0.0000	0.556268E-12	33.008	11
12 H2O(G)	0.0000	0.35917E-09	0.0000	0.239975E-13	18.016	12
13 N2(G)	77.8215	0.40214E+05	75.2755	0.268688E+01	28.016	13
14 O2(G)	20.6810	0.10687E+05	22.8491	0.714034E+00	32.000	14

INPUT MIXTURE

WT. %	HF(C/MOLE)	M.W.	MOLECULAR FORMULA	
1.000000	0.0	2.016	2.0000	H
0.013250	0.0	39.941	1.0000	A
0.231460	0.0	32.000	2.0000	O
0.755290	0.0	28.016	2.0000	N
0.000000	0.0	28.016	2.0000	N

RESULTING GRAM ATOMS, ELEMENTS

ELEMENT	AT. NO.	AT. WT.	VAL	GRAM ATOMS
H	1	1.008	1.0	2.811266
N	7	14.008	0.0	5.239056
O	8	16.000	-2.0	1.405631
A	18	39.941	0.0	0.032234

EQUIVALENCE RATIO	=	1.00000131
STOIC FUEL/OX RATIO	=	0.02916396
FUEL/OX RATIO(WF/WO)	=	0.02916400
OX/FUEL RATIO(WO/WF)	=	34.28884890
MIXTURE WT (Kg)	=	0.10000001

MIXTURE ENTH (J/Kg) = 0.00000000
ROC. EQ. FRAC. = 0.50000036

CROC OF APR 9, 1991
EXPAN OF NOVEMBER 3, 1986

******** RAMJET PERFORMANCE ANALYSIS ********

09/23/93

CASE: PC RJPA Test Calibration run
Scramjet Case eq6-1, Mach 15.0, Z= 39272 m, No Frozen H2, Crocco =1.0

COMBUSTOR RESULTS

WOF	= 0.342888E+02	XI	= 0.100000E+01
ERGG	= 0.999999E+06	WASS	= 0.126750E+02 KG/S
ERS	= 0.100000E+01	WAGG	= 0.000000E+00 KG/S
ERO	= 0.100000E+01	WF	= 0.369654E+00 KG/S
FSR	= 0.291640E-01	WCE	= 0.130447E+02 KG/S
CEFF	= 100.000130%	CF	= 0.000000E+00

CROCCO EPS	= 0.100000E+01	ACE	= 0.315100E-01 M2
PSPCI	= 0.100000E+01	ACI	= 0.300000E-01 M2
MCE	= 0.365160E+01	AGG	= 0.150000E-02 M2
MCE @ E.L.	= 0.100000E+01	ABASE	= 0.100000E-04 M2
PBASE (Pa)	= 0.516746E+05	ATOTAL	= 0.315100E-01 M2
PGG (Pa)	= 0.164066E+06	RHOGG	= 0.425461E-01 KG/M3

PRESSURE (Pa)	= 0.105275E+06	FROZEN MACH NUMBER	= 0.365160E+01
TEMPERATURE (K)	= 0.297527E+04	VELOCITY (M/S)	= 0.427321E+04
DENSITY (Kg/M3)	= 0.963793E-01	FRZ SOUND SPD (M/S)	= 0.117023E+04
ENTHALPY (J/Kg)	= 0.256152E+07	FROZEN GAMMA	= 0.126023E+01
ENTROPY (J/Kg-K)	= 0.119523E+05	MOL.WT. (Kg/KgMOLE)	= 0.227548E+02
PITOT PRESSURE (Pa)	= 0.000000E+00	A/W (M2-S/Kg)	= 0.241554E-02
TOTAL PRESSURE (Pa)	= 0.000000E+00	F/W (N-S/Kg)	= 0.452751E+04
TOTAL TEMP (K)	= 0.000000E+00	F/A (Pa)	= 0.187432E+07
W/A (Kg/S-M2)	= 0.413985E+03		
SENSIBLE ENTHALPY	= 0.423926E+07	WT.FRCT.COND.PROD.	= 0.000000E+00
EQ.SOUND SPD (M/S)	= 0.110897E+04	EQ.MACH NUMBER	= 0.385332E+01
EQ.GAMMA	= 0.113174E+01	EQ.CP (J/KG-K)	= 0.673249E+04
EQ.COMPRESS. (1/Pa)	= 0.465810E+03		

GAS COMPOSITION
TOTAL GAS MOLES = 0.43957214E+01 P/FN = 0.23636216E+00

PRODUCTS GAS	MOLE-PCT OF GAS	PARTIAL PRESSURE	WEIGHT PCT	MOLE /100-GM	MOLECULAR WEIGHT	
1 A(G)	0.7333	0.77198E+03	1.2875	0.322339E-01	39.941	1
2 H(G)	3.6630	0.38562E+04	0.1623	0.161015E+00	1.008	2
3 HO(G)	3.9632	0.41722E+04	2.9630	0.174210E+00	17.008	3
4 H2(R)	6.5298	0.68743E+04	0.5787	0.287033E+00	2.016	4
5 H2O2(G)	0.0001	0.54774E-01	0.0001	0.228707E-05	34.016	5

6	N(G)	0.0009	0.94397E+00	0.0006	0.394152E-04	14.008	6
7	NO(G)	1.2509	0.13169E+04	1.6500	0.549852E-01	30.008	7
8	NO2(G)	0.0002	0.20819E+00	0.0004	0.869284E-05	46.008	8
9	O(G)	1.3872	0.14604E+04	0.9757	0.609783E-01	16.000	9
10	HNO(G)	0.0002	0.15799E+00	0.0002	0.659677E-05	31.016	10
11	HO2(G)	0.0006	0.60039E+00	0.0008	0.250692E-04	33.008	11
12	H2O(G)	21.6340	0.22775E+05	17.1327	0.950970E+00	18.016	12
13	N2(G)	58.9666	0.62077E+05	72.6177	0.259201E+01	28.016	13
14	O2(G)	1.8701	0.19688E+04	2.6305	0.822047E-01	32.000	14

******** RAMJET PERFORMANCE ANALYSIS ********

09/23/93

CASE: PC RJPA Test Calibration run
Scramjet Case eq6-1, Mach 15.0, Z= 39272 m, No Frozen H2, Crocco =1.0

EQUILIBRIUM NOZZLE EXPANSION TO REQUIRED AREA

EXP = 1 J22 = 2
PEX = 0.600000E+00

PRESSURE (Pa)	= 0.309821E+04	FROZEN MACH NUMBER	= 0.526247E+01
TEMPERATURE (K)	= 0.207321E+04	VELOCITY (M/S)	= 0.495285E+04
DENSITY (Kg/M3)	= 0.438977E-02	FRZ SOUND SPD (M/S)	= 0.941164E+03
ENTHALPY (J/Kg)	= -.574789E+06	FROZEN GAMMA	= 0.125505E+01
ENTROPY (J/Kg-K)	= 0.119523E+05	MOL.WT. (Kg/KgMOLE)	= 0.244173E+02
PITOT PRESSURE (Pa)	= 0.000000E+00	A/W (M2-S/Kg)	= 0.459942E-01
TOTAL PRESSURE (Pa)	= 0.000000E+00	F/W (N-S/Kg)	= 0.509536E+04
TOTAL TEMP (K)	= 0.000000E+00	F/A (Pa)	= 0.110783E+06
W/A (Kg/S-M2)	= 0.217419E+02		
SENSIBLE ENTHALPY	= 0.262912E+07	WT.FRCT.COND.PROD.	= 0.000000E+00
EQ.SOUND SPD (M/S)	= 0.909563E+03	EQ.MACH NUMBER	= 0.544531E+01
EQ.GAMMA	= 0.117219E+01	EQ.CP (J/KG-K)	= 0.276246E+04
EQ.COMPRESS. (1/Pa)	= 0.153965E+05		
EXIT AREA (M**2)	= 0.599980E+00		

GAS COMPOSITION
TOTAL GAS MOLES = 0.40954533E+01 P/FN = 0.74660750E-02

	PRODUCTS GAS	MOLE-PCT OF GAS	PARTIAL PRESSURE	WEIGHT PCT	MOLE /100-GM	MOLECULAR WEIGHT	
1	A(G)	0.7871	0.24385E+02	1.2875	0.322339E-01	39.941	1
2	H(G)	0.1719	0.53269E+01	0.0071	0.704147E-02	1.008	2
3	HO(G)	0.4778	0.14805E+02	0.3328	0.195701E-01	17.008	3
4	H2(R)	1.3160	0.40771E+02	0.1087	0.538946E-01	2.016	4
5	H2O2(G)	0.0000	0.29776E-04	0.0000	0.393601E-07	34.016	5
6	N(G)	0.0000	0.35397E-04	0.0000	0.467908E-07	14.008	6
7	NO(G)	0.1363	0.42218E+01	0.1675	0.558071E-02	30.008	7
8	NO2(G)	0.0000	0.16078E-03	0.0000	0.212531E-06	46.008	8
9	O(G)	0.0457	0.14159E+01	0.0299	0.187162E-02	16.000	9
10	HNO(G)	0.0000	0.34815E-04	0.0000	0.460217E-07	31.016	10
11	HO2(G)	0.0000	0.27276E-03	0.0000	0.360550E-06	33.008	11

12	H2O(G)	32.6809	0.10125E+04	24.1132	0.133843E+01	18.016	12
13	N2(G)	63.8938	0.19796E+04	73.3106	0.261674E+01	28.016	13
14	O2(G)	0.4905	0.15196E+02	0.6428	0.200877E-01	32.000	14

******** RAMJET PERFORMANCE ANALYSIS ********

09/23/93

CASE: PC RJPA Test Calibration run
Scramjet Case eq6-1, Mach 15.0, Z= 39272 m, No Frozen H2, Crocco =1.0

FROZEN NOZZLE EXPANSION TO REQUIRED AREA

EXP = 1 J22 = 2
PEX = 0.600000E+00

PRESSURE (Pa)	= 0.201890E+04	FROZEN MACH NUMBER	= 0.634767E+01
TEMPERATURE (K)	= 0.124644E+04	VELOCITY (M/S)	= 0.490447E+04
DENSITY (Kg/M3)	= 0.443292E-02	FRZ SOUND SPD (M/S)	= 0.772641E+03
ENTHALPY (J/Kg)	= -.336245E+06	FROZEN GAMMA	= 0.131079E+01
ENTROPY (J/Kg-K)	= 0.119523E+05	MOL.WT. (Kg/KgMOLE)	= 0.227494E+02
PITOT PRESSURE (Pa)	= 0.000000E+00	A/W (M2-S/Kg)	= 0.459958E-01
TOTAL PRESSURE (Pa)	= 0.000000E+00	F/W (N-S/Kg)	= 0.499734E+04
TOTAL TEMP (K)	= 0.000000E+00	F/A (Pa)	= 0.108648E+06
W/A (Kg/S-M2)	= 0.217411E+02		
EQ.SOUND SPD (M/S)	= 0.000000E+00	EQ.MACH NUMBER	= 0.000000E+00
EQ.GAMMA	= 0.000000E+00	EQ.CP (J/KG-K)	= 0.000000E+00
EQ.COMPRESS. (1/Pa)	= 0.000000E+00		
EXIT AREA (M**2)	= 0.600000E+00		

GAS COMPOSITION
TOTAL GAS MOLES = 0.43957214E+01 P/PN = 0.45328070E-02

	PRODUCTS GAS	MOLE-PCT OF GAS	PARTIAL PRESSURE	WEIGHT PCT	MOLE /100-GM	MOLECULAR WEIGHT	
1	A(G)	0.7333	0.14805E+02	1.2875	0.322339E-01	39.941	1
2	H(G)	3.6630	0.73952E+02	0.1623	0.161015E+00	1.008	2
3	HO(G)	3.9632	0.80012E+02	2.9630	0.174210E+00	17.008	3
4	H2(R)	6.5298	0.13183E+03	0.5787	0.287033E+00	2.016	4
5	H2O2(G)	0.0001	0.10504E-02	0.0001	0.228707E-05	34.016	5
6	N(G)	0.0009	0.18103E-01	0.0006	0.394152E-04	14.008	6
7	NO(G)	1.2509	0.25254E+02	1.6500	0.549852E-01	30.008	7
8	NO2(G)	0.0002	0.39925E-02	0.0004	0.869284E-05	46.008	8
9	O(G)	1.3872	0.28007E+02	0.9757	0.609783E-01	16.000	9
10	HNO(G)	0.0002	0.30298E-02	0.0002	0.659677E-05	31.016	10
11	HO2(G)	0.0006	0.11514E-01	0.0008	0.250692E-04	33.008	11
12	H2O(G)	21.6340	0.43677E+03	17.1327	0.950970E+00	18.016	12
13	N2(G)	58.9666	0.11905E+04	72.6177	0.259201E+01	28.016	13
14	O2(G)	1.8701	0.37756E+02	2.6305	0.822047E-01	32.000	14

******** RAMJET PERFORMANCE ANALYSIS ********

09/23/93

CASE: PC RJPA Test Calibration run
Scramjet Case eq6-1, Mach 15.0, Z= 39272 m, No Frozen H2, Crocco =1.0

Q0 (Pa) = 0.501994E+05

COMBINED-- 0.667

NOZZ EFF (%)	THRUST(N)	CT	ISP(N-S/KG)
97.40	0.34890203E+04	0.115839	0.94386011E+03
97.66	0.36596199E+04	0.121503	0.99001123E+03
97.92	0.38302192E+04	0.127167	0.10361622E+04
98.18	0.40008188E+04	0.132831	0.10823134E+04
98.44	0.41714185E+04	0.138495	0.11284645E+04
98.70	0.43420176E+04	0.144159	0.11746156E+04
98.96	0.45126172E+04	0.149823	0.12207666E+04
99.22	0.46832173E+04	0.155487	0.12669178E+04
99.48	0.48538164E+04	0.161151	0.13130690E+04
99.74	0.50244160E+04	0.166815	0.13592200E+04
100.00	0.51950156E+04	0.172479	0.14053711E+04

FROZEN ONLY

NOZZ EFF (%)	THRUST(N)	CT	ISP(N-S/KG)
97.40	0.30739207E+04	0.102057	0.83156610E+03
97.66	0.32434121E+04	0.107684	0.87741748E+03
97.92	0.34129038E+04	0.113312	0.92326886E+03
98.18	0.35823953E+04	0.118939	0.96912018E+03
98.44	0.37518865E+04	0.124566	0.10149714E+04
98.70	0.39213779E+04	0.130193	0.10608228E+04
98.96	0.40908694E+04	0.135821	0.11066742E+04
99.22	0.42603608E+04	0.141448	0.11525255E+04
99.48	0.44298521E+04	0.147075	0.11983767E+04
99.74	0.45993438E+04	0.152703	0.12442281E+04
100.00	0.47688350E+04	0.158330	0.12900795E+04

EQUILIBRIUM ONLY

NOZZ EFF (%)	THRUST(N)	CT	ISP(N-S/KG)
97.40	0.43193438E+04	0.143406	0.11684818E+04
97.66	0.44921597E+04	0.149144	0.12152324E+04
97.92	0.46649756E+04	0.154882	0.12619832E+04
98.18	0.48377915E+04	0.160619	0.13087338E+04
98.44	0.50106079E+04	0.166357	0.13554845E+04
98.70	0.51834238E+04	0.172095	0.14022352E+04
98.96	0.53562397E+04	0.177832	0.14489858E+04
99.22	0.55290557E+04	0.183570	0.14957366E+04
99.48	0.57018716E+04	0.189308	0.15424873E+04
99.74	0.58746880E+04	0.195045	0.15892379E+04
100.00	0.60475039E+04	0.200783	0.16359886E+04

COMPONENT IMPULSE SUMMARY

DIFFUSER (N) = -.374817E+04

COMBUSTOR (N) = 0.237870E+04

```
FROZEN NOZZLE (N)       = 0.612875E+04
EQUILIBRIUM NOZZLE (N) = 0.740742E+04
END OF SIMULATION
```

B.3.3 - Test 3 Input File - T3-FRC

```
 PC RJPA Test Calibration Run
 Scramjet Case FRC15185, Mach 15.0, Z= 39272, No Frozen H2, Crocco =1.0
EJANAF.DAT
 5, 1, 1. 1, 1, 1 /
 3, 1.000000,     0.0,   2.0, 'H    ' /
 0, 0.013250,     0.0,   1.0, 'A    ' /
 0, 0.231460,     0.0,   2.0, 'O    ' /
 0, 0.755290      0.0,   2.0, 'N    ' /
 2.016 /
 14, 1,288,300,304,310,350,351,352,381,767,810,1271,1272,1273 /
 &FRSTR
  INIT=1, UNITS=SI,  PAR=15,   Z=39272,TEMP=249.05, PITI=0,
  AREF=0.6,  AISS=0.6, AIGG=0.0,  WOFINO=1.E11, &END

 &DIFFUSER   DIFF=1,    PAR1=0.03, EFF=0.976,
   HEAT=1,    QDIFF=342829.1400, PITD=0,
   GAMG1=1.2, GAMG2=1.3,    SWT=0.5 &END

 &SHCK  SHK=0, BET=90.0, DEL=0.0, PITS=0 &END

 &COMBUSTOR  COMB=6,      ICOMB=0,     FRC= 'CHEM15',
  ISPLINE=2, NOUT=1, ARTOL=1E-6,EMAX=1.0E-3,ATOLSP=1.0E-12,
  XATB=0.0,      40.0,     800.00,
  AATB=0.03151,  0.03151, 0.03151, NATB=3,
  MAXSTP=32000, PRINT=100.00,
  NPRNTS=1, &END

 &HEATFRICTION  &END

 &MIXER  MX=3,IWOFER=1,ER=1.0,WOFIN=34.288849, FSR=0.029164,
  PTOLI=0.0001, ERRI=0.00001,    NAA=4,   XDA=0.0, 0.001, 100.0, 800.0,
  DAA=0.0, 1.0,      1.0,   1.0,   NFF=4,  XDF=0.0, 0.001, 100.0, 800.0,
  DFF=0.0, 1.0,      1.0,   1.0,   &END

 &OXIDIZER  BETA=0.0, DPODX=-4.053E5, INERTO='ar' &END

 &FUEL  AGG=0.0015, TGG=935.0, MACHF=2.5,
  PGG=0.164066E6, DPFDX=-4.053E5, ALPHA=0.0 &END

 &PRODUCTS
  ALLM1P=F, ABASE=0.00001,
  TPP=1853.33, MACHP=5.22732, INERTP='ar',
  PBASE=.516746E5, DPPDX=-4.053E5 &END

 &NOZZLE
  EXP=1, EFFN=0.9740, J22=2,
  PEX=0.6, PITN=0, RATIOFE=0.6667 &END
```

B.3.3 - Test 3 Output File - T3-FRC

```
                    RAMJET PERFORMANCE ANALYSIS, VERSION 1.24
 PC RJPA Test Calibration Run
 Scramjet Case FRC15185, Mach 15.0, Z= 39272, No Frozen H2, Crocco =1.0
EJANAF.DAT

FOLLOWING DATA READ FROM JANAF THERMOCHEMICAL FILE:
  KEY           NAME                                  FORMULA        DATE    HF-298
     1   ARGON                              (G)   A(G)           A0672   0.00000E+00
   288   HYDROGEN, MONATOMIC                (G)   H(G)           J 674   0.52103E+02
   300   HYDROXYL                           (G)   HO(G)          J1270   0.94920E+01
   304   HYDROGEN, DIATOMIC                 (R)   H2(R)          J 361   0.00000E+00
   310   HYDROGEN PEROXIDE                  (G)   H2O2(G)        J1260  -0.32530E+02
   350   NITROGEN, MONATOMIC                (G)   N(G)           J 361   0.11297E+03
   351   NITRIC OXIDE                       (G)   NO(G)          J 663   0.21580E+02
   352   NITROGEN DIOXIDE                   (G)   NO2(G)         J 964   0.79100E+01
   381   OXYGEN, MONATOMIC                  (G)   O(G)           J 674   0.59553E+02
   767   NITROXYL                           (G)   HNO(G)         J 363   0.23800E+02
   810   HYDROPEROXYL                       (G)   HO2(G)         J 364   0.50000E+01
  1271 WATER-LOW TEMP. FITS                 (G)   H2O(G)         A 368  -0.57798E+02
  1272 NITROGEN-LOW TEMP. FITS              (G)   N2(G)          A 368   0.00000E+00
  1273 OXYGEN-LOW TEMP. FITS                (G)   O2(G)          A 368   0.00000E+00

 UNITS = si
 INIT  =  1
     PAR    =  0.15000000E+02
     Z      =  0.39272000E+05
     TEMP   =  0.24905000E+03
     PITI   =  0
     AREF   =  0.60000002E+00
     AISS   =  0.60000002E+00
     AIGG   =  0.00000000E+00
     WOFINO=   0.99999998E+11

 DIFF =  1
     PAR1   =  0.29999999E-01
     EFF    =  0.97600001E+00
     HEAT   =  1
     QDIFF =   0.34282913E+06
     PITD   =  0
     GAMG1 =   0.12000000E+01
     GAMG2 =   0.13000000E+01
     SWT    =  0.50000000E+00

 SHK   =  0
     BET   =  0.90000000E+02
     DEL   =  0.00000000E+00
     PITS =   0

 COMB =  6      ICOMB  =   0      FRC  = CHEM15
 ISTREAM =                 3       ARTOL  =  0.10000000E-05
 DJ       =  0.10132500E+06        PNORM  =  0.99999998E-02
```

```
ISPLINE = 2     NATB =   3
XATB =  0.00000000E+00  0.40000000E+02  0.80000000E+03
AATB =  0.31509999E-01  0.31509999E-01  0.31509999E-01

IENV1 = 0

IENV2 = 0

IENV3 = 0

IQST1 = 0

IQST2 = 0

MX   =   3      PTOLI   =  0.99999997E-04
NAA  =   4      NFF     =   4

XDA =  0.00000000E+00  0.10000000E-02  0.10000000E+03  0.80000000E+03
DAA =  0.00000000E+00  0.10000000E+01  0.10000000E+01  0.10000000E+01


XDF =  0.00000000E+00  0.10000000E-02  0.10000000E+03  0.80000000E+03
DFF =  0.00000000E+00  0.10000000E+01  0.10000000E+01  0.10000000E+01


BETA    =  0.00000000E+00      DPODX = -0.40530000E+06
ALLM1O = T      INERTO = ar

AGG     =  0.15000000E-02      TGG    =  0.93500000E+03
MACHF   =  0.25000000E+01      PGG    =  0.16406600E+06
ALPHA   =  0.00000000E+00      DPFDX = -0.40530000E+06
ALLM1F = T      INERTF =

ABASE   =  0.99999997E-05      TPP     =  0.18533300E+04
MACHP   =  0.52273202E+01      PBASE   =  0.51674602E+05
DPFDX   = -0.40530000E+06      ALLM1P = F
INERTP = ar

EXP =  1
    EFFN     =  0.97399998E+00
    J22      =  2
    PEX      =  0.60000002E+00
    PITN     =  0
    RATIOFE =  0.66670001E+00

RJPA OF SEPTEMBER 12, 1988

INPUT MIXTURE
WT. %     HF(C/MOLE)    M.W.    MOLECULAR FORMULA
1.000000        0.0   2.016  2.0000    H
0.013250        0.0  39.941  1.0000    A
0.231460        0.0  32.000  2.0000    O
0.755290        0.0  28.016  2.0000    N
```

0.000000 0.0 28.016 2.0000 N

RESULTING GRAM ATOMS, 4 ELEMENTS

ELEMENT	AT. NO.	AT. WT.	VAL	GRAM ATOMS
H	1	1.008	1.0	0.000000
N	7	14.008	0.0	5.391847
O	8	16.000	-2.0	1.446625
A	18	39.941	0.0	0.033174

EQUIVALENCE RATIO = 0.00000000
STOIC FUEL/OX RATIO = 0.02916396
FUEL/OX RATIO(WF/WO) = 0.00000000
OX/FUEL RATIO(WO/WF) =***************
MIXTURE WT (Kg) = 0.10000000
MIXTURE ENTH (J/Kg) = 0.00000000
ROC. EQ. FRAC. = 0.00000000

DIF OF JAN. 17, 1989

******** RAMJET PERFORMANCE ANALYSIS ********

10/13/93

CASE: PC RJPA Test Calibration Run
Scramjet Case FRC15185, Mach 15.0, Z= 39272, No Frozen H2, Crocco =1.0

INLET CONDITIONS

INIT = 1 PAR = 0.150000E+02
Z = 0.392720E+05 TEMP = 0.138361E+03

PRESSURE (Pa)	= 0.316877E+03	FROZEN MACH NUMBER	= 0.150000E+02
TEMPERATURE (K)	= 0.248336E+03	VELOCITY (M/S)	= 0.475183E+04
DENSITY (Kg/M3)	= 0.444636E-02	FRZ SOUND SPD (M/S)	= 0.316789E+03
ENTHALPY (J/Kg)	= -.505579E+05	FROZEN GAMMA	= 0.140817E+01
ENTROPY (J/Kg-K)	= 0.832862E+04	MOL.WT. (Kg/KgMOLE)	= 0.289653E+02
PITOT PRESSURE (Pa)	= 0.000000E+00	A/W (M2-S/Kg)	= 0.473297E-01
TOTAL PRESSURE (Pa)	= 0.000000E+00	F/W (N-S/Kg)	= 0.476684E+04
TOTAL TEMP (K)	= 0.000000E+00	F/A (Pa)	= 0.100716E+06
W/A (Kg/S-M2)	= 0.211284E+02		
SENSIBLE ENTHALPY	= -.505579E+05	WT.FRCT.COND.PROD.	= 0.000000E+00
TOTAL ENTH. (J/KG)	= 0.112433E+08		
EQ.SOUND SPD (M/S)	= 0.316817E+03	EQ.MACH NUMBER	= 0.149987E+02
EQ.GAMMA	= 0.140842E+01	EQ.CP (J/KG-K)	= 0.990281E+03
EQ.COMPRESS. (1/Pa)	= 0.315581E-02		

GAS COMPOSITION
TOTAL GAS MOLES = 0.34524100E+01 P/FN = 0.90584130E-03

PRODUCTS GAS	MOLE-PCT OF GAS	PARTIAL PRESSURE	WEIGHT PCT	MOLE /100-GM	MOLECULAR WEIGHT	
1 A(G)	0.9609	0.30448E+01	1.3250	0.331739E-01	39.941	1
2 H(G)	0.0000	0.43881E-22	0.0000	0.478089E-24	1.008	2

3	HO(G)	0.0000	0.43881E-22	0.0000	0.478091E-24	17.008	3
4	H2(R)	0.0000	0.43881E-22	0.0000	0.478089E-24	2.016	4
5	H2O2(G)	0.0000	0.43881E-22	0.0000	0.478089E-24	34.016	5
6	N(G)	0.0000	0.43881E-22	0.0000	0.478089E-24	14.008	6
7	NO(G)	0.0000	0.46543E-16	0.0000	0.507090E-18	30.008	7
8	NO2(G)	0.0000	0.16332E-09	0.0000	0.177941E-11	46.008	8
9	O(G)	0.0000	0.43881E-22	0.0000	0.478089E-24	16.000	9
10	HNO(G)	0.0000	0.43881E-22	0.0000	0.478089E-24	31.016	10
11	HO2(G)	0.0000	0.43881E-22	0.0000	0.478069E-24	33.008	11
12	H2O(G)	0.0000	0.45528E-07	0.0000	0.496032E-09	18.016	12
13	N2(G)	78.0882	0.24744E+03	75.5290	0.269592E+01	28.016	13
14	O2(G)	20.9509	0.66389E+02	23.1460	0.723312E+00	32.000	14

******** RAMJET PERFORMANCE ANALYSIS ********

10/13/93

CASE: PC RJPA Test Calibration Run
Scramjet Case FRC15185, Mach 15.0, Z= 39272, No Frozen H2, Crocco =1.0

DIFFUSER EXIT CONDITIONS

DIFF = 1 PAR1 = 0.300000E-01
EFF = 0.976000E+00 AOI = 0.600000E+00 M2
ADICAL = 0.300048E-01 M2

PRESSURE (Pa)	= 0.516746E+05	FROZEN MACH NUMBER	= 0.522732E+01
TEMPERATURE (K)	= 0.185333E+04	VELOCITY (M/S)	= 0.434886E+04
DENSITY (Kg/M3)	= 0.971521E-01	FRZ SOUND SPD (M/S)	= 0.831948E+03
ENTHALPY (J/Kg)	= 0.178375E+07	FROZEN GAMMA	= 0.130127E+01
ENTROPY (J/Kg-K)	= 0.906732E+04	MOL.WT. (Kg/KgMOLE)	= 0.289636E+02
PITOT PRESSURE (Pa)	= 0.000000E+00	A/W (M2-S/Kg)	= 0.236686E-02
TOTAL PRESSURE (Pa)	= 0.000000E+00	F/W (N-S/Kg)	= 0.447117E+04
TOTAL TEMP (K)	= 0.000000E+00	F/A (Pa)	= 0.188907E+07
W/A (Kg/S-M2)	= 0.422501E+03		
SENSIBLE ENTHALPY	= 0.176635E+07	WT.FRCT.COND.PROD.	= 0.000000E+00
EQ.SOUND SPD (M/S)	= 0.826369E+03	EQ.MACH NUMBER	= 0.526261E+01
EQ.GAMMA	= 0.128388E+01	EQ.CP (J/KG-K)	= 0.130132E+04
EQ.COMPRESS. (1/Pa)	= 0.919975E+03		

GAS COMPOSITION
TOTAL GAS MOLES = 0.34526138E+01 P/FN = 0.14771095E+00

	PRODUCTS GAS	MOLE-PCT OF GAS	PARTIAL PRESSURE	WEIGHT PCT	MOLE /100-GM	MOLECULAR WEIGHT	
1	A(G)	0.9608	0.49651E+03	1.3250	0.331739E-01	39.941	1
2	H(G)	0.0000	0.54749E-07	0.0000	0.365801E-11	1.008	2
3	HO(G)	0.0000	0.14784E-04	0.0000	0.987794E-09	17.008	3
4	H2(R)	0.0000	0.96913E-13	0.0000	0.647522E-17	2.016	4
5	H2O2(G)	0.0000	0.13038E-15	0.0000	0.871136E-20	34.016	5
6	N(G)	0.0000	0.58871E-05	0.0000	0.393341E-09	14.008	6
7	NO(G)	0.5233	0.27043E+03	0.5422	0.180686E-01	30.008	7
8	NO2(G)	0.0008	0.40388E+00	0.0012	0.269854E-04	46.008	8

9	O(G)	0.0126	0.65045E+01	0.0070	0.434594E-03	16.000	9
10	HNO(G)	0.0000	0.10370E-09	0.0000	0.692892E-14	31.016	10
11	HO2(G)	0.0000	0.83256E-08	0.0000	0.556268E-12	33.008	11
12	H2O(G)	0.0000	0.35917E-09	0.0000	0.239975E-13	18.016	12
13	N2(G)	77.8215	0.40214E+05	75.2755	0.268688E+01	28.016	13
14	O2(G)	20.6810	0.10687E+05	22.8491	0.714034E+00	32.000	14

INPUT MIXTURE

WT. %	HF(C/MOLE)	M.W.	MOLECULAR	FORMULA
1.000000	0.0	2.016	2.0000	H
0.013250	0.0	39.941	1.0000	A
0.231460	0.0	32.000	2.0000	O
0.755290	0.0	28.016	2.0000	N
0.000000	0.0	28.015	2.0000	N

RESULTING GRAM ATOMS, 4 ELEMENTS

ELEMENT	AT. NO.	AT. WT.	VAL	GRAM ATOMS
H	1	1.008	1.0	2.811266
N	7	14.008	0.0	5.239056
O	8	16.000	-2.0	1.405631
A	18	39.941	0.0	0.032234

EQUIVALENCE RATIO	=	1.00000131
STOIC FUEL/OX RATIO	=	0.02916396
FUEL/OX RATIO(WF/WO)	=	0.02916400
OX/FUEL RATIO(WO/WF)	=	34.28884890
MIXTURE WT (Kg)	=	0.10000001
MIXTURE ENTH (J/Kg)	=	0.00000000
ROC. EQ. FRAC.	=	0.50000036

1 distance-pressure version
+ general kinetics and sensitivity
program nasa lewis research center

STREAM NO. 3
time 0.00000E+00 sec area 9.99999975E-06 sq m

axial position 0.00000000E+00 m

flow properties		integration indicators	
pressure (n/m**2)	5.16746367E+04	steps from last print	0
velocity (m/sec)	4.34893457E+03	average step size	0.00000000E+00
density (kg/m**3)	9.71216261E-02	total number of steps	0
temperature (deg k)	1.85333000E+03		
mass flow rate (kg/sec)	4.22375603E-03		
entropy	9.07213281E+03	function evaluations	0

joule/kg/deg k)
mach number 5.22731972E+00 jacobian evaluations 0

gamma 1.30091176E+00

enthalpy 1.78767625E+06
(joule/kg)

chemical properties

species	concentration (moles/m**3)	mole fraction
h	3.35349E-10	1.00000E-07
o2	6.93536E-04	2.06810E-01
oh	0.00000E+00	0.00000E+00
o	4.22540E-07	1.26000E-04
h2	0.00000E+00	0.00000E+00
h2o	0.00000E+00	0.00000E+00
ho2	0.00000E+00	0.00000E+00
h2o2	0.00000E+00	0.00000E+00
no	1.75488E-05	5.23300E-03
no2	2.68279E-08	8.00000E-06
n	0.00000E+00	0.00000E+00
n2	2.60974E-03	7.78215E-01
hno	0.00000E+00	0.00000E+00
ar	3.22203E-05	9.60800E-03

derivatives (si units):

t	-7.65430E-02
rho	4.05111E-06
v	0.00000E+00

mixture molecular weight 0.289613E+02
total energy exchange rate 0.456544E+07
(joule-m**3/kg**2/sec)
mass fraction sum 0.100000E+01
1 initial conditions **

STREAM NO. 2
time 0.00000E+00 sec area 1.50000001E-03 sq m

axial position 0.00000000E+00 m

flow properties integration indicators

pressure 1.64066453E+05 steps from last print 0
(n/m**2)
velocity 5.79221924E+03 average step size 0.00000000E+00
(m/sec)
density 4.23303023E-02 total number of steps 0
(kg/m**3)
temperature 9.35000000E+02

```
 (deg k)
mass flow rate      3.67779613E-01
 (kg/sec)
entropy             7.99128828E+04   function evaluations         0
 joule/kg/deg k).
mach number         2.50000000E+00   jacobian evaluations         0

gamma               1.38497951E+00

enthalpy            1.03951710E+07
 (joule/kg)


          chemical properties

species     concentration    mole fraction  net
             (moles/m**3)                    tiv
 h           2.11048E-04      1.00000E-02
 h2          2.08937E-02      9.90000E-01

derivatives (si units):
t             1.01272E+02
rho          -4.29592E-03
v             0.00000E+00

mixture molecular weight     0.200572E+01
total energy exchange rate   -.203043E+12
 (joule-m**3/kg**2/sec)
mass fraction sum            0.100000E+01

initial conditions  **


STREAM NO.             1
 time   0.00000E+00  sec   area 3.00047994E-02  sq m

 axial position 0.00000000E+00  m


 flow properties                      integration indicators

pressure            5.16746367E+04   steps from last print        0
 (n/m**2)
velocity            4.34885986E+03   average step size   0.00000000E+00
 (m/sec)
density             9.71216261E-02   total number of steps        0
 (kg/m**3)
temperature         1.85333000E+03
 (deg k)
mass flow rate      1.26730785E+01
 (kg/sec)
entropy             9.07212988E+03   function evaluations         0
 joule/kg/deg k)
mach number         5.22723055E+00   jacobian evaluations         0
```

```
gamma               1.30091183E+00

enthalpy            1.78767450E+06
 (joule/kg)


         chemical properties


species     concentration   mole fraction
             (moles/m**3)
 o           4.22117E-07     1.25874E-04
 o2          6.93534E-04     2.06810E-01
 no2         2.62106E-08     7.81592E-06
 no          1.75498E-05     5.23330E-03
 n           0.00000E+00     0.00000E+00
 n2          2.60974E-03     7.78215E-01
 ar          3.22215E-05     9.60835E-03

derivatives (si units):
t           -8.32892E-04
rho          6.31959E-08
v            0.00000E+00

mixture molecular weight     0.289613E+02
total energy exchange rate   0.432198E+05
 (joule-m**3/kg**2/sec)
mass fraction sum            0.100000E+01


cpu time for initialization of gksp =     -0.001563 s


1
STREAM NO.             3
 time   2.34038E-02  sec   area 3.15099992E-02  sq m

 axial position 1.00000000E+02  m


 flow properties                      integration indicators

 pressure            1.05195672E+05  steps from last print      229
  (n/m**2)
 velocity            4.27283154E+03  average step size   1.83838715E+02
  (m/sec)
 density             9.68927816E-02  total number of steps      229
  (kg/m**3)
 temperature         2.97506944E+03
  (deg k)
 mass flow rate      1.30453472E+01
  (kg/sec)
```

```
entropy              1.19457744E+04   function evaluations      335
 joule/kg/deg k)
mach number          3.65173411E+00   jacobian evaluations      43

gamma                1.26103918E+00

enthalpy             2.56447250E+06
 (joule/kg)
```

chemical properties

species	concentration (moles/m**3)	mole fraction
h	1.53509E-04	3.60961E-02
o2	7.98369E-05	1.87729E-02
oh	1.72946E-04	4.06666E-02
o	5.90567E-05	1.38866E-02
h2	2.72491E-04	6.40735E-02
h2o	9.19386E-04	2.16185E-01
ho2	6.44058E-08	1.51444E-05
h2o2	2.04648E-09	4.81209E-07
no	5.10417E-05	1.20020E-02
no2	9.29532E-09	2.18570E-06
n	3.76818E-08	8.86051E-06
n2	2.51316E-03	5.90944E-01
hno	6.00396E-09	1.41177E-06
ar	3.12393E-05	7.34562E-03

```
derivatives (si units):
t              2.19049E-07
rho            5.71867E-13
v             -2.52185E-08

mixture molecular weight     0.227834E+02
total energy exchange rate   -.128005E+02
 (joule-m**3/kg**2/sec)
mass fraction sum            0.100000E+01
```

```
computer time (cpu) required:
for this step -  1.070844E+01  s
up to this time -  1.070844E+01  s

0(gksp:      end of this case

total cpu time (including i/o) required =       12.362187 s

0(gksp)      read data for next case
EXPAN OF NOVEMBER 3, 1986
```

******** RAMJET PERFORMANCE ANALYSIS ********

10/13/93

CASE: PC RJPA Test Calibration Run
Scramjet Case FRC15185, Mach 15.0, Z= 39272, No Frozen H2, Crocco =1.0

COMBUSTOR RESULTS

WOF	= 0.342888E+02	XI	= 0.100000E+01
ERGG	= 0.999999E+06	WASS	= 0.126731E+02 KG/S
ERS	= 0.100000E+01	WAGG	= 0.000000E+00 KG/S
ERO	= 0.100000E+01	WF	= 0.367780E+00 KG/S
FSR	= 0.291640E-01	WCE	= 0.130453E+02 KG/S
CEFF	= 100.494461%	CF	= 0.000000E+00

CROCCO EPS	= 0.100025E+01	ACE	= 0.315102E-01 M2
PSPCI	= 0.100000E+01	ACI	= 0.300048E-01 M2
MCE	= 0.365169E+01	AGG	= 0.150000E-02 M2
MCE @ E.L.	= 0.100016E+01	ABASE	= 0.100000E-04 M2
PBASE (Pa)	= 0.516746E+05	ATOTAL	= 0.315148E-01 M2
PGG (Pa)	= 0.164070E+06	RHOGG	= 0.423303E-01 KG/M3
PMODEL (Pa)	= 0.000000E+00		

PRESSURE (Pa)	= 0.105196E+06	FROZEN MACH NUMBER	= 0.365169E+01
TEMPERATURE (K)	= 0.297507E+04	VELOCITY (M/S)	= 0.427283E+04
DENSITY (Kg/M3)	= 0.968928E-01	FRZ SOUND SPD (M/S)	= 0.117010E+04
ENTHALPY (J/Kg)	= 0.256619E+07	FROZEN GAMMA	= 0.126104E+01
ENTROPY (J/Kg-K)	= 0.119538E+05	MOL.WT. (Kg/KgMOLE)	= 0.227834E+02
PITOT PRESSURE (Pa)	= 0.000000E+00	A/W (M2-S/Kg)	= 0.241542E-02
TOTAL PRESSURE (Pa)	= 0.000000E+00	F/W (N-S/Kg)	= 0.452683E+04
TOTAL TEMP (K)	= 0.000000E+00	F/A (Pa)	= 0.187414E+07
W/A (Kg/S-M2)	= 0.414007E+03		
SENSIBLE ENTHALPY	= 0.424493E+07	WT.FRCT.COND.PROD.	= 0.000000E+00
EQ.SOUND SPD (M/S)	= 0.110877E+04	EQ.MACH NUMBER	= 0.385366E+01
EQ.GAMMA	= 0.113235E+01	EQ.CP (J/KG-K)	= 0.673205E+04
EQ.COMPRESS. (1/Pa)	= 0.465779E+05		

GAS COMPOSITION

TOTAL GAS MOLES = 0.43891644E+01   P/FN = 0.23653717E+00

	PRODUCTS GAS	MOLE-PCT OF GAS	PARTIAL PRESSURE	WEIGHT PCT	MOLE /100-GM	MOLECULAR WEIGHT	
1	A(G)	0.7346	0.77273E+03	1.2877	0.322411E-01	39.941	1
2	H(G)	3.6096	0.37972E+04	0.1597	0.158432E+00	1.008	2
3	HO(G)	4.0667	0.42779E+04	3.0358	0.178492E+00	17.008	3
4	H2(R)	6.4073	0.67403E+04	0.5670	0.281229E+00	2.016	4
5	H2O2(G)	0.0000	0.50621E-01	0.0001	0.211211E-05	34.016	5
6	N(G)	0.0009	0.93209E+00	0.0005	0.388902E-04	14.008	6
7	NO(G)	1.2002	0.12626E+04	1.5808	0.526785E-01	30.008	7
8	NO2(G)	0.0002	0.22993E+00	0.0004	0.959341E-05	46.008	8
9	O(G)	1.3887	0.14608E+04	0.9752	0.609506E-01	16.000	9
10	HNO(G)	0.0001	0.14851E+00	0.0002	0.619650E-05	31.016	10

11	HO2(G)	0.0015	0.15931E+01	0.0022	0.664712E-04	33.008	11
12	H2O(G)	21.6185	0.22742E+05	17.0948	0.948870E+00	18.016	12
13	N2(G)	59.0944	0.62165E+05	72.6665	0.259375E+01	28.016	13
14	O2(G)	1.8773	0.19748E+04	2.6367	0.823971E-01	32.000	14

******** RAMJET PERFORMANCE ANALYSIS ********

10/13/93

CASE: PC RJPA Test Calibration Run
Scramjet Case FRC15185, Mach 15.0, Z= 39272, No Frozen H2, Crocco =1.0

EQUILIBRIUM NOZZLE EXPANSION TO REQUIRED AREA

EXP = 1 J22 = 2
PEX = 0.600000E+00

PRESSURE (Pa)	= 0.311581E+04	FROZEN MACH NUMBER	= 0.524407E+01
TEMPERATURE (K)	= 0.208344E+04	VELOCITY (M/S)	= 0.494616E+04
DENSITY (Kg/M3)	= 0.439555E-02	FRZ SOUND SPD (M/S)	= 0.943191E+03
ENTHALPY (J/Kg)	= -.538588E+06	FROZEN GAMMA	= 0.125499E+01
ENTROPY (J/Kg-K)	= 0.119538E+05	MOL.WT. (Kg/KgMOLE)	= 0.244313E+02
PITOT PRESSURE (Pa)	= 0.000000E+00	A/W (M2-S/Kg)	= 0.459958E-01
TOTAL PRESSURE (Pa)	= 0.000000E+00	F/W (N-S/Kg)	= 0.508948E+04
TOTAL TEMP (K)	= 0.000000E+00	F/A (Pa)	= 0.110651E+06
W/A (Kg/S-M2)	= 0.217411E+02		
SENSIBLE ENTHALPY	= 0.264375E+07	WT.FRCT.COND.PROD.	= 0.000000E+00
EQ.SOUND SPD (M/S)	= 0.910796E+03	EQ.MACH NUMBER	= 0.543059E+01
EQ.GAMMA	= 0.117027E+01	EQ.CP (J/KG-K)	= 0.280871E+04
EQ.COMPRESS. (1/Pa)	= 0.153126E+05		
EXIT AREA (M**2)	= 0.600031E+00		

GAS COMPOSITION
TOTAL GAS MOLES = 0.40934224E+01 P/FN = 0.75122197E-02

PRODUCTS GAS		MOLE-PCT OF GAS	PARTIAL PRESSURE	WEIGHT PCT	MOLE /100-GM	MOLECULAR WEIGHT	
1	A(G)	0.7876	0.24541E+02	1.2877	0.322411E-01	39.941	1
2	H(G)	0.1826	0.56882E+01	0.0075	0.747296E-02	1.008	2
3	HO(G)	0.5156	0.16064E+02	0.3590	0.211048E-01	17.008	3
4	H2(R)	1.3111	0.40853E+02	0.1082	0.536707E-01	2.016	4
5	H2O2(G)	0.0000	0.32971E-04	0.0000	0.433164E-07	34.016	5
6	N(G)	0.0000	0.40713E-04	0.0000	0.534870E-07	14.008	6
7	NO(G)	0.1496	0.46609E+01	0.1837	0.612333E-02	30.008	7
8	NO2(G)	0.0000	0.18730E-03	0.0000	0.246069E-06	46.008	8
9	O(G)	0.0524	0.16331E+01	0.0343	0.214556E-02	16.000	9
10	HNO(G)	0.0000	0.38546E-04	0.0000	0.506402E-07	31.016	10
11	HO2(G)	0.0000	0.31553E-03	0.0000	0.414532E-06	33.008	11
12	H2O(G)	32.5068	0.10129E+04	23.9728	0.133064E+01	18.016	12
13	N2(G)	63.9332	0.19920E+04	73.3195	0.261706E+01	28.016	13
14	O2(G)	0.5611	0.17482E+02	0.7349	0.229667E-01	32.000	14

******** RAMJET PERFORMANCE ANALYSIS ********

10/13/93

CASE: PC RJPA Test Calibration Run
Scramjet Case FRC15185, Mach 15.0, Z= 39272, No Frozen H2, Crocco =1.0

FROZEN NOZZLE EXPANSION TO REQUIRED AREA

EXP = 1 J22 = 2
PEX = 0.600000E+00

PRESSURE (Pa)	= 0.204442E+04	FROZEN MACH NUMBER	= 0.630807E+01
TEMPERATURE (K)	= 0.126307E+04	VELOCITY (M/S)	= 0.490044E+04
DENSITY (Kg/M3)	= 0.443682E-02	FRZ SOUND SPD (M/S)	= 0.776853E+03
ENTHALPY (J/Kg)	= -.313421E+06	FROZEN GAMMA	= 0.130972E+01
ENTROPY (J/Kg-K)	= 0.119538E+05	MOL.WT. (Kg/KgMOLE)	= 0.227851E+02
PITOT PRESSURE (Pa)	= 0.000000E+00	A/W (M2-S/Kg)	= 0.459931E-01
TOTAL PRESSURE (Pa)	= 0.000000E+00	F/W (N-S/Kg)	= 0.499448E+04
TOTAL TEMP (K)	= 0.000000E+00	F/A (Pa)	= 0.108592E+06
W/A (Kg/S-M2)	= 0.217424E+02		
EQ.SOUND SPD (M/S)	= 0.000000E+00	EQ.MACH NUMBER	= 0.000000E+00
EQ.GAMMA	= 0.000000E+00	EQ.CP (J/KG-K)	= 0.000000E+00
EQ.COMPRESS. (1/Pa)	= 0.000000E+00		
EXIT AREA (M**2)	= 0.599996E+00		

GAS COMPOSITION
TOTAL GAS MOLES = 0.43891644E+01 P/FN = 0.45939705E-02

PRODUCTS GAS	MOLE-PCT OF GAS	PARTIAL PRESSURE	WEIGHT PCT	MOLE /100-GM	MOLECULAR WEIGHT	
1 A(G)	0.7346	0.15018E+02	1.2877	0.322411E-01	39.941	1
2 H(G)	3.6096	0.73796E+02	0.1597	0.158432E+00	1.008	2
3 HO(G)	4.0667	0.83140E+02	3.0358	0.178492E+00	17.008	3
4 H2(R)	6.4073	0.13099E+03	0.5670	0.281229E+00	2.016	4
5 H2O2(G)	0.0000	0.98379E-03	0.0001	0.211211E-05	34.016	5
6 N(G)	0.0009	0.18115E-01	0.0005	0.388902E-04	14.008	6
7 NO(G)	1.2002	0.24537E+02	1.5808	0.526785E-01	30.008	7
8 NO2(G)	0.0002	0.44685E-02	0.0004	0.959341E-05	46.008	8
9 O(G)	1.3887	0.28390E+02	0.9752	0.609506E-01	16.000	9
10 HNO(G)	0.0001	0.28863E-02	0.0002	0.619650E-05	31.016	10
11 HO2(G)	0.0015	0.30962E-01	0.0022	0.664712E-04	33.008	11
12 H2O(G)	21.6185	0.44197E+03	17.0948	0.948870E+00	18.016	12
13 N2(G)	59.0944	0.12081E+04	72.6665	0.259375E+01	28.016	13
14 O2(G)	1.8773	0.38380E+02	2.6367	0.823971E-01	32.000	14

******** RAMJET PERFORMANCE ANALYSIS ********

10/13/93

CASE: PC RJPA Test Calibration Run
Scramjet Case FRC15185, Mach 15.0, Z= 39272, No Frozen H2, Crocco =1.0

Q0 (Pa) = 0.501994E+05

COMBINED-- 0.667

NOZZ EFF (%)	THRUST(N)	CT	ISP(N-S/KG)
97.40	0.34524001E+04	0.114633	0.93871448E+03
97.66	0.36228772E+04	0.120283	0.98506757E+03
97.92	0.37933542E+04	0.125943	0.10314205E+04
98.18	0.39638313E+04	0.131603	0.10777736E+04
98.44	0.41343086E+04	0.137263	0.11241267E+04
98.70	0.43047856E+04	0.142923	0.11704797E+04
98.96	0.44752627E+04	0.148583	0.12168328E+04
99.22	0.46457397E+04	0.154243	0.12631859E+04
99.48	0.48162168E+04	0.159903	0.13095389E+04
99.74	0.49866938E+04	0.165563	0.13558920E+04
100.00	0.51571709E+04	0.171223	0.14022450E+04

FROZEN ONLY

NOZZ EFF (%)	THRUST(N)	CT	ISP(N-S/KG)
97.40	0.30500652E+04	0.101265	0.82331879E+03
97.66	0.32194683E+04	0.106889	0.87537982E+03
97.92	0.33888713E+04	0.112514	0.92144086E+03
98.18	0.35582742E+04	0.118138	0.96750183E+03
98.44	0.37276775E+04	0.123762	0.10135629E+04
98.70	0.38970806E+04	0.129387	0.10596240E+04
98.96	0.40664836E+04	0.135011	0.11056849E+04
99.22	0.42358867E+04	0.140635	0.11517460E+04
99.48	0.44052896E+04	0.146260	0.11978070E+04
99.74	0.45746929E+04	0.151884	0.12438682E+04
100.00	0.47440957E+04	0.157508	0.12899291E+04

EQUILIBRIUM ONLY

NOZZ EFF (%)	THRUST(N)	CT	ISP(N-S/KG)
97.40	0.42571909E+04	0.141343	0.11575386E+04
97.66	0.44298164E+04	0.147074	0.12044758E+04
97.92	0.46024414E+04	0.152805	0.12514131E+04
98.18	0.47750669E+04	0.158537	0.12983502E+04
98.44	0.49476924E+04	0.164268	0.13452875E+04
98.70	0.51203179E+04	0.169999	0.13922246E+04
98.96	0.52929434E+04	0.175731	0.14391619E+04
99.22	0.54655688E+04	0.181462	0.14860990E+04
99.48	0.56381943E+04	0.187193	0.15330363E+04
99.74	0.58108193E+04	0.192925	0.15799735E+04
100.00	0.59834448E+04	0.198656	0.16269106E+04

COMPONENT IMPULSE SUMMARY

DIFFUSER (N) = -.374817E+04
COMBUSTOR (N) = 0.237418E+04
FROZEN NOZZLE (N) = 0.609928E+04
EQUILIBRIUM NOZZLE (N) = 0.733864E+04
END OF SIMULATION

APPENDIX C

H2SCRAM Output File

```
1            HYDROGEN FUELED SCRAMJET; EQUILIBRIUM FLOW
 ALTITUDE (ft) =     128844.          VELOCITY (ft/sec) =   15547.41
   MACH NUMBER =       15.00                Qo (lb/ft2) =    1042.31
            KD =        .853   KE =        .976   V2/V0 =     .91488
           f/a =      .02916   CE =        .990   Vf/V2 =       .000
    FUEL TEMP. (R) FOR Vf/V2 > 0 =          .0       Cv =       .990
   CROCCO NUM. =      1.0000

  ENGINE STATIONS           0           2           3           4
 T   (R)        -->     447.01     3323.87     5330.62     3596.23
 H   (BTU/lb)   -->     -21.51      765.30     1039.92     -327.66
 P   (lb/in2)   -->       .046       7.470      16.638        .433
 S   (BTU/lb-R) -->     1.9914      2.1675      2.8388      2.8388
 RHO (lb/ft3)   -->    .000277     .006065     .006655     .000275
 WM (lb/lb MOL) -->      28.96       28.96       22.88       24.49
 A   (ft/sec)   -->    1036.49     2706.74     3622.52     2943.60
 V   (ft/sec)   -->   15547.41    14224.07    13342.59    15700.43
 M   (MACH NO.) -->      15.00        5.26        3.68        5.33
 A0/A(?)        -->      1.000      20.001      20.002       1.000

 (A2+Af)/A2 =    1.000     A0/(A2+Af) =   20.001      A4/A2 =   20.001
      A3/A2 =    1.000     A3/(A2+Af) =    1.000      A4/A3 =   20.002
        Isp =   921.80         Ct(Ao) =    .1113       T/Wo =   26.883
```

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13. ABSTRACT *(Maximum 200 words)*
This study compared the performance of an equilibrium combustion model to a finite-rate-chemistry combustion model for a fixed geometry Scramjet flying at the flight conditions of Mach 12, 15, and 18 with a constant dynamic pressure of 50,000 Pa. An integrated PC-based code, developed specifically for this study, models the combustor as an equilibrium combustion process or as finite-rate-chemistry combustion process. This integrated program is based on two existing programs, Ramjet Performance Analysis (RJPA) and 3STREAM. The effects of mixing schedule, combustor length, and combustor exit area were investigated. The results of this study indicate that inefficient mixing is the primary cause of Scramjet performance loss regardless of the flight speed. Combustor length and combustor exit area also had a strong impact on performance.

14. SUBJECT TERMS
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