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INJECTION AND COMBUSTION OF HYPERGOLIC PROPELLANTS

**PART I REACTIVE STREAM IMPINGEMENT
PART II EXTENSION OF STEADY-STATE
COMBUSTION MODEL**

APRIL 1969

BY

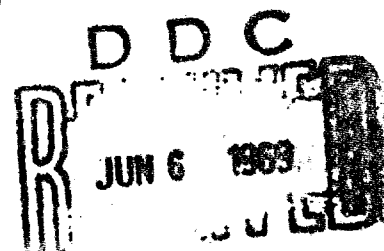
**B.P. BREEN, L.B. ZUNG, AND B.R. LAWVER
T.C. KOSVIC AND D.E. COATS**

DYNAMIC SCIENCE

**A Division of Marshall Industries
Monrovia, California**

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**AIR FORCE ROCKET PROPULSION LABORATORY
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UNITED STATES AIR FORCE
EDWARDS, CALIFORNIA**



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**INJECTION AND COMBUSTION OF
HYPERGOLIC PROPELLANTS**

Part I Reactive Stream Impingement

Part II Extension of Steady-State Combustion Model

April 1969

Final Technical Report F04611-68-C-0040

By

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**AIR FORCE ROCKET PROPULSION LABORATORY
DIRECTORATE OF LABORATORIES
AIR FORCE SYSTEMS COMMAND
UNITED STATES AIR FORCE
EDWARDS AIR FORCE BASE, CALIFORNIA**

FOREWORD

The research documented in this final report was sponsored by the Air Force Rocket Propulsion Laboratory, Directorate of Laboratories, Edwards, California, under Contract F04611-68-C-0040. The program was conducted by the Dynamic Science Division of Marshall Industries under the direction of Captain C. J. Abbe, Air Force Project Officer.

The Dynamic Science Program Manager was Dr. B. P. Breen and the Project Engineers were Mr. B. R. Lawver, Dr. L. B. Zung and Mr. T. C. Kosvic. Under Part I of the program, the efforts of Mr. Robert Wheelock of Wyle Laboratories (NORCO facility), and Mr. John White, Mr. Wm. Irwin and Mr. W. Yoshida of Dynamic Science, are acknowledged. Under Part II of the program, Capt. C. J. Abbe, Dr. J. O'Hara, and Mr. G. Langberg of the AFRPL and Mr. D. E. Coats of Dynamic Science contributed to the effort.

This technical report has been reviewed and is approved.

C. J. Abbe, Capt, USAF
Senior Project Officer

SUMMARY

The impingement of liquid hypergolic propellants following mixing and separation mechanisms is characterized by chemical reaction time and residence time criteria. Experimental results, obtained by hydrazine impinging with nitrogen tetroxide, agree very well with the limit defined by assuming that separation occurs when residence time is greater than reaction time. This criteria shows a strong influence of propellant temperature because reaction time is exponentially dependent upon temperature in this ignition region (the existence of an ambient temperature ignition region is the essence of the meaning of hypergolicity). Further experimental results indicate that chamber pressure had only a second order effect and that monomethyl hydrazine and "DMH/hydrazine (50/50 blend) impinging with nitrogen tetroxide separate at higher propellant temperatures than those obtained for the hydrazine-nitrogen tetroxide combination. Stream separation always occurred when impinging hydrazine with compound A (C_4F_8) in the experimental fuel and oxidizer temperature range (hydrazine -40 to $60^\circ F$ with compound A -0 to $30^\circ F$).

A second work area of the project concerned the extension of the Steady-State Combustion Computer Model undertaken as a joint technical effort between the Air Force Rocket Propulsion Laboratory and Dynamic Science. The computer program was generalized to allow increased versatility in running various propellant systems. The numerical procedures and organization of the program were substantially improved. Propellant property values were gathered for several systems of current interest. A computer program listing is presented.

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PART I. REACTIVE STREAM IMPINGEMENT

1. INTRODUCTION

The work reported here involves an experimental determination of the physical and design parameters which control the mechanisms of hypergolic propellant stream impingement. The need and usefulness for this work is discussed and a physical picture of hypergolic impingement was developed. This picture led to a model of hypergolic stream mixing reaction and blow-apart criteria and the criteria were used to define an experimental technique involving photographic observation of the impingement plane. Mix/separate criteria were measured for nitrogen tetroxide impingement with hydrazine, MMH, and 50-50 (hydrazine-UDMH). Compound A (ClF_5) was also investigated and photographically observed. The results of the experimental criteria were applied to demonstrate their effect on rocket engine design and were compared to large scale engine performance and injection mixing explosion measurements.

a. Propellant Injector Design

Injection spray patterns control O/F mixing and mass distribution within a rocket engine combustion chamber and, consequently, these spray patterns exert a major design influence over chamber performance, thrust chamber liner compatibility and combustion instability. Injector design was largely a matter of intuition and trial and error testing until the early work of Rupe, (Ref. 1) demonstrated the possibility of defining the relationship of design parameters to the uniformity of stream mixing. The mixing uniformity criteria were developed by Rupe for nonreactive impingement and involved two phases of injector design: first, the spray pattern emanating from the individual set of impinging elements must be defined in terms of the design parameters which affect impingement characteristics and, secondly, all the spray patterns together must be layed-out to give the most uniform mass flux within the constraint of the design manifolding. Design of unlike hypergolic injectors has remained a matter of trial and error, however, because the first phase determination, that of the spray pattern emanating from the individual set of unlike hypergolic impinging elements, has not been defined in terms of the design and operating parameters which affect impingement characteristics.

b. Hypergolic Impingement

The question which must be answered before trial and error testing of hypergolic injectors will lead to any fruitful intuition is: Do hypergolic streams mix nonreactively, or do they always separate (i.e., blow apart), or perhaps for different critical stream parameters is there mix/separate criteria? Previous work has indicated that hypergolic streams sometimes mix and sometimes separate. It was the purpose of this work, therefore, to experimentally define which parameters are most influential in defining the mix/separate phenomena of several hypergolic combinations.

In any impingement and atomization scheme the mixing uniformity would appear to be important and it can be related to a ratio such as the streams' momentum or stagnation pressures which involve the density, ρ ; velocity, v ; and orifice diameter, D . Now, for extension to hypergolic streams, the basic nature of hypergolicity must be considered as it involves chemical kinetics (exponentially influenced by temperature, T) and residence time within a heat balance control

volume. Another system parameter which affects chemical kinetics is chamber pressure, while orifice hydraulics (L/D) always affect turbulence level and mixing. Having listed these parameters, it is easily seen why trial and error engine testing of hypergolic impingement efficiency and popping has not been fruitful: the chemical kinetics of hypergolicity are exponentially temperature dependent while in full scale engine test programs this parameter is seldom considered; it is often not controlled from run-to-run; and is also often not even measured or available in data reduction.

c. Previous Work

Early investigations in this field have tended to be phenomenologically oriented. Thus, the work reported by Elverum and Staudhammer (Ref. 2), and Johnson (Ref. 3) noted that streams do separate and they continued to show the magnitude of the effect. The later work of Burrows (Ref. 4) gave indication that hypergolic streams do not always separate and measured specific conditions necessary for separation to occur. More extensive work has been carried out by Lawver and Breen (Ref. 5) to define regimes of stream mixing and separation. Their experiments used photographic observation of the actual impingement plane under a transparent window and correlation of the observed regime with the parameters of temperature and flow residence time. A review of the problem was presented by Kushida and Houseman (Ref. 6), where an analytical model was developed to predict mix/separate criteria in terms of pressure, temperature and impingement plane contact time. This model of liquid phase impingement made use of the heat release rate measurements of Feller and Somogyi (Ref. 7), and involved a sensible heat balance between Feller's heat release rate and the heat required to raise the liquid to its boiling point. The model presented by Lawver and Breen (Ref. 4) and that presented by Kushida and Houseman (Ref. 6) are different in that the first shows an exponential importance of temperature upon the reaction rate while the second shows a linear temperature effect in the boiling point heat balance, using a maximum heat release rate from Feller and Somogyi. It was more the point of view of Lawver and Breen, and is expressed in Feller's report, that the heat release rate shows a sharp change in temperature which should correspond to the inception of stream separation.

d. Summary of this Experimental Work

The experimental techniques developed by Lawver and Breen in Reference 5 were extended to allow high pressure (500 psia) operation with the family of hydrazine fuels N_2O_4 and compound A oxidizers. Experimental data were thus obtained showing the effect of velocity, orifice diameter, propellant temperature, impingement angle and chamber pressure. These curves define criteria which can be used by the design engineer to determine if hypergolic impingement spray pattern is within the mixed zone or the separate zone. At longer residence times, popping phenomenon was also encountered and the regions of popping are shown for the hydrazine, MMH, and 50-50 fuels impinging on N_2O_4 . A great many experimental difficulties were encountered in the observation of the compound A hydrazine impingement plane, but it appeared that the streams always separated within the limited range of temperature data.

The mix/separate criteria are reviewed in a discussion of their application. The popping phenomenon, observed at long residence time, has also been observed in engine test programs such as that reported by Weiss and Klopotek (Ref. 8) and extensively investigated by Clayton (Ref. 9). Beyond the immediate

injector design, the fact of impingement regime is also discussed as it affects such steady state combustion profile calculations as those reported by Dynamic Science (Ref. 10) and currently being successfully used to correlate engine stability by Abbe (Ref. 11).

2. IMPINGEMENT OF HYPERGOLIC STREAMS

Both research projects and full-scale engine firings with hypergolic propellant combinations have demonstrated that the unlike streams sometimes mix and sometimes separate causing large changes in injector and combustor performance. From previous work it is possible to develop a physical picture of the mix/separate phenomena and to transform this picture or model into analytical expressions defining the controlling parameters of chemical kinetics, residence time, and mixing.

a. The Physical Picture

For unlike impinging hypergolic streams, engine efficiency depends upon the degree of individual doublet mixing or separation, because generally secondary fan and droplet mixing is ineffective. This fact is demonstrated by the photographic comparison of the two different injection schemes studied by Marshall Burrows (Ref. 4). Figure 1a is a 6000 frame per second photograph of the hydrazine side of a quadruple impinging jet injector of 90° included angle while Figure 1b is the same injection scheme from N_2O_4 side. The injection scheme breaks the chamber into four quadrants as shown in Figures 1a and 1b. The N_2O_4 droplet vaporization causes the dark brown cloud of Figure 1b to exist axially down the chamber; the colorless hydrazine vapor of Figure 1a combusts sooner because of the tendency for hydrazine to decompose in high temperature environments. In both cases the combustion is efficient and is controlled by droplet vaporization. However, for the different injection scheme shown in Figure 1c the chamber is broken into only two halves and the N_2O_4/N_2H_4 systems separate or blow apart. The lack of O/F and mass distribution uniformity causes secondary gas mixing to control the combustion and the resulting stratified flow causes droplet vaporization throughout the chamber to be inefficient because of low temperatures and nonstoichiometric combustion.

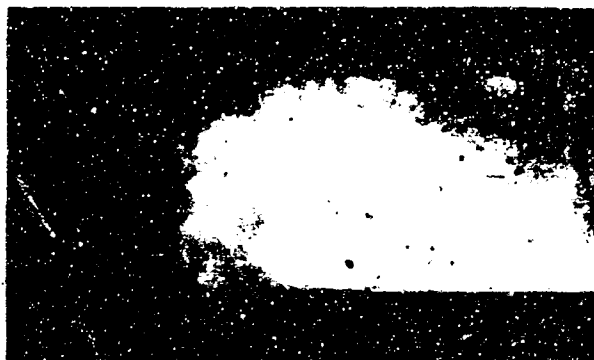
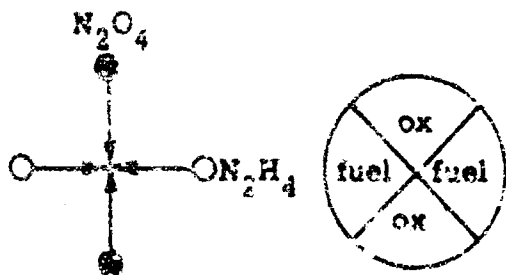
Observation of this separation and stratification problem led to the realization that it would be necessary to observe the details of the phenomena within the impingement plane and to experimentally define the controlling parameters.

A general and complete description near the stagnation point of impinging streams of hypergolic propellants requires a basic understanding of the interrelationships of propellant reaction kinetics and hydrodynamic flow properties. In more detail, the reaction kinetics involve:

- The rate of liquid phase reaction,
- The rate of gas phase reaction,
- The rate of heat release, and
- The rate of gas evolution.

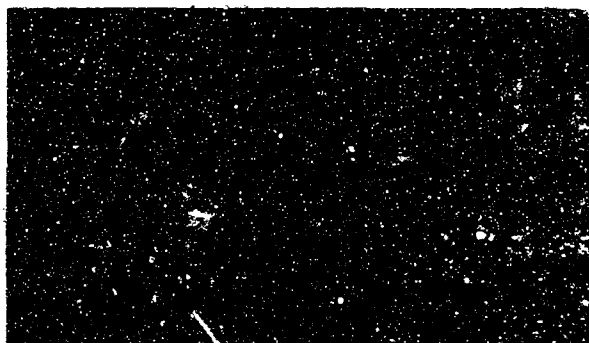
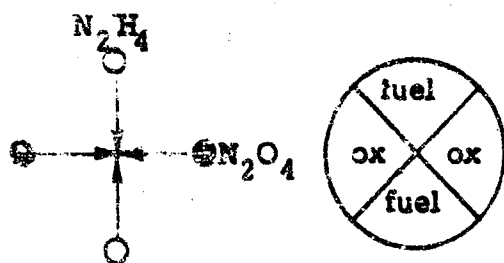
Aside from the stability problem associated with the fluid flow, important kinematic parameters are:

- The degree of mixing,
- The characteristic mixing time, and
- The residence time.



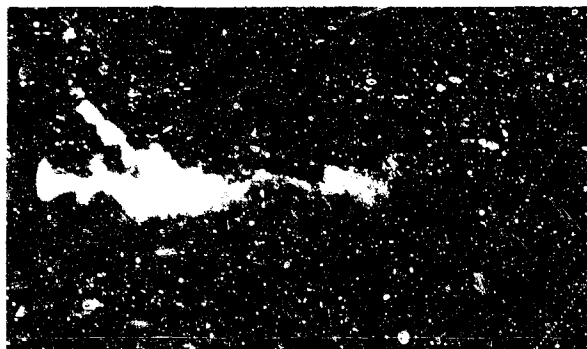
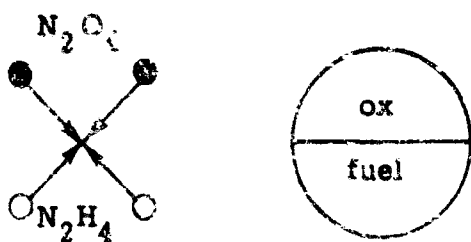
End view of impingement and resulting chamber quadrants

Figure 1a. Efficient N_2O_4/N_2H_4 Combustion from the Hydrazine Side.



End view of impingement and resulting chamber quadrants

Figure 1b. The same Combustor as in Figure 1a showing Efficient N_2O_4/N_2H_4 Combustion from the Nitrogen Tetroxide Side.



End view of impingement and resulting chamber quadrants

Figure 1c. Inefficient N_2O_4/N_2H_4 Combustion and Stratification Caused by Hypergolic Stream Impingement and Blow Apart.

Figure 1. The Effect of Impingement on Stream Blow Apart and Combustor Efficiency. (Ref. 13.)

The condition of jet separation can be viewed as the occurrence of a locally strong exothermic reaction, liberating sufficient heat and gas that the streams are blown apart before substantial mixing has taken place. This locally strong exothermic reaction is more likely to take place close to the stagnation point for it is there the propellants experience the longest residence time. Thus when initial surface mixing first occurs near the stagnation point and the chemical reaction rate is fast enough to liberate sufficient heat and gas before substantial mixing has taken place downstream of the stagnation point separated flow results. When reaction is slow enough to allow a certain degree of mixing to first take place, a uniform combustion spray pattern appears. This physical picture has developed from experimental observation of the impingement plane during research performed on contract NAS7-467 (Ref. 5). Typical separated and mixed flow patterns are shown in Figure 2a and 2b. The propellant systems are hydrazine and nitrogen tetroxide.

b. Data Correlation

The criteria of stream separation has been described in detail in Reference 5 as a comparison of two characteristic times, namely the chemical kinetic time constant, τ_{chm} , and the common interfacial residence time between the two streams, τ_{res} . The critical chemical reaction time, τ_{chm} , is the time required for the chemical reaction to liberate sufficient heat and product gas to cause the streams to separate. This time constant is very sensitive to temperature because by the very definition of hypergolicity, a "runaway" ignition temperature exists within the range of ambient propellant temperatures. The interfacial residence time, τ_{res} , is characterized by the geometry and velocity of the flow. Separation or mixing phenomena depend on whether τ_{res} is either smaller (separate) or greater (mix) than τ_{chm} . The limit for chemical reaction, blow-apart, and separation is defined when τ_{res} is equal to τ_{chm} .

The chemical kinetic time constant may be obtained by approximating the rate of consumption of one of the propellant species by the first order decay:

$$\frac{dY}{dt} = -kY \quad (1)$$

where Y is the species concentration and k is the kinetic rate constant of the chemical reaction. Denoting Y_0 as the initial propellant concentration, equation (1) gives:

$$\frac{Y}{Y_0} = e^{-kt} \quad (2)$$

and τ characteristic time to ignition, τ_{chm} , may be defined when $Y/Y_0 = e^{-1}$.

For temperatures below the ignition temperature this time is very long, while for temperatures greater than the ignition temperature the time constant is much less than the characteristic mass transfer or heat transfer time constants. Thus for ignition phenomena to occur the value of the characteristic kinetic time constant shifts from rate-controlling (at low temperature) to not controlling over a small increment of temperature change and thus the ignition temperature is closely defined for any chosen value of Y/Y_0 of the order of one. Thus τ_{chm} is defined from equation (2) as

$$\tau_{chm} = \frac{1}{k} \quad (3)$$

The reaction rate constant k may be assumed to follow the Arrhenius temperature dependence so that

$$\tau_{\text{chem}} = \frac{1}{A} e^{E/RT} \quad (4)$$

Thus the characteristic time of chemical reaction is exponentially dependent upon temperature.

The characteristic residence time for which the streams are in forced mixing contact is a function of stream dimensions, velocity, and impingement angle. Characteristically this may be obtained from the geometry of the situation as:

$$\tau_{\text{res}} = \frac{D}{\sin(\theta/2)} \frac{1}{V} \quad (5)$$

where θ is the included angle of impingement, D is the orifice diameter, and V is the injected stream velocity.

Whenever the chemical time constant is less than or equal to the residence time the streams will tend to blow apart due to the tremendous heat release rates associated with the ignition and combustion of stoichiometric rocket propellants within the residence interface. Thus the separation limit is defined in terms of operating temperature and flow parameters by equating the two time constants

$$\frac{e^{E/RT}}{A} = \frac{D}{\sin(\theta/2)V} \quad (6)$$

so that

$$\frac{D}{V} = \left[\frac{\sin(\theta/2)}{A} \right] e^{E/RT} \quad (7)$$

or

$$\ln \frac{D}{V} = \ln \left[\frac{\sin(\theta/2)}{A} \right] + \frac{E}{R} \frac{1}{T} \quad (8)$$

Postulation of the impingement process in terms of the physical parameters controlling reaction and stream separation indicates that the critical separation limit varies with D/V and is exponentially dependent upon $1/T$. Thus experimental data are correlated on a semilogarithmic scale as proportional to the log D/V and inversely proportional to propellant temperature.

c. Injection Mixing Explosions

Another very critical problem associated with the impingement of hypergolic streams is concerned with the often observed explosions near the injector plate since they can act as initiation sources of detonation waves or "pops". Typical explosions of this kind were identified experimentally at Dynamic Science under NASA research contract NAS7-467 (Ref. 12) and are shown photographically in Figure 3. In contrast to the separation phenomena which are basically due to a locally strong exothermic reaction, explosions appear to be caused by ignition within the entire impingement region of mixed liquid ligaments. In this respect,



NOTE UNIFORM COMBUSTION

Figure 2a. Mixing and Uniform Spray Combustion of N_2O_4/N_2H_4 at $14^\circ C$.
at 50 ft/sec and .050 inch Wide Stream.
Regime I-Mixing

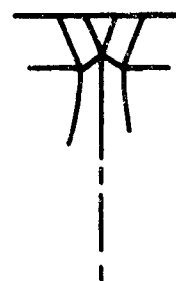
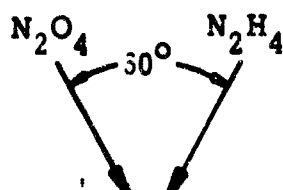


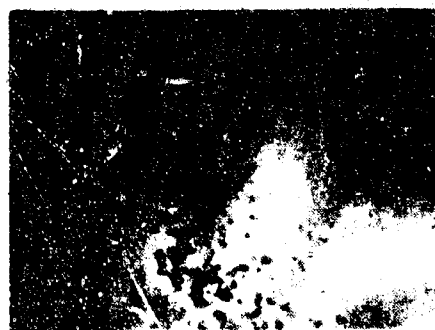
Figure 2b. Hydrazine/Nitrogen Tetroxide Impingement $25^\circ C$
at 100ft/sec and .100 inch Wide Stream.
Regime II-Separation



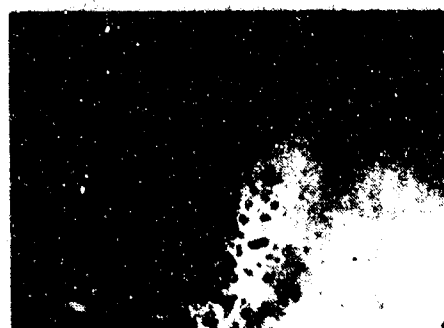
NOT REPRODUCIBLE



(1) TYPICAL SPRAY



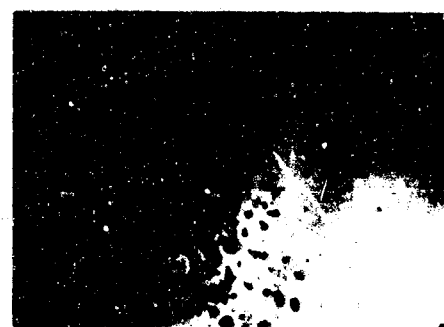
(1) TYPICAL SPRAY



(2) INJECTION MIXING EXPLOSION



(2) INJECTION MIXING EXPLOSION



(3) LIGAMENT SHATTERING
INJECTION MIXING EXPLOSION
CAUSING LIGAMENT SHATTERING



(3) SPRAY DETONATION
INJECTION MIXING EXPLOSION
CAUSING SPRAY DETONATION

N_2H_4 VELOCITY = 25 ft/sec

N_2O_4 VELOCITY = 20 ft/sec

N_2H_4 ORIFICE DIA = .050"

N_2O_4 ORIFICE DIA = .050"

PROPELLANT TEMPERATURE $50^\circ F$

25 μ sec EXPOSURE AT 2000 plc/sec

Figure 3. Injection Mixing Explosions Causing Ligament Shattering and Sometimes Spray Detonations (Taken from Reference 12).

Injection mixing explosions depend very much on the degree of mixing of the impingement region. First of all the temperature must be low enough that mixing phenomena predominate then the degree of mixing of impinging jets depends on contact surface area, intrinsic turbulent levels and turbulent shear stresses. Extensive experimental work (Ref. 1) has been carried out to measure the mixing level of nonreactive impinging streams. Maximum mixing is observed when the quantity $\rho_1 U_1^3 D_1 = \rho_2 U_2^3 D_2$. ρ and U are the stream density and velocity. D is the orifice diameter. Based on experimental findings degree of mixing can be defined in terms of a nondimensional number δ .

$$\delta = \frac{1}{1 + \frac{\rho_1 U_1^3 D_1}{\rho_2 U_2^3 D_2}} \quad (9)$$

Uniform mixing occurs at $\delta = 0.5$. It is anticipated that for δ close to 0.5, injection mixing explosions are more likely to occur. Figure 4 shows regions of stream mixing and separation as well as injection mixing explosions as functions of propellant temperature, D/V , and degree of mixing arbitrarily defined in terms of δ .

The present experiment is designed to study stream mix/separate phenomena. Propellant temperature T and the mixing time D/V were accurately varied in order to investigate the relationship expressed in equation (8). Photographic observations of the impingement region were recorded to define the mix/separate phenomena. The measurement of injection mixing explosions was not the primary concern of this research but could be observed qualitatively from chamber pressure noise and roughness.

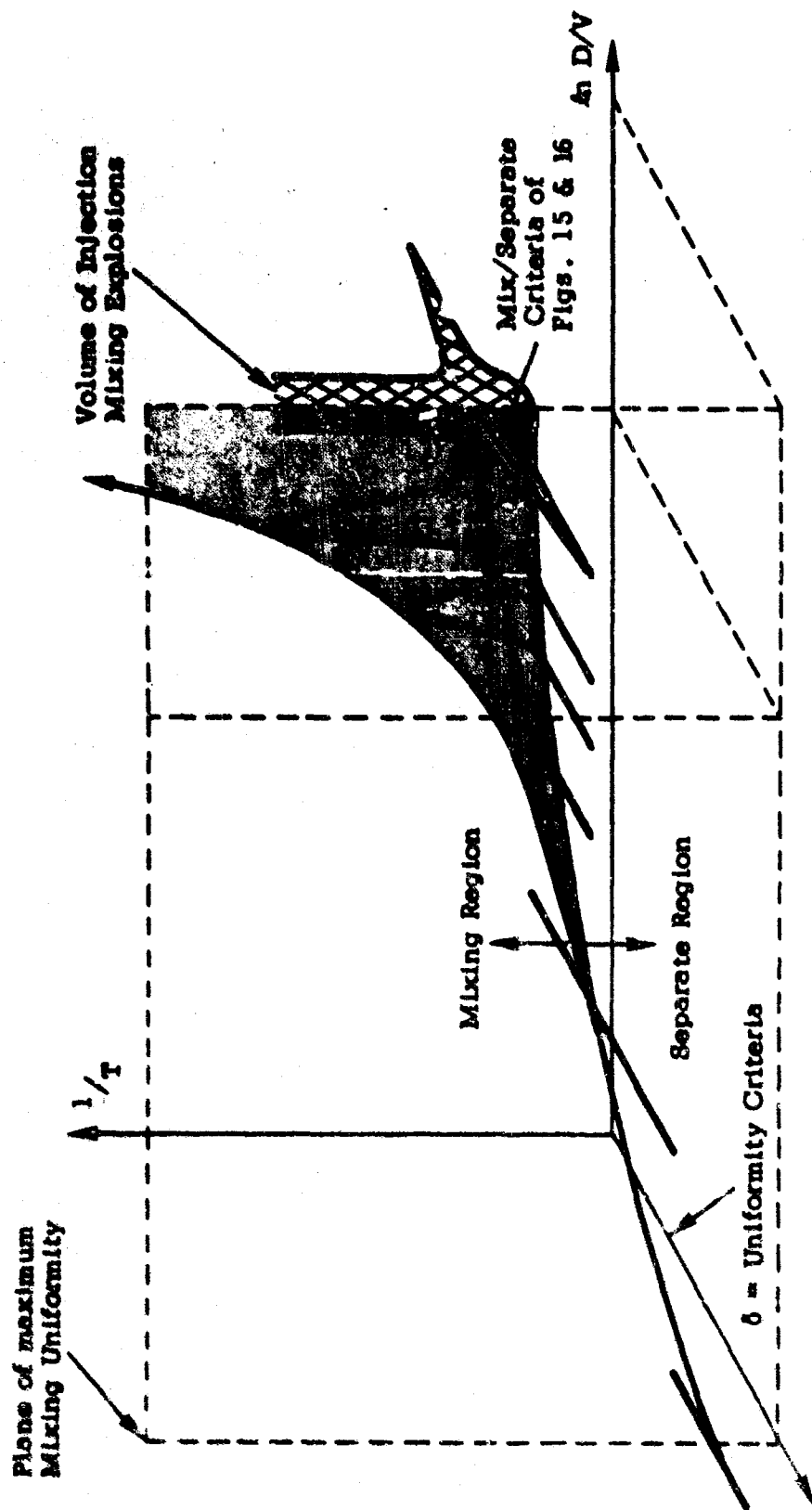


Figure 4. Apparent Effect of Uniformity Criteria on the Volume of Injection Mixing Explosions.

3. EXPERIMENTAL APPARATUS

a. Experimental Technique

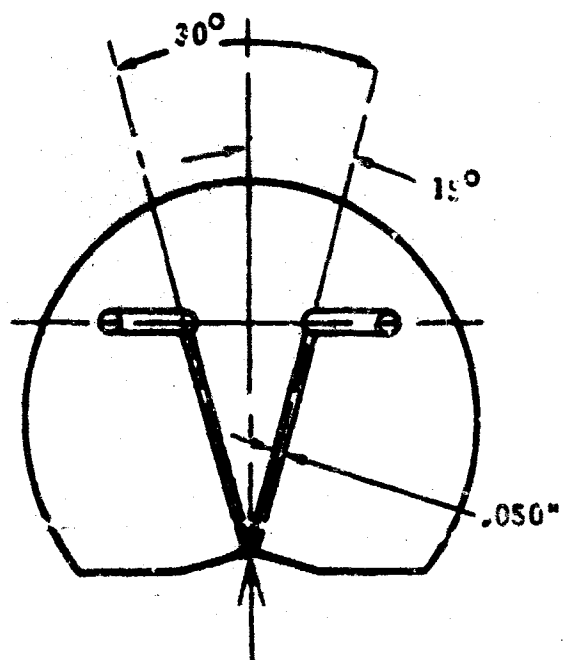
The experimental technique is based on photographic observation of the impingement region of a pair of rectangular jets. Injector plates of different orifice sizes and impingement angles are used. Various injector plates are shown in Figure 5. A pyrex or calcium fluoride window which extends beyond the impingement point, covers the front face of the injector plate. This allows photographic observations of the impinging streams flowing over the window and at the same time still retains the basic feature of a set of three dimensional impinging jets. Liquid interface of the impinging fuel and oxidizer streams can be distinctly observed. This technique allows liquid interface of the impinging streams to be clearly observed as compared with the impingement of two free streams. Mixing and separation phenomena are identified and defined based on these photographic results.

b. Impingement Model

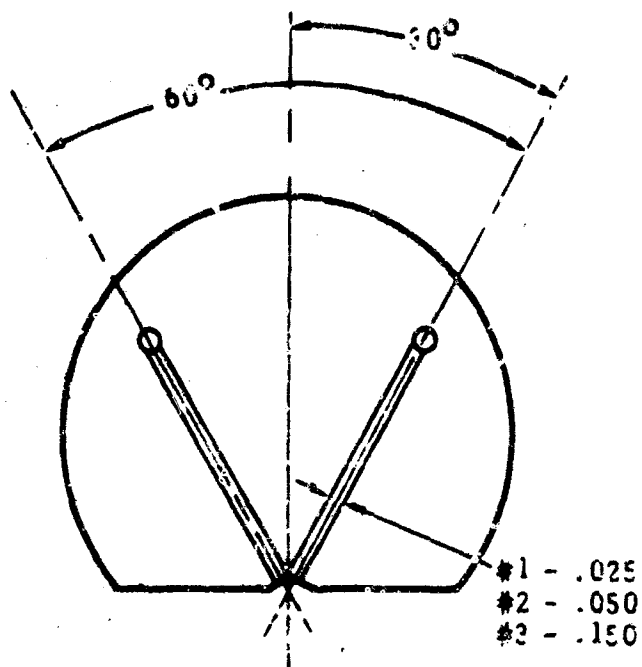
The stainless steel impingement test model is shown in Figure 6. The injector support and the orifice plate are fitted into a chamber block. The chamber is open along its whole length on one side. A lucite window with pyrex or calcium fluoride inserts is mounted on the open side of the chamber. This allows photographic observation of the impingement region. A nozzle is attached to the bottom of the chamber block. Chamber pressures of 500 psi can be easily attained by varying the nozzle sizes. A schematic of the chamber block and the injector support is shown in Figure 7. The support is designed for a triplet as well as a doublet injector plate. The propellants are temperature controlled up to the injector plate by means of coaxial lines.

c. Flow System

A schematic of the nitrogen tetroxide/hydrazine flow system is shown in Figure 8. The flow systems are fabricated with 304 stainless steel lines. The propellant tanks are designed for a working pressure of 1000 psi. The tank capacities are approximately 1/3 gallon. Pressurization of the tanks is controlled by a Grove regulator and a release valve which is set at 1000 psi. Two solenoid valves are used to vary the dome pressure of the regulator. The dome pressure is always set at approximately 950 psi. Propellant flow rates are controlled by variable area cavitating venturiles and are metered by turbine type flow meters. The flow controllers are micrometer head type. This device provides easy and precise control of the propellant flows and allows for more efficient testing with the ability to match desired stream momentum ratios. The propellant tanks and lines are provided with heat exchangers. Propellant temperature is controlled by flowing coolant at the desired temperature through the heat exchangers. The coolant temperature is regulated with a refrigeration unit with heat exchangers on the condenser and evaporator. Coolant temperature is controlled by throttling the flows through the condenser and evaporator heat exchangers. The propellants are first led to flow to the exhaust tank. When the desired temperature is achieved, the propellant is introduced into the impingement block. Pressurization of the exhaust tank is achieved by a two stage regulator. This enables recovery of the propellants from the exhaust tank.



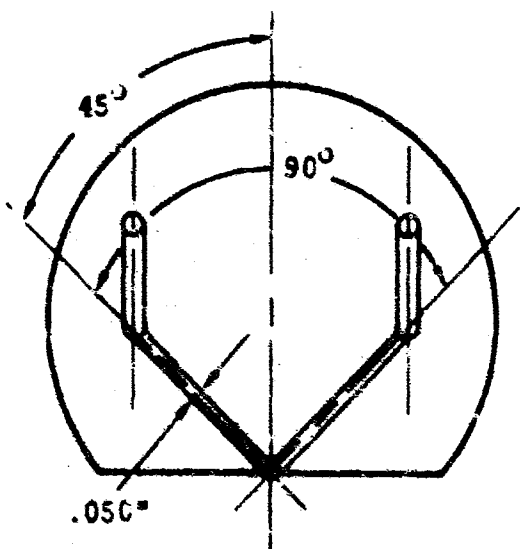
30° Doublet Injector (#4)



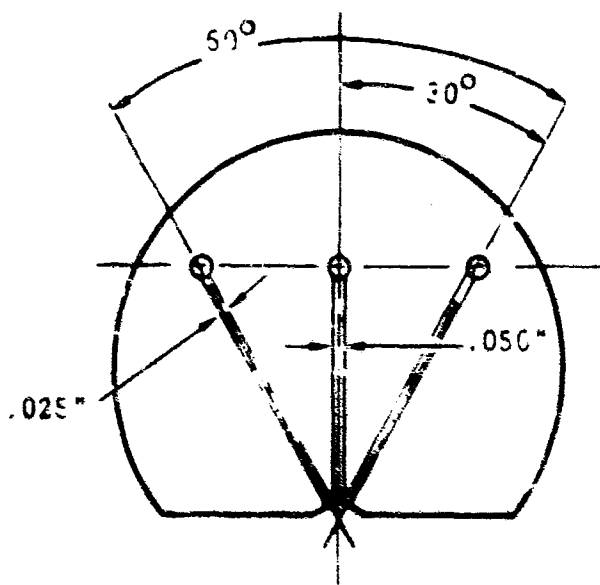
60° Doublet Injector (#1, 2, & 3)



.015" Orifice Depth Injector #1 - 3



90° Doublet Injector (#5)



Triplet Injector - (#5)

Figure 5. Injector Plates

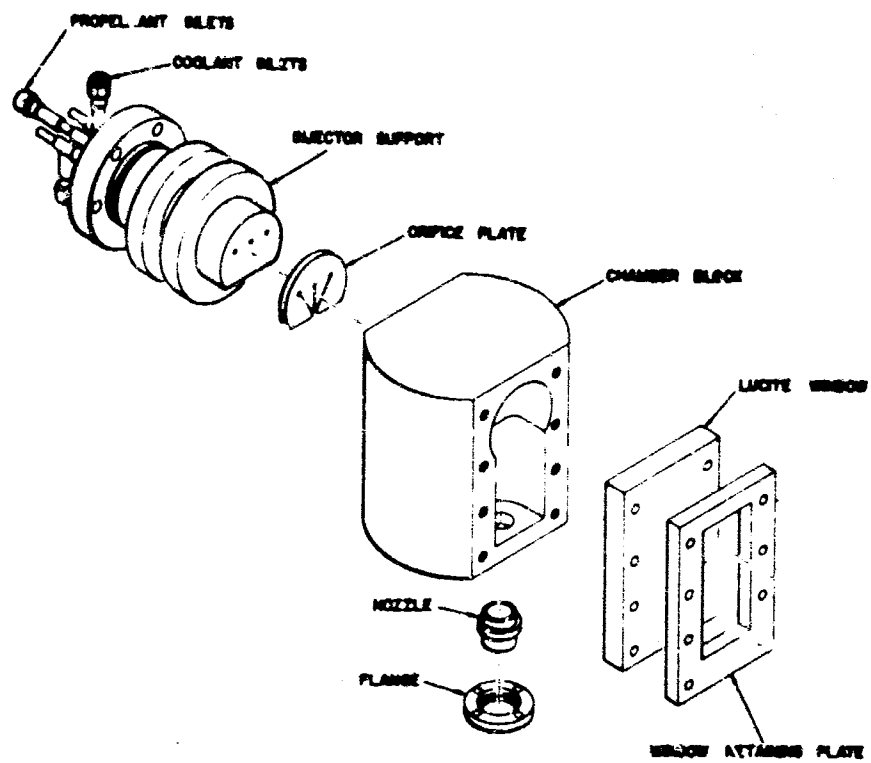


Figure 6. Impinging Stream Test Model.

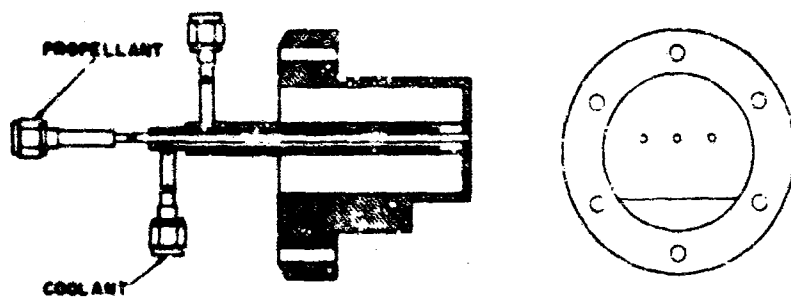


Figure 7a. Injector Mounting Support for Hot Firing

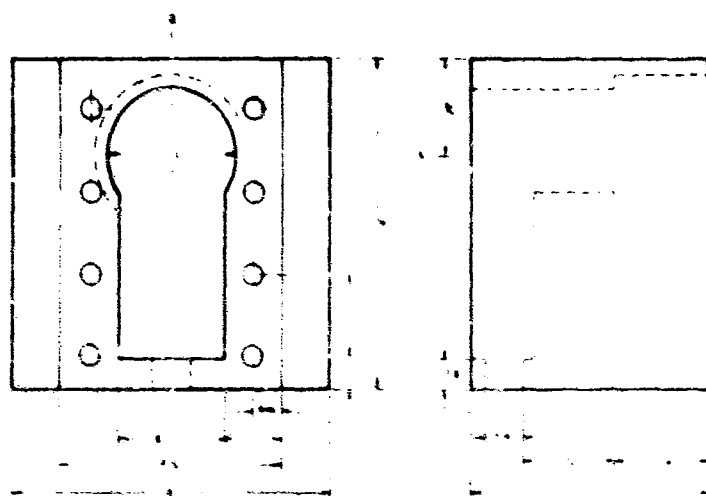


Figure 7b. Impinging Block for Hot Firing

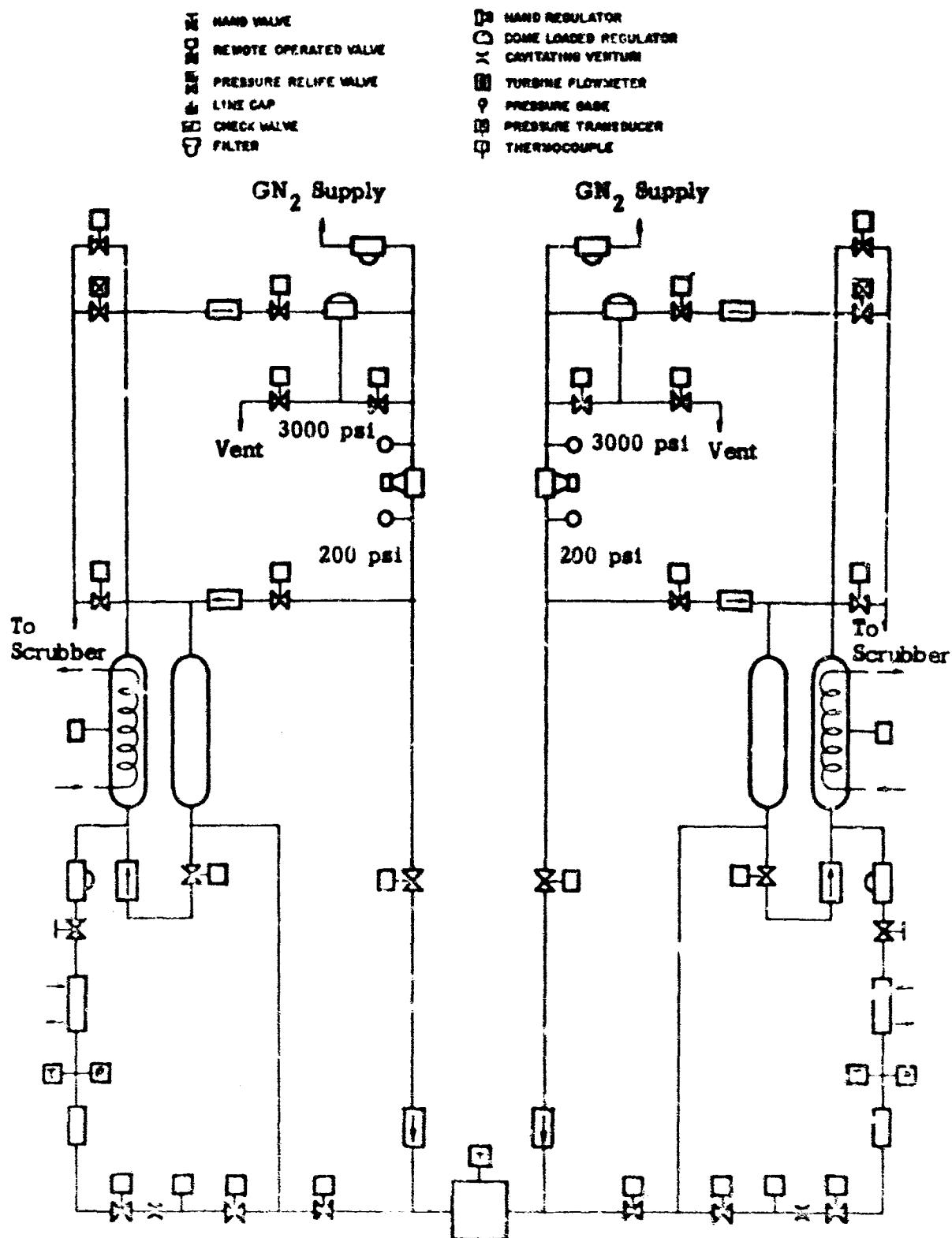


Figure 8. N_2O_4/N_2H_4 Flow System.

A separate flow system is used to provide liquid compound A to the impingement apparatus. The schematic of the liquid compound A supply system is shown in Figure 9. The system is designed for a working pressure of 1000 psi. Compound A temperature can be easily varied from -300° F to 120° F. All the nitrogen refrigerant and purging gas is provided by an 800 gallon liquid nitrogen storage dewar maintained at 40 psi, and located adjacent to the test area. This supports the test setup with extremely dry nitrogen gas for the various purging cycles and cold liquid and gas nitrogen to provide low temperature conditioning. Propellant temperatures above ambient conditions is achieved by heating the nitrogen gas. Compound A is stored in cylinders and transferred to the run tank, as required, during the test program. Pressurization of the run tank is achieved with helium gas. To insure the moisture content of the helium gas is within acceptable limits, all helium used for propellant pressurization is passed through a liquid nitrogen refrigerated molecular sieve dryer.

The vent gas of the flow system is neutralized with a charcoal reactor before being exhausted into the atmosphere. Combustion products from the test chamber are aspirated with nitrogen gas, scrubbed with water, and periodically neutralized in the disposal ponds.

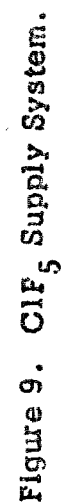
The flow system is being operated remotely during test runs. Various solenoid valves and pneumatic controlled ball valves are used for the hydrazine and nitrogen tetroxide supply systems. Pneumatic controlled Nupro bellow valves are used for the compound A system.

Pressure is measured by strain gauge transducers. The strain gauge is powered by a six-volt power supply. The transducer output is fed through the patch panel into an amplifier to the oscillograph galvanometer. The strain gauge system is provided with a zero balance circuit and an electrical calibration unit which is put into the circuit through a selector switch. The pressure transducers have a natural frequency of 8000 CPS and a linearity of $\pm 0.5\%$. The transducers are calibrated with nitrogen gas using a high accuracy Bourdan gage. The Bourdan gage is calibrated to an NBS standard and is accurate to $\pm 0.25\%$.

Hydrazine and nitrogen tetroxide flow rates are measured with Cox turbine type flow meters. Compound A flow rates are measured with two Potter flow meters. The flow meter output signals are fed into an amplifier to the oscillograph. The flow rate is determined from the meter frequency output and the propellant density.

Propellant temperatures are measured with I/C thermocouples. The thermocouple output is fed through the patch board into an amplifier to the oscillograph.

The impingement test stand with compound A supply system is shown in Figure 10a. A close view of the test stand is shown in Figure 10b.



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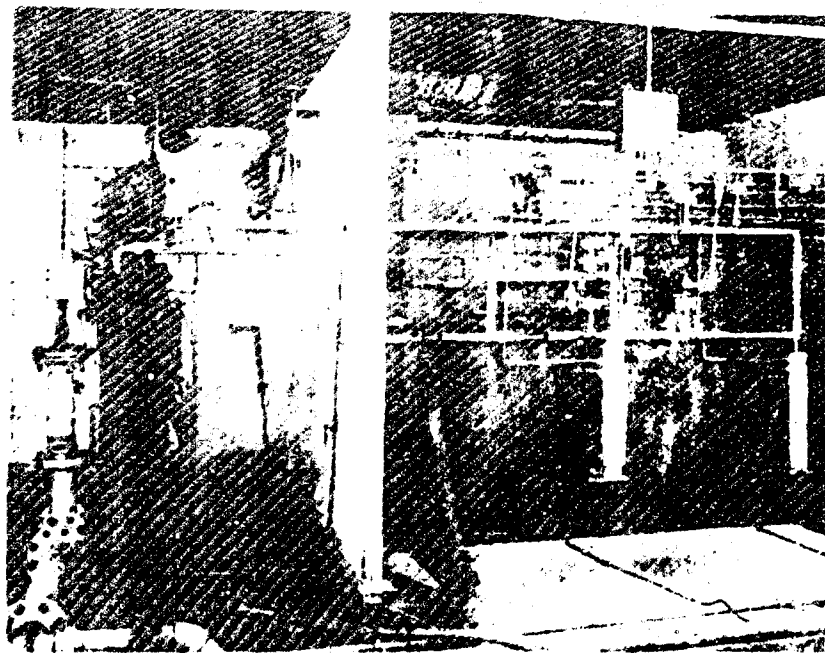


Figure 10a. Test Stand with Compound A Supply System.

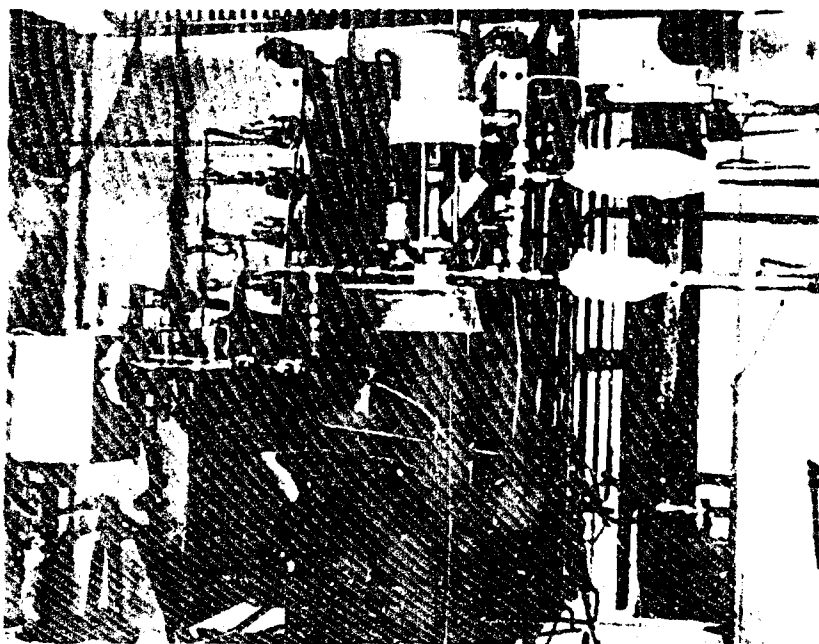


Figure 10b. Close View of Impingement Test Stand.

d. Control Console

The test control console houses the facility and propellant control panel, a test sequence unit, amplifier, and recording oscillograph with related components. The console is shown in Figure 11. The instrumentation system is centered around a Midwestern 801 recording oscillograph. Propellant temperatures at the injector plates, propellant flow rates and the chamber pressure are recorded on the oscillograph. Propellant tank pressures are recorded on a two channel strip recorder. Propellant temperatures downstream of cavitating venturies, tank temperatures, and flow meter temperatures are recorded on a multipoint recorder.

e. Photography

The impingement region is photographed using a Graphex 4x5 still camera. A Wratten No. 34 filter is used to mask out the flame light. This filter transmits only in the blue and red region. Polaroid color film is used with a carbon arc lamp and photoflood front lighting techniques.

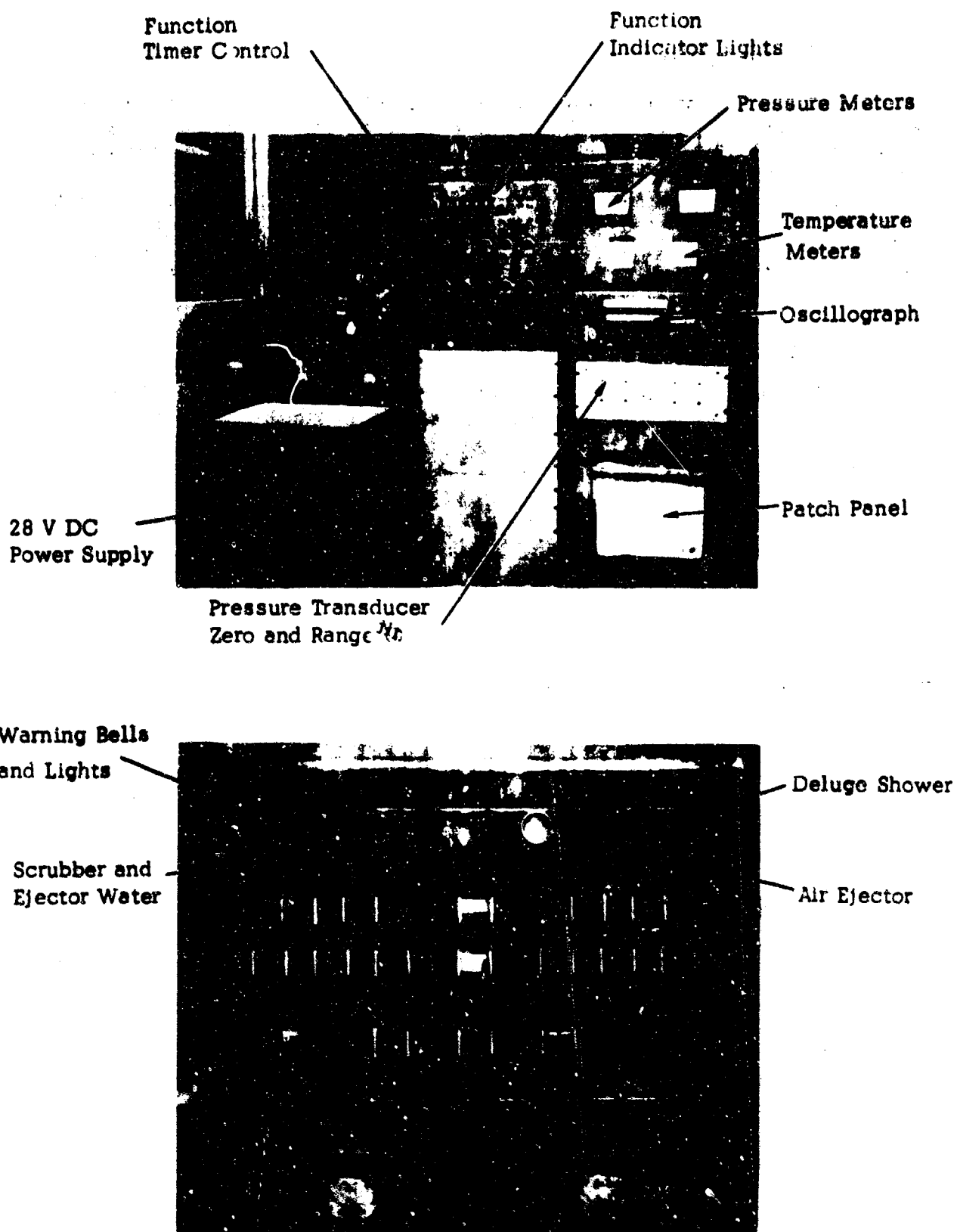


Figure 11. Control Console with Facility Control Panel.

4. IMPINGEMENT OF NITROGEN TETROXIDE/HYDRAZINE FAMILY PROPELLANT SYSTEMS.

a. Experimental Data

Impingement experiments were conducted by impinging streams of hydrazine, monomethyl-hydrazine and mixtures of hydrazine and unsymmetric-di-methyl hydrazine (A-50) with nitrogen tetroxide. Propellant temperatures were varied from 40°F to 120°F. The characteristic mixing time, D/V was varied from 0.2×10^{-4} seconds to 3×10^{-4} seconds. To evaluate the effect of pressure, chamber pressure is varied between 15 psi to 500 psi.

Figures 12, 13, and 14 are photographs of impingement region of hydrazine family fuels with nitrogen tetroxide. A Wratten No. 34 filter is used to mask out the flame light. A dark purple region along the contact surface is present for monomethyl-hydrazine/nitrogen tetroxide impingement (Fig. 13a). This is most probably due to certain hydrocarbon intermediates.

Figure 15 is the impingement data for nitrogen tetroxide and hydrazine streams (Ref. 5) for both rectangular and circular jets. The data are presented in terms of the propellant temperature expressed as $1/T$ and the mixing time D/V . The experiments are conducted at the ambient pressure of ≈ 15 psi. The experimental data in terms of the inverse of the absolute propellant temperature and D/V agree very well with the relationship suggested in Equation (8). Figure 16 is nitrogen tetroxide/hydrazine impingement data for chamber pressures varying between 15 psi and 500 psi. The angle of impingement is generally 60°. Impingement angles of 30° and 90° are also used occasionally. Chamber pressure does not seem to play any significant role with respect to stream separation phenomena. Figures 17 and 18 are impingement data for nitrogen tetroxide/monomethyl hydrazine and nitrogen tetroxide/aerozine 50 respectively. Separation limit for these propellants differs significantly from that of nitrogen tetroxide and hydrazine.

b. Discussion

The impingement model outlined in Section 2b relating the propellant temperature and the mixing time (Eqn. 8) allows good correlation with experimental data. Beyond this correlation the order of magnitude of the "overall activation energy" E , can be estimated based on the slope of the limiting curve. E assumes a value of approximately 20 kcal/mole of reactants. A more detailed calculation has been carried out by Jaye and Blauer (Ref. 14) for the data of Figure 15. By assuming that ignition occurs at 1% of the total reaction and using $\sin \theta/2 = 1/2$ for a 60° impingement, they calculated that E and $\log A$ are respectively 24 ± 3 kcal/mole and 15.7 ± 0.5 cc/mole/sec.

As observed by Jaye and Blauer, rate constants obtained from the impingement results are in excellent agreement with the work of Sawyer and Glassman, (Ref. 15). They obtained $E = 26.7 \pm 1.1$ kcal/mole and $\log A = 15.8 \pm 0.6$ cc/mole/sec for the gas phase ignition process. Jaye and Blauer continue that this agreement leads to the conclusion that either the rate controlling process (of stream separation) occurs in the gas phase or the reaction mechanism is the same in both the liquid and gas phases. This very interesting observation is supported by consideration of surface physics. When two liquid surfaces are in contact, the surface layer molecules which contact the opposite surface would tend to follow

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Figure 12a. Stream Doublet Separation ($\text{N}_2\text{H}_4/\text{N}_2\text{O}_4$).



Figure 12b. Stream Doublet Mixing ($\text{N}_2\text{H}_4/\text{N}_2\text{O}_4$).

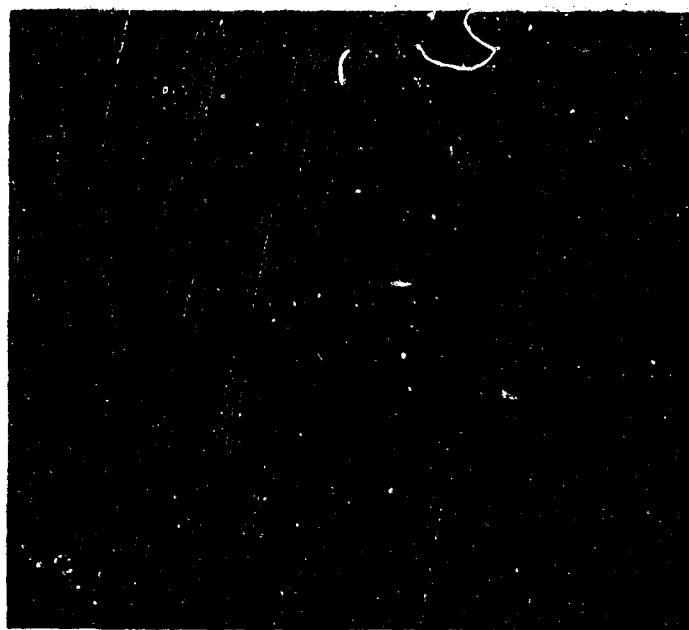


Figure 13a. Stream Doublet Separation (MMH/N₂O₄).



Figure 13b. Stream Doublet Mixing (MMH/N₂O₄).

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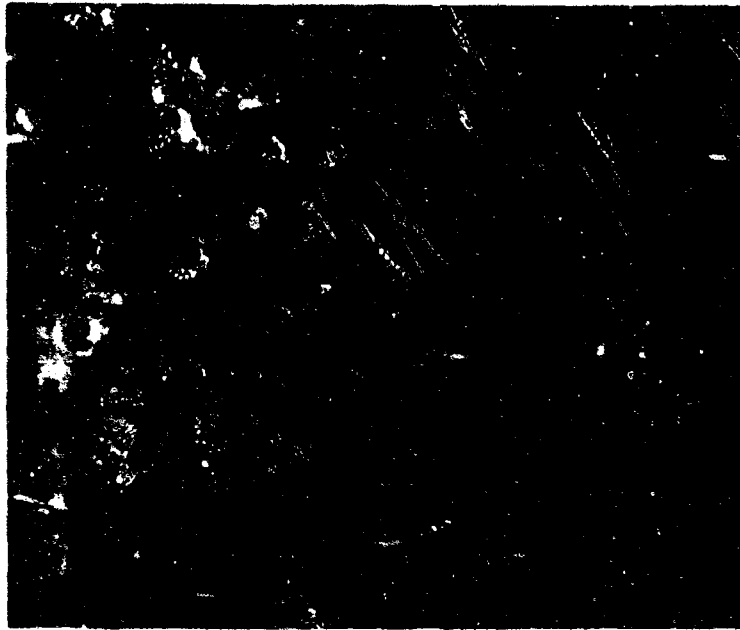


Figure 14a. Stream Doublet Separation (A-50/ N_2O_4).



Figure 14b. Stream Doublet Mixing (A-50/ N_2O_4).

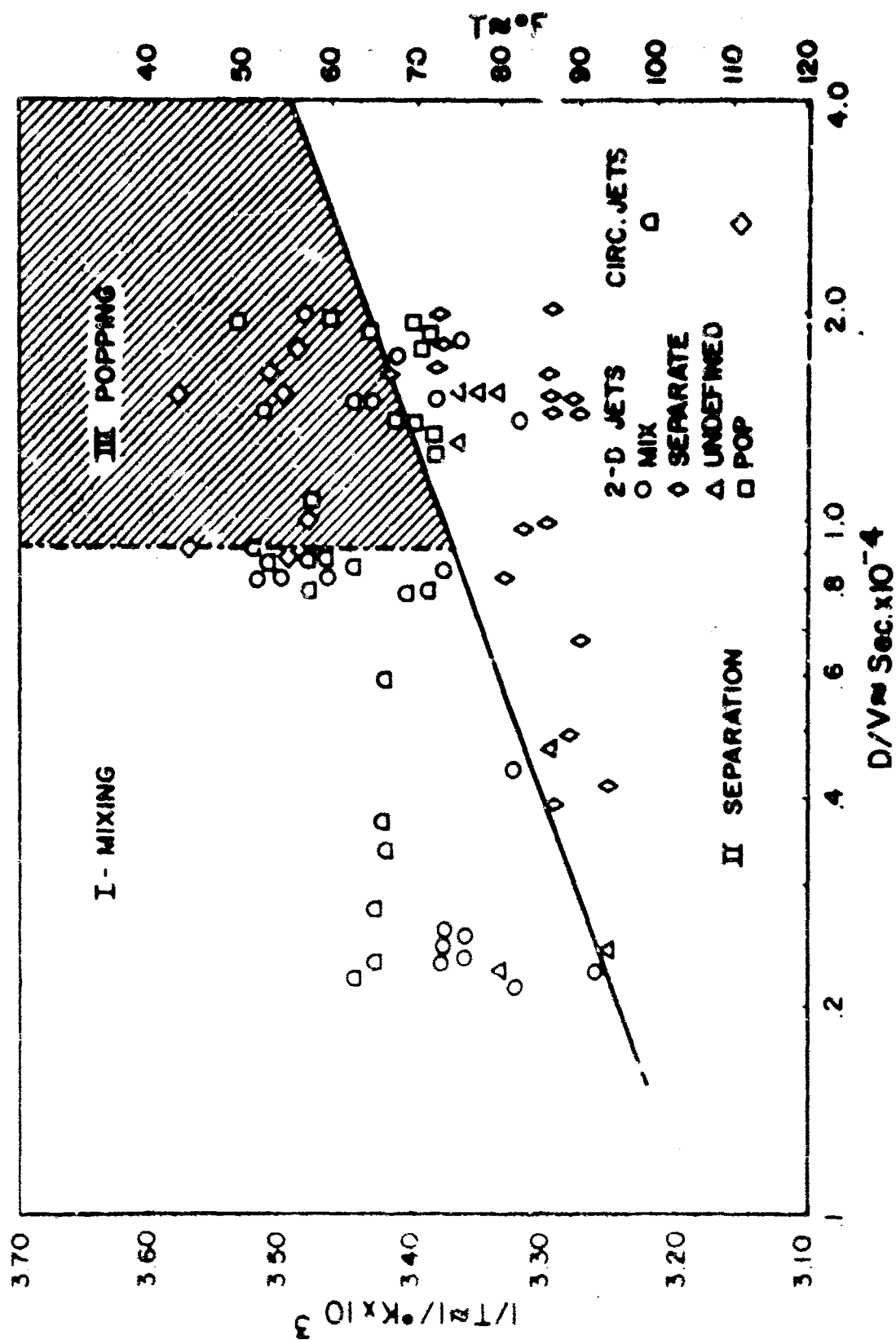


Figure 15. Jet Separation Data for N_2O_4/N_2H_4 System.

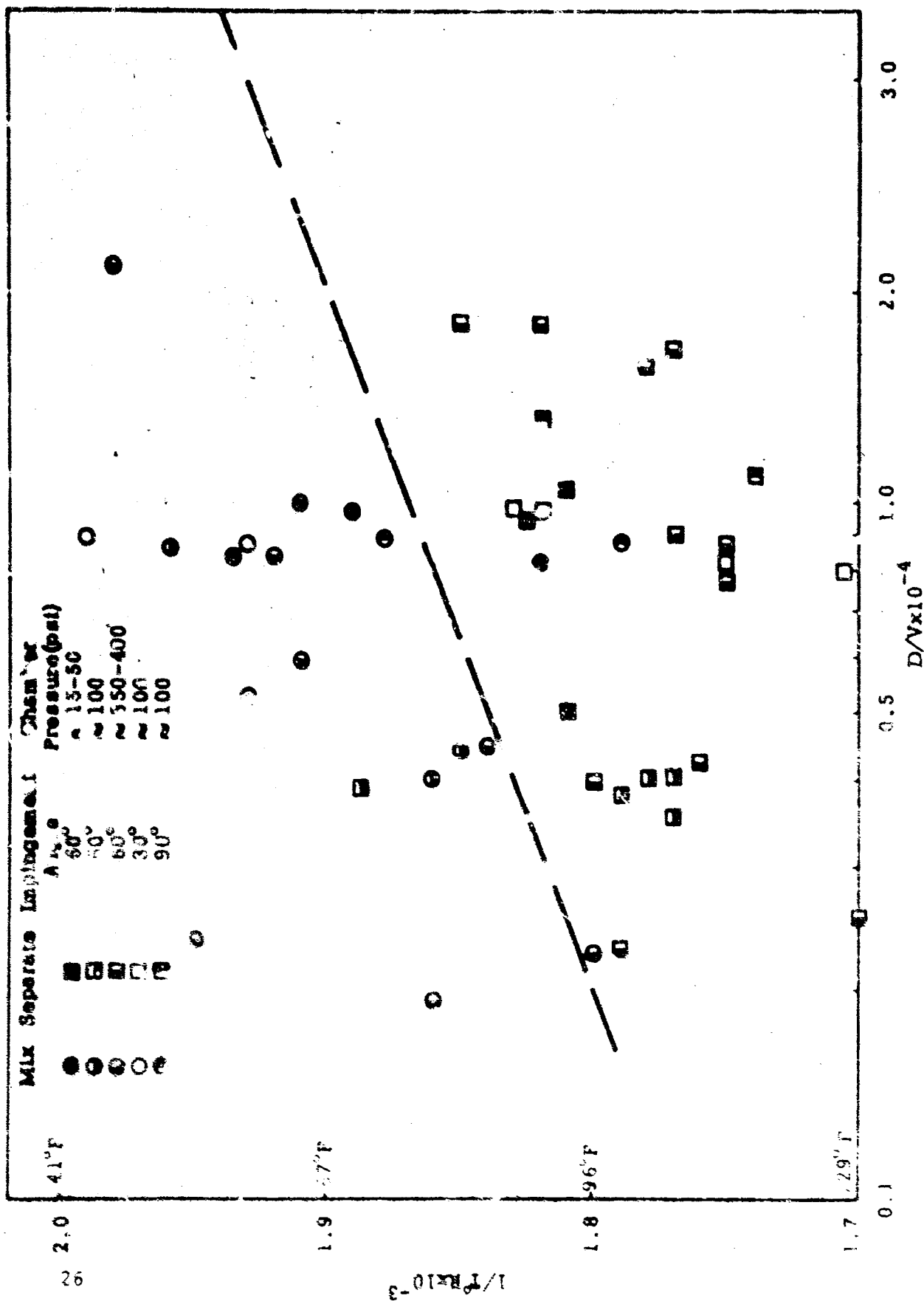


Figure 16. Separation Data for $\text{N}_2\text{O}_4/\text{N}_2\text{H}_4$ System for Different Chamber Pressures.

vapor pressure kinetics rather than fully mixed liquid phase kinetics. This model is supported by motion pictures of Weiss, Fisher, Gerstein, and Johnson (Ref. 16) through which they observed that nitrogen tetroxide drops appeared to be immiscible in hydrazine and maintained their original surface identity.

The data presented in Figure 16 definitely indicate that stream separation does not depend on the chamber pressure. When a locally strong exothermic reaction takes place between the propellants to liberate sufficient gas products and heat to vaporize the propellants and the reaction intermediates so as to blow the stream apart, chamber pressure only plays a secondary role of increasing the boiling point of the liquid. Since the latent heat is the dominating factor, the effect of chamber pressure does not play a significant role. To further illustrate this point, the boiling point of N_2O_4 at 15 psi and 500 psi are $530^\circ R$ and $700^\circ R$ respectively. The latent heat of vaporization within these temperature ranges are approximately 400 Btu/lb and the specific heat C_p is approximately $0.3 \text{ Btu/lb}^\circ R$. The significance of pressure can be evaluated by the ratio:

$$\frac{C_p [T_b(500 \text{ psi}) - T_b(15 \text{ psi})]}{\text{latent heat}} = \frac{0.3(170)}{400} \approx 12\%$$

This indicates that a 500 psi pressure increase only causes a first order effect on the separate/mix temperature criteria. When the order of magnitude of the ratio of the sensible heat difference to the combustion heat available is compared, the amount of heat used in reaching different boiling points is even less significant.

Preliminary tests on nitrogen tetroxide/aerozone 50 and nitrogen tetroxide/monomethyl-hydrazine systems have been carried out. Separation limits of these propellant systems are to be compared with that of nitrogen tetroxide/hydrazine systems. For a given mixing time D/V , separation limits of these propellant systems occur at a higher temperature than that of hydrazine. This indicates that the nitrogen tetroxide/hydrazine is a more reactive propellant system as compared with that of nitrogen tetroxide/monomethyl-hydrazine and nitrogen tetroxide/aerozone 50 systems. Based on jet separation phenomena, at a given temperature and mixing time, aerozone 50 and monomethyl-hydrazine with tetroxide will more readily mix and therefore give a more intense initial combustion zone than the hydrazine with nitrogen tetroxide. However in each case the separation temperature may be reached, depending upon the use of regenerative cooling and resulting injection temperature.

c. Engine Design Application

Stream separation influences the engine performance in many respects. When reactive streams are blown apart the result can be a high degree of flow striation. This leads to poor combustion efficiency. When separation occurs maximum striation and efficiency loss is associated with a single element injector. The striation effect upon efficiency losses would diminish for larger numbers of injector elements. This effect was established experimentally, (Ref. 17), and indicated that the combustion efficiency loss for a single element, four on one, injector is roughly twice that of a ten element injector.

The influence of nonuniform mixture ratio distribution, which can be induced by stream blow apart, has been theoretically calculated based on a

stratified supersonic nozzle flow field (Ref. 18) and internally, based on non-uniform vaporization streamtubes (Ref. 19). Various prescribed oxidizer to fuel ratio profiles have been used to evaluate their effect on performance. Nitrogen tetroxide/aerozine 50 and fluorine/hydrogen systems generally indicated losses from 1.0 to 4.0% in specific impulse. Liquid oxygen/hydrocarbon (LOX/RP-1) system exhibited a specific impulse loss of approximately 8%.

The mix/separate criteria presented in this report also point out the importance of proper injector design upon thrust chamber liner compatibility. Proper injector design must include the influence of propellant temperature upon whether or not the fuel-rich stream separates and remains next to the liner; or in the low temperature case (mixing) forms an intense combustion zone. This effect will be found not only in the fuel-rich barrier zone but also in the intense stoichiometric combustion of the primary zone. If the primary injector zone is within the mixing regime it may actually blow through the fuel-rich combustion of the barrier zone. Thus liner compatibility is as strongly dependent upon propellant temperature as it is upon propellant distribution.

It has been shown in the previous section that by properly controlling the propellant temperature, propellant injection velocity and orifice size, regimes of mix/separate phenomena can be defined. This knowledge can be used to great advantage by design engineers. Based on data similar to those presented in Figures 15 to 18, characteristic parameters such as propellant temperature and mixing time, D/V can be defined in order to achieve proper combustion mixing leading to better engine performance, stability, and compatibility. Particularly when anomalous engine behavior is observed, attention should be paid to the operating region of mix or separate mechanisms, at the very least this work points out the importance of controlling and monitoring propellant temperature during engine firing test programs.

Engine instability is another problem which is sometimes directly attributed to separation phenomena. High pressure transients have often been observed at chamber wall pressure transducer stations during full-scale engine development and test programs (Refs. 3 and 9). These transients are rather arbitrarily termed "pops," depending upon amplitude and frequency. However, their initiation source is the subject of much speculation. During the course of this impingement research and in previous impingement experiments conducted at NASA/Lewis (Ref. 13) and at Dynamic Science (Ref. 12), it was found that injection mixing explosions often occurred reproducibly in the lower temperature (mix) regime, at long residence time. Their occurrence also appears to increase under these conditions when the streams have a high degree of mixing as shown in Figure 4, (i.e. δ defined on page 7 to be approximately 0.5 or that the streams have approximately equal momentum or stagnation pressures.)

High speed motion picture cameras have been used to record the explosion of the impingement region (Ref. 12). This explosion phenomena is very detrimental to stable engine operation because they can serve as triggering source for spray detonation as shown in Figure 3. This detonation wave at the impingement zone also causes injector flow irregularities with apparent "flow shutoff" of a few milliseconds resulting in rough engine operation. The pictures on Figure 3 were obtained with long interfacial residence time and substantial liquid mixing throughout the impingement region. Unlike the separation phenomena which are caused by a

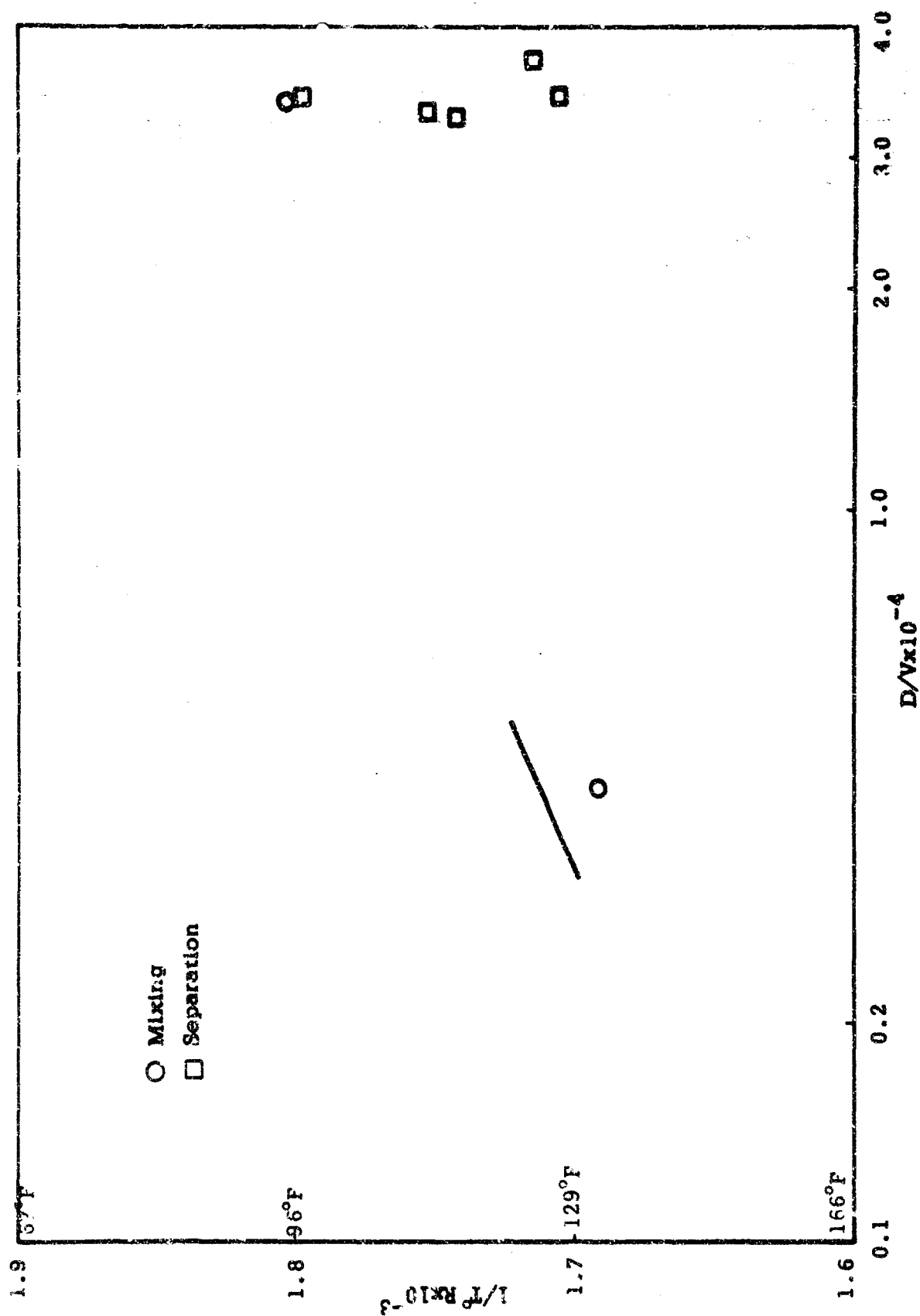


Figure 17. Separation Data for N_2O_4/Ad_{300} di System.

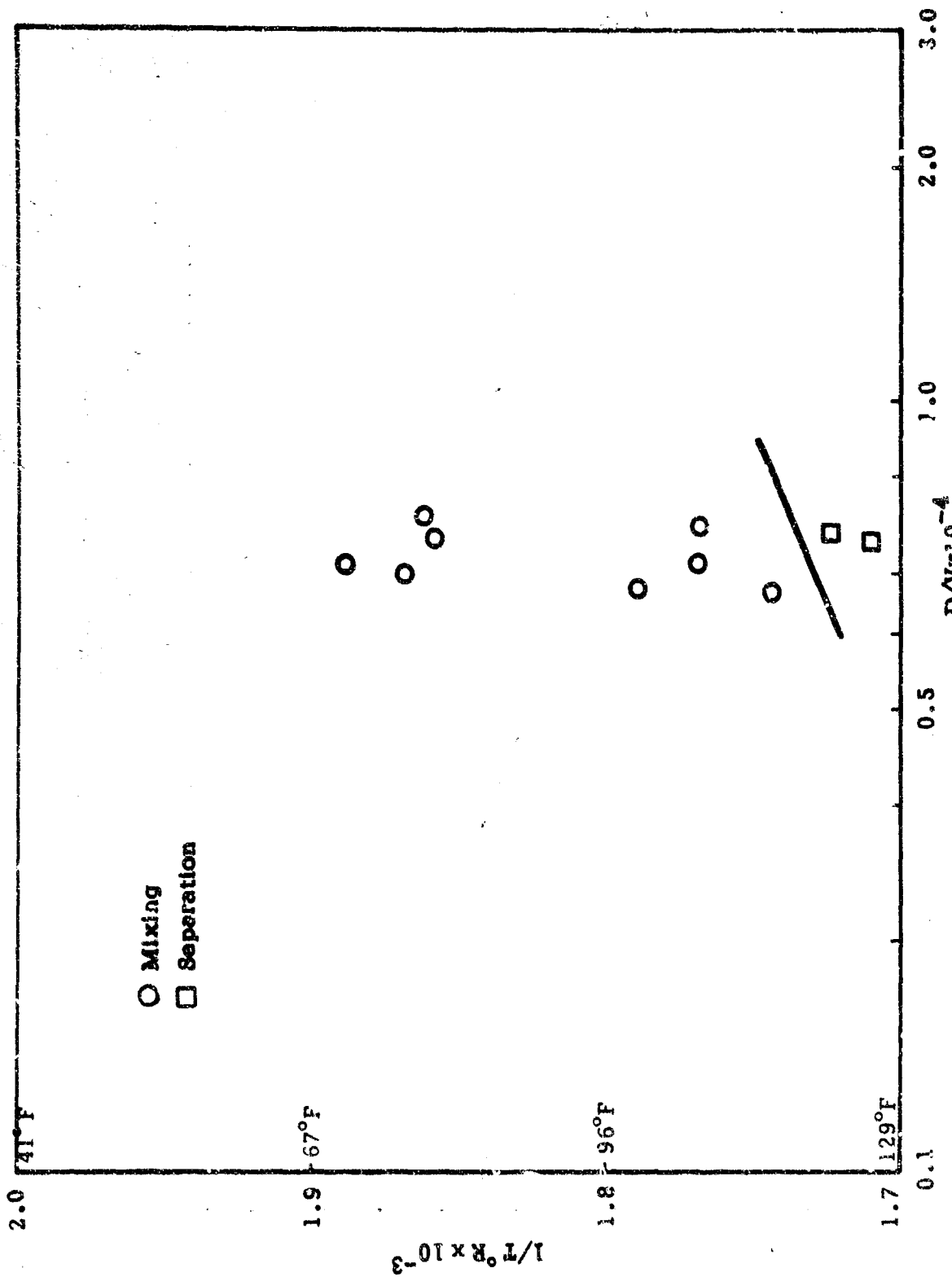


Figure 18. Separation Data for $N_2O_4/A-50$ System.

locally exothermic reaction, the reaction within the entire impingement region results in spray detonation. For smooth engine operation the design engineer has to avoid these conditions which lead to detonation waves. The occurrence of these explosions will be unavoidable with unlike hypergolic propellant injection unless care is taken to insure that each set of elements within the injector are operating within the same regime. Because of manifold layout and L/D orifice problems this is often impossible but it should always be a major consideration for the removal of "pop" and roughness. If each set of elements are different there may be a random set sometimes passing through the injector mixing explosion regime. The use of a single element system such as a center flow injection scheme overcomes the element randomness.

5. COMPOUND A IMPINGEMENT WITH HYDRAZINE

a. Experimental Difficulties

The impingement model (Fig. 6) for nitrogen tetroxide/hydrazine tests is also used to study the jet separation of compound A and hydrazine. A separate flow system (Figs. 7 and 8a) is used for delivering compound A. Propellant is temperature regulated up to the injector plate (Figure 7a), since heat transfer between the plate which is initially at ambient temperatures and compound A which is close of 0°F only increases the propellant temperature by a fraction of a degree.

Impinging compound A with hydrazine presents many additional difficulties. Compound A is a more reactive and corrosive propellant as compared with nitrogen tetroxide. This often causes substantial damage to the viewing window of the impingement test model. Lucite is certainly not compatible with compound A and this is evidenced with the initial runs using lucite windows. Reactions between lucite and compound A upstream of the impingement point is shown in Figure 19. The bright flame along the entire length of the compound A nozzle is the reaction of compound A with lucite. This in turn caused substantial damage to the injector plate as shown in Figure 20. To partly remedy this problem, the injector plate is modified as shown in Figure 21. This also allows impingement to take place away from the window. Lucite with pyrex or calcium fluoride inserts are used for window materials. Damages on these windows are very often too severe to obtain quality photographs. The chamber window following a compound A/hydrazine impingement reaction is shown in Figure 22. It is a lucite window with a pyrex insert 1/4 inch thick. In addition to the severe burning of the window by compound A, much damage is caused by the thermal stresses resulting from the strong exothermic reactions at the impingement region. A typical photograph using calcium fluoride insert is shown in Figure 23. By closely investigating the calcium fluoride insert following the impingement test, damage was found to be mainly caused by thermal stresses since the window is 3/8 inch thick. It appears that calcium fluoride is compatible with the compound A at these high temperatures. Better quality photographs might be obtained with thin calcium fluoride inserts.

The vent gas of the flow system is neutralized with a charcoal reactor before vented into the atmosphere. Refractory cement is used as a heat insulator for the charcoal scrubber. The strong exothermic reaction between compound A and charcoal sometimes "melts" this cement insulator which is shown in Figure 24.

b. Results

A photograph of impinging streams of hydrazine and compound A is shown in Figure 25. The fuel and oxidizer flow rates are 0.022 lb/sec and 0.0343 lb/sec. The initial temperatures are 56°F and 0°F. Based on photographs of the impingement region, mix/separate phenomena is less distinct as compared with nitrogen tetroxide and hydrazine. Unlike nitrogen tetroxide which is brown colored Compound A is colorless.

Approximately fifty impingement tests using hydrazine and compound A have

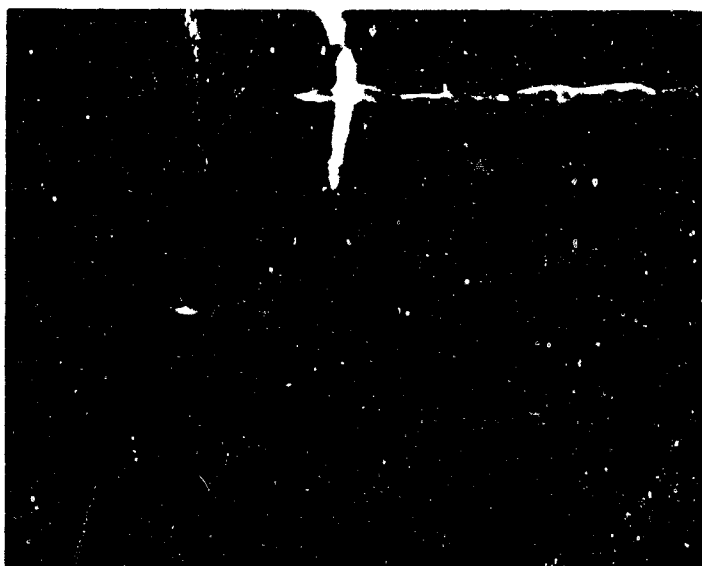


Figure 19. Reaction of Lucite Window in Compound A Stream.



Figure 20. Injector Plate Following Compound A/ N_2H_4 Reaction.

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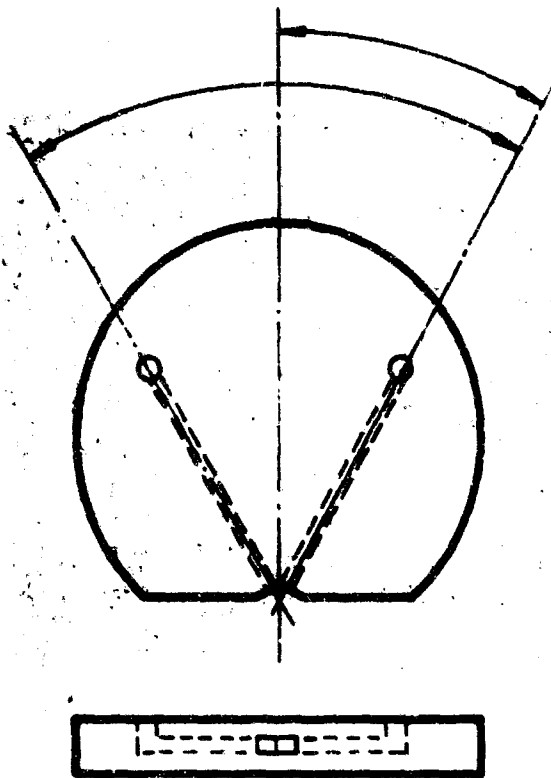


Figure 21. Modified Injector Plate for Compound A Propellant.

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Figure 22. Lucite Chamber Window with Pyrex Insert following Compound A/Hydrazine Reaction.



Figure 23. Lucite Window with Calcium Fluoride Insert.



Figure 24. Melted Refractory Cement of Charcoat Scrubber.

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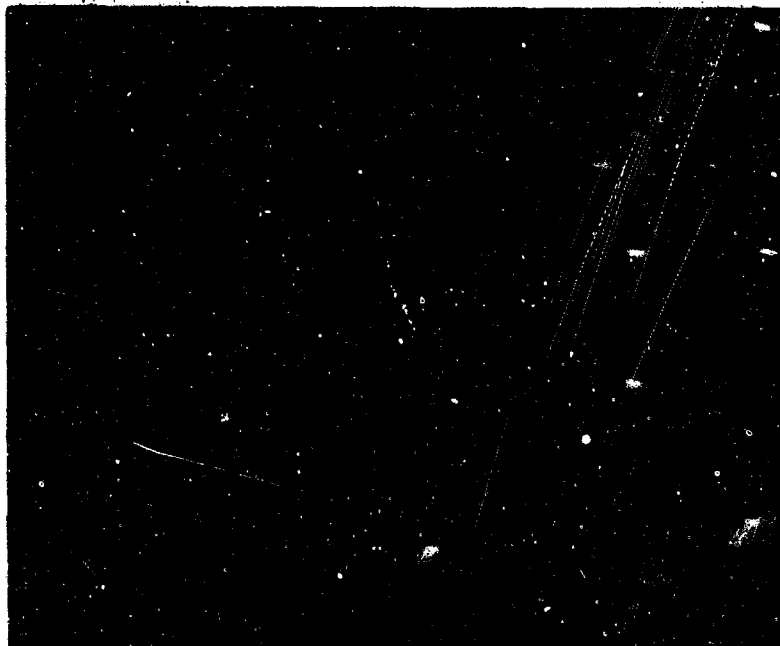


Figure 25. Hydrazine/Compound A Impingement.
(Compound A, Left Injector
Hydrazine, Right Injector).

been carried out. The chamber pressure was varied from 15 psia to over 100 psia. Hydrazine and Compound A temperatures ranged from 40°F to 60°F and 0°F to 30°F respectively. The mixing time, D/V was within 0.2×10^{-4} sec to 2×10^{-4} sec. Within these temperature and velocity ranges, it appeared that impingement of compound A and hydrazine always resulted in separation.

The separation phenomena are partly attributed to the high vapor pressure of compound A. Its boiling temperature at atmospheric pressure is 7°F, while the hydrazine had to be maintained above 35°F to keep it from freezing. Thus the compound A would boil on contact with the hydrazine at pressures below 45 psia (corresponding to hydrazine temperature of 60°F). Under such circumstances chamber pressure is indeed important to, first of all, assure liquid-liquid contact. The significance of chamber pressure in this case is not contradictory to the data of Figure 16 which show no pressure effect, but merely indicate that a boiling mechanism will cause separation up to the point where the chamber pressure allows liquid-liquid contact.

It is believed that better experimental results can be achieved with the viewing window further away from the impingement region. A lucite window with calcium fluoride inserts was compatible with compound A at the elevated temperatures. In the present experiment, test periods are approximately two seconds. Reducing testing periods will minimize possible window damage. This can be achieved by improving the existing by-pass line in the flow system so as to reduce the transient effects. Possibility of coloring one of the propellants can be investigated so as to obtain better photographs.

6. CONCLUSION

Based on experimental results of hypergolic propellant impingement studies, mixing or separation phenomena are usually observed. Corresponding to the first Damkohler number, a nondimensionalized number $\beta = \tau_{\text{chm}} / \tau_{\text{mix}}$ can be defined. τ_{chm} and τ_{mix} are characteristic chemical reaction time and mixing time. Separation limit is defined by assuming $\beta = 1$.

Impinging nitrogen tetroxide with hydrazine family fuels, the separation limit $\beta = 1$ agrees very well with the experiment. Chamber pressures varied from 15 psi to 500 psi. The predicted pressure effects (Ref. 6) were not observed. In fact, in the regime that was investigated, stream separation is independent of pressure. This is anticipated when chemical kinetics are governed by the rate of liquid phase reaction. Separation limits are observed at higher temperatures for A-50/ N_2O_4 and MMH/ N_2O_4 as compared with N_2H_4 / N_2O_4 system indicating N_2H_4 / N_2O_4 is a more reactive system.

It appears that stream separation always occurs by impinging Compound A and hydrazine with oxidizer and fuel temperatures varying between 0°F to 30°F and 40°F to 60°F respectively. Better experimental results can be obtained by reducing the testing period and using lucite windows with thin calcium fluoride inserts.

PART II

EXTENSION OF STEADY-STATE COMBUSTION MODEL

1. INTRODUCTION

The Dynamic Science steady-state combustion computer program has been in use at several installations for a number of years. It has been shown by many investigators to be a useful tool to investigate the performance and stability of liquid rocket engines. The program provides the linkage between propellant, engine, and injector parameters, and the performance of the system and guides the designer/analyst in making changes necessary to correct system deficiencies.

This section describes a project performed jointly by personnel of the AFRL and Dynamic Science under the direction of Capt. Charles J. Abbe to improve the operational versatility and economics of use of the steady-state combustion program.

2. PROGRAM DESCRIPTION

The basic model used in the Steady-State Combustion Program is an extension of the original work of Priem (Ref. 20). The model considers the conservation equations governing the heat, mass, and momentum transfer of a spray of liquid fuel drops traveling through a channel filled with oxidizer vapor. The assumption is made that propellant vaporization is the rate governing mechanism of the combustion process and that vaporization of the drop can be expressed by a Ranz and Marshall type correlation.

Dynamic Science extended this work (Refs. 21 and 22) to include the simultaneous vaporization of fuel and oxidizer sprays; thereby calculating vapor and liquid phase O/F along the chamber length. The thermophysical property calculations were also substantially improved. A valuable routine added to the program included the monopropellant burning effect of hydrazine type propellants and allowed calculated and measured combustion efficiencies to be correlated with these propellant systems (Ref. 23).

The program as listed in Reference 20 included all these effects but was still in an engineering development stage not entirely suited to production running. This work, in this computer extension phase, involved breaking the program up into subroutines of size suitable for manipulation, replacing the second order Runge-Kutta integration with a predictor-corrector type scheme, and improvement of program versatility. The bulk of the work was performed for the improvement of program versatility, i.e., generalizing the program to provide the capability of easily switching from one propellant combination to another. This involved segregating the property routines and generalizing their input, gathering the property data available and converting to the proper units.

and specifying estimation procedures for properties not readily available. The majority of programming and all debugging were performed at the AFRL computing facility.

The documentation cited here is only an attempt to provide a knowledge of the changes that have been made in the program. For a more complete description of the model and program, see References 19 and 20.

3. PHYSICAL PROPERTY ROUTINES

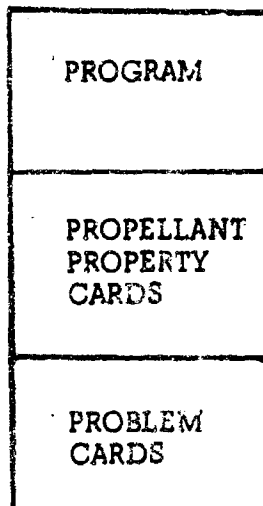
The following is a list of the physical property routines and units required by the program. The properties may be broken down into those of the fuel and oxidizer (both liquid and vapor) and those of the individual species comprising the combustion gas. The independent variable against which values are to be interpolated is also given. Oxidizer properties may be related in the program to the integer $I = 1$ and fuel properties by $I = 2$.

Fuel and Oxidizer Properties		
Subroutines	Property (Units)	Independent Variable (Units)
PVAP	vapor pressure (psia)	liquid temperature ($^{\circ}\text{R}$)
TBL	boiling temperature ($^{\circ}\text{R}$)	pressure (psia)
RHØ	liquid density (lb/in ³)	liquid temperature ($^{\circ}\text{R}$)
VISCV	vapor viscosity (lb/in-sec)	temperature ($^{\circ}\text{R}$)
CVAP	vapor specific heat (Btu/lb- $^{\circ}\text{F}$)	temperature ($^{\circ}\text{R}$)
FKA	vapor thermal conductivity (Btu/in-sec- $^{\circ}\text{F}$)	temperature ($^{\circ}\text{R}$)
CPL	liquid specific heat (Btu/lb- $^{\circ}\text{F}$)	liquid temperature ($^{\circ}\text{R}$)
ALM	heat of vaporization (Btu/lb)	liquid temperature ($^{\circ}\text{R}$)

Combustion Species Properties

Subroutine	Property (Units)	Independent Variable (Units)
COMP	combustion gas composition (mole fraction)	O/F ratio at different pressures (psia); maximum of 3 pressures
WTMINT	combustion gas molecular weight	O/F ratio at different pressures (psia); maximum of 3 pressures
TGINT	flame temperature ($^{\circ}\text{R}$)	O/F ratio at different pressures (psia); maximum of 3 pressures
VKIGAS	viscosity (lb/in-sec) for each species	temperature ($^{\circ}\text{R}$)
	specific heat (Btu/mole- $^{\circ}\text{F}$) for each species	temperature ($^{\circ}\text{R}$)
	(thermal conductivity calculated from μ and c_p)	
	molecular weight of each species	
DIFFU	calculates diffusion coefficient of fuel and oxidizer through combustion mixture	
	Lennard Jones Parameters	
	σ_1 , atomic radius of oxidizer ($\text{\AA}$)	
	σ_2 , atomic radius of fuel ($\text{\AA}$)	
	σ_j , atomic radius for each species ($\text{\AA}$)	
	ϵ_1/k , interaction energy of oxidizer ($^{\circ}\text{K}$)	
	ϵ_2/k , interaction energy of fuel ($^{\circ}\text{K}$)	
	ϵ_j/k , interaction energy for each species ($^{\circ}\text{K}$)	

4. ORGANIZATION OF DECK



5. INPUT FORMAT

The input cards may be divided into two types: (1) propellant property cards and (2) problem cards.

The propellant property cards contain all the data shown in Section 3 for the particular propellant system being run. The properties are those of the fuel and oxidizer (both liquid and vapor) and the species comprising the combustion gases.

Input Format for the Propellant Property Cards:

- *Read Propellant Combination Title (A Format) in Fields 1-10, and 11-20.
- *Read NR, NSP, NTL(1), NTL(2), NTFLM(1), NTFLM(2), NT use 110 format.
- *Read NSP species names, (Fields of 12), 6 fields to a card, in same order that species concentrations will be read.
- *Read O/F ratios (F format), seven values to a card, until NR O/F ratios are listed.

For each of up to 3 pressures:

- *Read pressure.
- *For each species, read composition as function of O/F (seven values per card). Start new card for each species.
- *Read average molecular weight versus O/F.
- *Read gas temperature versus O/F.
- GO BACK AND START NEXT PRESSURE
- *Read $\ln \gamma$ versus O/F (at any selected pressure).
- *Read NT temperatures.
- *Read viscosity ($\times 10^6$) versus NT for each species. Start new card for each species.
- *Read specific heat versus NT for each species. Start new card for each species.

*means start new card

- *Read in molecular weight for each species. Be sure to maintain correct species order in all input data.
- *Read species interaction energy for each species.
- *Read propellant molecule interaction energy for ox, then fuel (in second field).
- *Read species molecular diameter for each species.
- *Read propellant molecular diameter for ox, then fuel.
- *Read molecular weight of ox, then fuel.
- *Read oxidizer liquid temperature, vapor pressure, liquid density, liquid specific heat, and heat of vaporization (F format). Continue on new card up to NTL(1) values of oxidizer liquid temperatures.
- *Repeat preceding for fuel (NTL(2) cards).
- *Read oxidizer vapor film temperature, vapor viscosity ($\times 10^6$), vapor conductivity ($\times 10^6$), and vapor specific heat for NTFLM(1) values of oxidizer film temperatures.
- *Repeat above for fuel (NTFLM(2) cards).
- *Read LØØse: I10 format

Fuel decomposition flame exists, LØØSE = 1

No fuel decomposition flame exists, LØØSE = 0

Definitions

- NR = Number of O/F ratios
- NSP = Number of species
- NTL = Number of liquid phase temperature
- NTFLM = Number of gas phase (vapor film) temperatures
- NT = Number of species gas phase temperatures
- (1) = Oxidizer
- (2) = Fuel

Follow above propellant property data with engine data, as shown on coding sheet.

Input Format for Problem Cards

(See chart following).

Card 9 describes the geometry of a conventionally shaped combustion chamber according to the following definitions:

Par 1 = Z_c , inches

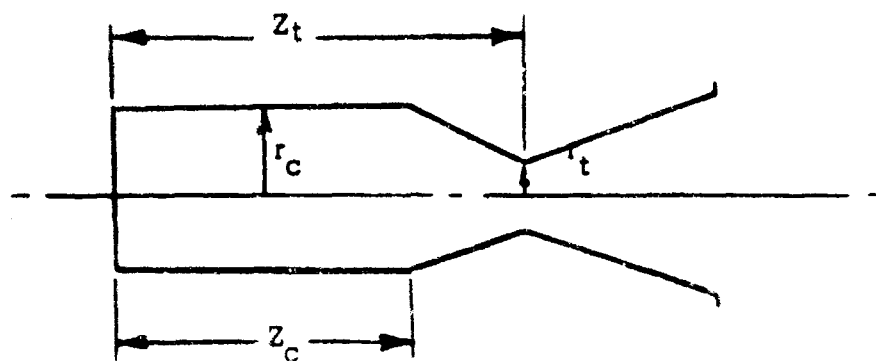
Par 2 = πr_c^2 , in²

Par 3 = (Par 4) $Z_c + r_c$, inches

Par 4 = $(r_c - r_t) / (Z_t - Z_c)$, dimensionless

Par 5 = $2\pi (\text{Par 4})^2$, dimensionless

Par 6 = $2\pi (\text{Par 3})(\text{Par 4})$, inches



Input for Sample Problem

See following pages.

INPUT FORMAT FOR PROBLEM CARDS

START, Inches (Norm. -0.2)	Max. Step Size (Norm. -0.2 to 2)	Mis. Error (Norm. -0.0001)	Max. Error (Norm. -0.01)	COMMENT			Card #1
NSW - Print indicated (Norm. -10)	MP = Power of 2 variation between max. and min. step (Norm. 2-4)	Print every NOCYCLES (Norm. -1)	Print every NPLLOT=1, NO NPLLOT=2, YES				Card #2
Chamber Pressure, Pounds	Min. M.R. (Norm. -0.6)	Max. M.R. (Norm. -5.0)	Throat Area (in ²)				Card #3
Flow Rate (lb/sec)	Inj. Velocity (in/sec)	Inj. Liquid Temp (R)	Mass median Drop Radius (in)				Card #4
	This card same as #7 but values given for fuel						Card #5
PAR 1*	PAR 2*	PAR 3*	PAR 4*	PAR 5*	PAR 6*		Card #6
							Card #7
							Card #8
							Card #9
							Card #10
							Card #11
							Card #12
							Card #13
							Card #14
							Card #15
							Card #16
							Card #17
							Card #18
							Card #19
							Card #20
							Card #21
							Card #22
							Card #23
							Card #24
							Card #25
							Card #26
							Card #27
							Card #28
							Card #29
							Card #30
							Card #31
							Card #32
							Card #33
							Card #34
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							Card #89
							Card #90
							Card #91
							Card #92
							Card #93
							Card #94
							Card #95
							Card #96
							Card #97
							Card #98
							Card #99
							Card #100

INPUT FOR SAMPLE PROBLEM

	470	4244		10	13	7	6	6
	9	9	42	420			40	72
	4		40	0				
	434							
15.	10.	5.	2.	1.	.5	.2		
.1	.065							
100.								
			.007	.02	.001			
			.020	.140	.408	.560		
.612	.531							
.113	.161	.274	.425	.348	.219	.090		
.046	.030							
.391	.360	.373	.391	.392	.349	.348		
.340	.339							
		.005	.045	.013				
.553	.479	.339	.079	.002				
		.011	.020					
			.040					
29.01	29.32	26.54	22.74	18.75	15.13	12.53		
11.62	11.32							
1903.	2533.	3855.	5290.	5278.	4018.	2693.		
2156.	1964.							
100.								
			.004	.015				
			.016	.179	.410	.560		
.612	.524							
.113	.161	.274	.437	.396	.219	.090		
.045	.030							
.391	.360	.372	.393	.396	.396	.348		
.341	.337							
		.002	.041	.011				
.553	.479	.339	.076					
	.002							
		.010	.020					
			.007					
29.02	29.32	26.54	22.90	18.85	15.14	12.53		
11.63	11.33							
1913.	2533.	3855.	5424.	5398.	4025.	2695.		
2158.	1969.							
1000.								

			.002	.009		
			.012	.120	.411	.559
.009	.625					
.113	.160	.273	.447	.402	.220	.090
.045	.039					
.391	.360	.373	.394	.309	.370	.347
.340	.337		.037	.007		
.536	.477	.339	.076			
.003	.003					
		.010	.023			
			.004			
29.01	28.32	26.5	23.05	18.96	15.14	12.54
11.66	11.38					
1903.	2532.	3872.	5558.	5564.	4014.	2696.
2145.	1984.					
1.310	1.297	1.253	1.225	1.232	1.248	1.318
1.344	1.353					
540.	1080.	1980.	3060.	4860.	7020.	
.419	.659	.975	1.292	1.741	2.207	
.50	.792	1.179	1.564	2.108	2.672	
.614	1.203	2.202	3.252	4.693	6.121	
.995	1.508	2.357	3.146	4.242	5.378	
1.102	1.781	2.640	3.511	4.737	6.064	
1.156	1.912	2.853	3.790	5.130	6.506	
.593	1.173	2.052	2.932	4.100	5.283	
1.075	1.795	2.697	3.571	4.833	6.130	
1.056	1.747	2.616	3.468	4.687	5.944	
2.5	2.5	2.5	2.5	2.5	2.5	
7.0	7.05	7.35	7.99	8.62	9.11	
8.08	8.73	10.22	11.75	13.2	14.01	
7.0	7.24	8.0	8.51	8.85	9.09	
7.0	7.04	7.45	8.09	8.73	9.1	
7.07	7.7	8.47	8.89	9.44	9.92	
8.55	10.72	14.0	16.53	18.43	19.35	
7.17	7.5	8.28	8.69	8.97	9.12	
5.26	5.09	5.02	5.01	5.02	5.12	
1.	2.	18.	28.	17.	32.	17.
30.	16.					
37.	59.7	809.	71.4	79.8	106.7	558.
116.7	106.7					
331.9	502.8					
2.71	2.83	2.64	3.80	5.15	3.47	2.9
3.49	3.05					
3.269	4.029					
46.	32.					
400.	.27	.033	.35	435.		
440.	.85	.0526	.35	430.		
480.	8.94	.0541	.353	422.		
521.	11.8	.0527	.372	412.		

500.	30.	.04385	.388	403.
600.	80.	.0487	.414	392.
800.	180.	.0453	.464	370.
680.	330.	.0435	.543	365.
720.	660.	.03935	.70	344.
750.	1200.	.0324	.87	315.
400.	.001	.035	.686	700.
500.	.08	.0356	.70	680.
550.	.48	.0337	.72	650.
600.	1.9	.0344	.74	620.
650.	6.0	.0338	.75	590.
700.	15.5	.0328	.77	550.
750.	37.	.0317	.78	510.
800.	75.	.0305	.80	470.
850.	160.	.0292	.82	430.
900.	250.	.0281	.83	390.
950.	430.	.0270	.85	370.
1000.	660.	.0250	.87	340.
1050.	960.	.0250	.89	310.
400.	.524	.094	.231	
600.	.92	.224	.238	
1000.	1.57	.485	.253	
1600.	2.34	.675	.269	
2400.	3.21	1.39	.246	
3200.	3.91	5.91	.297	
4000.	4.57	2.44	.300	
400.	.42	.14	.32	
400.	.80	.30	.50	
1200.	1.19	.45	.61	
2000.	1.95	.95	.74	
2600.	2.71	1.5	.82	
4000.	2.85	2.4	.90	

1
 V244-44H STABILITY 7 JAN 69 RUN 183 (DOURLET-V244) INGE80
 DELVS VINJ NO CORRECTIONS
 IC3PG 5TH CONF.

0.0	.05	.0001	.01	1.5	0.0
311.	.2	5.	12.46	128.8	1.4
12.99	648.	534.	.00555	2.3	5
11.24	1607.	532.	.00280	2.3	5
5.	128.2				

6. PROGRAM LISTING

```

PROGRAM STEADY(INPUT,OUTPUT,TAPE5=INPUT,TAPE4=OUTPUT)
$IRFTC TRSL LIST,REF
000003 COMMON /E/FC,NM/R/BD/C/TA/FP/AR,AU,BCDX,BCDY,LOR
000003 COMMON /LINKA/ LOOSE
000003 COMMON /PRPS/ PRPSYS(4) /SPEC/ NSP, SPNAME(2, 15)
000003 DIMENSION FC(80),NM(20),BD(10,20,12),TA(1000),AR(150),
1 AJ(100,90),BCDX(7),BCDY(3),LOR(9),TITLE(24)
2,ZM(10,20,2), DM(10,20,2),YLA(10,20,2), DT(10,20,2)
3,V(10,20,2), DV(10,20,2), WTMOL(2)
000003 EQUIVALENCE (FC(14), TSTOP), (NM(5), MPTN), (BD(1, 1, 1), FM(1, 1,
11)), (RD(1, 1, 3), DM(1, 1, 1)), (RD(1, 1, 5),YLA(1, 1, 1)), (RD(1
2, 1, 7), DT(1, 1, 1)), (BD(1, 1, 9), V(1, 1, 1)), (BD(1, 1, 11), D
3V(1, 1, 1)), (FC(1), T), (NM(15), MLOT), (TA(46), WTMOL)
000003 COMMON /TRFGAM/ FGAMT(13) /OF/ R(15), NR /CMPTAR/
1YSP(15, 15, 3) /PRSSR/ PRSS(3) /PVY/ PV(15, 2) /TLX/ TL(15, 2) /DT
2L/ NTL(2) /TFLMX/ TFLM(15, 2) /VISCY/ VVIS(15, 2) /DTFLM/ NTFLM(
32) /RHOLY/ RHOL(15, 2) /KVAPY/ KVAP(15, 2) /CPVPY/ CPVAP(15, 2) /CP
4Y/ CP(15, 2) /LAMY/ LAM(15, 2) /WTH/ WMTAB(15, 3) /TG1/ TC1(15, 3)
5/TABT/ ITAB(15) /VKSGS/ VSP(15, 15), CPTAB(15, 15) /BT/ NT /DIFFUS
6/ EPSI(15,2), SIGMA(15, 2), EPSOF(2), SIGOF(2) /MW/ WM(15)
000003 REAL KVAP, LAM
000003 READ (5, 601) PRPSYS
000011 601 FORMAT (4A5)
000011 READ (5, 60) NR, NSP, NTL, NTFLM, NT
000027 50 FORMAT (7I10)
000027 READ (5, 603)(SPNAME(1, I), SPNAME(2, I), I = 1, NSP)
000046 603 FORMAT (12A6)
000046 READ(5,901)( R(I) , I=1,NR )
000061 DO 15 IND=1,3
000077 READ(5,901) PRSS(IND)
000087 DO 12 I=1,NSP
000072 READ(5,901) ( YSP( J,I,IND), J=1,NR )
000109 12 CONTINUE
000112 READ(5,901) ( WMTAB(I,IND), I=1,NR )
000125 READ(5,901) ( TC1( I,IND) ,I= 1,NR)
000141 15 CONTINUE
000143 READ(5,901) ( FGAMT(J),J=1,NR)
000156 READ(5,901)( ITAR(I), I=1,NT)
000171 DO 17 I=1,NSP
000173 READ (5,901) ( VSP(J,I),J=1,NT)
000206 17 CONTINUE
000211 DO 19 I=1,NSP
000217 READ (5,901) ( CPTAB(J,I), J=1,NT)
000225 19 CONTINUE
000230 READ(5,901) ( WM(I), I=1,NSP)
000242 READ(5,901) ( EPSI(I,1),I=1,NSP)
000255 READ(5,901) EPSOF
000263 READ(5,901) ( SIGMA(I,1), I=1,NSP)
000274 READ(5,901) SIGOF
000304 READ(5,901) WTMOL

```

```

000312      DO 20 I=1,2
000314      NTLCT=NTL(I)
000316      READ(5,902) ( TL(J,I) , PV(J,I),RHOL(J,I),CP(J,I), LAM(J,I),
1          J=1,NTLCT )
000346      20 CONTINUE
000350      DO 23 I=1,2
000352      NTFCT= NTF_M(I)

000354      READ(5,903) (TFILM(J,I),VVIS(J,I),KVAP(J,I),CPVAP(J,I),J=1,NTFCT)
000401      23 CONTINUE
000403      READ(5,904) LOOSE
000411      901 FORMAT( 7E10,4)
000411      902 FORMAT( 5E10,4)
000411      903 FORMAT( 4E10,4)
000411      904 FORMAT(110)
000411      5 CALL REED
000412      CALL JRG
000413      CALL RSET
000414      10 CALL PROP(NSP)
000416      CALL DERIV(NSP)
000420      CALL VAD4(DM,EM,1)
000422      CALL VAD4(DT,TLA,2)
000426      CALL VAD4(DV,V , 3)
000431      CALL SUM
000432      IF(4*INS) 40,35,40
000433      35 CALL PRINT
C          CONTROLS STEP PRINT AND STORES PLOT VALUES
C          NEXT TEST FOR TIME STOP
000434      IF( T - TSTOP) 40, 38, 3A
000437      38 IF(INPLOT ,NE, 0) GO TO 5
000440      CALL PLOTT
000441      GO TO 5
000442      40 CALL SHIFT
000443      GO TO 10
000444      12345 CALL EXIT
000445      END

```

```

      FUNCTION A(X)
000003 COMMON / ADDRHM / PAR1, PAR2, PAR3, PAR4, PAR5, PAR6
000003 IF (X .GT. PAR1) GO TO 1
000004 A = PAR2
000007 RETURN
000007 1 A = 3.1416 * (PAR3 - PAR4 * X) ** 2
000013 RETURN
000014 END

```

```

      FUNCTION AP(X)
000003 COMMON / ADDRHM / PAR1, PAR2, PAR3, PAR4, PAR5, PAR6
000003 IF (X .GT. PAR1) GO TO 1
000006 AP=0.
000006 RETURN
000007 1 AP = PAR5 * X - PAR6
000012 RETURN
000013 END

```

```

      SUBROUTINE BOIL(J,I)
000005 DIMENSION F2(80),NM(20),GN(10,20,12),TA(1000),BETA(20,2),RS(20,2)
1 FNUM(20,2),WW(20,2),DM(10,20,2),DT(10,20,2),V(10,20,2),
000005 2 TL(10,20,2),EM(10,20,2),FNUM(20,2)
      EQUIVALENCE (TA(30),P),(TA(392),RV),(TA(474),FKAV),
1 (TA(25),THOPI),(TA(475),CPA),(TA(482),GJR),(TA(264),TG),
2 (TA(647),BETA),(TA( 96),RS),(TA(433),FNUM),(RD(401),DM),
3 (DD(1201),DT),(BD(801),TL),(BD(1),EM),(RD(1601),V)
4, (TA(482), GJR) ,(TA(393),FNUM) ,(TA(216),WW)
      COMMON/EC,NM/R/BD/C/TA
000005 150 TR = T3L(?,I)
000005 WRITE(6,2000) J,I
000011 2000 FORMAT (1X, 5HODROP, 12, 13, 10HIS BOILING)
000021 K1 = 0
000022 W1 = AMINI(ABS(-DM(2, J, 1) * V(1, J, 1)), 1.E-6)
000043 RRS = RV*RS(J,I)**2
000050 COE = FNUM(J,I)*FKAV*RS(J,I)*THOPI/CPA
000062 COE = ABS(COE)
000063 152 W = COE * ALOG(1. + CPA * (TG - TR) / (ALM(TR, I) + GJR * (W1 / RR
15) ** 2))
000104 WR = ABS((W - W1) / W)
000110 K1 = K1 + 1
000112 IF (K1 .GT. 15) GO TO 154
000115 153 W1 = (W+W1)/2.0
000120 IF (WR .GT. .02) GO TO 152
000123 154 DM(1,J,I) = -W/V(1,J,I)
000137 DT(1,J,I) = 0.0
000143 TL(1,J,I) = TR
000151 BETA(J,I) = W/RS(J,I)/FNUM(J,I)
000164 W(J,I) = W
000170 RETURN
000170 END

```

```

0000001
0000005 10 CD = A-141(50), 27, RE=*(A-1.84)
0000014 RETURN
0000015 20 IF (RE-1.84) 30, 30, 40
0000020 30 CD = 0, 271-RE**, 217
0000025 RETURN
0000025 40 CD=2,
0000027 RETURN
0000027 END

```

```

0000003 SJ3ROUTINE DERIV(NSP)
0000003 COMMON /E/FC,NM/B/BD/C/TA
0000003 COMMON /LIVKA/ LOOSE
0000003 DIMENSION FC(80),NM(20), RD(10, 20, 12), TA(1000),NSET(2)
1, ENMP(2), KDISC(20,2), VD(20,2), EM(10,20,2),TL(10,20,2)
2,V(10,20,2), HS(20,2), WTMOL(2), PR(20,2), SC(20,2), RE(20,2)
3,REP(20,2), FNUH(20,2), FNUM(20,2),DM(10,20,2), DT(10,20,2)
4,DV(10,20,2), EMINT(20,2)
0000003 EQUIVALENCE (TA(46),NSET), (TA(479),ENMP), (TA(270),KDISC)
1,(TA(257),RAT),(TA(30),P),(TA(476),PA), (TA(475),CPA)
2,(TA(392),RV), (TA(311),VD), (TA(28),FTP1),(TA(29),THRD)
3,(RD(1),E4), (BD(401),TL), (BD(1601),V), (TA(96),RS)
4,(TA(25),R), (TA(48),WTMOL),(TA(478),U), (TA(391),RHOVS)
5,(TA(493),WTML), (TA(474),FKAV), (TA(473),DPOT),(TA(487),PR)
6,(TA(527),SC), (TA(567),RE), (TA(607),REP), (TA(393),FNUM)
7,(TA(433),FNUH),(BD(401),DM), (BD(1201),DT), (BD(2001),DV)
8,(TA(494),RHOG),(TA(264),TG), (TA(56),EMINT)

```

```

0000003 C
0000003 P2 = P*2,
0000005 120 DO 200 I=1,2
0000007 N=NSET(I)
0000011 ENMP(I)=0,
0000013 DO 200 J=1,N
0000014 KDISC(J,I) = 0
0000020 IF (EM(1,J, I)) 200, 200, 130
0000025 130 THR = (TG + TL(1,J,I))/2,
0000035 CALL VKSGAS (RAT,P,THR,VISB,FKB,CPB,NSP)
0000043 PA=A41V1(,99*P,PVAP(TL(1,J,I),I))
0000057 PA2P=PA/P2
0000061 DPA2P=1,-PA2P
0000063 CPA=CVAP(THR,I)
0000066 RH = RHO(TL(1,J,I),I)
0000074 RV = WTMOL(I)*P/R/TL(1,J,I)
0000107 VD(J,I) = (I - V(1,J,I))
0000120 RS(J,I) = (EM(1,J,I)/FTP1/RH)**THRD
0000134 RE(J,I) = RS(J,I) + RHOVS + ARS(VH(J,I))
0000147 WTMAY = PA2P*WTMOL(I) + DPA2P*WTML
0000153 VISAV = VISCV(THR,I)*PA2P + DPA2P*VISB
0000161 FKAV = PA2P*FKA(THR,I) + DPA2P*FKR
0000167 RHOAV = P*WTMAY/R/THR
0000173 CPAV = (PA2P*WTMOL(I)*CPA + DPA2P*WTML*CPB)/WTMAY

```

```

000202      REPR(J,1) = 2. * RS(J,1) * RHOAV * ABS(VD(J,1)) / VISAV
000215      PAIP = PA / 2.
000217      CALL DIFFU (HAT,P,TRR,PAIP,1,DFU,NSP)
000226      DPOY = DFU*P/TRR
000231      PR(J,1) = CPAV*VISAV/FKAV
000237      SC(J,1) = VISAV/RHOAV/DFU
000244      IF (PR(J,1) .GT. 0. .AND. SC(J,1) .GT. 0.) GO TO 979
000261 978  WRITE (6,797) PR(J,1),SC(J,1)
000277 797  FORMAT(140,18HSTATEMENT 978 PR =, F10.3,6H SC =,F10.3)
000277 979  RTRE = SORT(REP(J,1))
000305      FNJ4(J,1) = 2.0 + .6*SC(J,1)**THRD*RTRE
000321      FNJ4(J,1) = 2.0 + .6*PR(J,1)**THRD*RTRE
C      CHECK FOR ENTRANCE TO DISSOCIATION LOOP
000333      IF (LOSSE ,EQ, 0) GO TO 149
000335      GO TO (149, 160), I
000343 160 CONTINUE
000343      BEE = 2. * RS(J,1)/(FNUH(J,1) - 2.)
000354      CALL DVCHK(KNOW)
000356      GO TO (161, 162), KNOW
000365 161 BEE = 1.E30
000367 162  RL = RT( RS(J,1))
000375      IF(BEE- RL) 149,163, 163
000400 163  CALL TWFL (J,1)
000402      GO TO 156
000404 149  PMDP=0.99*3
000406      IF (PA .LT. PMDP) GO TO 155
000411 150  CALL BOIL (J,1)
000413      GO TO 156
000415 155  CALL VAPOR(J,1)
000417 156  DV(1, J, 1) = RHOG * .375 / RS(J, 1) * ARS(VD(J, 1)) / V(1, J, 1
1* VD(J, 1) / RH * CD(RE(J, 1))
000451 200  CONTINUE
000457      RETURN
000457      END

```

```

      FUNCTION FGAM(OFR)
000003  COMMON /OF/ R(15), NR /TRFGAM/ FGAMT(15)
000003  CALL LVGRIN (OFR, FGAM, R, FGAMT, OFDT, NR)
000007  RETURN
000011  END

```

```

SUBROUTINE LNGRIN (ARG,VARG,X,Y,DYDX,N)
000011      DIMENSION X(1),Y(1)
000011      C
000011      NV=N
000011      C
000011      IF(NV,NE,1) GO TO 1
000014      VARG=Y(1)
000014      DYDX=0.
000015      RETURN
000016      C
000016      1  XV=ARG
000017          IF(X(NV).LT,X(1)) GO TO 3
000023      DO 2 J=2,NV
000024          IF(X(J).GE.XV) GO TO 4
000027      2  CONTINUE
000032          GO TO 5
000032      3  DO 4 J=2,NV
000034          IF(X(J).LE.XV) GO TO 6
000037      4  CONTINUE
000042      5  J=NV
000044      6  I=J-1
000046          DYDX=(Y(J)-Y(I))/(X(J)-X(I))
000054          VARG=Y(I)+DYDX*(XV-X(I))
000061      C
000061      RETURN
000061      END

```

```

      SUBROUTINE LOGNRM(RM,SIG,N,RS)
C     COMPUTES RADII OF N DROPS ABOUT WHICH 1/N TH OF THE MASS IS
C     CENTERED IN THE LOGARITHMICO-NORMAL DISTRIBUTION WITH MASS-MEAN
C     RADIUS RM AND STANDARD DEVIATION LN SIG.  XP, THE INVERSE
C     PROBABILITY FUNCTION IS APPROXIMATED BY A RATIONAL FRACTION.
000007    DIMENSION RS(20)
000007    DEL = 1. / FLOAT(N)
000010    SIGLN = ALOG(SIG)
000015    P=-DEL/2.
000017    NP4 = N+4
000021    MED = (N+1)/2 + 4
000023    J = NP4
000025    DO 4 I = 1,NP4
000027    IF(I-2)10,15,11
000031    10 P=P+ 0.5*DEL
000034    GO TO 2
000035    11 IF(I-5) 15,15,20
000040    15 P=P+0.2*DEL
000043    GO TO 2
000044    20 P=P+DEL
000046    30 IF (I ,GT. MED) GO TO 5
000052    2 T = SURT(-ALOG(P + P))
000060    XP=1*(2.30753+.27061*T)/(1.+T*(.99229+.04481*T))
000072    ESIGX = EXP(SIGLN + XP)
000075    IF(I-3)4,3,40
000103    40 IF(I-5)4,49,50
000106    49 P = DEL/2.0
000110    GO TO 4
000111    50 J=N - T + 9
000114    3 RS(J)=P*ESIGX
000117    4 RS(I)=P/ESIGX
000124    5 RETURN
000125    END

```

```

      SUBROUTINE MASSET(EMO,RHO,RS,EMDOT,N,DROPN)
000011    DIMENSION EMO(20),RS(20),DROPN(20)
000011    CRHO=4.188790204*RHO
000012    FRAC = EMDOT / FLOAT(N)
C
000014    FRAC1 = FRAC/5.0
000016    NP4 = N+4
000020    DO 2 I =1,5
000021    EMO(I) = CRHO*RS(I)+3
000024    2 DROPN(I) = FRAC1/EMO(I)
000031    DO 5 I=5,NP4
000033    EMO(I)=CRHO*RS(I)+3
000036    5 DROPN(I)=FRAC/EMO(I)
000043    RETURN
000044    END

```

```

SUBROUTINE NADM(YP,Y,KK)
000006    DIMENSION YP(210), Y(210), FC(80), NM(20), WT(3),NST(2),NED(2)
000006    COMMON /E/ FC,NM
000006    EQUIVALENCE (FC(3),H), (FC(11),WT), (FC(10), E1), (FC(9), EMAX),
1 (FC(8), EMIN), (NM(2), INDR), (NM(7), NSW), (NM(4), MGAM),
2 (NM(3), MALP), (NM(17), NS1), (NM(19), NED)
C *****
C MGAM=-1,0,1 INDICATES PREDICTOR-RUNGE-KUTTA OR CORRECTORPHASE
C MALP-INDICATES PERT OF RUNGE KUTTA PHASE
C NSW- PRINT SWITCH FOR ERROR INDICATION
C E1 = CONTAINS MAXIMUM ERROR FOR EACH CYCLE
C YP = ADDRESS OF DERIVATIVE ARRAY
C Y = ADDRESS OF THE ORDINATE ARRAY
C *****
000006    IF (MGAM) 40, 10, 60
C *****
C THIS ROUTINE EMPLO'S A FOURTH ORDER RUNGE-KUTTA STARTER
C *****
000010    10 IF (MALP = 2) 20, 15, 15
000013    15 K = 4 - MALP
000015    DO 19 KL = 1,2
000017    LS = NST(KL)
000021    LE = NED(KL)
000023    DO 19 I = LS,LE,10
000025    J = I + K
000027    Y(I+9) = Y(J) + H*YP(I)
000034    19 CONTINUE
000040    GO TO 99
000041    20 DO 22 KL = 1,2
000043    LS = NST(KL)
000045    LE = NED(KL)
000047    DO 22 I = LS,LE,10
000051    Y(I+9) = Y(I+3) + H/6,*(YP(I)+2,*(YP(I+1)+YP(I+2)) + YP(I+3))
000064    22 CONTINUE
000070    GO TO 99
C *****
C ADAMS-BASHFORTH FIFTH ORDER PREDICTOR FORMULA
C *****
000070    40 DO 42 KL = 1,2
000072    LS = NST(KL)
000074    LE = NED(KL)
000076    DO 42 I = LS,LE,10
000100    Y(I+9) = Y(I) + H*(2,6442777777*YP(I) -3,8527777777*YP(I+1)
1 + 3,5333333333*YP(I+2) + 1,7694444444*YP(I+3)
2 + ,3445111111*YP(I+4))
000120    42 CONTINUE
000124    GO TO 99
C *****
C ADAMS-MOULTON FIFTH ORDER CORRECTOR FORMULA
C *****

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000125      60      DO 99 KL = 1,2
000127          LS = NST(KL)
000131          LE = NEN(KL)
000133          DO 99 I = LS,LE,10
000135              Y(I) = Y(I+1)+H*(,3486111111111+YP(I)+ ,897222222222+YP(I+1)-
                  1 0,346666666666+YP(I+2) + ,147222222222+YP(I+3)
                  2 = ,0263888888888+YP(I+4))
000154      62 FRR = ABS(Y(I) - Y(I+9))*WT(KK)
000162          IF(Y(I)) 70, 80, 70
000164      70 ER = ER/ ABS(Y(I))
000170      80 IF(ER - EMAX) 85, 95, 95
000173      85 IF(ER- EMIN) 98, 87, 87
          C *****
          C RELATIVE ERROR CHECK-BRANCH TO 99 INDICATES ERROR SMALLER THAN
          C ALLOWABLE ERROR=ADDING ONE TO INDR INDICATES VARIABLE WITHIN
          C ERROR ALLOWED
          C *****
000176      87 INDR = INDR + 1
000200          IF(NSW) 88, 98, 88
000201      88 WRITE ( 6,2) KK
000207      2 FORMAT(1H0, 8HVARIBLE, 13, 13HWITHIN LIMITS)
000207          GO TO 98
          C *****
          C ONE HUNDRED IS SUBTRACTED FOR EACH VARIABLE LARGER THAN THE
          C ERROR LIMITS
          C *****
000212      95 INDR = INDR - 100
000214          IF(NSW) 97, 98, 97
000215      97 WRITE( 6,3) KK
000223      3 FORMAT(1H0, 8HVARIBLE, 14, 20HOUTSIDE ERROR LIMITS)
          C *****
          C E1 CONTAINS MAXIMUM ERROR OCCURING DURING THE CYCLE
          C *****
000223      98 E1 = MAX1(ER,E1)
000235      99 RETURN
000236          END

```

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000002      SUBROUTINE DNG
000002      DIMENSION FC(80), NM(20), W(3), NSET(2), NST(2), NED(2), TA(100)
000002      COMMON /E/ FC, NM, W, TA
000002      EQUIVALENCE (FC(1),T), (FC(2),RKT), (FC(3),H), (FC(4),HO),
1 (FC(5),HMIN), (FC(6),HMAX), (FC(7),HZD2), (FC(8),EMIN),
2 (FC(9),EMAX), (FC(11),W), (FC(10),E1),
3 (NM(1),IM), (NM(2),INDR), (NM(3),HALP), (NM(4),MGAM),
4 (NM(5),MPTN), (NM(6),MPTS), (NM(7),NSW), (NM(8),NCOU),
5 (NM(9),MP), (NM(10),NV), (NM(11),NO)
6, (TA(46),NSET), (NM(17),NST), (NM(19),NED)
C      *****
C      DESCRIPTION OF THE LISTED VARIABLES
C      T - THIS CELL CONTAINS CURRENT INTEGRATION TIME
C      RKT - START TIME OR PREVIOUS BEGINING OF RK TIME
C      H - CURRENTLY USED STEP SIZE IN COMPUTING
C      HO - STORED STEP SIZE
C      HZD2 - HALF OF STORED STEP SIZE
C      HMIN - MINIMUM STEP SIZE
C      HMAX - MAXIMUM ALLOWABLE STEP
C      EMIN - EMAX MIN AND MAX ALLOWABLE ERROR
C      W - ARRAY OF WEIGHTS TO WEIGHT ERROR CONSIDERATION
C      IM - NO OF GOOD POINTS FROM R,K START
C      INDR - INDICATOR FOR ERROR OUTSIDE OR WITHIN MIN MAX TOLERANCE
C      HALP - COUNTER FOR R,K INTERMEDIATE POINTS
C      MGAM - PHASE INDICATOR =1,PREDICTOR,0,R,K 1, CORRECTOR
C      MPTN - PRINT COUNTER, CURRENT
C      MPTS - TOTAL NO OF POINTS IN PRINT INTERVAL
C      NSW - PRINT INDICATOR IN NADM ROUTINE
C      NCOU - TOTAL NO OF COMPUTED POINTS DURING INTEGRATION CYCLE
C      MP - POWER OF 2 VARIATION FROM HMIN TO HMAX
C      HMAX, MP, NO, NSW, NV AND W(I) MUST EITHER BE READ INTO CORE OR
C      INITIALIZED BY AN ADDITIONAL ROUTINE
C      *****
000002      HMIN = HMAX/2.**MP
000007      HO = HMIN
000010      HZD2 = HO/2.0
000012      H = HZD2
000013      RKT = T
000014      E1 = 0.0
C      *****
C      FIXED POINT INITIALIZATIONS
C      *****
000015      IM = 0
000016      HALP = 4
000017      MGAM = 0
000020      MPTN = 0
000021      MPTS = NO*2.**MP
000026      INDR = 0
000027      NCOU = 0
000030      NST(1) = 1
000031      NST(2) = 201
000032      NED(1) = (NSET(1)+3)*10+1
000036      NED(2) = (NSET(2) + 3)*10 + 201
C      *****
C      MPTN SET TO ZERO TO PRINT INITIAL CONDITIONS
C      *****
000042      RETURN
000042      END

```

```

COMMON /E/FE,FM/8/B/7/C/TA/EP/48,A
COMMON /PRCT/ XPR[12]
LOGICAL LUT[12]
DIMENSION AR(150),AU(100,90),TA(1000),FC(80),AM(20),RD(10,20,12)
1 ,ENMP(2),TA(2),EMDOT(2),CA(20,2),RS(20,2),V(10,20,2),BETA(20,2)
2 ,VD(20,2),VDOUT(20,2),NSET(2),EM(10,20,2),DM(10,20,2)
3 ,EMINT(20,2)
4 ,TITLE(24)
5 ,YL(10,20,2),          KDISC(20,2)
6 ,DNT(2),RE(20,2)
7 ,S(12,2),XM(3),XTAB(20),YTAB(20),TM(2),RB(6,3),XL(3)
8 ,DVS(6,3),RED(6,3),DRAG(3)
000002 EQUIVALENCE (FC(1),X),(TA(33),AXMIN),(TA(257),RAT),(TA(35),
1 OFSTOC),(TA(479),ENMP),(TA(258),EMD),(TA(50),FA),(TA(486),SDSPD)
2 ,(TA(36),EMDOT),(TA(96),RS),          (TA(136),DN),(RD(1401),V),
3 (TA(647),BETA),(TA(311),VD),(TA(478),U),(TA(264),TG),(TA(265),
4 TSTG),(TA(38),P),(TA(266),PD),(TA(405),EMACH),(TA(46),NSET),
5 (RD(1),EM),(TA(56),EMIN7),(RD(401),DM),(TA(1),TITLE)
6 ,(RD(801),YL),(TA(270),KDISC),(TA(52),DNT)
7 ,(TA(391),RHVS),(TA(481),PHI),(NM(13),IPLOT),(TA(29),THRD)
8 ,(FC(3),DX),(NM(12),JZ),(NM(14),IRZ),(TA(567),PE)
9 ,(TA(484),RHOG),(TA(486),SDSPD)

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```

C
000002 AX = A(X)
000005 PHIP = -(ENMP(1) + ENMP(2))
000007 RAN = SQRT (AX/3,14159)
000014 ETA = AX / AXMIN
000016 IF(RAT - OFSTOC) 31,31,32
000020 31 RCOMB = -ENMP(1) * (1./OFSTOC + 1.) / EMD
000025 FCOMB = FA(1) * (1. + 1./OFSTOC) / EMD
000030 GO TO 33
000030 32 RCOMB = -ENMP(2) * (OFSTOC + 1.) / EMD
000034 FCOMB = FA(2) * (1. + OFSTOC) / EMD
000036 33 RLCOMB = RCOMB + RAN / ETA
000041 REC=RHVS*SDSPD
000043 FVAP1=FA(1)/EMDOT(1)
000045 FVAP2=FA(2)/EMDOT(2)
000047 FVAP = (FA(1) + FA(2))/EMD
000051 RVAP1=-ENMP(1)/EMDOT(1)
000053 RVAP2=-ENMP(2)/EMDOT(2)
000055 RVAP = PHIP/EMD

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```

C
000056 ITEST = ITEST + IPLOT * IPLOT - 187
000058 IF (ITEST) 324, 324, 328
000064 324 CONTINUE
000064 GO TO 1
000065 328 AB(JZ) = X
000070 AU(JZ,1) = RAT
000072 AU(JZ,2) = FVAP2
000073 AU(JZ,3) = FVAP1
000075 AU(JZ,4) = FVAP
000076 AU(JZ,5) = RVAP2
000100 AU(JZ,6) = RVAP1
000101 AU(JZ,7) = RVAP
000103 AU(JZ,8) = EMACH

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000104      AU(JZ,49) = J
000106      AU(JZ,50) = FCOMR
000107      AU(JZ,51) = WCOMR
000111      AU(JZ,19) = R
000112      AU(JZ,25) = RO
000114      AU(JZ,39) = TG
000116      AU(JZ,48) = TSTG
000117      JZ = JZ + 1
000120      1 CONTINUE
000120      329 1BZ = 13Z + 1

C
000122      ILLIT = MOD(1BZ - 1, KPRINT) ,NE. 1 .AND. KPRINT ,NE. 1
000133      IF (ILLIT) GO TO 60
000134      WRITE (5, 330) (TITLE(I), I = 1, 24)
000146      330 FORMAT (1H1/ (1H , 10A6))
000146      WRITE(5,340)X,U,TG,TSTG,P,PO,RAT,EMACH
000172      340 FORMAT(3H0X=F6,3,4H U=F7,1,4H T=F5,0,4H TO=F5,0,4H P=F7,2,
1          4H PO=F7,2,6H O/F=F7,3,7H NACH=F5,3)
000172      WRITE(5,350)FVAP1,FVAP2,FVAP ,FCOMR
000206      350 FORMAT(26H VAPORIZED FRACTION          OF9,6,4H FF9,4,7H BOTHFF9,6
1          ,3X,44COM3,F9,6)
000206      WRITE(5,360)RVAP1,RVAP2,RVAP ,RCOMR
000222      360 FORMAT(26H VAPORIZATION RATE/IN      OF9,6,4H FF9,6,7H BOTHFF9,6
1          ,3X,44COM3,F9,6)

C
000222      WRITE(5,370)
000226      370 FORMAT(70HOOXIDIZER DROPS   R(MIL)  MASS(LB)  V(IN/SEC) U=V/A  TEM
1P      NUMBER )
000226      60 I = 1
000227      N=NSET(I)
000232      DO 380 J=1,N
000233      VDOUT(J,I) = VN(J,I)/SDSPD
000242      375 RPD = OM(1,J,I)/EMINT(J,I)
000253      377 FRACT = (EMINT(J,I) - EM(1,J,I))/EMINT(J,I)
000265      GO TO 2
000265      379 MVM = J + 8
000267      AU(JZ-1,MVM) = RS(J,I)*1,F+3
000277      MZM = J + 28
000300      AU(JZ-1,MZM) = ABS (VDOUT(J,I))
000310      MZN = J + 49
000312      AU(JZ-1,MZN) = V(1,J,I)
000322      2 CONTINUE
000322      IF (ILLIT) GO TO 380
000324      WRITE(5,390)J,RS(J,I),EM(1,J,I),V(1,J,I),VDOUT(J,I),TL(1,J,I),
1      VN(J,I), FRACT, RPD
000375      390 FORMAT(13X,I2,3PF9,4,0PE13.5 ,      F5,0,F9,4,F8,2,E11,3,4X,
1      E11,3,4X:E11,3)
000373      380 CONTINUE

C
000376      IF (ILLIT) GO TO 61
000377      WRITE(5,400)
000403      400 FORMAT(12HOFUEL DROPS   )
000403      51 I = 2
000404      N=NSET(I)
000407      DO 410 J=1,N
000410      VDOUT(J,I) = VN(J,I)/SDSPD
000417      405 RPD = OM(1,J,I)/EMINT(J,I)
000430      407 FRACT = (EMINT(J,I) - EM(1,J,I))/EMINT(J,I)

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000448      DO 10 J=1,2
000449      DO 10 K=1,12
000450      A(JZ-1,MZM)*RS(J,I)*1.E+3
000451      MZM=J+3*
000452      A(JZ-1,MZM)*ABS(VDOU(J,I))
000453      MZM=J+99
000454      A(JZ-1,MZM)=V(1,J,I)
000455      CONTINUE
000456      IF (ILLI) GO TO 410
000457      WRITE (6,391) J,RS(J,I),FM(1,J,I),V(1,J,I),VDOU(J,I),
000501      1 TL(1,J,I),DN(J,I),FRACT,RPD,KDISC(J,I)
000554      391 FORMAT(13X,I2,3PF9.4,0PE13.5,1F5.0,F9.4,F8.2,E11.3,
000554      1E11.3,4X,E11.3,I15)
000554      410 CONTINUE

C
000557      DO 10 I=1,2
000560      DO 10 K=1,12
000561      10 S(K,I)=0.
000571      DO 12 I=1,2
000572      N=VSET(I)
000574      DO 12 J=1,N
000576      IF(V(1,J,I).LE.0.) GO TO 12
000603      S(1,I)=S(1,I)+DN(J,I)/V(1,J,I)
000616      S(2,I)=S(2,I)+DN(J,I)/V(1,J,I)*EM(1,J,I)
000635      S(3,I)=S(3,I)+DN(J,I)/V(1,J,I)*RS(J,I)
000652      S(4,I)=S(4,I)+DN(J,I)/V(1,J,I)*RS(J,I)**2
000666      S(5,I)=S(5,I)+DN(J,I)/V(1,J,I)*RS(J,I)**3
000703      S(6,I)=S(6,I)+DN(J,I)*DM(1,J,I)
000714      S(7,I)=S(7,I)+DN(J,I)*DM(1,J,I)*RS(J,I)**2
000730      S(8,I)=S(8,I)+DN(J,I)/V(1,J,I)*BETA(J,I)*RS(J,I)
000746      S(9,I)=S(9,I)+DN(J,I)/V(1,J,I)*BETA(J,I)*RS(J,I)**1.5
000767      S(10,I)=S(10,I)+CD(RH(J,I))*DN(J,I)*EM(1,J,I)
001017      1 /RHO(TL(1,J,I),I)/V(1,J,I)/RS(J,I)
001024      1.2 CONTINUE
001024      XM(1)=S(2,1)/S(1,1)
001026      XM(2)=S(2,2)/S(1,2)
001030      XM(3)=(S(2,1)+S(2,2))/(S(1,1)+S(1,2))
001032      DO 14 I=1,2
001034      N=VSET(I)
001036      DO 13 J=1,N
001040      YTAB(J)=TL(1,J,I)
001046      13 XTAB(J)=EM(1,J,I)
001056      CALL LUGRIN(XM(1),TM(1),XTAB,YTAB,DYDX,N)
001063      14 RH(1,I)=(.238733+XM(1)/RHO(TM(1),I))*3333333333
001101      RH03=(RHO(TM(1),I)*(1.-FVAP1)*EMDOT(1)+RHO(TM(2),I)*(1.-FVAP2)*EMDOT(2))
001124      1 EMDOT(2))/(1.-FVAP1)*EMDOT(1)+(1.-FVAP2)*EMDOT(2))
001124      RB(1,3)=(.238733+XM(3)/RHO3)*3333333333
001131      DO 15 I=1,2
001133      RB(2,I)=(S(5,I)/S(1,I))*3333333333
001146      RB(3,I)=SQRT(S(5,I)/S(3,I))
001160      RB(4,I)=S(5,I)/S(4,I)
001167      RB(5,I)=SQRT(S(7,I)/S(6,I))
001177      RB(6,I)=(S(9,I)/S(8,I))*2
001206      15 CONTINUE
001210      RB(2,3)=(S(5,1)+S(5,2))/(S(1,1)+S(1,2))*3333333333
001217      RB(3,3)=SQRT((S(5,1)+S(5,2))/(S(3,1)+S(3,2)))
001226      RB(4,3)=(S(5,1)+S(5,2))/(S(4,1)+S(4,2))
001232      RB(5,3)=SQRT((S(7,1)+S(7,2))/(S(6,1)+S(6,2)))

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001240      RE(6,3) = ((S(9,1)+S(9,2))/(S(8,1)+S(8,2)))**2
C
001244      RAVE = RAV/ETA
001246      XL(1) = RVAP1*RAVE
001247      XL(2) = RVAP2*RAVE
001251      XL(3) = RVAP*RAVE
001252      DO 17 I=1,2
001254      N=VSET(I)
001256      DO 17 K=1,5
001260      CALL LVGRIN(RH(K,I),DVR(K,I),RS,VDOUT,DYDX,N)
001270 17 CONTINUE
001274      DO 18 K=1,5
001276      DVR(K,3) = (ABS(DVR(K,1))*(1,-FVAP1)*EMDOT(1)+
1          ABS(DVR(K,2))*(1,-FVAP2)*EMDOT(2))/
2          ((1,-FVAP1)*EMDOT(1)+(1,-FVAP2)*EMDOT(2))
001322 18 CONTINUE
001324      DO 19 I=1,3
001326      DO 19 K=1,5
001327 19 RED(K,I) = RB(K,I)*REC
001342      DC = .375*RAVE*ETA/AX
001346      DRAG(1) = S(10,1)*DC
001347      DRAG(2) = S(10,2)*DC
001351      DRAG(3) = (S(10,1)+S(10,2))*DC
C
001353      GO TO 4
001353 20 AU(JZ-1,82) = RED(6,1)
001355      AU(JZ-1,83) = RED(6,2)
001357      AU(JZ-1,84) = RED(6,3)
001360      AU(JZ-1,85) = RL COMB
001362      AU(JZ-1,86) = XL(3)
001363      AU(JZ-1,87) = ABS(DVR(6,1))
001366      AU(JZ-1,88) = ABS(DVR(6,2))
001370      AU(JZ-1,89) = ABS(DVR(6,3))
001373      4 CONTINUE
C
001373      IF (ILLIT) GO TO 62
001375      WRITE (6,90)
001400 90 FORMAT(1H0,///8X,6H RADIUS,15X,8HOXIDIZER,22X,4HFUEL,26X,5HTOTAL,/,
1 24X,14R,8X,2HDV,8X,3HRED,8X,14R,8X,2HDV,8X,3HRED,AX,14R,8X,
2 2HDV,8X,3HRED,/)
001400      WRITE (6,91) ((RH(K,I),DVR(K,I),RED(K,I),I=1,3),K=1,5)
001430 91 FORMAT(20H MASS MEAN DROP,3(3PF10,4,0PF10,4,F10,1),//,
1 20H VOL, MEAN DROP,3(3PF10,4,0PF10,4,F10,1),//,
2 20H VOL, DIAM, MEAN,3(3PF10,4,0PF10,4,F10,1),//,
3 20H VOL, SURFACE MEAN,3(3PF10,4,0PF10,4,F10,1),//,
4 20H MASS LOSS MEAN,3(3PF10,4,0PF10,4,F10,1),//,
5 20H STABILITY MEAN,3(3PF10,4,0PF10,4,F10,1),//)
001430      WRITE (6,92) (XL(I),I=1,3),RL COMB,(DRAG(I),I=1,3)
001452 92 FORMAT(///,31X,8HOXIDIZER,4X,4HFUEL,5X,5HTOTAL,4X,8HCOMBUST,/,
1 ,23H BURNING RATE PARAMETER,7X,4F10,6,/,
2 ,15H DRAG PARAMETER,15X,3F10,2,/)
001452      WRITE (6,55)DX
001460 55 FORMAT(18H0INTEGRATION STEP=F7.4)
C
001460 52 DA=RAN/RH03/SDSPD/AX/,592
001465      DAOX=DA*EMDOT(1)*RVAP1
001467      DAFU=DA*EMDOT(2)*RVAP2
001471      DATOT=DA*(EMDOT(1)+EMDOT(2))*RVAP

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001474      DACO=DA*(EMDOT(1)+EMDOT(2))+RCOMR
001477      BROX=RAY*RVAP1+EMDOT(1)/AX      *1.4389/1.0601
001503      BRFU=RAY*RVAP2+EMDOT(2)/AX      *1.4389/1.0601
001506      BRTO=RAY*RVAP*(EMDOT(1)+EMDOT(2))/AX*1.4389/1.0601
001514      BRCO=RAY*RCOMH*(EMDOT(1)+EMDOT(2))/AX*1.4389/1.0601
001521      IF (ILLIT) GO TO 63
001523      WRITE(5,93) DAOX,DAFU,DATOT,DACO,BROX,BRFU,BRTO,BRFO
001546      93  FORMAT(///,30X,4F10,2,/)
001546      63  RETURN
001547      END

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SUBROUTINE PROG(NSP)
COMMON /E/FC,NH/B/BD/C/TA
DIMENSION PC(80), NH(20), RD(10, 20, 12), TA(1000)
EQUIVALENCE (TA(30), P), (TA(257), RAT), (TA(265), TSTG)
1, (TA(264), TG), (TA(266), PO), (TA(267), VIS), (TA(268), FKG)
2, (TA(269), CPG), (TA(391), RHQVS), (TA(483), WTML)
3, (TA(484), RHOG), (TA(485), EMACH), (TA(486), SDSPD), (TA(259), GAM1)
4, (TA(260), GAM2), (TA(261), GAM3), (TA(262), GAM4), (TA(263), GAM5)
5, (TA(25), R), (TA(27), G), (TA(478), U)

C
C *****
C
C ***** OBTAIN STAGNATION TEMP, TSTG, AND THE DERIVATIVE OF TEMP
C WITH RESPECT TO O/F, TGOD
C
000003      CALL TGINT (RAT,P,TSTG,TGOD)
C
C ***** OBTAIN MOLECULAR WEIGHT OF PRODUCTS AS FUNCTION O/F
000006      CALL WTINT (RAT,P,WTML,WTMLDT)
C
000011      RG=R/WTML
000013      GAM = FGAM(RAT)
000016      GAM1=GAM-1,
000020      GAM2=GAM1/2,
000022      GAM3=GAM2/GAM
000024      GAM4=GAM1/GAM
000025      GAM5 = GAM/GAM1
000027      U2=U*U
C ***** CALCULATE STATIC TEMP, FROM TOTAL TEMP, AND GAMMA
000030      TG=TSTG*(1.-GAM3*U2/RG/TSTG/G)
C
C
C ***** CALCULATE GAS DENSITY
000036      RHOG=P/RG/TG
C
C ***** CALCULATE VISCOSITY, THERMAL CONDUCTIVITY, AND SPECIFIC HEAT
C OF GAS AS FUNCTION OF P, TG, O/F
000041      CALL VISCAS (RAT,P,TG,VIS,FKG,CPG,NSP)
C
000050      PHQVS=P*RG/VIS 2,
000053      RHOE=,375*RHOG
C
C CALCULATE TOTAL PRESSURE
000054      RO = P*(TSTG/TG)**GAM5
000062      RR = RG - TG
000064      SDSPD = SQRT(RR * GAM * G)
000071      EMACH=J/SDSPD
000072      IF(EMACH .GT. 1.0) STOP
000077      EMACH2 = EMACH**2
C
000101      RETURN
000101      END

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SUBROUTINE REED
000602 DIMENSION FC(80), NM(20), BD(10,20,12),TA(1000),TITLE(24)
000609 COMMON /NLV/ LINES, LNS
000602 COMMON /E/ FC,NM /B/BD /C/TA
000602 COMMON / ADDRPM / PAR1, PAR2, PAR3, PAR4, PAR5, PAR6
000602 COMMON /PRVT/ KPRINT
000602 COMMON /PRPS/ PRPSYS(4) /SPEC/ NSP, SPNAME(2, 15) /OF/ R(15), NR
1/DTL/ NTL(2) /DTFLM/ NTFLM(2) /BT/ NT /PRSSR/ PRSS(3) /CHPTAR/ VSP
2(15, 15, 3) /WTH/ WMTAR(15, 3) /TQI/TC1(15, 3) /YBFGAM/ FGAMT(15)
3/TABT/ TTA3(15) /VKSGS/ VSP(15, 15), CPTAR(15, 15) /MW/ WM(15)
4/DIFFUS/ EPSI(15, 2), SIGMA(15, 2), EPSOF(2), SIGOF(2) /TLX/ TL(15
5, 2) /PVY/ PV(15, 2) /RHOY/ RHOL(15, 2) /CPY/ CP(15, 2) /LAMY/
6LAM(15, 2) /TFLMX/ TFLM(15, 2) /VISCY/ VVIS(15, 2) /KVAPV/ KVAP
7(15, 2) /CPVRY/ CPVAP(15, 2) /LINKA/ LOOSE
000602 EQUIVALENCE (TA(1), TITLE(1)), (TA(25),RR), (TA(26), TWOPI)
1, (TA(27), G), (TA(28), FTP1), (TA(29), THRD), (FC(1), T)
2, (FC( 6), HMAX), (FC(8),EMIN), (FC(9),EMAX), (FC(14),TSTOP)
3, (NM(7), NSW), (NM(9), MP), (NM(11), NO), (NM(10),NV)
4, (TA(30), P), (TA(31), RATMN), (TA(32),RATMX), (TA(33),AXMIN)
5, (TA(34), AXMAX), (TA(35), OFSTOC), (TA(38), V), (TA(36),EMDOT)
6, (TA(40),TLL), (TA(42), RM), (TA(44), SIG), (TA(46), NSET)
7, (TA(48), WTHOL), (FC(11), W), (TA(478), U), (TA(482),GJR)
8, (NM(15),NPLOT)
000602 DIMENSION V(2),EMDOT(2),TLL(2), RM(2), SIG(2), NSET(2)
1, WTHOL(2), W(3)
000602 RR= 18340,
000604 TWOPI = 6.2831853
000605 G = 386.4
000607 FTP1 = 4.1587902
000610 THRD = .33338333
000612 GJR = 9.78E-30
000613 READ (5, 1) (TITLE(I), I = 1, 24)
000625 1 FORMAT (10A6)
000625 WRITE (5, 700) (TITLE(I), I = 1, 24)
000637 700 FORMAT (1H1,20A6/ (1X10A6))
000637 READ(5,5) T, HMAX, EMIN, EMAX, TSTOP, II
000657 5 FORMAT (7E10,6)
000657 READ (3,8) NSW, MP, NO, NPLOT, KPRINT
000675 8 FORMAT(6I10)
000675 READ (3,9) P, RATMN, RATMX, AXMIN, AXMAX, OFSTOC
000615 READ (3,9) (EMDOT(I), V(I),TLL(I), RM(I),SIG(I),NSET(I),I=1,2)
0006146 9 FORMAT(5E10,6,I10)
0006146 READ (5, 6000) PAR1, PAR2, PAR3, PAR4, PAR5, PAR6
0006166 6000 FORMAT (5F9,0)
0006166 W(1) = 1.0
0006170 W(2) = 1.0
0006171 W(3) = 1.0
0006172 NM(13)=1
0006173 NM(12)=1
0006174 NM(14)=1
0006175 WRITE (6, 602) PRPSYS
0006202 602 FORMAT (16A0)INPUT FOR OX = 2A6, 9H, FUEL = 2A6/)
0006202 WRITE (5, 70) NR, NSP, NTL, NTFLM, NT
0006220 70 FORMAT ( 24H NUMBER OF O/F RATIOS = 12/ 21H NUM
19ER OF SPECIES = 12/ 38H NUMBER OF LIQUID TEMPERATURES (OX) = 12/
240H NUMBER OF LIQUID TEMPERATURES (FUEL) = 12/ 38H NUMBER OF FILM
3TEMPERATURES (OX) = 12/ 38H NUMBER OF FILM TEMPERATURES (FUEL) = 1

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42/ 36H NUMBER OF GAS PHASE TEMPERATURES = 12/)
000220      LINES = 14
000221      NTL1 = VTL(1)
000223      NTL2 = VTL(2)
000224      NTFLM1 = NTFLM(1)
000226      NTFLM2 = NTFLM(2)
000227      WRITE (6, 701)
000233      701 FORMAT (11+ O/F RATIOS/)
000233      WRITE (6, 702) (R(I), I = 1, NR)
000246      702 FORMAT (12X6E20,8)
000246      IF (NR .GT. 12) LNS = 5
000252      IF (NR .LE. 12) LNS = 4
000255      IF (NR .LE. 6) LNS = 3
000260      LINES = LINES + LNS
000262      DO 15 IND=1,3
000263      WRITE (6, 703) IND, PRSS (IND)
000273      703 FORMAT (4H0PC(11, 4H) = E15,8, 5H PSIA/)
000273      LINES = LINES + 3
000275      IF (LINES .GE. 50) WRITE (6, 704)
000303      704 FORMAT (1H1)
000303      IF (LINES .GE. 50) LINES = 0
000307      WRITE (6, 705)
000313      705 FORMAT (23+ SPECIES MOLE FRACTIONS/)
000313      LINES = LINES + 1
000315      IF (LINES .GE. 50) WRITE (6, 704)
000323      IF (LINES .GE. 50) LINES = 0
000327      DO 12 I=1,VSP
000331      WRITE (6, 7020) SPNAME(1, I), SPNAME(2, I), (YSP(J, I, IND), J = 1,
1, VR)
000356      7020 FORMAT (1H0246, E19,8, 5E20,8/ (12X6F20,8))
000356      IF (NR .GT. 12) LNS = 4
000362      IF (NR .LE. 12) LNS = 3
000365      IF (NR .LE. 6) LNS = 2
000370      LINES = LINES + LNS
000372      IF (LINES .GE. 50) WRITE (6, 704)
000400      12 IF (LINES .GE. 50) LINES = 0
000407      WRITE (6, 706)
000412      706 FORMAT (18+0AVE, GAS MOL. WT./)
000412      WRITE (6, 702) (WMTAB(I, IND), I = 1, NR)
000427      CALL PAGER(NR)
000431      WRITE (6, 707)
000435      707 FORMAT (32+0EQUILIBRIUM GAS TEMP, (RANKINE)/)
000435      WRITE (6, 702) (TC1(I, IND), I = 1, NR)
000452      15 CALL PAGER(NR)
000456      WRITE (6, 708)
000462      708 FORMAT (6H0GAMMA/)
000462      WRITE (6, 702) (FGAMT(J), J = 1, NR)
000475      CALL PAGER(NR)
000477      WRITE (6, 709)
000503      709 FORMAT (26+0GAS PHASE TEMP, (RANKINE)/)
000503      WRITE (6, 702) (TTAB(I), I = 1, NT)
000516      CALL PAGER(NT)
000520      WRITE (6, 710)
000524      710 FORMAT (51+0GAS PHASE VISC. ((LBS MASS / IN - SEC) X 10 ** +6)/)
000524      LINES = LINES + 3
000526      IF (LINES .GE. 50) WRITE (6, 704)
000534      IF (LINES .GE. 50) LINES = 0
000540      DO 17 I=1,VSP

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000542      WRITE (5, 702) (VSP(J, 1), J = 1, NT)
000556      17 CALL P3R(NT)
000563      WRITE (5, 711)
000564      711 FORMAT (3440GAS PHASE CP (BTU / MOLE - DEG R)/)
000566      LINES = LINES + 3
000570      IF (LINES .GE. 50) WRITE (6, 704)
000574      IF (LINES .GE. 50) LINES = 0
000402      DO 19 I=1, NSP
000404      WRITE (5, 702) (CPTAR(J, I), J = 1, NT)
000620      19 CALL P3R(NT)
000625      WRITE (5, 712)
000630      712 FORMAT (1740SPECIES MOL. WT./)
000630      WRITE (5, 702) (WM(I), I = 1, NSP)
000643      CALL PAGER(NSP)
000645      WRITE (5, 713)
000651      713 FORMAT (3540SPECIES INTERACTION ENERGY (DEG K)/)
000651      WRITE (5, 702) (EPSI(I, 1), I = 1, NSP)
000664      CALL PAGER(NSP)
000666      WRITE (5, 714)
000672      714 FORMAT (3540PROP. INTERACTION ENERGY (DEG K)/)
000672      WRITE (5, 702) EPSOF
000700      CALL PAGER(2)
000702      WRITE (5, 715)
000706      715 FORMAT (3040SPECIES MOL. DIA. (ANGSTROMS)/)
000706      WRITE (5, 702) (SIGMA(I, 1), I = 1, NSP)
000721      CALL PAGER(NSP)
000723      WRITE (5, 716)
000727      716 FORMAT (2840PROP. MOL. DIA. (ANGSTROMS)/)
000727      WRITE (5, 702) SIGOF
000735      CALL PAGER(2)
000737      WRITE (5, 717)
000743      717 FORMAT (1540PROP. MOL. WT./)
000743      WRITE (5, 702) WTMOL
000751      CALL PAGER(2)
000753      WRITE (5, 718)
000757      718 FORMAT (2540OX, LIQ. TEMP. (RANKINE)/)
000757      WRITE (5, 702) (TL(J, 1), J = 1, NTL1)
000772      CALL PAGER(NTL1)
000774      WRITE (5, 720)
001000      720 FORMAT (2540OX, VAPOUR PRESS. (PSIA)/)
001000      WRITE (5, 702) (PV(J, 1), J = 1, NTL1)
001013      CALL PAGER(NTL1)
001015      WRITE (5, 722)
001021      722 FORMAT (3840OX, LIQ. DENSITY (LBS MASS / CU INCH)/)
001021      WRITE (5, 702) (RHOL(J, 1), J = 1, NTL1)
001034      CALL PAGER(NTL1)
001036      WRITE (5, 724)
001042      724 FORMAT (3640OX, LIQ. CP (BTU / LB MASS - DEG R)/)
001042      WRITE (5, 702) (CP(J, 1), J = 1, NTL1)
001055      CALL PAGER(NTL1)
001057      WRITE (5, 726)
001063      726 FORMAT (3340OX, HEAT OF VAP. (BTU / LB MASS)/)
001063      WRITE (5, 702) (LAM(J, 1), J = 1, NTL1)
001076      CALL PAGER(NTL1)
001100      WRITE (5, 719)
001104      719 FORMAT (2640FUEL LIQ. TEMP. (RANKINE)/)
001104      WRITE (5, 702) (TL(J, 2), J = 1, NTL2)
001117      CALL PAGER(NTL2)

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001121      WRITE (6, 721)
001125      721 FORMAT (2040FUEL VAPOUR PRESS, (PSIA)/)
001129      WRITE (6, 702) (PV(J, 2), J = 1, NTL2)
001140      CALL PAGER(NTL2)
001142      WRITE (6, 723)
001146      723 FORMAT (3940FUEL LIQ. DENSITY (LBS MASS / CU INCH)/)
001146      WRITE (6, 702) (VHOL(J, 2), J = 1, NTL2)
001161      CALL PAGER(NTL2)
001163      WRITE (6, 725)
001167      725 FORMAT (3740FUEL LIQ. CP (BTU / LB MASS - DEG R)/)
001167      WRITE (6, 702) (CP(J, 2), J = 1, NTL2)
001202      CALL PAGER(NTL2)
001204      WRITE (6, 727)
001210      727 FORMAT (3440FUEL HEAT OF VAP. (BTU / LB MASS)/)
001210      WRITE (6, 702) (LAM(J, 2), J = 1, NTL2)
001223      CALL PAGER(NTL2)
001225      WRITE (6, 728)
001231      728 FORMAT (2740OX, VAPOUR TEMP. (RANKINE)/)
001231      WRITE (6, 702) (TFILM(J, 1), J = 1, NTFLM1)
001244      CALL PAGER(NTFLM1)
001246      WRITE (6, 730)
001252      730 FORMAT (5240OX, VAPOUR VISC. ((LBS MASS / IN - SEC) X 10 ** +6)/)
001252      WRITE (6, 702) (VVIS(J, 1), J = 1, NTFLM1)
001265      CALL PAGER(NTFLM1)
001267      WRITE (6, 732)
001273      732 FORMAT (6240OX, VAPOUR CONDUCTIVITY ((BTU / IN - SEC - DEG R) X 10
001273      1 ** +6)/)
001273      WRITE (6, 702) (KVAP(J, 1), J = 1, NTFLM1)
001306      CALL PAGER(NTFLM1)
001310      WRITE (6, 734)
001314      734 FORMAT (3840OX, VAPOUR CP (BTU / LB MASS - DEG R)/)
001314      WRITE (6, 702) (CPVAP(J, 1), J = 1, NTFLM1)
001327      CALL PAGER(NTFLM1)
001331      WRITE (6, 729)
001335      729 FORMAT (2840FUEL VAPOUR TEMP. (RANKINE)/)
001335      WRITE (6, 702) (TFILM(J, 2), J = 1, NTFLM2)
001350      CALL PAGER(NTFLM2)
001352      WRITE (6, 731)
001356      731 FORMAT (5340FUEL VAPOUR VISC. ((LBS MASS / IN - SEC) X 10 ** +6)/)
001356      WRITE (6, 702) (VVIS(J, 2), J = 1, NTFLM2)
001371      CALL PAGER(NTFLM2)
001373      WRITE (6, 733)
001377      733 FORMAT (6340FUEL VAPOUR CONDUCTIVITY ((BTU / IN - SEC - DEG R) X 1
001377      0 ** +6)/)
001377      WRITE (6, 702) (KVAP(J, 2), J = 1, NTFLM2)
001412      CALL PAGER(NTFLM2)
001414      WRITE (6, 735)
001420      735 FORMAT (3940FUEL VAPOUR CP (BTU / LB MASS - DEG R)/)
001429      WRITE (6, 702) (CPVAP(J, 2), J = 1, NTFLM2)
001433      CALL PAGER(NTFLM2)
001435      IF (LOGSE .EQ. 0) WRITE (6, 736)
001442      IF (LOGSE .EQ. 1) WRITE (6, 737)
001450      736 FORMAT (2440NO FUEL THERMAL DECOMP.)
001450      737 FORMAT (2140FUEL THERMAL DECOMP.)
001450      16 WRITE (6, 20) (TITLE(I), I = 1, 24)
001462      20 FORMAT (44411SN7002 STEADY-STATE SPRAY COMBUSTION MODEL/(14.1046))
001462      WRITE(6,40)(ENDOT(I),RM(I),SIG(I),WTMOL(I),
001505      40 FORMAT(140

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1 8X      50M MASS FLOW      RM      SIG      MOLE WT
12M 0      F15.2,      E12.3,      2F7.2      /
22M F      F15.2,      F12.3,      2F7.2      )
001505      WRITE (5, 50) 4P
001513      50 FORMAT (19H0HMAX / HM[N = 2 **, 12)
001513      RETURN
001514      END

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```

SUBROUTINE RSET
000002      DIMENSION FC(80), VM(20), RD(10, 20, 12), TA(1000), FA(2), ENMP(2)
000002      COMMON /E/ FC, NM /H/ RD /C/ TA
000002      EQUIVALENCE (NM(14), IRZ), (NM(12), JZ), (TA(50), FA)
1, (TA(479), ENMP), (TA(481), PHI), (TA(258), EMD), (TA(36), EMDOT)
2, (TA(52), DNT), (TA(54), WCON), (TA(42), RM), (TA(44), SIG)
3, (TA(46), VSET), (TA(40), TTL), (TA(38), VV), (RD(801), TL)
4, (RD(1501), V), (RD(1), EM), (TA(56), EMINT), (TA(96), RS)
5, (TA(135), DN), (TA(176), KK), (TA(216), WW), (TA(25), R)
6, (TA(237), RAT), (TA(256), DNTT), (TA(48), WTMOL)
7, (TA(31), RATHN), (TA(32), RATHX)
000002      DIMENSION EMDOT(2), DNT(2), WCON(2), RM(2), SIG(2), NSET(2)
1, TTL(2), VV(2), FMS(20), DNS(20), RSS(20), TL(10, 20, 2), WW(20, 2)
2, KK(20, 2), RS(20, 2), DN(20, 2), EMINT(20, 2), EM(10, 20, 2)
3, V(10, 20, 2), WTMOL(2)
000002      IRZ = 0
000003      JZ = 1
000004      PHI = 0.0
000005      EMD = EMDOT(1) + EMDOT(2)
000007      DO 100 I = 1, 2
000011      FA(I) = EMDOT(I)
000014      ENMP(I) = 0.0
000016      DNT(I) = 0.0
000020      WCON(I) = 6.2831853 * WTMOL(I) / R
000024      N = NRET(I)
000026      CALL L33NRM(RM(I), SIG(I), N, RSS)
000032      CALL MASSSET(FMS, RHO(TTL(I), 1), RSS, EMDOT(I), N, DNS)
000043      VSET(I) = V * 4
000046      V = VSET(I)
000050      DO 100 J = 1, N
000052      TL(1, J, 1) = TTL(I)
000060      V(1, J, 1) = VV(I)
000066      EM(1, J, 1) = EMS(J)
000074      EMINT(J, 1) = EMS(J)
000101      RS(J, 1) = RSS(J)
000106      DN(J, 1) = DNS(J)
000113      DNT(I) = DNT(I) + DNS(J)
000117      KK(J, 1) = 1
000123      WW(J, 1) = 0.0
000127      100 CONTINUE
000133      DNTT = DNT(1) + DNT(2)
000135      RAT = EMDOT(1) / EMDOT(2)
000137      RAT = AMIN1(RATHX, AMAX1(RATHN, RAT))
000146      RETURN
000146      END

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      FUNCTION HT(RS)
      C  CALCULATES DISTANCE OF DISSOCIATION FLAME AS FUNCTION OF RADIUS
000003  DIMENSION RRB(5),RRT(5)
000003  DATA RRS, RRT/ 0., 100., 200., 300., 500., 8., 13., 17., 1A., 18./
      C  CONVERT RS(K) TO MICRONS
000003  RST = RS
000004  RST =RST * 2.54E+4
000006  CALL LV3R1V (RST,RT,RRS,RRT,DRTDRS,5)
000017  RT = RT / 2.54E+4
000014  RETURN
000014  END

```

```

SUBROUTINE SHIFT
  DIMENSION FC(80), NM(20), HD(2400), NST(2), NED(2)
  COMMON /F/ FC, NM /R/ HD
  EQUIVALENCE (NM(5),MPTN),(NM(4),MGAM),(NM(3),MALP),
1 (NM(1),IM),(FC(3),H),(FC(7),HZD2),(NM(10),NV),(FC(4),-Q),
2 (FC(1),T),(NM(2),INDR),(FC(10),F1),(NM(8),NCOU),
3 (FC(6),HMAX),(NM(6),MPTS),(FC(5),NMJN),(FC(9),FMAX),
4 (FC(2),RKT),(NM(17),NST),(NM(19),NED)
  C *****
  C SHIFT UPDATES THE VARIABLES SO THAT PROPER POSITIONING
  C OCCURS DURING THE PROPER CYCLE
  C *****
100002  IF (MPTN) 15, 10, 15
000003  10 MPTN = MPTS
000005  15 MGAM = -MGAM
000006  IF (MGAM) 80, 20, 60
000010  20 IF (MALP - 2) 25, 48, 48
000013  25 IM = IM + 1
000015  MPTN = MPTN - 1
000016  NCOU = NCOU + 1
000020  IF (3 - IM) 35, 30, 30
000022  30 MALP = 4
000023  H = HZD2
000025  GO TO 40
000025  35 MGAM = -1
000026  40 DO 42 J=1,6
000030  DO 42 KL = 1,2
000031  LS = NST(KL) + 400*(J-1)
000036  LE = NED(KL) + 400*(J-1)
000044  DO 42 I = LS,LE,10
000046  HD(I+1) = HD(I+3)
000050  HD(I+2) = HD(I+4)
000051  HD(I+3) = HD(I+5)
000053  HD(I+4) = HD(I+6)
000054  HD(I+5) = HD(I+7)
000054  42 HD(I) = HD(I+9)
000066  RETURN
  C *****
  C SHIFTING OCCURS AFTER PREDICTOR CYCLE IS COMPLETE
  C *****
000066  44 MALP = MALP + 1
000070  IF (MALP - 2) 55, 50, 55
000072  50 H = H0
000074  GO TO 55
000074  55 T = T + HZD2
000076  GO TO 55
000077  50 T = T + H
000101  55 DO 75 J = 1,6
000103  DO 75 KL = 1,2
000104  LS = NST(KL) + 400*(J-1)
000111  LE = NED(KL) + 400*(J-1)
000117  DO 75 I=LS,LE,10
000121  HD(I+8) = HD(I+7)
000127  HD(I+7) = HD(I+6)
000124  HD(I+6) = HD(I+5)
000126  HD(I+5) = HD(I+4)
000127  HD(I+4) = HD(I+3)

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```

000131      BD(I+3) = BD(I+2)
000132      BD(I+2) = BD(I+1)
000134      BD(I+1) = BD(I)
000136      *5 BD(I) = BD(I+9)
000140      RETURN
C      .....
C      THE FOLLOWING STATEMENTS EXIST FOR CHANGING THE STEP SIZE
C      .....
000146      90 IF(INDR) 175, 135, 124
000150      124 IM = -1
000151      125 MPTN = MPTN + 1
000153      130 IM = IM + 1
000155      INPR = 0
000156      E1 = 0.0
000157      NCOU = NCOU + 1
000160      RETURN
C      .....
C      DOUBLE THE INTERVAL IF POSSIBLE
C      .....
000161      135 IF(IM = 8) 125, 140, 140
000164      140 KZ = MPTN/2
000166      IF(2*KZ = MPTN) 150, 125, 150
C      .....
C      IF MPTN IS ODD THERE IS AN EVEN NUMBER OF POINTS LEFT TO COMPUTE
C      .....
000167      150 IF((I-MAX)/HMAX) 155, 125, 125
000172      155 IF(MPTS = 1) 125, 125, 140
000175      160 MPTS = MPTS/2
000177      MPTN = MPTN/2
000200      IM = 5
000201      DO 165 J = 1,6
000202      DO 165 KL=1,2
000203      LS = NST(KL) + 400*(J-1)
000210      LE = NED(KL) + 400*(J-1)
000216      DO 165 I = LS,LE,10
000220      BD(I+1) = BD(I+2)
000222      BD(I+2) = BD(I+4)
000223      BD(I+3) = BD(I+6)
000225      165 BD(I+4) = BD(I+8)
000234      M = 2,4
000236      GO TO 130
C      .....
C      HALF THE STEP SIZE IF POSSIBLE
C      .....
000236      175 IF((M-HMIN)/HMIN) 124, 124, 180
000241      180 N = ALG3(E1/EMAX + 1,)/.6031471805
000250      DO 185 I = 1,N
000252      K = 1
000253      IF(M/2, **K = HMIN) 195, 190, 185
000262      185 CONTINUE
000265      190 K = K
000267      GO TO 200
000267      195 K = K + 1
000271      200 M*ALP = 4
000272      M*GM = 3
000273      IF( IM = 4) 210, 215, 210
000275      210 Y = Y+4
000277      NEXT = Y

```

```

000300      NV = 1
000301      GO TO 214
000302 215 T = RKT
000304      MPTN = MPTN + 4
000305      NV = 5
000306 214 MPTS = MPTS + 2**N
000313      MPTN = MPTN + 2**N
000320      DO 222 J = 1,6
000322      DO 222 KL = 1,2
000323      LS = VST(KL) + 400*(J-1)
000330      LF = VEB(KL) + 400*(J-1)
000336      DO 222 I = LS,LF,10
000340      K = I + NV
000342 222 EO(I) = MD(K)
000353      HQ = H/2.**N
000357      H/2 = 40/2,
000361      H = H/2
000362      IM = 0
000362      INDR = 0
000363      RETURN
000364      END

```

```

SUBROUTINE SUM
DIMENSION NSET(2),ENMP(2),DN(20,2),DM(10,20,2),FA(2),
1 EM(10,20,2),V(10,20,2),DV(10,20,2),TL(10,20,2),RS(20,2),
2 VD(20,2),DNT(2),BD(10,20,12),TA(1000),FC(40),NM(20)
3,DT(10,20,2),EMDOT(2)
4,EMINT(20,2)
000002 EQUIVALENCE (TA(46),NSET), (TA(479),ENMP), (TA(136),DN),
1 (BD(401),DM), (BD(1),EM), (BD(1601),V), (BD(2001),DV),
2 (TA(50),FA), (TA(478),U), (FC(3),DX), (BD(401),TL),
3 (TA(95),RS), (TA(311),VD), (TA(52),DNT), (FC(1),X),
4 (TA(484),RHOG), (TA(27),G), (TA(30),P), (TA(257),RAT), (TA(9
5 RATP), (TA(31),RATMX), (TA(32),RATMX)
6, (BD(1201),IT), (TA(36),EMDOT)
7, (TA(55),EMINT)
000002 COMMON /E/FC,NM /H/HQ/C/TA
000002 ENMP(1) = 0,
000003 ENMP(2) = 0,
000004 SUMP = 0,
000005 S MPA = 0,
000006 DO 200 I = 1,2
000007 FA(I) = EMDOT(I)
000012 F = NSET(I)
000014 DO 200 J = 1,N
000014 IF (EM(1,J,1) .GT. 101*EMINT(1,1)) GO TO 20
000030 1 F(1,J,1) = 0,0
000034 TL(1,J,1) = 0,0
000043 V(1,J,1) = 0,0
000050 EM(10,J,1) = 0,0
000055 TL(10,J,1) = 0,0
000062 V(10,J,1) = 0,0
000067 DM(10,J,1) = 0,0
000074 DT(10,J,1) = 0,0

```

```

000101      DV(10,J,I) = 0,0
000106      DV( 1,J,I) = 0,0
000113      DM( 1,J,I) = 0,0
000120      DT( 1,J,I) = 0,0
000125      NM(I+16) = J*10+1+200*(I-1)
000134      RS(J,I) = 0,
000137      VD(J,I) = 0,
000143      DNT(I) = DNT(I) + DN(J,I)
000150      DN(J,I) = 0,
000154      20 CONTINUE
000154      ENMP(I) = ENMP(I) + DN(J,I) + DM(1,J,I)
000166      SUMP = SUMP + DN(J,I) + DM(1,J,I) + (V(1,J,I)-U) * DX
000207      SUMPA = SUMPA + DV(1,J,I) + EM(1,J,I) + DN(J,I) * DX
000222      FA(I) = FA(I) + DN(J,I) + EM(1,J,I)
000233      FA(I)=AMAX1(FA(I),0,49E+10)
000240      200 CONTINUE
000244      AX = A(X)
000246      A1 = AX - AP(X) * DX
000252      A2 = AX
000253      A1DA2 = A1/A2
000255      PHIP = -(ENMP(1) + ENMP(2))
000257      PHI = FA(1) + FA(2)
000261      U = PHI / RHOG / AX
000264      P1 = U * (-PHIP) * DX / (G*A2)
000271      P2 = *SJMP / (G*A2)

000273      P3 = *SJMPA / (G*A2)
000275      P4 = *R4OG * U**2 * (A1/A2 -1,0)/G
000303      P = P1+P2+P3+P4 *P
000310      RAT=EMDOT(1)/EMDOT(2)
000312      IF(FA(1)+FA(2),GT, 1,E+10) RAT=FA(1)/FA(2)
000317      RAIR = (FA(1)/FA(2)+ENMP(2)-ENMP(1)) / FA(2)
000323      IF (RAT,GE, RATMN) GO TO 1262
000325      RAT = RATMN
000326      RATP = 0,
000327      1262 IF (RAT,LE, RATMX) GO TO 1264
000332      RAT = RATMX
000337      RATP = 0,
000333      1264 CONTINUE
000333      RETURN
000334      END

```

```

SUBROUTINE TWFL(J,I)
010005 DIMENSION KK(20,2),KDISC(20,2),XENTR(20,2),WENTR(20,2),WW(20,2),
1RS(20,2),TL(10,20,2),TWBINT(20,2), DELX(20,2),V(10,20,2),
2 EM(10,20,2),DUMITL(20,2),DUMTL(20,2),DM(10,20,2),BETA(20,2),
3FNUM(20,2),DT(10,20,2),FC(20),NM(20),BD(10,20,12),TA(1000)
000005 EQUIVALENCE (TA(176),KK),(TA(270),KDISC), (TA(689),XENTR),
1(TA(729),WENTR), (TA(213),EM), (TA(96),RS), (BD(801),TL)
2 (TA(769),TWBINT), (TA(200),DELX), (BD(1601),V), (BD(1),EM),
3 (TA(849),DUMITL), (TA(889),DUMTL), (BD(401),DM), (TA(647),BETA),
4 (TA(433),FNUM), (BD(1201),DT), (FC(1),X), (TA(26),TWOPI),
5 (TA(473),CPA), (TA(474),FKAV), (FC(3),DX)
COMMON/E/FC,NM/H/RD/C/TA
000005 153 II = KK(J,I)
000005 KDISC(J,I) = 1
010011 GO TO (164,165),II
000015 164 KK(J,I) = 2
000022 IF(X) 501, 601, 600
000026 600 XENTR(J,I) = X
000030 WENTR(J,I) = WW(J,I)
000034 XL = XK(RS(J,I))
000043 W = XL * TWOPI * RS(J,I) * RHO(TL(1,J,I),I)
000052 ZZ = W * CPA /FKAV * RT(RS(J,I)) /2, /TWOPI/RS(J,I)/RS(J,I)
000070 GO TO 602
000106 601 XENTR(J,I) = -.001
000106 XL = XK(RS(J,I))
000112 WENTR(J,I) = XL*TWOPI*RS(J,I)*RHO(TL(1,J,I),I)
000121 ZZ = WENTR(J,I) * CPA * RT(RS(J,I))/FKAV/2./TWOPI/RS(J,I)/RS(J,I)
000142 602 TWBINT(J,I) = A17,
000163 DELX(J,I) = V(1,J,I)*EM(1,J,I)*CPL(TL(1,J,I),I) * (TWBINT(J,I)-
000167 1 TL(1,J,I))/TWOPI/RS(J,I)/RHO(TL(1,J,I),I)/542./XL
000242 DUMITL(J,I) = TL(1,J,I)
000252 DUMTL(J,I) = TL(1,J,I)
000262 155 XL = XK(RS(J,I))
000271 W = XL * TWOPI * RS(J,I)*RHO(TL(1,J,I),I)
000307 ZZ = W * CPA /FKAV * RT(RS(J,I)) /2, /TWOPI/RS(J,I)/RS(J,I)
000325 TWR = A17,
000326 XTRA = XENTR(J,I) + DELX(J,I)
000335 IF(X-XTRA)166,167,167
000340 166 CONTINUE
000340 W = WENTR(J,I) + (W-WENTR(J,I)) / DELX(J,I) + (X-XENTR(J,I))
000360 TWR = DUMITL(J,I) + (TWR-DUMITL(J,I))/DELX(J,I)*(X-XENTR(J,I))
000377 DT(1,J,I) = (TWR-DUMTL(J,I))/DX
000411 DUMTL(J,I) = TWR
000415 DM(1,J,I) = -W/V(1,J,I)
000431 BETA(J,I) = W/RS(J,I)/FNUM(J,I)
000444 WW(J,I) = W
000450 GO TO 156
000450 157 DM(1,J,I) = -W/V(1,J,I)
000464 DT(1,J,I) = (TWR-DUMTL(J,I))/DX
000475 DUMTL(J,I) = TWR
000501 BETA(J,I) = W/RS(J,I)/FNUM(J,I)
000514 155 RETURN
000515 END

```

```

SUBROUTINE VAPOR(J,I)
COMMON /E/FB,NM/B/BD/C/TA
DIMENSION FB(80), NM(20), BD(10,20,12), YA(1000), WCON(2)
1, PE(2), BETA(20,2), RS(20,2), FNUM(20,2), M(10,20,2), DT(10,20,2)
2, FNUH(20,2), VL(10,20,2), EM(10,20,2), V(10,20,2)
3, DM(10,20,2), WW(20,2)
EQUIVALENCE (TA(257), RAT), (TA(30), P), (TA(54), WCON)
1, (TA(687), PE), (TA(473), DPOT), (TA(476), PA), (TA(647), BETA)
2, (TA( 96), RB), (TA(433), FNUM), (BD(401), DM), (BD(1201), DT)
3, (TA(26), THOP1), (TA(393), FNUH), (TA(474), FKAV), (TA(264), TG)
4, (BD(801), TL), (BD(1), EM), (BD(1601), V), (TA(475), CPA)
5, (TA(492), GJR), (TA(392), RV)
6, (TA(216), WW), (BD(401), DM)
000005      PE(1) = 0.0
000006      PE(2) = 0.0
000007      BETA(J,I) = WCON(1)*DPOT*ALOG((P-PE(1))/(P-PA))
000025      W = BETA(J,I)*RS(J,I)*FNUM(J,I)
000040      IF (W) 190, 192, 192
000041      190      W = 0.0
000042      WRITE (6, 2050)
000046      2050      FORMAT( 19MCW NEG, SET TO ZERO)
000046      DM(1,J,I) = 0.0
000054      DT(1,J,I) = THOP1*FKAV*RS(J,I)*FNUH(J,I)/EM(1,J,I)*(TG - TL(1,
1J, I)) / CPL(TL(1, J, I), I) / V(1, J, I)
000125      WW(J, I) = W
000131      RETURN
000132      192 DM(1, J, I) = -W / V(1, J, I)
000146      WW(J, I) = W
000152      Z = W/THOP1*CPA/RS(J,I)/FNUH(J,I)/FKAV
000164      EX = EXP (Z)-1,
000170      DIF= ALN(TL(1,J,I),I) - CPA*(TG- TL(1,J,I))*EX + GJR*(W/RV/RS(J,I)
1/RS(J,I))*2
000220      CPLTL = CPL(TL(1, J, I), I)
000230      200 FORMAT (1H1)
000230      DT(1,J,I) = -DIF/CPL(TL(1,J,I),I)/EM(1,J,I)*W/V(1,J,I)
000264      IF(DT(1,J,I) + 100.) 7711, 156, 156
000273      7711      DT(1,J,I) = -100,
000301      156      RETURN
000302      END

```

```

FUNCTION XK(RS)
C      CALCULATES DISSOCIATION BURNING RATE CONSTANT AS FUNCTION OF
C      RADIUS
000003      DIMENSION XXX(5),RRS(5)
000003      DATA XK, RRS/ 3.2, 6.3, 7.3, 8.2, 11., 0., 100., 200., 300., 500.
1/
C      CONVERT RS(K) TO MICRONS
000003      RST = RS
000004      RST = RST * 2.54E+4
000006      CALL LV3R1V (RST,XK,RRS,XXX,DXKDRS,5)
000012      XK = XK *1.E-3/2.54/2.54
000014      RETURN
000014      END

```

```

000002      SUBROUTINE PLUTY
000003      RETURN
000003      END

```

```

000007      SUBROUTINE COMP (OFR, P, Y, NSP)
000007      C      COMPOSITION OF COMBUSTION GASES AT ADIABATIC FLAME TEMPERATURE
000007      C      AS A FUNCTION OF      O/F RATIO, PRESSURE
000010      COMMON /CHPTAH/ YSP(15, 15, 3) /PRSSR/ PRSS(3) /OF/ R(15), NR
000013      DIMENSION Y(NSP), YSPB(15, 15)
000016      NS = NSP
000016      IF (P .LE. PRSS(2)) IND = 1
000016      IF (P .GT. PRSS(2)) IND = 2
000023      A = (P - PRSS(IND)) / (PRSS(IND + 1) - PRSS(IND))
000023      DO 1 J = 1, NR
000024      DO 1 I = 1, NS
000025      1 YSPB(J, I) = YSP(J, I, IND) + A * (YSP(J, I, IND + 1) - YSP(J, I, IND))
000055      DO 2 I = 1, NS
000054      2 CALL LVGRIN (OFR, Y(I), R, YSPB(1, I), DYDX, NR)
000073      SUM = 0.
000074      DO 3 I = 1, NS
000075      IF (Y(I) .GE. 0.) GO TO 3
000077      Y(I) = 0.
000101      3 SUM = SUM + Y(I)
000106      DO 4 I = 1, NS
000110      4 Y(I) = Y(I) / SUM
000114      RETURN
000115      END

```

```

000005      FUNCTION TBL(P, I)
000005      C      BOILING TEMP OF OX(I = 1), FUEL(I = 2)
000005      COMMON /PVY/ PV(15, 2) /TLX/ TL (15, 2) /DTL/ NTL(2)
000017      CALL LVGRIN(P, TBL, PV(1, 1), TL(1, 1), DTDPR, NTL(1))
000021      RETURN
000021      END

```

```

000005      FUNCTION VISC(V, I)
000005      C      VAPOR VISCOSITY FOR OX(I = 1), FUEL(I = 2)
000005      COMMON /TXLHX/ TFLM(15, 2) /VISCY/ VVIS(15, 2) /DTFL/ NTFM(2)
000017      CALL LVGRIN(V, VISC, TFLM(1, 1), VVIS(1, 1), DVISDT, NTFM(1))
000021      VISC = VISC * 1.0E-4
000021      RETURN
000021      END

```

```

      FUNCTION RHO (T,I)
      C  LIQUID DENSITY OF OX(I = 1), FUEL(I = 2)
000009  COMMON /TLX/ TL(15, 2) /RHOY/ RHOL(15, 2) /DTL/ NTL(2)
000009  CALL LV3RIN(T, RHO, TL(1, I), RHOL(1, I), DRHODT, NTL(I))
000017  RETURN
000021  END

```

```

      FUNCTION PVAP (T,I)
      C  VAPOR PRESSURE OF OX(I = 1), FUEL(I = 2)
000009  COMMON /TLX/ TL(15, 2) /PVY/ PV(15, 2) /DTL/ NTL(2)
000009  CALL LV3RIN(T, PVAP, TL(1, I), PV(1, I), DPVDT, NTL(I))
000017  RETURN
000021  END

```

```

      FUNCTION FKA (T,I)
      C  VAPOR THERMAL CONDUCTIVITY OF OX(I = 1), FUEL(I = 2)
000009  REAL KVAP
000009  COMMON /TFLMX/ TFILM(15, 2) /KVAPY/ KVAP(15, 2) /DTFLM/ NTFLM(2)
000009  CALL LV3RIN(T, FKA, TFILM(1, I), KVAP(1, I), DKVDTF, NTFLM(I))
000017  FKA=FKA*1.0E-06
000021  RETURN
000021  END

```

```

      FUNCTION CVAP (T,I)
      C  VAPOR SPECIFIC OF OX(I = 1), FUEL(I = 2)
000009  COMMON /TFLMX/ TFILM(15, 2) /CPVPY/ CPVAP(15, 2) /DTFLM/ NTFLM(2)
000009  CALL LV3RIN(T, CVAP, TFILM(1, I), CPVAP(1, I), DCPDT, NTFLM(I))
000017  RETURN
000021  END

```

```

      FUNCTION CPL (T,I)
      C  LIQUID SPECIFIC HEAT OF OX(I = 1), FUEL(I = 2)
000009  COMMON /TLX/ TL(15, 2) /CPY/ CP(15, 2) /DTL/ NTL(2)
000009  CALL LV3RIN(T, CPL, TL(1, I), CP(1, I), DCPDT, NTL(I))
000017  RETURN
000021  END

```

```

      FUNCTION ALM (T,I)
      C  HEAT OF VAPORIZATION OF OX(I = 1), FUEL(I = 2)
000009  REAL LAM
000009  COMMON /TLX/ TL(15, 2) /LAMY/ LAM(15, 2) /DTL/ NTL(2)
000009  CALL LV3RIN(T, ALM, TL(1, I), LAM(1, I), DALMDT, NTL(I))
000017  RETURN
000021  END

```

```

SUBROUTINE WTHINT (OFR,P,WM,DOFRWM)
C MOLECULAR WT OF COMBUSTION GASES AS A FUNCTION OF O/F RATIO
000007 COMMON /WT4/ WMTAB(15, 3) /PRSSR/ PRSS(3) /OF/ R(15), NR
000007 DIMENSION WMT(3)
000007 DO 1 I = 1, 3
000010 1 CALL LVGRIN(OFR, WMT(I), R, WMTAB(1, I), DUMDOF, NR)
000025 CALL LVGRIN(P, WM, PRSS, WMT, DOFRWM, 3)
000031 RETURN
000032 END

```

```

SUBROUTINE TGINT (OFR,PC,T,DTCDOFR)
C ADIABATIC FLAME TEMPERATURE AS A FUNCTION OF O/F RATIO , PRESS.
000007 COMMON /TGI/ TC1(15, 3) /PRSSR/ PRSS(3) /OF/ R(15), NR
000007 DIMENSION TT(3)
000007 DO 1 I = 1, 3
000010 1 CALL LVGRIN(OFR, TT(I), R, TC1(1, I), DTCDOF, NR)
000025 CALL LVGRIN(PC, T, PRSS, TT, DTCDOFR, 3)
000031 RETURN
000032 END

```

```

SUBROUTINE VKSGAS (OFR, P, T, VISG, YKG, CPB, NSP)
C      VISCOSITY, THERMAL CONDUCTIVITY, AND SPECIFIC HEAT OF
C      COMBUSTION GASES AS A FUNCTION OF O/F RATIO, PRESSURE, AND
C      TEMPERATURE
000012 COMMON /TAB/ TTAB(15) /VKSGS/ VSP(15, 15), CPTAB(15, 15) /BT/ NT
000012 1/MW/ WM(15)
000012 DIMENSION SUM(15), V(15), Y(15), VR(15), WMR(15), PHI(15), YPHI(15)
000012 1), CP(15)
000012 NS = NSP
000013 DO 1 I = 1, NS
000015 1 CALL LVRIN(T, V(I), TTAB, VSP(1, I), NYDX, NT)
000035 CALL COMP(OFR, P, Y, NS)
000037 SUMVIS = 0.
000040 DO 20 I = 1, NS
000045 IF (Y(I) .LT. .001) GO TO 20
000051 9 SUM(I) = 0.
000053 DO 10 J = 1, NS
000055 VR(J) = V(I)/V(J)
000062 WMR(J) = WM(J)/WM(I)
000067 PHI(J) = (1. + SQRT (VR(J)*SQRT (WMR(J))))**2/(2.828 + SQRT (
1 1. + 1. / WMR(J)))
000112 YPHI(J) = Y(J) + PHI(J)/Y(I)
000120 10 SUM(I) = SUM(I) + YPHI(J)
000132 SUMVIS = SUMVIS + V(I) / SUM(I)
000136 20 CONTINUE
000141 VISG = SUMVIS /1.E6
000142 DO 25 I = 1, NS
000144 25 CALL LVRIN(T, CP(I), TTAB, CPTAB(1, I), DCPDT, NT)
000164 SIGA = 0.
000165 SIGB = 0.
000166 DO 30 I = 1, NS
000167 SIGA = SIGA + Y(I) * CP(I)
000174 30 SIGB = SIGB + Y(I) * WM(I)
000207 CP3 = SIGA / SIGB
000204 YKG = VISG * (CPB + 2.484/ SIGB)
000207 RETURN
000207 END

```

SUBROUTINE DIFFU(OFN,P,T,VP02,I,DEU,NSPEC)

C
C
C
C

THIS SUBROUTINE CALCULATES THE DIFFUSIVITY OF OX THRU
MIX(I=1) AND FUEL THRU MIX (I=2)

```
000012 COMMON/C/ TA(1000)
000012 DIMENSION WTMOL(2), OMEGT(29),XKTOET(29),Y(15)
000012 EQUIVALENCE ( WTMOL(1),TA(48))
000012 COMMON/DIFFUS/EPST(15,2),SIGMA(15,2),EPSOF(2),SIGOF(2)/MW/M(15)
000012 DATA KS/0/,NPTS/29/
000012 DATA OMEGT/ 2.662, 2.318, 2.066, 1.877, 1.720,
* 1.512, 1.517, 1.439, 1.32, 1.233, 1.167,
* 1.116, 1.075, 0.9996, 0.949, 0.912, 0.8836,
* 0.861, 0.8422, 0.8124, 0.7712, 0.7424, 0.6640,
* 0.5232, 0.596, 0.5756, 0.5596, 0.5352, 0.517/
000012 DATA XKTOET/ .3, .4, .5, .6, .7,
* .8, .9, 1.0, 1.2, 1.4, 1.6,
* 1.8, 2.0, 2.5, 3.0, 3.5, 4.0,
* 4.5, 5.0, 6.0, 8.0, 10.0, 20.0,
* 30.0, 40.0, 50.0, 60., 80.0, 100.0/
000012 IF(KS)100,10,100
```

C
C
C

CALC CONSTANT FOR THIS PROPELLANT SYSTEM

```
000013 10 NS=NSPEC
000015 KS=1
000016 NSAVE=1
000017 DO 20 K=1,NS
000020 EPST(K,2)=EPST(K,1)
000023 SIGMA(K,2)=SIGMA(K,1)
000025 20 CONTINUE
000027 DO 50 J=1,2
000031 DO 50 K=1,NS
000032 EPST(K,J)=SQRT(EPSOF(J)*EPST(K,J))
000042 SIGMA(K,J)=(0.5*(SIGOF(J)+SIGMA(K,J)))*2/0.00422188/
1 SQRT( 1.0/WTMOL(J) + 1.0/M(K))
000063 50 CONTINUE
000075 100 CALL COMP(OFN,P,Y,NS)
000075 SUMD=0.0
000076 XNUM=1.0- VP02/P
000104 T1=T/1.8
000106 T32=T1*SQRT(T1)
000111 DO 300 K=1,NS
000116 Y(K)=Y(K)*(P-VP02)/P
000122 F= T1/EPST(K,1)
000125 CALL LN3RIN(F,OMEG,XKTOET,OMEGT,DYDX,NPTS)
000131 PD=T32/OMEG3/SIGMA(K,1)
000142 SUMD=SUMD +Y(K)/PD
000146 300 CONTINUE
000150 DEJ= XNUM/SUMD/P
000152 RETURN
000152 END
```

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Mixing and separation criteria of hypergolic propellants are characterized by a chemical reaction time and a mixing time. Separation limit is defined by assuming the two characteristic times to be equal. Experimental results with hydrazine and nitrogen tetroxide propellants agree very well with this separation limit, and also show that the effect of chamber pressure is not significant. MMH and A-50 with nitrogen tetroxide give separation limits at higher propellant temperatures. It appears that stream separation always occurs by impinging compound A and hydrazine with oxidizer and fuel temperatures varying between 0°F to 30°F and 40°F to 60°F. A second work area of the project was concerned with the extension of the Steady-State Combustion Computer Model. The computer program was generalized to allow increased versatility in running various propellant systems. The numerical procedures and organizations of the program were substantially improved. Propellant property values were gathered for several systems of current interest. A computer program listing is presented.		

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A-50						
Compound A						
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