SIMULATION OF GASEOUS CORE
NUCLEAR ROCKET MIXING CHARACTERISTICS
USING COLD AND ARC HEATED FLOWS

by Peter M. Williams and Jerry Grey

Prepared by
PRINCETON UNIVERSITY
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SIMULATION OF GASEOUS CORE NUCLEAR ROCKET MIXING CHARACTERISTICS USING COLD AND ARC HEATED FLOWS

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FOREWORD

The research described herein, which was conducted at the Guggenheim Laboratories for the Aerospace Propulsion Sciences, Department of Aerospace and Mechanical Sciences, Princeton University, was performed under NASA Contract NASr-216/31-001-028. Captain William A. Yingling, NASA Headquarters, and Robert G. Ragsdale, Nuclear Systems Division, NASA Lewis Research Center, were the Technical Managers. The work made use of computer facilities supported in part by NSF Grant N8EGP579.
ABSTRACT

Mixing phenomena of cold and arc heated jets of one and two centimeters in diameter exhausting into coaxial flows of either helium or nitrogen were investigated over ranges of jet temperatures between room and 9000°R, of jet Reynolds numbers between 10 and $10^4$ and of coaxial to jet velocity ratios from 0 to 780. Velocity, temperature, and composition profiles were obtained at the jet exit plane and downstream locations of 1/2, 1 and 2 jet diameters at a total of 47 different flow conditions including three variations of the coaxial flow injection scheme.

This work was undertaken to investigate the mixing processes related to the coaxial flow nuclear rocket concept in which a central flow of nuclear fuel in the gaseous state is surrounded by a flow of hydrogen at much greater velocity. The appropriate experimental data have been correlated in terms of the separation ratio for the two streams and show a consistent agreement in the effects of velocities, temperatures, Reynolds numbers, molecular weights, and an exit plane mixing factor. Under conditions of interest to the coaxial flow rocket the mixing processes were strongly dominated by an apparent wake phenomena at the exit plane and thus could not be described by even an empirical application of the arcjet mixing theory developed in earlier work. Immediate application of these studies to the question of the feasibility of the coaxial flow rocket is premature since the effect of scale on the exit plane mixing factor is unknown.
I. INTRODUCTION

The key to feasibility of any gaseous core nuclear rocket concept is the ability of the rocket to retain a suitably high fraction of the fissioning gaseous fuel while propellant is expelled at comparatively attractive temperatures and flow rates. A 1957 analytical study by Kerrebrock and Meghrebian\textsuperscript{1} considered vortex motion as a scheme to effect the required separation and since this time other possible variations and concepts of the gaseous core rocket have received attention\textsuperscript{2,3}.

The concept proposed in 1960 by Weinstein and Ragsdale\textsuperscript{4} has formed the stimulus for the experiments reported here and is diagrammed in Figure 1. A central jet flow of fissioning material is surrounded by a coaxial flow of propellant at substantially greater velocity. The concept eliminates many of the characteristic problems of vortex containment, but since particle contact must be minimized to prevent sweeping the fuel along with the propellant, heat transmission from the core to the coaxial flow is necessarily by radiation. It, therefore, appears necessary to "seed" the relatively transparent coaxial hydrogen flow with small particles of high-emissivity material.

Through use of the arcjet it is possible to simulate some of the fluid mechanics and heat transfer features of the coaxial concept. In this work the fluid mechanics has been investigated using both cold and arc heated flows.
THE COAXIAL FLOW GASEOUS CORE NUCLEAR ROCKET
Weinstein and Ragsdale showed analytically that in the reactor cavity, if the flow remains laminar, there would be little mixing of the fuel and propellant, and that the degree of fuel retention in the cavity would be sufficient for economic feasibility. This concept has received substantial analytical and experimental attention in recent years. The nuclear criticality requirements were investigated by Ragsdale and Hyland, a turbulent flow jet mixing experiment was performed by Ragsdale, Weinstein and Lanzo, and recently an analytical study by Ragsdale illustrated the advantages of both turbulent and laminar mixing of a buffer flow between the main stream of coaxial propellant flow and the fuel flow.

The arcjet simulation experiments have been underway at Princeton since early 1963, making use of previously developed diagnostic techniques and an analytical formulation developed for laminar arcjet mixing. Early Princeton experiments were addressed to mixing characteristics of a laminar jet, since it was the laminar case which showed such high promise in the initial conceptual studies. The results of this research, reported in References 12, 13, and 14 showed that with coaxial flows, even well below the jet velocity, laminar jet flow could not be maintained. Otherwise, mechanisms favorable to the concept were apparent, and it was thus decided to extend the investigation to the case of turbulent flows.

The practical operating conditions of the arcjet differ considerably, of course, from the design characteristics of the gaseous-core nuclear rocket. The electric arc does,
however, provide a very high temperature jet which offers an
approach to investigate large differences in temperature,
molecular weight and velocity between central and coaxial
flows. It is, therefore, possible to examine mixing character-
istics of some pertinence to the coaxial gaseous-core scheme
over a wide range of variables, with the aim of bringing to
light the fluid mechanical properties of most apparent signifi-
cance to the coaxial concept. The basic technique was to
radially probe the mixing region for velocity, composition and
enthalpy at axial stations beginning at the exit plane and
down to two initial central-jet diameters. The mixing profiles
are presented in detail in this report.

A detailed search of the literature has revealed
no data of hot jet mixing of coaxial-to-core velocity ratios
greater than unity, and no profiles of cold mixing within a
few diameters of the nozzle exit plane. Alpinieri\textsuperscript{15} offers
cold mixing profiles in the range greater than two jet diameters
downstream for the jets of carbon dioxide or hydrogen mixing
with air, and Ragsdale, et. al.,\textsuperscript{6} have presented average
composition data for a cold bromine jet mixing with coaxial
flowing air. Neither of those experiments give data directly
comparable with those reported here.

In addition to presentation of the data in a manner
suitable for general fluid mechanics interest, certain of the
data have been correlated in terms of the separation ratio \( S \),
the parameter which relates directly to the feasibility of any
gaseous core nuclear rocket concept. The separation ratio is defined as the ratio of the life of propellant particles to the life of fuel particles in the reactor cavity, and for the coaxial flow concept, this results in the simple expression

\[ s = \frac{V_c}{V_e}, \]

where \( V_c \) and \( V_e \) are the average velocities of the core (or jet) flow and the exterior (or coaxial) flow respectively. It has been argued by Bussard and DeLauer\(^{16}\) that for economic feasibility \( S \) must be less than \( 10^{-3} \). Weinstein and Ragsdale\(^4\) suggested a range of \( 10^{-2} \) to \( 10^{-3} \), while Rom\(^{22}\) gives \( 10^{-2} \).
II. TECHNIQUES AND EQUIPMENT

A. General

The technique and equipment used in the simulation experiments are direct outgrowths of earlier work, and for this reason only equipment which was developed specifically for the current research is described in detail. Figure 2 is an overall diagram of the equipment, showing the plasma generator which delivers an argon jet into a test chamber containing a movable calorimetric probe. Measured quantities are indicated on the diagram. The main difference from the apparatus used earlier\textsuperscript{8,12,14, etc.} is provision for injection of high speed coaxial flow through a two-inch-long injection section surrounding the jet nozzle. This arrangement is illustrated by Figure 3, which shows one of the several configurations used. All arcjets were generated by a Thermal Dynamics Corporation F-80 Plasma Flame Torch modified both to accommodate the special nozzle arrangements and to operate with a two-inch-long arc. Detailed experiments performed as part of an Air-Force-sponsored program\textsuperscript{17} show improved plasma generator performance with the longer arc, since for a given arc power the current is roughly inversely proportional to arc length. With lower currents a more uniform arcjet is obtained. Figure 4 shows that portion of the plasma generator in which separately cooled constrictor segments have been added to form a longer arc passage.
1. TEMPERATURE
2. PRESSURE
3. MASS FLOW RATE
4. THERMAL CONDUCTIVITY
5. VOLTAGE
6. CURRENT

**Diagram of Apparatus**
INJECTION PLATE & NOZZLE FOR MODIFIED F-80 ARCJET TORCH
FOR USE WITH HIGH COAXIAL FLOWS
FIGURE 4

MODIFIED F-80 PLASMA GENERATOR
B. Calorimetric Sampling Probe

The calorimetric probe is an instrument which measures enthalpy, stagnation pressure, and composition of gases at temperatures up to 25,000°F. It has been used for some time in arcjet diagnosis, and since it has been described in detail elsewhere, only its general nature is outlined here. A photograph of the probe is given in Figure 5.

The construction of the probe itself is of copper, with a brass base. Cooling water from a high-pressure source (up to 1,000 psi) enters through the mounting block, passes through the outer channel to the tip, and leaves via the inner channel. Sheathed, ungrounded thermocouple junctions are located where the probe cooling water flow enters and leaves the sampling tube. A steady flow of sample gas can be drawn by a vacuum pump from the probe tip, through the central tube past a thermocouple junction located in the tube, and then through the support shaft to valving and instrumentation.

The flow of the hot sample gas in the central tube causes the probe cooling water to rise in temperature a greater amount than when the gas sample flow is not permitted to flow through the tube. A flowmeter measures the probe coolant flow and a critical orifice measures the gas flow. These measurements are sufficient to compute the enthalpy of the gas sample at the point where it enters the probe.

The composition of the two-component gas sample is determined by measuring its thermal conductivity in a
carefully calibrated commercial cell, and stagnation pressure is measured when the gas sample is not flowing by simply diverting, through appropriate valving, the gas sample line from the vacuum pump to a water manometer. Enthalpy can be converted to temperature, once the gas composition is known, from an equilibrium theory such as the Saha equation. The measured stagnation pressure is converted to velocity using the Bernoulli equation for lower Mach numbers while the compressible flow equation is used for Mach numbers greater than 0.3. The complete data reduction procedure is given in Appendix B.

The sensitivity and calibration of the probe under similar experimental conditions have been described elsewhere. In previous work, energy and mass balances showed that the probe's accuracy (standard deviation from the mean) was about 3 per cent.

C. Test Operations

The range of operating variables investigated is given in Table I together with the identification of conditions for the rocket. In all experiments the heavy core flow was simulated by argon and the effect of molecular weight ratio was studied by using either helium or nitrogen as the coaxial flow material. Jet diameters of one and two centimeters were studied with the coaxial flow stream sufficiently wide so that its exterior boundary condition had no effect on the central mixing process for at least two central jet diameters. Jet
CALORIMETRIC PROBE

FIGURE 5
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<td>27</td>
<td>N₂</td>
<td>1/16 &quot;</td>
<td>0.68</td>
<td>708</td>
<td>2</td>
<td>3157</td>
<td></td>
<td></td>
</tr>
<tr>
<td>HP 1</td>
<td>130</td>
<td>N₂</td>
<td>Porous</td>
<td>1.01</td>
<td>1,478</td>
<td>1</td>
<td>2684</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
temperatures from room temperature to a peak of 9000°R were studied, with jet Reynolds number varying between 10 and $10^4$, and coaxial to core velocity ratios ranging from 0 to 780. Three different coaxial-flow injection configurations were also investigated. In total, 47 runs were performed in which composition, velocity and temperature profiles were obtained at the nozzle exit plane, and at downstream locations of 1/2, 1 and 2 nozzle diameters. Because of the great number of different test conditions studied, the number of data points per profile was substantially lower than that usually taken in flow experiments, particularly in the case of high velocity coaxial flows where cost considerations limited the run duration. The use of many different test conditions gives good statistical weight to the empirical correlation developed, although because of limited profile data good agreement between analytical predictions and any single mixing profile cannot always be expected.

Figures 6 and 7 show the nozzle and coaxial flow geometry for the two nozzle diameters studied, and include notation giving flow characteristics of the injection sections used. It can be seen that the nozzle wall has appreciable thickness relative to the nozzle diameter, and was, therefore, tapered at the exit plane. This thickness was necessary to accommodate water cooling passages, but, of course, leads to difficulty in establishing the exact conditions at the nozzle exit plane. However, Schlieren photography has established that
NITROGEN

OPTIONAL INJECTOR SECTION

1. $\frac{1}{8}$ TUBE BUNDLE - 104 TUBES, 0.101" ID, 0.125 O.D., OPEN
FLOW AREA = 1.47 SQ. IN.

2. $\frac{1}{16}$ TUBE BUNDLE - 447 TUBE, 0.045" I.D., 0.062 O.O.,
OPEN FLOW AREA = 1.04 SQ. IN.

3. POROUS PLUG, $\frac{1}{2}$" THK., 10 MICRONS, AREA = 2.02 SQ. IN.

FLOW INJECTION GEOMETRY — 1CM JET

FIGURE 6
NITROGEN

OPTIONAL INJECTOR SECTION

\( \frac{1}{16} \) TUBE BUNDLE - 618 TUBES, 0.045" ID, 0.062 O.D., OPEN
FLOW AREA = 1.09 SQ. IN.

FLOW INJECTION GEOMETRY - 2CM JET

FIGURE 7
at jet flow velocities of ten feet per second, no separation occurs and the jet is expanded to the full dimension of the nozzle taper. In those cases studied for which the flow velocity was greater than ten feet per second, the initial jet diameter needed to compute the average initial velocity, was taken as the internal diameter of the nozzle, i.e., it was assumed that the jet separated from the tapered portion of the nozzle.

The effect of the injection tubing on the character of the coaxial flow is illustrated by typical Schlieren photography in Figures 8A and 8B. In Figure 8A, where jet and coaxial velocities were nearly equal, it can be seen that the injection tubing inhibits large-scale turbulence to about one jet diameter downstream. Note that for this case there is visible radiation from the arcjet because mixing has been relatively slow. In Figure 8B, a high-velocity-ratio run, it can be seen that coaxial flow is stratified in individual jets for even a greater distance than the earlier case. Flow concentration caused by the injection tubing has the effect that individual coaxial velocity measurements near the exit plane exceed what would be the average value of the exterior velocity. The average exterior velocity is best represented by the nominal coaxial velocity listed in Table I. The nominal coaxial velocity, later identified as \( u_e \), was computed from the measured mass flow and the total coaxial flow cross sectional area, not taking account of the flow area occupied by the injection tubes. One or two jet diameters downstream, the
RUN HA-7 NOMINAL COAXIAL VELOCITY 67 FT/SEC VELOCITY RATIO 0.42

RUN E-2, NOMINAL COAXIAL VELOCITY 780 FT/SEC VELOCITY RATIO 33

SCHLIEREN ILLUSTRATIONS OF MIXING REGION

FIGURE 8
injection flow characteristics vanish, as illustrated by the Schlieren photographs of Figure 8A and 8B and the nominal coaxial velocity, as can be seen from the profile data in Appendix C is the same as the measured value.

D. Electrostatic Probe

Experiments performed under an Air Force contract had shown that a water-cooled electrostatic probe would yield current-voltage characteristics which were influenced by the degree of the jet turbulence.\textsuperscript{19} Figure 9 shows a typical current-voltage trace for both laminar and turbulence arcjets. Also under Air Force sponsorship a criterion was developed for predicting electron-heavy-particle non-equilibrium in a cooling arcjet.\textsuperscript{20,21} Consequently, work was undertaken in the simulation studies to evaluate the potential of an electrostatic probe as an instrument for quantitatively measuring the degree of turbulence in a mixing arcjet. The electrostatic probe used was the same as the calorimetric probe, except the entire probe surface but for a small region at the tip was electrically insulated with a ceramic coating.

After initial tests it was concluded that the best procedure was not to use the full current-voltage trace as shown in Figure 9, but rather to obtain a signal proportional to the rms value of the probe current when the probe was connected directly to ground (zero applied voltage). In this way the probe current would be proportional to the random current of electrons (the ion random current was shown in Reference 19 to be negligible.
VOLTAGE-CURRENT TRACES OF AN ELECTROSTATIC PROBE IN TURBULENT AND LAMINAR ARCJETS

FIGURE 9
by comparison). Thus the measured current is directly proportional to the local number density of the electrons and the square root of their temperatures.

The probe current was observed on a Ballantine rms voltage meter connected across a 10-ohm resistor placed between the probe and ground. Oscillographs of the voltage fluctuation in a laminar and turbulent test case are shown in Figure 10. Similar oscillographs and corresponding rms measurements were obtained for a number of conditions, some corresponding to runs HA-3, HA-4, HA-5, HA-6, HA-8 and HA-12. The repeatable variations observed in the laminar signal were traced to the ripple in the selenium rectifiers supplying power to the arc, and are considered background noise in the measurement.

In spite of the very obvious ability of the electrostatic probe to respond to turbulence, it was not found possible within the scope of the present contract to relate the measurements directly to the relative scale of turbulence. The essence of the problem resides in the fact that at the extremely low temperatures of the mixed jet (usually below 2,000°F), it is not possible to identify the amount of contribution to the probe current from the electron density and the electron temperature. The reason for this is that the ionized fraction at these temperatures is in an extreme nonequilibrium condition. For higher temperatures, if a relationship between temperature and density is known (e.g., the Saha equation), the scale of
LAMINAR VERTICAL SENSITIVITY = -50 mu/cm
HORIZONTAL SWEEP = 2 msec/cm

RESPONSE OF GROUNDED ELECTROSTATIC PROBE TO LAMINAR AND TURBULENT ARCJETS

FIGURE 10
turbulence could be readily identified in terms of either electron density fluctuations or electron temperature fluctuations. Note that the electrostatic probe does not utilize the same velocity-sensitive-cooling relationship of the conventional hot-wire, and therefore, does not provide the usual velocity correlation measurements.

III. MIXING DATA

Profiles and centerline decay curves of velocity and composition for unheated jets and similar graphs of velocity, composition and temperature for arc-heated jets are presented in Appendix C. Test conditions are identified on the profiles, and details of each test are tabulated on separate pages together with certain other information of use in the empirical correlation to be discussed later.

Because of the necessary limitations on the amount of profile data obtained, the accuracy of individual profiles cannot in general be expected to be as good as the profiles presented in the earlier laminar mixing experiments.\textsuperscript{12,13,14} This degradation in individual accuracy is probably more acute in the cases of the higher velocity profiles, since in some cases asymmetries were observed which necessitate adjustment of the location of the jet centerline. As will be seen later, it has been possible to correlate results obtainable from the higher velocity profiles into a single expression, however, so
that the random individual errors have been statistically mini-
mized in conclusions regarding the mixing processes involved.

Unlike the cited laminar mixing experiments\textsuperscript{12,13,14} and earlier turbulent mixing experiments,\textsuperscript{21} the data are not compared with an analytical treatment. Originally it was believed that use could have been made of the detailed machine computa-
tion program developed for laminar mixing by modifying the transport properties to include turbulence exchange coefficients. Experimentally it was found; however, that within a few diameter of the nozzle with the high coaxial velocity ratios of greatest interest, there was little resemblance to conventional jet mixing, and use of conventional jet mixing theory would be both fruitless and misleading.

The experimental discrepancy between the present data and what might normally be expected in turbulent jet mixing can be seen from profiles of the higher velocity-ratio experiments, where at the center of the jet exit plane the composition is not pure argon but was measured as a mixture of coaxial gas and jet gas. Also it should be noted that in many cases the measured velocity data have been omitted from the plots. In these cases stagnation pressure measurements in the jet close to the exit plane were highly unsteady, and often even below the static pressure. The physical explanation of such behavior, of course, is that a wake-like flow pattern extends all the way to the jet centerline as a result of complete domination by the high velocity coaxial flow. The presence of this wake phenomenon had not been previously observed or accounted for (e.g., in References 6 or 7), and is an important result of the present
experiments. As will be discussed later, understanding of the factors causing and controlling this phenomenon is believed to be the most important remaining question in the fluid mechanics of the coaxial gaseous-core nuclear rocket.

A number of additional phenomena can be observed by inspection of the mixing profiles and are summarized in Table II. The validity of any comprehensive theory which might be established for high-velocity coaxial mixing should be checked against these tabulated observations. That is, any theory must consider that when the coaxial velocity exceeds the jet velocity, the coaxial flow spreads into the jet and the jet material is accelerated. When the jet is heated, this process is augmented because of the reduced density of the cooling jet and the increased diffusion rates of the heated coaxial gas. To this simplified description must be added the effects of the wake phenomena already discussed; e.g., is the wake purely a shear effect, dependent only on velocity ratio and independent of the dimensions of the flow field, or is it a base-drag phenomenon, whose characteristics are a direct function of the jet diameter? Also, we must consider the general effect of turbulence, which, as can be seen from the Schlieren photographs, is not consistent in scale over the mixing region.

IV. SEPARATION RATIO CORRELATION

As we have just seen, any theory using the usual jet mixing techniques is not adequate to predict the flow behavior at high ratios of coaxial to jet velocity with a few diameters of the nozzle. Development of a turbulent wake analysis
**TABLE II**

**GENERAL OBSERVATIONS OF MIXING EXPERIMENTS**

1. The dominant mixing process for both heated and unheated jet (core) flows is the acceleration of the core due to the inflow of the exterior gas and the inflow of momentum.

2. Containment of argon within a cylinder defined by nozzle diameter is essentially complete for cases of high velocity exterior (coaxial) flows.

3. Effects of core temperature on composition profiles are observable but not large.

4. Differences in centerline velocity and exterior velocity are well preserved even under widely differing initial flow conditions.

5. Cooling and composition decay are more rapid at higher velocity ratios.

6. Mixing at the same exterior flow velocity is more rapid when the exterior flow injector is a porous plug than when it is either the 1/16 or 1/8 tube bundle.

7. There was no significant effect on mixing caused by using a 1/16 tubing injector in place of a 1/8 inch tubing injector.

8. Decay characteristics are more rapid for 2 cm jets than 1 cm jets.

9. A lower degree of mixing occurs with higher velocity jets.

10. In some cases the "turbulent wake effect" at the exit plane apparently caused reversal of the usual mixing gradients.
of the exit plane region is clearly a portion of the indicated approach, but this work is far beyond the scope of the present program. In view of these theoretical difficulties, an empirical technique has been developed to correlate the data. The value of this approach is primarily to demonstrate the degree of consistency of the data, rather than to establish a model of immediate application to the coaxial flow rocket. The empirical correlation has nevertheless been cast in terms of the separation ratio, because in this way quantities plainly obvious to the feasibility of the coaxial flow rocket can be emphasized.

We have stated previously that the expression for the separation ratio $S$, for the coaxial rocket is

$$S = \frac{V_c}{V_e}$$

where $V_c$ and $V_e$ are the average velocities of the core (or jet) flow and the exterior (or coaxial) flow respectively. By the methods described in Appendix D, the profile data are used to compute average local values of the core (or jet) velocity $u_c$, at the exit plane and at the downstream locations of 1/2, 1 and 2 jet diameters and, as we have seen in Section II-C, the average local coaxial velocity $u_e$ is most appropriately taken as the initial nominal coaxial velocity, $u_e$.

The expression for $S_L$ becomes,
\[
S_L = \frac{u_c}{u_e} = \frac{u_c}{u_c^0}
\]

\(S_L\) is correlated with the various experimental conditions, including the ratio of the length of the core to its initial diameter, \(Z/D\). Then the separation ratio can be found by averaging the local separation ratio over the length of interest:

\[
S = \frac{\int_0^L S_L \, dz}{\int_0^L dz}
\]

where \(L\) would be the chamber length of the gaseous-core rocket (Figure 1). In the simulation experiments, \(L\) is simply the final downstream position studied in initial jet diameters.

In order to arrive at correlations for \(S\), all velocity data were first displayed as shown in Figure 11 to determine a region in which correlation is suitable. In this plot the ratio of the local jet velocity \(u_c\) to the nominal initial jet velocity \(u_c^0\) is plotted against the ratio of the coaxial velocity \(u_e\) to \(u_c\). The plot is in essence the fractional change in core velocity versus the initial velocity ratio. The nominal initial jet velocity \(u_c^0\) is computed on the basis of the measured argon mass flow rate, the nozzle cross-sectional flow area and the average jet temperature at the exit plane.
FRACTIONAL CHANGE IN JET VELOCITY, $u_e/u_c^o$ vs VELOCITY RATIO

- HELIUM COAXIAL FLOW, UNHEATED ARGON JET
- HELIUM COAXIAL FLOW, HEATED ARGON JET
- NITROGEN COAXIAL FLOW, UNHEATED ARGON JET
- NITROGEN COAXIAL FLOW, HEATED ARGON JET

AXIAL LOCATION, $Z/D$

0 1 2

FRACTIONAL CHANGE IN JET VELOCITY vs VELOCITY RATIO

FIGURE 11
The 45° line drawn in this plot represents a separation ratio of unity; i.e., equal core velocity and exterior velocity. When the initial velocity ratio $\frac{u_c}{u_e}$ exceeds unity, the points fall below the line, i.e., the core must be accelerated to approach the exterior velocity, whereas when $\frac{u_c}{u_e}$ is less than unity the jet is being decelerated and the points fall above the line. The data with initial velocity ratios greater than two are suitable for correlation because evidently the wake phenomenon which dominates the mixing process has become well developed at this point. Points near a velocity ratio of unity and below are excluded from the correlation, because there is relatively little similarity between the fundamental flow phenomena in these cases and those of the high velocity ratio data. The data obtained in this lower region of velocity ratio were used to complete the picture of the mixing process as described in Table II.

The empirical correlation for values of separation ratio $S$ is based on the following argument. First, if there were no influence by the exterior flow on the core flow, we could define an "uninfluenced" separation ratio, $S^*$

$$S^* = \frac{u_c^*}{u_e} = \frac{1}{V_R}$$

where the nominal velocity ratio $V_R$ is defined as the ratio of the nominal coaxial velocity $u_c^*$ divided by the nominal
initial jet velocity $u_c^0$. The definition and computational procedure for both the core and exterior nominal initial velocities have been discussed previously.

We now define an "influence function" $f$ such that the actual separation ratio is given by

$$S_L = S^0 f$$

Within the scope of the present experiments, this influence function can be empirically expressed as

$$f = f (\alpha, V_R, R_C, T_C, \frac{Z}{D}, \epsilon)$$

where $\alpha = \frac{\text{molecular weight of exterior gas}}{\text{molecular weight of core gas (argon)}} = \frac{M_e}{M_c}$

$V_R = \text{initial velocity ratio}$

$R_C = \text{initial nominal core (jet) Reynolds number}$

$T_C = \frac{\text{initial average core temperature}}{\text{initial temperature of the exterior flow}} = \frac{T_C}{T_e}$

$Z = \text{downstream distance from exit plane}$

$D = \text{initial core diameter}$

$\epsilon = \text{exit plane mixing factor}$

Using data from 14 of the 16 experiments in the region of interest identified in Figure 11, $f$ is determined empirically by

$$f = \epsilon \alpha R_C T_C V_R (1 + \alpha \epsilon^2 \frac{Z}{D})$$
Numerically, the turbulent wake factor $\epsilon$ is 0.53 with a statistical probable error of 7%. Appendix E identifies the data used to compute $\epsilon$ and lists the computed values.

Using this formulation for $f$, with appropriate numerical values,

$$S_L = [0.53 + 0.15 \frac{z}{D}] \times \left( \frac{V_R C_T}{1,000} \right)^0.1$$

The single most important feature of the resulting correlation is the apparent dominance of exit plane mixing represented by $\epsilon$. This is intuitively apparent from Figure 11 since in spite of the wide range of variables studied all points are relatively close to the diagonal line representing $S_L = 1$. It should be noted that jet Reynolds number, temperature, and velocity ratio have little effect on the calculated value of $S_L$. Actually, velocity ratio is dominant in the expression for the coaxial flow influence function $f$, but since the initial velocity ratio itself is the inverse of the initial separation ratio, the velocity ratio appears as a weak term in the expression for $S_L$. The chief influence of the molecular weight ratio is evidently to diminish almost to insignificance the effects of geometry, as expressed by the ratio of axial position to initial jet diameter.

It is evident then, both from considering the nature of the above correlations and inspection of the profile
data, that wake mixing phenomena at the exit plane are strongly
dominant in the regime studied, and that normal jet spreading
and mixing characteristics are only very weakly present. The
factors controlling the influence of these wake phenomena are
not obvious from analysis of the data. The delay of large
scale turbulence to a point well beyond the exit plane by
the injection tubing had little apparent effect on mixing at
the exit plane.

Scale, rather than injection techniques, may
be the factor determining the degree of the wake mixing effect
on separation ratio. The maximum jet diameter studied was two
centimeters, and no discernable difference between the one-
centimeter jets can be found, although reference to Appendix E
does show the values of $E$ at the exit plane for the two-
centimeter jets were among the lowest recorded. If increasing
scale could be shown to have a truly diminishing affect on $E$,
this knowledge would be of extreme importance to the coaxial
flow concept. The present experiments must be regarded as
inconclusive in this matter.

The almost negligible effect on the separation
ratio of jet Reynolds number and temperature, which are
included in the term $V_R R_C T_C$, further emphasizes the fact
that at high velocity ratios it is the character of the
external flow which dominates the mixing process. It is of
some interest, nevertheless, to investigate the product
$V_R R_C T_C$. Assuming roughly that the equation of state for a
perfect gas is applicable, and that viscosity increases as the
square root of temperature, it can be readily shown that
Here $P$ is the pressure, $R$ is the universal gas constant, and $\mu$ is the viscosity taken at a reference temperature $T_e$. The other terms have been defined previously. Note that the core velocity does not appear, and that the result can be written as a Reynolds number which contains a gas density based on the geometric mean temperature of the core gas and exterior gas. It is seen that even in this relatively weak expression exterior flow properties dominate, and, in particular, the core temperature has only a weak influence on the overall mixing process.

The expression for the overall separation ratio $S$ is obtained as discussed previously:

$$S = \frac{\int_0^L S_L \, dZ}{L} = (\xi + \frac{3}{2D} \frac{L}{\alpha}) \alpha 0.1 \left( \frac{V_{R+C}}{1.000} \right)^{0.1}$$

where $L$ in all cases is the maximum length studied and is equal to 2 initial core diameters.

It is premature to use the above expression to predict the feasibility of the coaxial flow rocket. The present work has chiefly shown that exterior flow characteristics dominate the separation ratio, but has shed little light on the dependence of $\xi$ on system dimensions. An experiment mainly concerned with exit plane mixing phenomena is indicated at this point, before further arcjet simulation experiments are warranted.
REFERENCES


22. Rom, Frank "Nuclear Rocket Propulsion", NASA SP-20, NASA Lewis Research Center, Cleveland, Ohio, December 1962, pp. 3-16.
APPENDIX A: List of Symbols

Symbols used in the main body of the report and in Appendix B are listed here. Special symbols used in Appendix D are defined in Figure Appendix D-1.

\begin{itemize}
    \item $C_P$: Specific heat (Btu/lb-°F)
    \item $\bar{C}_P$: Effective specific heat (Btu/lb-°F)
    \item $C^*$: Cold helium mole fraction
    \item D: Nozzle diameter (appropriate units)
    \item f: Influence function (dimensionless)
    \item h: Total enthalpy (Btu/lb)
    \item I: Ionization energy per ionization (erg)
    \item k: Boltzmann constant ($1.38 \times 10^{-16}$ erg/°K)
    \item L: Chamber length, also maximum downstream location
    \item M: Molecular weight
    \item m: Mass flow rate (gm/sec)
    \item n: Number density
    \item P: Static pressure (psi or dynes/cm$^2$)
    \item $R$: Universal gas constant
    \item R: Reynolds number
    \item S: Separation ratio
    \item T: Temperature (°R or °K)
    \item u: Local axial velocity
    \item V: Average axial velocity
    \item $V_R$: Initial velocity ratio
    \item $X_i$: Mole fraction of species i
\end{itemize}
List of Symbols Contd.

\[ \bar{X} = \frac{X_{AR}}{M_{AR}} + \frac{M_{E}}{M_{AR}} + X_{E} \]

\[ \bar{z} \quad \text{Axial coordinate} \]

**Greek Letters**

- \( \alpha \): Molecular weight ratio, exterior to core
- \( \mu \): Viscosity
- \( \rho \): Density
- \( \epsilon \): Exit plane mixing factor
- \( \chi \): Argon mole fraction

**Subscripts**

- \( a \): Atmosphere
- \( Ar \): Argon atoms
- \( AI \): Argon atoms and ions
- \( c \): Core (jet)
- \( E \): Electrons
- \( e \): Exterior (coaxial)
- \( L \): Local value
- \( 1 \): Exit plane location
- \( 2 \): 1/2 Nozzle diameter downstream
- \( 3 \): 1 Nozzle diameter downstream
- \( 4 \): 2 Nozzle diameters downstream

**Superscript**

- \( o \): Nominal initial conditions
APPENDIX B: Data Reduction

The necessary input data for the computerized data reduction program are the output from the thermal conductivity cell, probe water thermocouples, gas sample exit temperature thermocouple, radial position potentiometer, probe water flow, and critical orifice stagnation pressure. These data were obtained in the following manner:

The probe was aligned optically with the left and right edges of the nozzle to calibrate the radial potentiometer position indicator. The thermal conductivity cell readings for pure argon and pure helium (nitrogen for certain tests) were used to set zero and range on the recording potentiometer. The 1,000-gallon test tank was evacuated and filled with the desired atmosphere.

The probe was then placed at the desired axial position and moved radially through a series of positions, each of which constituted a data "point". After passing through the region of interest the probe was moved to another axial location and the procedure repeated. During the time the gas sample was flowing, recordings were taken of the thermal conductivity cell reading, the gas sample flow rate manometer levels, the probe water differential temperature, and the probe exit gas temperature. When the gas sample was shut off for the "tare" reading, the stagnation pressure manometer indication was also recorded. The torch readings, consisting of coolant flow rate and tempera-
ture rise, torch current and voltage, and argon flow rate, all of which remained constant during the taking of a "point", were recorded while waiting for the probe instrumentation to stabilize. The outputs from the thermal conductivity cell, probe water thermocouples, gas sample exit temperature thermocouple, and radial position potentiometer were recorded on Leeds and Northrop recording potentiometers in the Guggenheim Laboratories central recording room. All other data were noted visually from the control panel in the test cell.

The above mentioned data, along with the barometric pressure, were listed on a data sheet from which IBM punched cards were made. The information was then processed on an IBM 1620 computer. The computer output gave values of temperature, velocity, gas composition, degree of ionization, mass flow, and jet power at each data point.

The computer program contained all the necessary calibrations to convert the probe output into useful information. From this information the enthalpy at the probe tip was given by

\[ h = \Delta^2 T_w \frac{m_w}{m_g} - C_{go} T_{go} \]

where \( \Delta^2 T_w \) was the change in temperature rise of the probe water for the gas "flow" and "no flow" conditions. In a plasma with any degree of ionization the enthalpy is a complex function of temperature and helium mole fraction.
(nitrogen will be discussed later). It is impossible to compute the temperature directly since the true helium mole fraction in the plasma is not the same as the value measured in the thermal conductivity cell. The two values are related by

\[
C^* = (1 - X_E) C
\]

The value of \( X_E \) is determined, assuming thermal equilibrium and low ionization fractions, by use of the Saha equation

\[
K_n = \frac{n_e^2}{n_{Ar}} = \frac{X_e^2}{X_{Ar}} \quad n = \text{const.} \ T^{3/2} e^{-E_{ion} / kT}
\]

Define

\[
K_x = \frac{X_e^2}{X_{Ar}} = \frac{K_n kT}{P}
\]

Assuming a perfect gas,

\[
P = n kT
\]

and

\[
K_x = \frac{X_e^2}{X_{Ar}} = \frac{K_n kT}{P}
\]

Putting in the values for argon gives:

\[
K_x = 2.309 \times 10^{-6} T^{2.55} e^{-1.8282 \times 10^{-5}/T}
\]

From continuity

\[
X_A + 2X_E = 1 - C^*
\]
By assuming initial values of $T$ and $C^*$, the composition and enthalpy are computed. The computed values of enthalpy and "cold" (cell reading) helium mole fraction are compared to the known experimental values. Using a Newton-Raphson technique, the actual temperature and composition are obtained by iterating until computed and experimental values agree. A flow diagram from the temperature determination loop is given at the end of this Appendix.

The procedure for determining the temperature when the secondary gas was nitrogen was essentially the same; however, several added problems arise. The secondary gas can now dissociate and ionize, and the specific heat is now a function of temperature. In order to simplify the calculations it was assumed that the nitrogen would not ionize, since only very small amounts of nitrogen would be found in the regions of the jet hot enough to cause any measurable degree of ionization. This assumption was verified experimentally.

The amount of dissociated nitrogen was determined from the relations:

$$\frac{\left[ n_n \right]^2}{\left[ n_{N_2} \right]} = \frac{K_s}{K_R} = K_n$$

$$K_x = \frac{K_n}{n} = \frac{R}{P} K_n$$

Thus

$$X_e = -K_x + \sqrt{K_x^2 + K_n(1 - C^*)}$$
Putting in the values for nitrogen gives:

\[
K_x = \left[ \frac{X_N}{X_{N_1}} \right]^2 = 1.57 \times 10^3 \frac{T}{P_0} e^{-113,200/T}
\]

From continuity:

\[
\frac{X_N}{K_x} + X_N = X_{N_1}^*
\]

where

\[X_{N_1}^*\] is the mole fraction of nitrogen as read by the thermal conductivity cell.

Thus:

\[
X_N = -\frac{K_x}{2} + \frac{1}{2} \sqrt{K_x^2 + 4K_x X_{N_1}^*}
\]

Since the enthalpy of the sample gas must be computed theoretically, the enthalpy of the nitrogen was calculated as follows:

\[
C_V = C_{V\ text{\ translation}} + C_{V\ text{\ rotation}} + C_{V\ text{\ vibration}}
+ C_{V\ text{\ excitation}}
\]

\[C_{V\ text{\ translation}} = \frac{3}{2} R\]

\[C_{V\ text{\ rotation}} = R\]

\[C_{V\ text{\ vibration}} = \sum_{i} \frac{R \left( \frac{\Theta_i}{T} \right)^2 \frac{\Theta_i}{T}}{\left( e^{\Theta_i/T} - 1 \right)^2} \]

where for nitrogen \[\Theta_i = 3400^\circ K\]

\[C_p = C_V + R\]
Thus

$$C_P = \frac{7}{2} R + \sum \frac{R \left(\frac{3400}{T} \right)^2 e^{2400/T}}{\left(e^{3400/T} - 1 \right)^2} + C_{\text{excitation}}$$

where $C_P$ was determined from tabulated data.

By definition:

$$H = \int C_P (T) \, dT$$

Defining an effective specific heat

$$\bar{C}_P = \int_{0}^{T} C_P (T') \, dT'/T$$

$$H = \bar{C}_P T$$

$\bar{C}_P$ was computed by numerical integration of the above definitions.

Knowing the temperature and composition, the density was computed using the perfect gas law. Velocity could then be computed using the Bernoulli equation or the equation for compressible flow, as appropriate.
TEMPERATURE LOOP
FLOW DIAGRAM

C & H

\[ T = \frac{H}{C_{p_{go}}} \]

IF \( T \leq 27,000 \)

\[ T = 27,000 \]

COMPOSITION
SUBROUTINE

IF \( x_e \leq 0.001 \)

\[ \text{COMPUTE } H' \]

IF \( (C_1^* - C_2^*) \leq 0.001 \)

\[ T = T - \frac{H - H'}{\frac{dH}{dT}} \]

IF \( (H - H') \leq 10.0 \)

\[ \text{COMPUTE } \rho \& V \]
APPENDIX C: Mixing Data

Conditions for each experiment together with the coordinates used in obtaining average characteristics are tabulated separately, mixing profiles for each run are then presented.

Runs E-1, G-4, G-5, H-1, and H-2 were not used in the correlation developed and are not listed in Table I. These mixing profiles are included, however, for information purposes.
DATA SUMMARY, JET - COAXIAL FLOW MIXING EXPERIMENTS

RUN NO. A-1

NOZZLE DIAMETER = 1.0 CM  ARGON MASS FLOW = 0.10Gm/SEC
COAXIAL FLOW GAS - NITROGEN  NOMINAL CUAXIAL VELOCITY = 100 FT/SEC
FLOW STRAIGHTENER TUBE DIAM., 1/16 IN.

NOMINAL INITIAL CONDITIONS

JET VELOCITY 1.4 FT/SEC  JET REYNOLDS NO. 238.
VELOCITY RATIO 71.39

PROFILE COORDINATES

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AVERAGE CHARACTERISTICS OF JET COLUMN

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DATA SUMMARY, JET - COAXIAL FLOW MIXING EXPERIMENTS

---

RUN NO. A-2

NOZZLE DIAMETER = 1.0 CM ARGON MASS FLOW = 2.32G/M SEC
COAXIAL FLOW GAS - NITROGEN NOMINAL COAXIAL VELOCITY = 100. FT/SEC
FLOW STRAIGHTENER TUBE DIAM., 1/16 IN.

NOMINAL INITIAL CONDITIONS

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PROFILE COORDINATES

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DATA SUMMARY, JET - COAXIAL FLOW MIXING EXPERIMENTS

RUN NO. A-3

NOZZLE DIAMETER = 1.0 CM ARGON MASS FLOW = 5.74 GM/SEC
COAXIAL FLOW GAS - NITROGEN NOMINAL COAXIAL VELOCITY = 100. FT/SEC
FLOW STRAIGHTENER TUBE DIAM., 1/16 IN.

NOMINAL INITIAL CONDITIONS

JET VELOCITY 150.9 FT/SEC JET REYNOLDS NO. 18748.
VELOCITY RATIO .66

PROFILE COORDINATES

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DATA SUMMARY, JET - COAXIAL FLOW MIXING EXPERIMENTS

RUN NO. A-4

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NOZZLE DIAMETER= 1.0 CM ARGON MASS FLOW= .40GM/SEC
COAXIAL FLOW GAS-NITROGEN NOMINAL COAXIAL VELOCITY= 308.0 FT/SEC
FLOW STRAIGHTENOR TUBE DIAM., 1/8 IN.

NOMINAL INITIAL CONDITIONS

---

JET VELOCITY  5.6 FT/SEC  JET REYNOLDS NO.  953.
VELOCITY RATIO  54.97

PROFILE COORDINATES

---

AXIAL
POSITION
NOZZLE
(DIAMETERS)
EXIT  0.  0.  0.000  0.  0.730  0.027  0.270
1/2  0.  0.  0.000  0.  0.807  0.019  0.250
1  0.  0.  0.000  0.  0.865  0.014  0.195
2  0.  0.  0.000  0.  0.967  0.003  0.100

AVERAGE CHARACTERISTICS OF JET COLUMN

---

AXIAL POSITION (NOZZLE DIAMS)  EXIT  1/2  1  2

VELOCITY, FT/SEC  276.  286.  293.  304.5
LOCAL SEPARATION RATIO  .89  .92  .95  .98
ARGON MOLE FRACTION  .14318  .09998  .06622  .01439
TEMPERATURE RATIO  1.00000  1.00000  1.00000  1.00000
DATA SUMMARY, JET - COAXIAL FLOW MIXING EXPERIMENTS

RUN NO. A-5

NOZZLE DIAMETER= 1.0 CM   ARGON MASS FLOW= .90GM/SEC
COAXIAL FLOW GAS=NITROGEN   NOMINAL COAXIAL VELOCITY= 305 FT/SEC
FLOW STRAIGHTENOR TUBE DIAM., 1/8 IN.

NOMINAL INITIAL CONDITIONS

JET VELOCITY 23.6 FT/SEC    JET REYNOLDS NO. 2939.
VELOCITY RATIO 12.89

PROFILE COORDINATES

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(DIAMETERS)

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AVERAGE CHARACTERISTICS OF JET COLUMN

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DATA SUMMARY, JET - COAXIAL FLOW MIXING EXPERIMENTS

RUN NO. A-6

NOZZLE DIAMETER = 1.0 CM  ARGON MASS FLOW = 4.10GM/SEC
COAXIAL FLOW GAS - NITROGEN  NOMINAL COAXIAL VELOCITY = 308.0 FT/SEC
FLOW STRAIGHTENER TUBE DIAMETER, 1/8 IN.

NOMINAL INITIAL CONDITIONS

JET VELOCITY 107.7 FT/SEC  JET REYNOLDS NO. 13391.
VELOCITY RATIO 2.85

PROFILE COORDINATES

AXIAL POSITION
NOZZLE (DIAMETERS) P Q S T A G B
EXIT 0.0 0.0 0.000 0.0 0.000 0.100 0.517
1/2 0.0 0.0 0.000 0.0 0.018 0.098 0.480
1 0.0 0.0 0.000 0.0 0.135 0.087 0.395
2 0.0 0.0 0.000 0.0 0.775 0.023 0.390

AVERAGE CHARACTERISTICS OF JET COLUMN

AXIAL POSITION (NOZZLE DIAMS) EXIT 1/2 1 2
VELOCITY, FT/SEC 176. 184. 209. 282.0
LOCAL SEPARATION RATIO .57 .59 .67 .91
ARGON MOLE FRACTION .69756 .65751 .52709 .13644
TEMPERATURE, R 550.0 550.0 550.0 550.0
TEMPERATURE RATIO 1.00000 1.00000 1.00000 1.00000
DATA SUMMARY, JET - COAXIAL FLOW MIXING EXPERIMENTS

RUN NO. A-7

NOZZLE DIAMETER = 1. CM ARGON MASS FLOW = 4.40GM/SEC
COAXIAL FLOW GAS-NITROGEN NOMINAL COAXIAL VELOCITY = 573. FT/SEC
FLOW STRAIGHTENOR TUBE DIAM., 1/8 IN.

NOMINAL INITIAL CONDITIONS

JET VELOCITY = 61.6 FT/SEC JET REYNOLDS NO. = 10490.
VELOCITY RATIO = 9.29

PROFILE COORDINATES

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AVERAGE CHARACTERISTICS OF JET COLUMN

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DATA SUMMARY, JET - COAXIAL FLOW MIXING EXPERIMENTS

RUN NO. A-8

NOZZLE DIAMETER = 1.0 CM, ARGON MASS FLOW = 2.20 GM/SEC
COAXIAL FLOW GAS - NITROGEN NOMINAL COAXIAL VELOCITY = 563.0 FT/SEC
FLOW STRAIGHTENOR TUBE DIAM., 1/8 IN.

NOMINAL INITIAL CONDITIONS

JET VELOCITY 57.8 FT/SEC JET REYNOLDS NO. 7185.
VELOCITY RATIO 9.73

PROFILE COORDINATES

AXIAL POSITION

NOZZLE (DIAMETERS) P Q S T A G B
EXIT 0.0 0.0 0.000 0.0 0.346 0.065 0.530
1/2 0.0 0.0 0.000 0.0 0.732 0.027 0.720
1 0.0 0.0 0.000 0.0 0.808 0.019 0.460
2 0.0 0.0 0.000 0.0 0.907 0.009 0.560

AVERAGE CHARACTERISTICS OF JET COLUMN

AXIAL POSITION (NOZZLE DIAMS) EXIT 1/2 1 2
VELOCITY, FT/SEC 379. 471. 513. 536.
LOCAL SEPARATION RATIO .67 .83 .91 .95
ARGON MOLE FRACTION .46280 .23290 .12571 .06804
TEMPERATURE RATIO 1.00000 1.00000 1.00000 1.00000
DATA SUMMARY, JET - COAXIAL FLOW MIXING EXPERIMENTS

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

RUN NO. A-9
-----------------------------

NOZZLE DIAMETER= 1. CM
ARGON MASS FLOW= 4.10GM/SEC
COAXIAL FLOW GAS-NITROGEN
NOMINAL COAXIAL VELOCITY= 560 FT/SEC
FLOW STRAIGHTENER TUBE DIAM., 1/8 IN.

NOMINAL INITIAL CONDITIONS
-----------------------------

JET VELOCITY 107.7FT/SEC
JET REYNOLDS NO. 13391.
VELOCITY RATIO 5.19

PROFILE COORDINATES
-----------------------------

AXIAL
POSITION
NOZZLE
(DIAMETERS)
EXIT 0. 0. 0.000 0. .040 .096 .520
1/2 0. 0. 0.000 0. .330 .067 .500
1 0. 0. 0.000 0. .650 .035 .540
2 0. 0. 0.000 0. .830 .017 .470

AVERAGE CHARACTERISTICS OF JET COLUMN
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AXIAL POSITION (NOZZLE DIAMS) EXIT 1/2 1 2

LOCAL SEPARATION RATIO .53 .68 .83 .92
ARGON MOLE FRACTION .67188 .45867 .25041 .11257
TEMPERATURE RATIO 1.00000 1.00000 1.00000 1.00000
DATA SUMMARY, JET - COAXIAL FLOW MIXING EXPERIMENTS

RUN NO. B-1
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NOZZLE DIAMETER= 1. CM ARGON MASS FLOW= .10GM/SEC
COAXIAL FLOW GAS-HELIUM NOMINAL COAXIAL VELOCITY= 10. FT/SEC
FLOW STRAIGHTENOR TUBE DIAM., 1/8 IN.

NOMINAL INITIAL CONDITIONS
-----------------------------
JET VELOCITY 1.4 FT/SEC JET REYNOLDS NO. 238.
VELOCITY RATIO 7.13

PROFILE COORDINATES
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AXIAL
POSITION
NOZZLE (DIAMETERS) P Q S T A G B
EXIT 0. 0. 0.000 0. 0.257 0.074 0.275
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1 0. 0. 0.000 0. 0.345 0.066 0.185
2 0. 0. 0.000 0. 0.675 0.033 0.170

AVERAGE CHARACTERISTICS OF JET COLUMN
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AXIAL POSITION (NOZZLE DIAMS) EXIT 1/2 1 2
VELOCITY, FT/SEC 3. 4. 4. 6.
LOCAL SEPARATION RATIO .38 .41 .43 .60
ARGON MOLE FRACTION .39606 .35036 .31687 .15485
TEMPERATURE RATIO 1.00000 1.00000 1.00000 1.00000
DATA SUMMARY, JET - COAXIAL FLOW MIXING EXPERIMENTS

RUN NO. B-2
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NOZZLE DIAMETER= 1.0 CM ARGON MASS FLOW= 2.15GM/SEC
COAXIAL FLOW GAS-HELIUM NOMINAL COAXIAL VELOCITY= 10.0FT/SEC
FLOW STRAIGHTENER TUBE DIAM., 1/8 IN.

NOMINAL INITIAL CONDITIONS
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JET VELOCITY  56.5FT/SEC JET REYNOLDS NO. 7022.
VELOCITY RATIO  .17

PROFILE COORDINATES
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DATA SUMMARY, JET - COAXIAL FLOW MIXING EXPERIMENTS

RUN NO. B-3

NOZZLE DIAMETER = 1.0 CM  ARGON MASS FLOW = .10 GM/SEC
COAXIAL FLOW GAS HELIUM  NOMINAL COAXIAL VELOCITY = 49.0 FT/SEC
FLOW STRAIGHTENOR TUBE DIAM., 1/8 IN.

NOMINAL INITIAL CONDITIONS

JET VELOCITY 1.4 FT/SEC  JET REYNOLDS NO. 238.
VELOCITY RATIO 34.98

PROFILE COORDINATES

AXIAL
POSITION
NOZZLE
(DIAMETERS) P Q S T A G B
EXIT 0. 0. 0.000 0. 680 0.032 0.170
1/2 0. 0. 0.000 0. 725 0.028 0.180
1 0. 0. 0.000 0. 775 0.023 0.190
2 0. 0. 0.000 0. 965 0.004 0.550

AVERAGE CHARACTERISTICS OF JET COLUMN

AXIAL POSITION (NOZZLE DIAMS) EXIT 1/2 1 2

VELOCITY, FT/SEC 29. 30. 32. 43.
LOCAL SEPARATION RATIO .59 .62 .66 .89
ARGON MOLE FRACTION .15220 .13248 .10960 .02529
TEMPERATURE RATIO 1.00000 1.00000 1.00000 1.00000
DATA SUMMARY, JET - COAXIAL FLOW MIXING EXPERIMENTS

RUN NO. B-4

NOZZLE DIAMETER = 1.0 CM  ARGON MASS FLOW = .80GM/SEC  
COAXIAL FLOW GAS-HELIUM  NOMINAL COAXIAL VELOCITY = 48 FT/SEC  
FLOW STRAIGHTENER TUBE DIAMETER, 1/8 IN.

NOMINAL INITIAL CONDITIONS

JET VELOCITY  21.0 FT/SEC  JET REYNOLDS NO.  2612.  
VELOCITY RATIO  2.31

PROFILE COORDINATES

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AVERAGE CHARACTERISTICS OF JET COLUMN

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### DATA SUMMARY, JET - COAXIAL FLOW MIXING EXPERIMENTS

**RUN NO. C-1**

**NOZZLE DIAMETER** = 1.0 CM  
**ARGON MASS FLOW** = 0.10GM/SEC  
**COAXIAL FLOW GAS** = HELIUM  
**NOMINAL COAXIAL VELOCITY** = 10.0 FT/SEC  
**FLOW STRAIGHTENER** = TUBE DIAM. = 1/16 IN.

**NOMINAL INITIAL CONDITIONS**

- **JET VELOCITY** = 1.4 FT/SEC  
- **JET REYNOLDS NO.** = 238. 
- **VELOCITY RATIO** = 7.13

**PROFILE COORDINATES**

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**AVERAGE CHARACTERISTICS OF JET COLUMN**

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DATA SUMMARY, JET - COAXIAL FLOW MIXING EXPERIMENTS

RUN NO. C-2

NOZZLE DIAMETER = 1.0 CM  ARGON MASS FLOW = .90GM/SEC
COAXIAL FLOW GAS - HELIUM  NOMINAL COAXIAL VELOCITY = 49.0 FT/SEC
FLOW STRAIGHTENER OR TUBE DIAM., 1/16 IN.

NOMINAL INITIAL CONDITIONS

JET VELOCITY 23.6 FT/SEC  JET REYNOLDS NO. 2939.
VELOCITY RATIO 2.07

PROFILE COORDINATES

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AVERAGE CHARACTERISTICS OF JET COLUMN

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DATA SUMMARY, JET - COAXIAL FLOW MIXING EXPERIMENTS

RUN NO. D-1

NOZZLE DIAMETER = 1.0 CM ARGON MASS FLOW = 2.20GM/SEC
COAXIAL FLOW GAS - NITROGEN NOMINAL COAXIAL VELOCITY = 565.0 FT/SEC
FLOW STRAIGHTENER TUBE DIAM., 1/16 IN.

NOMINAL INITIAL CONDITIONS

JET VELOCITY 57.8 FT/SEC JET REYNOLDS NO. 7185
VELOCITY RATIO 9.76

PROFILE COORDINATES

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AVERAGE CHARACTERISTICS OF JET COLUMN

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DATA SUMMARY, JET - COAXIAL FLOW MIXING EXPERIMENTS

RUN NO. E-2

NOZZLE DIAMETER= 1. CM  ARGON MASS FLOW= .90GM/SEC
COAXIAL FLOW GAS-NITROGEN  NOMINAL COAXIAL VELOCITY= 780.FT/SEC
FLOW STRAIGHTENER TUBE DIAM., 1/16 IN.

NOMINAL INITIAL CONDITIONS

JET VELOCITY 23.6FT/SEC  JET REYNOLDS NO. 2939.
VELOCITY RATIO 32.96

PROFILE COORDINATES

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AVERAGE CHARACTERISTICS OF JET COLUMN

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DATA SUMMARY, JET - COAXIAL FLOW MIXING EXPERIMENTS

RUN NO. E-3

NOZZLE DIAMETER= 1. CM  ARGON MASS FLOW= 4.00GM/SEC
COAXIAL FLOW GAS-NITROGEN  NOMINAL COAXIAL VELOCITY= 780. FT/SEC
FLOW STRAIGHTENER TUBE DIAM., 1/16 IN.

NOMINAL INITIAL CONDITIONS

JET VELOCITY 105.1FT/SEC  JET REYNOLDS NO. 13064.
VELOCITY RATIO 7.41

PROFILE COORDINATES

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AVERAGE CHARACTERISTICS OF JET COLUMN

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DATA SUMMARY, JET - COAXIAL FLOW MIXING EXPERIMENTS

RUN NO. F-1
--------------------
NOZZLE DIAMETER = 1.0 CM ARGON MASS FLOW = 1.20 GM/SEC
COAXIAL FLOW GAS = HELIUM NOMINAL COAXIAL VELOCITY = 0 FT/SEC
FLOW STRAIGHTENER TUBE DIAM. = 1/16 IN.

NOMINAL INITIAL CONDITIONS
-----------------------------
JET VELOCITY 31.5 FT/SEC JET REYNOLDS NO. 3919.
VELOCITY RATIO 0.00

PROFILE COORDINATES
---------------------
| AXIAL POSITION | P | Q | S | T | A | G | B |
| NOZZLE (DIAMETERS) | | | | | | | |
| EXIT | 0.0 | 0.0 | 0.000 | 0.0 | 0.000 | 100.0 | 390.0 |
| 1/2 | 0.0 | 0.0 | 0.000 | 0.0 | 0.000 | 100.0 | 370.0 |
| 1 | 0.0 | 0.0 | 0.000 | 0.0 | 0.000 | 100.0 | 315.0 |
| 2 | 0.0 | 0.0 | 0.000 | 0.0 | 0.020 | 0.98 | 1.85 |

AVERAGE CHARACTERISTICS OF JET COLUMN
--------------------------------------
| AXIAL POSITION (NOZZLE DIAMS) | EXIT | 1/2 | 1 | 2 |
| VELOCITY, FT/SEC | 30.0 | 30.0 | 30.0 | 29.0 |
| LOCAL SEPARATION RATIO | 3.05 | 3.05 | 3.03 | 2.98 |
| ARGON MOLE FRACTION | 0.60583 | 0.59249 | 0.55735 | 0.46229 |
| TEMPERATURE, R | 550.0 | 550.0 | 550.0 | 550.0 |
| TEMPERATURE RATIO | 1.00000 | 1.00000 | 1.00000 | 1.00000 |
DATA SUMMARY, JET - COAXIAL FLOW MIXING EXPERIMENTS

RUN NO. F-2

NOZZLE DIAMETER= 1. CM ARGON MASS FLOW= 2.40GM/SEC
COAXIAL FLOW GAS-HELIUM NOMINAL COAXIAL VELOCITY= 0. FT/SEC
FLOW STRAIGHTENOR TUBE DIAM., 1/16 IN.

NOMINAL INITIAL CONDITIONS

JET VELOCITY 63.0FT/SEC JET REYNOLDS NO. 7838.
VELOCITY RATIO 0.00

PROFILE COORDINATES

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AVERAGE CHARACTERISTICS OF JET COLUMN

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DATA SUMMARY, JET - COAXIAL FLOW MIXING EXPERIMENTS
------------------------------------------------------

RUN NO. F-3
----------
NOZZLE DIAMETER= 1.0 CM  ARGON MASS FLOW= 2.40G/M SEC
COAXIAL FLOW GAS-HELIUM  NOMINAL COAXIAL VELOCITY= 29.4/SEC
FLOW STRAIGHTENER TUBE DIAM., 1/16 IN.

NOMINAL INITIAL CONDITIONS
-------------------------------
JET VELOCITY 63.0FT/SEC  JET REYNOLDS NO. 7838.
VELOCITY RATIO 0.46

PROFILE COORDINATES
----------------------

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AVERAGE CHARACTERISTICS OF JET COLUMN
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DATA SUMMARY, JET - COAXIAL FLOW MIXING EXPERIMENTS

RUN NO. F-4

NOZZLE DIAMETER = 1.0 CM  ARGON MASS FLOW =  .10GM/SEC
COAXIAL FLOW GAS-HELIUM  NOMINAL COAXIAL VELOCITY =  1.0 FT/SEC
FLOW STRAIGHTENER TUBE DIAM. = 1/16 IN.

NOMINAL INITIAL CONDITIONS

JET VELOCITY = 1.4 FT/SEC  JET REYNOLDS NO. = 238.
VELOCITY RATIO = .71

PROFILE COORDINATES

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AVERAGE CHARACTERISTICS OF JET COLUMN

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DATA SUMMARY, JET - COAXIAL FLOW MIXING EXPERIMENTS

RUN NO. F-5

NOZZLE DIAMETER= 1. CM  ARGON MASS FLOW= .20GM/SEC
COAXIAL FLOW GAS=HELIUM  NOMINAL COAXIAL VELOCITY= 3. FT/SEC
FLOW STRAIGHTENOR TUBE DIAM=.1/16  IN.

NOMINAL INITIAL CONDITIONS

JET VELOCITY  2.8FT/SEC  JET REYNOLDS NO.  476.
VELOCITY RATIO  1.07

PROFILE COORDINATES

AXIAL
POSITION
NOZZLE 
(DIAMETERS)
EXIT  0.  0. 0.000  0.  0.000  .100  .190
1/2  0.  0. 0.000  0.  0.000  .100  .185
1  0.  0. 0.000  0.  0.000  .100  .185
2  0.  0. 0.000  0.  .027  .097  .150

AVERAGE CHARACTERISTICS OF JET COLUMN

AXIAL POSITION (NOZZLE DIAMS)  EXIT  1/2  1  2
VELOCITY, FT/SEC  2.  2.  2.  2.
LOCAL SEPARATION RATIO .94  .94  .94  .94
ARGON MOLE FRACTION  .48597  .48336  .48336  .45287
TEMPERATURE RATIO  1.00000  1.00000  1.00000  1.00000
DATA SUMMARY, JET - COAXIAL FLOW MIXING EXPERIMENTS

RUN NO. G-1

NOZZLE DIAMETER = 1. CM ARGON MASS FLOW = 2.40 GM/SEC
COAXIAL FLOW GAS - NITROGEN NOMINAL COAXIAL VELOCITY = 0. FT/SEC
FLOW STRAIGHTENOR TUBE DIAM., 1/16 IN.

NOMINAL INITIAL CONDITIONS

| JET VELOCITY | 63.0 FT/SEC | JET REYNOLDS NO. | 7838 |
| VELOCITY RATIO | 0.00 |

PROFILE COORDINATES

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AVERAGE CHARACTERISTICS OF JET COLUMN

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DATA SUMMARY, JET - COAXIAL FLOW MIXING EXPERIMENTS

RUN NO. G-2

NOZZLE DIAMETER= 1 CM ARGON MASS FLOW= .10GM/SEC
COAXIAL FLOW GAS-NITROGEN NOMINAL COAXIAL VELOCITY= 1 FT/SEC
FLOW STRAIGHTENOR TUBE DIAM., 1/16 IN.

NOMINAL INITIAL CONDITIONS

JET VELOCITY 1.4FT/SEC JET REYNOLDS NO. 238.
VELOCITY RATIO .71

PROFILE COORDINATES

AXIAL POSITION
NOZZLE (DIAMETERS) P Q S T A G B
EXIT 0. 0. 0.000 0.005 0.099 0.125
1/2 0. 0. 0.000 0.040 0.096 0.120
1 0. 0. 0.000 0.100 0.090 0.105
2 0. 0. 0.000 0.324 0.068 0.110

AVERAGE CHARACTERISTICS OF JET COLUMN

AXIAL POSITION (NOZZLE DIAMS) EXIT 1/2 1 2
VELOCITY, FT/SEC 1. 1. 1. 1.
LOCAL SEPARATION RATIO 1.23 1.22 1.21 1.16
ARGON MOLE FRACTION .44791 .43309 .39973 .30204
TEMPERATURE RATIO 1.00000 1.00000 1.00000 1.00000
DATA SUMMARY, JET - COAXIAL FLOW MIXING EXPERIMENTS

RUN NO. G-3

NOZZLE DIAMETER= 1. CM  ARGON MASS FLOW= .20GM/SEC
COAXIAL FLOW GAS-NITROGEN  NOMINAL COAXIAL VELOCITY= 3. FT/SEC
FLOW STRAIGHTENER TUBE DIAM., 1/16 IN.

NOMINAL INITIAL CONDITIONS

JET VELOCITY 2.8FT/SEC  JET REYNOLDS NO. 476.
VELOCITY RATIO  1.07

PROFILE COORDINATES

AXIAL
POSITION
NOZZLE
(DIAMETERS)
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1/2 0. 0. 0.000 0. 0.000 .100 .240
1 0. 0. 0.000 0. 0.000 .100 .200
2 0. 0. 0.000 0. 0.040 .096 .195

AVERAGE CHARACTERISTICS OF JET COLUMN

AXIAL POSITION (NOZZLE DIAMS)  EXIT 1/2  1  2

VELOCITY, FT/SEC  2.  2.  2.  2.
LOCAL SEPARATION RATIO  .96  .96  .96  .96
ARGON MOLE FRACTION  .51311  .51311  .49125  .46906
TEMPERATURE RATIO  1.00000  1.00000  1.00000  1.00000
DATA SUMMARY, JET - COAXIAL FLOW MIXING EXPERIMENTS

RUN NO. P-2

NOZZLE DIAMETER = 1.0 CM  ARGON MASS FLOW = 2.20GM/SEC  COAXIAL FLOW GAS-NITROGEN  NOMINAL COAXIAL VELOCITY = 100.0 FT/SEC  FLOW STRAIGHTENOR TUBE DIAM., POROUS

NOMINAL INITIAL CONDITIONS

JET VELOCITY 57.8 FT/SEC  JET REYNOLDS NO. 7185  VELOCITY RATIO 1.72

PROFILE COORDINATES

AXIAL
POSITION
NOZZLE
(DIAMETERS)

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AVERAGE CHARACTERISTICS OF JET COLUMN

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DATA SUMMARY, JET - COAXIAL FLOW MIXING EXPERIMENTS

RUN NO. P-3

NOZZLE DIAMETER= 1.0 CM ARGON MASS FLOW= 2.20GM/SEC
COAXIAL FLOW GAS-NITROGEN NOMINAL COAXIAL VELOCITY= 100. FT/SEC
FLOW STRAIGHTENER TUBE DIAM., POROUS

NOMINAL INITIAL CONDITIONS

JET VELOCITY 57.8 FT/SEC JET REYNOLDS NO. 7185.
VELOCITY RATIO 1.72

PROFILE COORDINATES

AXIAL
POSITION
NOZZLE
(DIAMETERS)
EXIT 0. 0. 0.000 0. 0.020 0.098 0.380
1/2 0. 0. 0.000 0. 0.195 0.080 0.520
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AVERAGE CHARACTERISTICS OF JET COLUMN

AXIAL POSITION (NOZZLE DIAMS) EXIT 1/2 1 2
VELOCITY, FT/SEC 74. 75. 85. 94.
LOCAL SEPARATION RATIO .74 .75 .85 .94
ARGON MOLE FRACTION .58714 .56340 .31387 .12835
TEMPERATURE RATIO 1.00000 1.00000 1.00000 1.00000
DATA SUMMARY, JET - COAXIAL FLOW MIXING EXPERIMENTS

RUN NO. 2CA

NOZZLE DIAMETER = 2.0 CM ARGON MASS FLOW = .39 GM/SEC
COAXIAL FLOW GAS - NITROGEN NOMINAL COAXIAL VELOCITY = 1.0 FT/SEC
FLOW STRAIGHTENER TUBE DIAM., 1/16 IN.

NOMINAL INITIAL CONDITIONS

JET VELOCITY 2.5 FT/SEC JET REYNOLDS NO. 636.
VELOCITY RATIO .67

PROFILE COORDINATES

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AVERAGE CHARACTERISTICS OF JET COLUMN

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DATA SUMMARY, JET - COAXIAL FLOW MIXING EXPERIMENTS
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RUN NO. 2CB
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COAXIAL FLOW GAS-NITROGEN  NOMINAL COAXIAL VELOCITY= 37. FT/SEC
FLOW STRAIGHTENOR TUBE DIAM., 1/16 IN.

NOMINAL INITIAL CONDITIONS
-----------------------------
JET VELOCITY 12.8 FT/SEC  JET REYNOLDS NUM. 3200.
VELOCITY RATIO 2.87

PROFILE COORDINATES
----------------------
AXIAL
POSITION
NOZZLE (DIAMETERS)  P  Q  S  T  A  G  B
EXIT 0. 0. 0.000 0. .050 .095 1.999
1/2 0. 0. 0.000 0. .500 .050 1.999
1 0. 0. 0.000 0. .620 .040 1.999
2 0. 0. 0.000 0. .750 .025 1.320

AVERAGE CHARACTERISTICS OF JET COLUMN
---------------------------------------------
AXIAL POSITION (NOZZLE DIAMS)  EXIT 1/2  1  2
LOCAL SEPARATION RATIO .44 .71 .78 .89
ARGON MOLE FRACTION .88631 .46648 .35319 .17491
TEMPERATURE RATIO  1.00000 1.00000 1.00000 1.00000
DATA SUMMARY, JET - COAXIAL FLOW MIXING EXPERIMENTS

RUN NO. 2CC

NOZZLE DIAMETER = 2.0 CM ARGON MASS FLOW = 6.30GM/SEC
COAXIAL FLOW GAS - NITROGEN NOMINAL COAXIAL VELOCITY = 176.0 FT/SEC
FLOW STRAIGHTENOR TUBE DIAM., 1/16 IN.

NOMINAL INITIAL CONDITIONS

JET VELOCITY = 41.4 FT/SEC JET REYNOLDS NO. = 10288.
VELOCITY RATIO = 4.25

PROFILE COORDINATES

AXIAL POSITION
NOZZLE (DIAMETERS)

EXIT 0.0 0.0 0.0 0.900 0.010 1.999
1/2 0.0 0.0 0.0 0.920 0.008 1.999
1 0.0 0.0 0.0 0.960 0.004 1.000
2 0.0 0.0 0.0 0.980 0.002 1.000

AVERAGE CHARACTERISTICS OF JET COLUMN

AXIAL POSITION (NOZZLE DIAMS) EXIT 1/2 1 2

VELOCITY, FT/SEC 165.0 167.0 173.0 174.0
LOCAL SEPARATION RATIO .93 .94 .98 .99
ARGON MOLE FRACTION .09329 .07463 .02433 .01216
TEMPERATURE, R 550.0 550.0 550.0 550.0
TEMPERATURE RATIO 1.00000 1.00000 1.00000 1.00000
DATA SUMMARY, JET - COAXIAL FLOW MIXING EXPERIMENTS

RUN NO. HA 3

NOZZLE DIAMETER = 1. CM ARGON MASS FLOW = 1.00GM/SEC
COAXIAL FLOW GAS - NITROGEN NOMINAL COAXIAL VELOCITY = 200. FT/SEC
FLOW STRAIGHTENER TUBE DIAM., 1/16 IN.

NOMINAL INITIAL CONDITIONS

| JET VELOCITY | 167.1 FT/SEC | JET REYNOLDS NO. | 1295. | VELOCITY RATIO | 1.19 |

PROFILE COORDINATES

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AVERAGE CHARACTERISTICS OF JET COLUMN

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DATA SUMMARY, JET - COAXIAL FLOW MIXING EXPERIMENTS

RUN NO. HA 4

NOZZLE DIAMETER= 1. CM ARGON MASS FLOW= 1.00GM/SEC
COAXIAL FLOW GAS-NITROGEN NOMINAL COAXIAL VELOCITY= 135. FT/SEC
FLOW STRAIGHTENER TUBE DIAM., 1/16 IN.

NOMINAL INITIAL CONDITIONS

JET VELOCITY 139.6 FT/SEC JET REYNOLDS NO. 1416.
VELOCITY RATIO .96

PROFILE COORDINATES

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AVERAGE CHARACTERISTICS OF JET COLUMN

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DATA SUMMARY, JET - COAXIAL FLOW MIXING EXPERIMENTS

RUN NO. HA 5
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NOZZLE DIAMETER= 1. CM  ARGON MASS FLOW= 1.00GM/SEC
COAXIAL FLOW GAS-NITROGEN  NOMINAL COAXIAL VELOCITY= 67. FT/SEC
FLOW STRAIGHTENER TUBE DIAM., 1/16  IN.

NOMINAL INITIAL CONDITIONS
---------------------------

JET VELOCITY 144.6FT/SEC  JET REYNOLDS NO. 1392.
VELOCITY RATIO .46

PROFILE COORDINATES
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AVERAGE CHARACTERISTICS OF JET COLUMN
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DATA SUMMARY, JET - COAXIAL FLOW MIXING EXPERIMENTS
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RUN NO. HA 6
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NOZZLE DIAMETER= 1. CM ARGON MASS FLOW= 1.00GM/SEC
COAXIAL FLOW GAS-NITROGEN NOMINAL COAXIAL VELOCITY= 130. FT/SEC
FLOW STRAIGHTENOR TUBE DIAM., 1/16 IN.

NOMINAL INITIAL CONDITIONS
----------------------------
JET VELOCITY 58.3 FT/SEC JET REYNOLDS NO. 2191.
VELOCITY RATIO 2.22

PROFILE COORDINATES
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AVERAGE CHARACTERISTICS OF JET COLUMN
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DATA SUMMARY, JET - COAXIAL FLOW MIXING EXPERIMENTS

RUN NO. HA 7
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NOZZLE DIAMETER = 1.0 CM  ARGON MASS FLOW = 1.00G/M SEC
COAXIAL FLOW GAS = HELIUM  NOMINAL COAXIAL VELOCITY = 67 FT/SEC
FLOW STRAIGHTENOR TUBE DIAM = 1/16 IN.

NOMINAL INITIAL CONDITIONS
---------------------------
JET VELOCITY = 158.2 FT/SEC  JET REYNOLDS NO. = 1331.
VELOCITY RATIO = 0.42

PROFILE COORDINATES
---------------------
AXIAL
POSITION
NOZZLE
(DIAMFTERS)
EXIT 7580. 6822. 500 550. 0.000 .100 .980
1/2 6800. 6120. 400 550. 0.000 .100 .980
1 6570. 5913. 400 550. 0.040 .096 .840
2 4250. 3830. 320 550. 0.350 .065 .300

AVERAGE CHARACTERISTICS OF JET COLUMN
----------------------------------------
AXIAL POSITION (NOZZLE DIAMS) EXIT 1/2 1 2
 VELOCITY, FT/SEC 153. 143. 140. 110.
 LOCAL SEPARATION RATIO 2.29 2.13 2.09 1.64
 ARGON MOLE FRACTION .57717 .57717 .54447 .29266
 TEMPERATURE, R 3309. 2861. 2775. 1849.
 TEMPERATURE RATIO 6.01780 5.20242 5.04630 3.36334
DATA SUMMARY, JET - COAXIAL FLOW MIXING EXPERIMENTS

RUN NO. HA 8

NOZZLE DIAMETER= 1. CM ARGON MASS FLOW= 1.000GM/SEC
COAXIAL FLOW GAS-NITROGEN NOMINAL COAXIAL VELOCITY= 170.FT/SEC
FLOW STRAIGHTENER TUBE DIAM., 1/16 IN.

NOMINAL INITIAL CONDITIONS

| JET VELOCITY | 139.8FT/SEC | JET REYNOLDS NO. | 1416. |
| VELOCITY RATIO | 1.21 |

PROFILE COORDINATES

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AVERAGE CHARACTERISTICS OF JET COLUMN

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DATA SUMMARY, JET - COAXIAL FLOW MIXING EXPERIMENTS

RUN NO. HA 9

NOZZLE DIAMETER = 1. CM ARGON MASS FLOW = 3.00GM/SEC
COAXIAL FLOW GAS - NITROGEN NOMINAL COAXIAL VELOCITY = 355. FT/SEC
FLOW STRAIGHTENER TUBE DIAM. 1/16 IN.

NOMINAL INITIAL CONDITIONS

JET VELOCITY 289.2FT/SEC JET REYNOLDS NO. 5116.
VELOCITY RATIO 1.22

PROFILE COORDINATES

AXIAL POSITION
NOZZLE (DIAMETERS)
EXIT 4100. 3690. .600 550. 0.000 .100 1.000
1/2 3650. 3300. .600 550. .010 .099 .680
1 3150. 2840. .400 550. .092 .090 .600
2 2000. 1800. .200 550. .380 .062 .280

AVERAGE CHARACTERISTICS OF JET COLUMN

AXIAL POSITION (NOZZLE DIAMS) EXIT 1/2 1 2
VELOCITY, FT/SEC 311. 309. 301. 310.
LOCAL SEPARATION RATIO .87 .87 .84 .87
ARGON MOLE FRACTION .60833 .52368 .46360 .27687
TEMPERATURE, R 2017. 1834. 1500. 1013.
TEMPERATURE RATIO 3.66757 3.33575 2.72848 1.84212
DATA SUMMARY, JET - COAXIAL FLOW MIXING EXPERIMENTS

RUN NO. HA10

NOZZLE DIAMETER= 1. CM  ARGON MASS FLOW= 3.00GM/SEC
COAXIAL FLOW GAS-NITROGEN  NOMINAL COAXIAL VELOCITY= 530.FT/SEC
FLOW STRAIGHTENOR TUBE DIAM., 1/16 IN.

NOMINAL INITIAL CONDITIONS

JET VELOCITY 473.6FT/SEC   JET REYNOLDS NO. 3998.
VELOCITY RATIO 1.11

PROFILE COORDINATES

AXIAL
POSITION
NOZZLE
(DIAMETERS)

P     Q     S     T     A     G     B
EXIT  7650  6880  .480  550  0.000  .100  1.100
1/2   5950  5350  .440  550  .030  .100  .760
1     4850  4360  .480  550  .080  .090  .600
2     3600  3240  .360  550  .320  .065  .280

AVERAGE CHARACTERISTICS OF JET COLUMN

AXIAL POSITION (NOZZLE DIAMS) EXIT 1/2 1 2
VELOCITY, FT/SEC 490. 464. 455. 464.
LOCAL SEPARATION RATIO .92 .87 .86 .87
ARGON MOLE FRACTION .63558 .53244 .46916 .30186
TEMPERATURE, R 3302 2589 2207 1641
TEMPERATURE RATIO 6.00494 4.70749 4.01338 2.98364
DATA SUMMARY, JET - COAXIAL FLOW MIXING EXPERIMENTS

RUN NO. HA12

NOZZLE DIAMETER= 1. CM ARGON MASS FLOW= .80GM/SEC
COAXIAL FLOW GAS-NITROGEN NOMINAL COAXIAL VELOCITY= 300 FT/SEC
FLOW STRAIGHTENER TUBE DIAM, 1/16 IN.

NOMINAL INITIAL CONDITIONS

JET VELOCITY 82.5FT/SEC JET REYNOLDS NO. 1319.
VELOCITY RATIO 3.63

PROFILE COORDINATES

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AVERAGE CHARACTERISTICS OF JET COLUMN

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DATA SUMMARY, JET - COAXIAL FLOW MIXING EXPERIMENTS

RUN NO. HA13

NOZZLE DIAMETER = 1. CM ARGON MASS FLOW = .80GM/SEC
COAXIAL FLOW GAS - NITROGEN NOMINAL COAXIAL VELOCITY = 780 FT/SEC
FLOW STRAIGHTENOR TUBE DIAM., 1/16 IN.

NOMINAL INITIAL CONDITIONS

JET VELOCITY 51.2FT/SEC JET REYNOLDS NO. 1673.
VELOCITY RATIO 15.21

PROFILE COORDINATES

AXIAL POSITION
NOZZLE (DIAMETERS)

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AVERAGE CHARACTERISTICS OF JET COLUMN

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DATA SUMMARY, JET - COAXIAL FLOW MIXING EXPERIMENTS

RUN NO. 2HA1
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NOZZLE DIAMETER= 2.0 CM ARGON MASS FLOW= 2.60 GM/SEC
COAXIAL FLOW GAS-NITROGEN NOMINAL COAXIAL VELOCITY= 74.0 FT/SEC
FLOW STRAIGHTENER TUBE DIAM., 1/16 IN.

NOMINAL INITIAL CONDITIONS
-----------------------------
JET VELOCITY 139.6 FT/SEC JET REYNOLDS NO. 1485.
VELOCITY RATIO .52

PROFILE COORDINATES
---------------------
AXIAL
POSITION
NOZZLE
(DIAMETERS)
EXIT 8000. 7200. 1.000 550. 0.000 .100 1.580
1/2 7150. 6435. .800 550. 0.000 .100 1.560
1 7700. 6930. .600 550. .010 .090 .760
2 5250. 4725. .600 550. .172 .083 .600

AVERAGE CHARACTERISTICS OF JET COLUMN
----------------------------------------
AXIAL POSITION (NOZZLE DIAMS) EXIT 1/2 1 2
VELOCITY, FT/SEC 131. 118. 107. 90.
LOCAL SEPARATION RATIO 1.77 1.60 1.45 1.22
ARGON MOLE FRACTION .78262 .77596 .53865 .42320
TEMPERATURE, R 4495. 3648. 3529. 2500.
TEMPERATURE RATIO 8.17424 6.63333 6.41666 4.54575
DATA SUMMARY, JET - COAXIAL FLOW MIXING EXPERIMENTS

RUN NO. 2H81

---

NOZZLE DIAMETER = 2. CM ARGON MASS FLOW = 1.83GM/SEC
COAXIAL FLOW GAS-NITROGEN NOMINAL COAXIAL VELOCITY = 45. FT/SEC
FLOW STRAIGHTENER TUBE DIAM., 1/16 IN.

NOMINAL INITIAL CONDITIONS

---

JET VELOCITY 105.8FT/SEC JET REYNOLDS NO. 1007.
VELOCITY RATIO .42

PROFILE COORDINATES

---

AXIAL POSITION
NOZZLE (DIAMETERS)

P  Q  S  T  A  G  B
EXIT 8650 7785 1000 550 000 100 1520
1/2 8600 7740 .760 550 000 100 1.360
1 8250 7425 .760 550 .028 .097 .740
2 3850 3465 .640 550 .280 .072 .680

AVERAGE CHARACTERISTICS OF JET COLUMN

---

AXIAL POSITION (NOZZLE DIAMS) EXIT 1/2 1 2
VELOCITY, FT/SEC 97. 90. 81. 56.
LOCAL SEPARATION RATIO 2.17 2.00 1.80 1.25
ARGON MOLE FRACTION .76277 .71189 .52765 .38086
TEMPERATURE, R 4842. 4244. 4083. 1945.
TEMPERATURE RATIO 8.80454 7.71795 7.42386 3.53680
DATA SUMMARY, JET - COAXIAL FLOW MIXING EXPERIMENTS

RUN NO. 2HB2

NOZZLE DIAMETER = 2. CM  ARGON MASS FLOW = 1.83GM/SEC
COAXIAL FLOW GAS - NITROGEN  NOMINAL COAXIAL VELOCITY = 134. FT/SEC
FLOW STRAIGHTENER TUBE DIAM., 1/16 IN.

NOMINAL INITIAL CONDITIONS

JET VELOCITY = 94.6FT/SEC  JET REYNOLDS NO. 1065.
VELOCITY RATIO = 1.41

PROFILE COORDINATES

AXIAL POSITION
NOZZLE (DIAMETERS)
EXIT 8400  7560  .840  550  0.000  .100  .760
1/2  6450  5800  .880  550  .010  .099  .840
1  6450  5800  .720  550  .197  .083  1.080
2  1900  1700  .800  550  .570  .043  .480

AVERAGE CHARACTERISTICS OF JET COLUMN

AXIAL POSITION (NOZZLE DIAMS)  EXIT  1/2  1  2
VELOCITY, FT/SEC  110.  104.  105.  117.
LOCAL SEPARATION RATIO  .82  .78  .78  .87
ARGON MOLE FRACTION  .54769  .56148  .50644  .20873
TEMPERATURE, R  4329  3450  3184  1158
TEMPERATURE RATIO  7.87208  6.27408  5.79069  2.10666
DATA SUMMARY, JET - COAXIAL FLOW MIXING EXPERIMENTS

RUN NO. 2HB3

NOZZLE DIAMETER = 2. CM ARGON MASS FLOW = 1.83GM/SEC
COAXIAL FLOW GAS - NITROGEN NOMINAL COAXIAL VELOCITY = 450. FT/SEC
FLOW STRAIGHTENER TUBE DIAM. = 1/16 IN.

NOMINAL INITIAL CONDITIONS

JET VELOCITY 51.4 FT/SEC JET REYNOLDS NO. 1445.
VELOCITY RATIO 8.74

PROFILE COORDINATES

AXIAL POSITION
NOZZLE (DIAMETERS)

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<th>T</th>
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AVERAGE CHARACTERISTICS OF JET COLUMN

AXIAL POSITION (NOZZLE DIAMS) EXIT 1/2 1 2
VELOCITY, FT/SEC 299. 375. 420. 440.
LOCAL SEPARATION RATIO .66 .83 .93 .97
ARGON MOLE FRACTION .4771 1 .23651 .09311 .02840
TEMPERATURE, R 2352. 1609. 905. 643.
TEMPERATURE RATIO 4.27713 2.92606 1.64609 1.16969
DATA SUMMARY, JET - COAXIAL FLUID MIXING EXPERIMENTS

RUN NO. 2HC1

NOZZLE DIAMETER = 2. CM ARGON MASS FLOW = 1.04 GM/SEC
COAXIAL FLOW GAS - NITROGEN NOMINAL COAXIAL VELOCITY = 27 FT/SEC
FLOW STRAIGHTENER TUBE DIAM., 1/16 IN.

NOMINAL INITIAL CONDITIONS

JET VELOCITY 39.2 FT/SEC JET REYNOLDS NO. 708.
VELOCITY RATIO .68

PROFILE COORDINATES

AXIAL
POSITION
NOZZLE
(DIAMETERS)
EXIT 7200. 6660. 450 550. 0.000 100 300
1/2 6500. 5850. 400 550. 025 100 420
1 5070. 4570. 600 550. 160 084 200
2 2200. 1980. 480 550. 590 060 280

AVERAGE CHARACTERISTICS OF JET COLUMN

AXIAL POSITION (NOZZLE DIAMS) EXIT 1/2 1 2
VELOCITY, FT/SEC 34. 32. 30. 26.
LOCAL SEPARATION RATIO 1.26 1.20 1.13 .97
ARGON MOLE FRACTION .45025 .46283 .36316 .19450
TEMPERATURE, R 3157. 2749. 2427. 1172.
TEMPERATURE RATIO 5.74024 4.99878 4.41381 2.13226
DATA SUMMARY, JET - COAXIAL FLOW MIXING EXPERIMENTS

RUN NO. HP 1

NOZZLE DIAMETER = 1. CM  ARGON MASS FLOW = 1.00G/M/SEC
COAXIAL FLOW GAS - NITROGEN  NOMINAL COAXIAL VELOCITY = 130. FT/SEC
FLOW STRAIGHTENOR TUBE DIAM., POROUS

NOMINAL INITIAL CONDITIONS

JET VELOCITY 128.3 FT/SEC  JET REYNOLDS NO. 1478.
VELOCITY RATIO  1.01

PROFILE COORDINATES

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AVERAGE CHARACTERISTICS OF JET COLUMN

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APPENDIX D: Mixing Data Reduction Procedure

Average values of composition and temperature were computed from the mixing profile data by a simplified integration technique deemed adequate within the accuracy of the experiments. Figure Appendix D-1 identifies the quantities obtained from composition and temperature profiles, respectively. It is seen that data curves have been approximated by fitted triangular and trapezoidal regions which are identified as regions I and II respectively.

For the case of the composition profiles it was observed (see Table II) that no measurable amount of argon was found exterior to the cylindrical column formed by the jet nozzle. Thus the expression for the average composition of the profile \( \tilde{y}_j \) is found by the present technique as follows:

\[
\tilde{y}_j = \frac{\int y(x) 2\pi x \, dx}{\int 2\pi x \, dx}
\]

where the \( 2\pi x \) term appears because the plane representation must be rotated to provide a three-dimensional average.

\[
y_j(x) = \alpha + y_I(x) + y_{II}(x)
\]

where \( y_I(x) = \frac{2g_x}{b} \), \( \frac{b}{2} \leq |x| \leq b \),

\[
y_I(x) = 0 \quad , \quad |x| > \frac{b}{2}
\]
\[ \psi (x) = \frac{(x - \frac{b}{a})(c - q)}{(1 - \frac{b}{a})} , \quad |x| > \frac{b}{a} \]

\[ = 0 , \quad |x| < \frac{b}{a} \]

The result is:

\[ \bar{y} = a + \frac{b}{6} + \frac{[1-(a+q)]}{(1-\frac{b}{a})} \left[ \frac{2}{3} - \frac{b}{2} + \frac{b}{24} \right] \]

By a similar argument it may be readily shown that the average temperature \( \bar{T} \) is,

\[ \bar{T} = \frac{s^3}{12} (p - q) + \frac{a - t}{1 - \frac{s}{2}} \left( \frac{s^3}{12} - \frac{1}{6} - \frac{s^2}{8} \right) + q \]

The velocities used in calculating the separation ratio were computed from the composition data. As mentioned in the test, velocity data were not obtainable at many conditions of interest, and thus a formulation utilizing the composition data was developed from the following momentum considerations:

\[ \overline{\rho U^2} = \overline{\rho U^2} = \chi p^2 \bar{U}_e^2 + \rho_e (1 - \chi) \bar{U}_e^2 \]

Assuming the equation of state for a perfect gas, it can readily be shown that:

\[ \frac{\bar{U}_e}{\bar{U}_c} = \left\{ \frac{1}{\chi + (1 - \chi) \frac{M_e}{M_{Ar}}} \left[ \chi \frac{T}{T_c} + (1 - \chi) \frac{M_e}{M_{Ar}} \left( \frac{V_R}{T_c} \right)^2 \right] \right\}^{\frac{1}{2}} \]
In most cases of high velocity ratio experiments, velocity data are not available in the core at and near the exit plane, as discussed earlier, but velocity data are generally available at two jet diameters downstream. The agreement between the above method of computation and measured velocities two diameters downstream is good.

The data summary sheet prepared for each run defines the complete test conditions. Computation techniques for quantities appearing in this summary and not discussed elsewhere were as follows:

**Nominal Initial Jet Velocity, $U_c^\circ$ in ft/sec**

\[
U_c^\circ = \frac{\dot{m}_{Ar}}{\rho_{Ar} \pi D^2} = \frac{4 \dot{m}_{Ar} \rho \pi T}{\pi D^2 \rho_{Ar} \pi P} = \frac{0.0475T \rho_{Ar}}{D^2}
\]

for $D$ in cm, $T$ in $^\circ$R, $P = 1$ atm, $\dot{m}_{Ar}$ in gm/sec

**Nominal Initial Jet Reynolds Number, $Re_c$**

\[
Re_c = \frac{4 \dot{m}_{Ar}}{\pi D \mu} = \frac{7.66 \times 10^4 \dot{m}_{Ar}}{D \sqrt{T}}
\]

PROFILE INTEGRATION NOMENCLATURE

FIGURE D-1
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<th>$S_3$</th>
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\[
\varepsilon_n \approx \frac{S_{n}}{\left[1 + 3 \alpha \left(\frac{h}{D}\right)_n\right]} \cdot \left(\frac{V_R R_c T_R}{1000}\right)^{0.1} \cdot \frac{1}{\alpha} \left(\frac{V_R R_c T_R}{1000}\right)^{0.1}, \quad \varepsilon = -\frac{\varepsilon_1 + \varepsilon_2}{2} + \varepsilon_3 + \varepsilon_4 \]
AVERAGE CONDITIONS
AT NOZZLE EXIT PLANE
ARGON JET REYNOLDS No. 238
VELOCITY RATIO, N₂/Ar 71

VELOCITY, FT./SEC

N₂ FLOW
ARGON JET
N₂ FLOW

RADIAL POSITION (INCHES)

1.0 .8 .6 .4 .2 0 .2 .4 .6 .8 1.0

1.0 .8 .6 .4 .2 0 .2 .4 .6 .8 1.0

NITROGEN MOLE FRACTION

RUN No. A-1

PROFILES OF ARGON JET MIXING ISOTHERMALLY WITH COAXIAL NITROGEN FLOW
AVERAGE CONDITIONS DOWNSTREAM AT NOZZLE EXIT PLANE

ARGON JET REYNOLDS No. 7,577

VELOCITY RATIO, $N_2$/Ar 1.6

RUN No. A-2

ARGON JET FLOW

NITROGEN FLOW

PROFILES OF ARGON JET MIXING ISOTHERMALLY WITH COAXIAL NITROGEN FLOW
AVERAGE CONDITIONS AT NOZZLE EXIT PLANE
ARGON JET REYNOLDS No. 18,748
VELOCITY RATIO, $N_2/Ar = 0.66$

DOWNSTREAM LOCATIONS
○ EXIT PLANE
□ 1/2 DIAMETER
△ 1 DIAMETER
◇ 2 DIAMETER

RUN No. A-3

PROFILES OF ARGON JET MIXING ISOTHERMALLY WITH COAXIAL NITROGEN FLOW
AVERAGE CONDITIONS AT NOZZLE EXIT PLANE

ARGON JET REYNOLDS No. 953

VELOCITY RATIO, $N_2 / \alpha \approx 54.97$

I.0 .8 .6 .4

JET FLOW

t, $t_1$

.2 .4 .6 .8 I.0

DOWNSTREAM LOCATIONS

○ EXIT PLANE

□ 1/2 DIAMETER

△ 1 DIAMETER

◇ 2 DIAMETER

1.0 .8 .6 .4 .2 0

RADIAL POSITION (INCHES)

VELOCITY, FT/SEC

400

300

200

100

500

0

$N_2$ FLOW

ARGON JET

$N_2$ FLOW

PROFILES OF ARGON JET MIXING ISOTHERMALLY WITH COAXIAL NITROGEN FLOW

RUN No. A-4
AVERAGE CONDITIONS AT NOZZLE EXIT PLANE
ARGON JET REYNOLDS No. 2,939
VELOCITY RATIO, \( N_2 / Ar \) 12.89

DOWNSTREAM LOCATIONS
• EXIT PLANE
□ 1/2 DIAMETER
△ 1 DIAMETER
◊ 2 DIAMETER

RUN No. A-5

Profiles of argon jet mixing isothermally with coaxial nitrogen flow.
PROFILES OF ARGON JET MIXING ISOTHERMALLY WITH COAXIAL NITROGEN FLOW
AVERAGE CONDITIONS AT NOZZLE EXIT PLANE

ARGON JET REYNOLDS NO. 10,490
VELOCITY RATIO, N₂/Ar 9.29

DOWNSTREAM LOCATIONS
○ EXIT PLANE
□ 1/2 DIAMETER
△ 1 DIAMETER
◊ 2 DIAMETER

RUN No. A-7

PROFILES OF ARGON JET MIXING ISOTHERMALLY WITH COAXIAL NITROGEN FLOW
(LEFT HAND PROFILE MEASURED, RIGHT HAND PROFILE DRAWN SYMMETRICALLY)
AVERAGE CONDITIONS
AT NOZZLE EXIT PLANE

ARGON JET REYNOLDS No. 7,185
VELOCITY RATIO, $N_2/Ar = 9.73$

VELOCITY, FT/SEC

1000
800
600
400
200
0

$N_2$ FLOW

ARGON JET

$N_2$ FLOW

RADIAL POSITION (INCHES)

NITROGEN MOLE FRACTION

1.0
0.8
0.6
0.4
0.2
0.0
0.1
0.3
0.5
0.7
0.9
1.0

RADIAL POSITION (INCHES)

profiles of argon jet mixing isothermally with coaxial nitrogen flow
(left hand profile measured, right hand profile drawn symmetrically)
Profiles of Argon Jet Mixing Isothermally with Coaxial Nitrogen Flow (Left hand profile measured, right hand profile drawn symmetrically)
AVERAGE CONDITIONS AT NOZZLE EXIT PLANE

ARGON JET REYNOLDS No. 238 VELOCITY RATIO, \( \frac{N_2}{Ar} \) 7.13

NOT MEASUREABLE

NOT MEASUREABLE

PROFILES OF ARGON JET MIXING ISOTHERMALLY WITH COAXIAL HELIUM FLOW
AVERAGE CONDITIONS DOWNSTREAM AT NOZZLE EXIT PLANE

ARGON JET REYNOLDS No. 7,022
VELOCITY RATIO, $N_2/Ar = 0.17$

RUN No. B-2

NOT MEASURABLE

PROFILES OF ARGON JET MIXING ISOTHERMALLY WITH COAXIAL HELIUM FLOW
AVERAGE CONDITIONS AT NOZZLE EXIT PLANE

ARGON JET REYNOLDS No. 238
VELOCITY RATIO, $N_2/Ar$ 34.98

VELOCITY, FT/SEC

HELIO MPE FRACTION

PROFILES OF ARGON JET MIXING ISOTHERMALLY WITH COAXIAL HELIUM FLOW
AVERAGE CONDITIONS
AT NOZZLE EXIT PLANE

ARGON JET REYNOLDS No. 2,612
VELOCITY RATIO, $N_2/Ar$ 2.31

DOWNSTREAM LOCATIONS
○ EXIT PLANE
□ 1/2 DIAMETER
△ 1 DIAMETER
◇ 2 DIAMETER

RUN No. B-4

PROFILES OF ARGON JET MIXING ISOTHERMALLY WITH COAXIAL HELIUM FLOW
AVERAGE CONDITIONS AT NOZZLE EXIT PLANE

ARGON JET REYNOLDS No = 238
VELOCITY RATIO, $N_2 / A_r = 7.13$

NOT MEASUREABLE

PROFILES OF ARGON JET MIXING ISOTHERMALLY WITH COAXIAL HELIUM FLOW
AVERAGE CONDITIONS AT NOZZLE EXIT PLANE

ARGON JET REYNOLDS No. 2,939
VELOCITY RATIO, N2/Ar = 2.07

DOWNSTREAM LOCATIONS
○ EXIT PLANE
□ 1/2 DIAMETER
△ 1 DIAMETER
◊ 2 DIAMETER

RUN No. C-2

PROFILES OF ARGON JET MIXING ISOTHERMALLY WITH COAXIAL HELIUM FLOW
AVERAGE CONDITIONS AT NOZZLE EXIT PLANE

ARGON JET REYNOLDS NO. 7,185

VELOCITY RATIO, \( N_2/Ar \) 9.76

PROFILE OF ARGON JET MIXING ISOTHERMALLY WITH COAXIAL NITROGEN FLOW

(RIGHT HAND PROFILE DRAWN SYMMETRICALLY)

PROFILES OF ARGON JET MIXING ISOTHERMALLY WITH COAXIAL NITROGEN FLOW

(LEFT HAND PROFILE MEASURED, RIGHT HAND PROFILE DRAWN SYMMETRICALLY)
PROFILES OF ARGON JET MIXING ISOTHERMALLY WITH COAXIAL NITROGEN FLOW
(LEFT HAND PROFILE MEASURED, RIGHT HAND PROFILE DRAWN SYMMETRICALLY)
PROFILES OF ARGON JET MIXING ISOTHERMALLY WITH COAXIAL NITROGEN FLOW
(LEFT HAND PROFILE MEASURED, RIGHT HAND PROFILE DRAWN SYMMETRICALLY)
AVERAGE CONDITIONS DOWNSTREAM AT NOZZLE EXIT PLANE

ARGON JET REYNOLDS NO* 13,064
VELOCITY RATIO, $N_2/Ar$ 7.41

RUN No. E-3

ARGON JET MIXING ISOTHERMALLY WITH COAXIAL NITROGEN FLOW (LEFT HAND PROFILE MEASURED, RIGHT HAND PROFILE DRAWN SYMMETRICALLY)
AVERAGE CONDITIONS
AT NOZZLE EXIT PLANE

ARGON JET REYNOLDS NO.
VELOCITY RATIO, $\frac{N_A}{A_r}$

VELOCITY, FT/SEC

0 8 16 24 32 40

0 .1 .2 .3 .4 .5 .6 .7 .8 .9 1.0

RADIAL POSITION (INCHES)

PROFILES OF ARGON JET MIXING ISOTHERMALLY WITH COAXIAL HELIUM FLOW

DOWNSTREAM
LOCATIONS

RUN No. F-1

EXIT PLANE

1/2 DIAMETER

1 DIAMETER

2 DIAMETER

HELUM MOLE FRACTION

NOZZLE WALL

RADIAl POSITION (INCHES)
AVERAGE CONDITIONS AT NOZZLE EXIT PLANE

ARGON JET REYNOLDS NO. 7,838  
VELOCITY RATIO, $H_e/A_r$ 0.00

DOWNSTREAM LOCATIONS

RUN No. F-2

PROFILES OF ARGON JET MIXING ISOTHERMALLY WITH COAXIAL HELIUM FLOW  
(LEFT HAND PROFILE MEASURED, RIGHT HAND PROFILE DRAWN SYMETRICALLY)
AVERAGE CONDITIONS AT NOZZLE EXIT PLANE
ARGON JET REYNOLDS No. 7,838
VELOCITY RATIO, N₂/Ar 0.46

RUN No. F-3

PROFILEs OF ARGON JET MIXING ISOTHERMALLY WITH COAXIAL HELIUM FLOW
Profiles of Argon Jet Mixing Isothermally with Coaxial Helium Flow
Profile of Argon Jet Mixing Isothermally with Coaxial Helium Flow
AVERAGE CONDITIONS AT NOZZLE EXIT PLANE

ARGON JET REYNOLDS No. 7,838
VELOCITY RATIO, $N_2/Ar$ 0.00

VELOCITY, FT/SEC

RADIAL POSITION (INCHES)

NITROGEN MOLE FRACTION

PROFILES OF ARGON JET MIXING ISOTHERMALLY WITH COAXIAL NITROGEN FLOW
AVERAGE CONDITIONS AT NOZZLE EXIT PLANE
ARGON JET REYNOLDS No. 238
VELOCITY RATIO, $N_2/Ar = 0.71$

RUN No. G-2

NOT MEASUREABLE

PROFILES OF ARGON JET MIXING ISOTHERMALLY WITH COAXIAL NITROGEN FLOW
AVERAGE CONDITIONS
AT NOZZLE EXIT PLANE
ARGON JET REYNOLDS No. 476
VELOCITY RATIO, \( \frac{N_2}{Ar} \) 1.07

NOT MEASUREABLE

VELOCITY, FT/SEC

\( N_2 \) FLOW
ARGON JET
\( N_2 \) FLOW

RADIAL POSITION (INCHES)

0.10

0.00

RUN No·G-3

PROFILES OF ARGON JET MIXING ISOTHERMALLY WITH COAXIAL NITROGEN FLOW
AVERAGE CONDITIONS AT NOZZLE EXIT PLANE

ARGON JET REYNOLDS No. 5,870
VELOCITY RATIO, $N_2/Ar$ .466

NOT MEASURABLE

PROFILES OF ARGON JET MIXING ISOTHERMALLY WITH COAXIAL NITROGEN FLOW
AVERAGE CONDITIONS AT NOZZLE EXIT PLANE

ARGON JET REYNOLDS No: 14,700
VELOCITY RATIO, $N_2/Ar\cdot 465$

DOWNSTREAM LOCATIONS
- EXIT PLANE
- 1/2 DIAMETER
- 1 DIAMETER
- 2 DIAMETER

RUN No. G-5

PROFILES OF ARGON JET MIXING ISOTHERMALLY WITH COAXIAL NITROGEN FLOW
AVERAGE CONDITIONS AT NOZZLE EXIT PLANE

ARGON JET REYNOLDS No 7,185
VELOCITY RATIO, $N_{2}/Ar$ 1.72

DOWNSTREAM LOCATIONS

RUN No. P-2

PROFILES OF ARGON JET MIXING ISOTHERMALLY WITH COAXIAL NITROGEN FLOW
AVERAGE CONDITIONS AT NOZZLE EXIT PLANE
ARGON JET REYNOLDS No. 7,185
VELOCITY RATIO, N₂/Ar 1.72

VELOCITY, FT/SEC

RADIAL POSITION (INCHES)

0 0.2 0.4 0.6 0.8 1.0

N₂ FLOW ARGON JET FLOW NOZZLE WALL

0
1.0
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0

NITROGEN MOLE FRACTION

RADIAL POSITION (INCHES)

0 0.2 0.4 0.6 0.8 1.0

PROFILES OF ARGON JET MIXING ISOHERMALLY WITH COAXIAL NITROGEN FLOW

RUN No. P-3
AVERAGE CONDITIONS AT NOZZLE EXIT PLANE
ARGON JET REYNOLDS No. 4,550
VELOCITY RATIO, $N_2/Ar \approx 0$

DOWNSTREAM LOCATIONS
- EXIT PLANE
- 1/2 DIAMETER
- 1 DIAMETER
- 2 DIAMETER

RUN No. H-1

NOT MEASUREABLE

PROFILES OF ARGON JET MIXING ISOTHERMALLY WITH COAXIAL ARGON FLOW
AVERAGE CONDITIONS AT NOZZLE EXIT PLANE
ARGON JET REYNOLDS NO. 14,700
VELOCITY RATIO, $N_2/Ar = 0$

AVERAGE CONDITIONS DOWNSTREAM AT NOZZLE EXIT PLANE LOCATIONS

RUN NO. H-2

PROFILES OF ARGON JET MIXING ISOTHERMALLY WITH COAXIAL ARGON FLOW
AVERAGE CONDITIONS AT NOZZLE EXIT PLANE

ARGON JET REYNOLDS No. 636 VELOCITY RATIO, $N_2/Ar$ .67

NOT MEASUREABLE

NITROGEN MOLE FRACTION

PROFILES OF ARGON JET MIXING ISOTHERMALLY WITH COAXIAL NITROGEN FLOW
AVERAGE CONDITIONS AT NOZZLE EXIT PLANE
ARGON JET REYNOLDS No. 3,200
VELOCITY RATIO, $N_2/Ar$ 2.87

DOWNSTREAM LOCATIONS
○ EXIT PLANE
□ 1/2 DIAMETER
△ 1 DIAMETER
◊ 2 DIAMETER

RUN No. 2CB & 2CB-A

PROFILES OF ARGON JET MIXING ISOTHERMALLY WITH COAXIAL NITROGEN FLOW
AVERAGE CONDITIONS AT NOZZLE EXIT PLANE

ARGON JET REYNOLDS No. 10,288
VELOCITY RATIO, \( \frac{N_2}{Ar} \) 4.25

RUN No. 2CC

Profiles of Argon Jet mixing isothermally with coaxial Nitrogen flow
(Left hand profile measured, right hand profile drawn symmetrically)
AVERAGE CONDITIONS AT NOZZLE EXIT PLANE

ARGON JET REYNOLDS No. 1300
VELOCITY RATIO, $N_2/Ar$ 1.20
JET TEMPERATURE, °R 3500

RUN NO. HA-3

HALF-PROFILES OF ARGON ARCJET JET MIXING WITH COAXIAL NITROGEN FLOW
AVERAGE CONDITIONS AT NOZZLE EXIT PLANE

ARGON JET REYNOLDS No.1400
VELOCITY RATIO, $N_2/Ar$ 0.96
JET TEMPERATURE, °R 2920

DOWNSTREAM LOCATIONS
○ EXIT PLANE
□ 1/2 DIAMETER
△ 1 DIAMETER
◊ 2 DIAMETER

RUN NO. HA-4

HALF-PROFILES OF ARGON ARCJET JET MIXING WITH COAXIAL NITROGEN FLOW
AVERAGE CONDITIONS AT NOZZLE EXIT PLANE

ARGON JET REYNOLDS No.1400
VELOCITY RATIO, N₂/Ar 0.46
JET TEMPERATURE, °R 3025

HALF-PROFILES OF ARGON ARCJET JET MIXING WITH COAXIAL NITROGEN FLOW

VELOCITY, FT/SEC

NITROGEN MOLE FRACTION

TEMPERATURE, °R x 10³
AVERAGE CONDITIONS AT NOZZLE EXIT PLANE

ARGON JET REYNOLDS No. 2190
VELOCITY RATIO, N₂/Ar 2.2
JET TEMPERATURE, °R 1220

HALF-PROFILES OF ARGON ARCJET JET MIXING WITH COAXIAL NITROGEN FLOW

RUN NO. HA-6

NITROGEN MOLE FRACTION

TEMPERATURE, 10³ X R

RADIAL POSITION IN NOZZLE RADII
(NOZZLE RADIUS = 0.5 CM.)
HALF-PROFILES OF ARGON ARCJET JET MIXING WITH COAXIAL HELIUM FLOW
AVERAGE CONDITIONS AT NOZZLE EXIT PLANE

ARGON JET REYNOLDS No. 1415
VELOCITY RATIO, N₂/Ar 1.21
JET TEMPERATURE, °R 2925

NOMINAL N₂ VELOCITY

RUN NO. HA-8

DOWNSTREAM LOCATIONS
○ EXIT PLANE
□ 1/2 DIAMETER
△ 1 DIAMETER
◇ 2 DIAMETER

HALF-PROFILES OF ARGON ARCJET JET MIXING WITH COAXIAL NITROGEN FLOW
HALF-PROFILES OF ARGON AERCJET JET MIXING WITH COAXIAL NITROGEN FLOW
AVERAGE CONDITIONS AT NOZZLE EXIT PLANE

ARGON JET REYNOLDS No. 4000
VELOCITY RATIO, $N_2/Ar$ 1.11
JET TEMPERATURE, $^\circ$R 3300

DOWNSTREAM LOCATIONS

- EXIT PLANE
- 1/2 DIAMETER
- 1 DIAMETER
- 2 DIAMETER

AVG N$_2$ - NITROGEN MOLE FRACTION

RUN NO. HA-10

HALF-PROFILES OF ARGON ARCJET JET MIXING WITH COAXIAL NITROGEN FLOW
HALF-PROFILES OF ARGON ARCJET JET MIXING WITH COAXIAL NITROGEN FLOW
AVERAGE CONDITIONS AT NOZZLE EXIT PLANE

ARGON JET REYNOLDS No. 1670
VELOCITY RATIO, $N_2/Ar$ 15.2
JET TEMPERATURE, °R 1340

DOWNSTREAM LOCATIONS
○ EXIT PLANE
■ 1/2 DIAMETER
▲ 1 DIAMETER
◇ 2 DIAMETER

RUN NO. HA-13

HALF-PROFILES OF ARGON ARCJET JET MIXING WITH COAXIAL NITROGEN FLOW
AVERAGE CONDITIONS
AT NOZZLE EXIT PLANE

ARGON JET REYNOLDS No. 1475
VELOCITY RATIO, \( N_2 / Ar \) 1.01
JET TEMPERATURE, °R 2680

HALF-PROFILES OF ARGON ARCJET JET MIXING WITH COAXIAL NITROGEN FLOW
AVERAGE CONDITIONS AT NOZZLE EXIT PLANE

ARGON JET REYNOLDS No. 1485
VELOCITY RATIO, N₂/Ar .52
JET TEMPERATURE, °R 4500

DOWNSTREAM LOCATIONS
○ EXIT PLANE
□ 1/2 DIAMETER
△ 1 DIAMETER
◊ 2 DIAMETER

RUN NO. 2HA-1

HALF-PROFILES OF ARGON ARCJET JET MIXING WITH COAXIAL NITROGEN FLOW
**AVERAGE CONDITIONS AT NOZZLE EXIT PLANE**

ARGON JET REYNOLDS No. 1010
VELOCITY RATIO, $N_2/Ar .42$
JET TEMPERATURE, $^\circ R$ 4840

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**RUN NO. 2BH-1**

**HALF-PROFILES OF ARGON ARCJET JET MIXING WITH COAXIAL NITROGEN FLOW**
AVERAGE CONDITIONS AT NOZZLE EXIT PLANE

ARGON JET REYNOLDS NO. 1065
VELOCITY RATIO, $N_2/Ar$ 1.41
JET TEMPERATURE, °R 4330

NOT AVAILABLE

AVG $N_2$ mole fraction

VELOCITY, FT/SEC

NITROGEN MOLE FRACTION

DOWNSTREAM LOCATIONS
- EXIT PLANE
- 1/2 DIAMETER
- 1 DIAMETER
- 2 DIAMETER

RUN NO. 2BH-2

TEMPERATURE, $10^3 X ^{°R}$

HALF-PROFILES OF ARGON ARCJET JET MIXING WITH COAXIAL NITROGEN FLOW
AVERAGE CONDITIONS
AT NOZZLE EXIT PLANE

ARGON JET REYNOLDS No.1445
VELOCITY RATIO, N$_2$/Ar 8.8
JET TEMPERATURE, *R 2350

HALF-PROFILES OF ARGON ARCJET JET MIXING WITH COAXIAL NITROGEN FLOW
AVERAGE CONDITIONS AT NOZZLE EXIT PLANE

ARGON JET REYNOLDS No. 708
VELOCITY RATIO, N₂/Ar 0.68
JET TEMPERATURE, °R 3160

VELOCITY RATIO, N₂/Ar 0.68
JET TEMPERATURE, °R 3160

100

JET 1 WALL

60

200

AR JET NOZZLE N₂ FLOW

VELOCITY, FT/SEC

RADIAL POSITION IN NOZZLE RADII (NOZZLE RADIUS = 1.0 CM.)

HALF-PROFILES OF ARGON ARCJET JET MIXING WITH COAXIAL NITROGEN FLOW

DOWNSTREAM LOCATIONS

• EXIT PLANE
• 1/2 DIAMETER
• 1 DIAMETER
• 2 DIAMETER

NITROGEN MOLECULAR FRACTION

TEMPERATURE, 10³ × R

RUN NO. 2 HCl
AXIAL LOCATION, INITIAL JET DIAMETERS

CENTERLINE TEMPERATURE
HEATED ARGON JETS IN COAXIALLY FLOWING NITROGEN

* COAXIAL HELIUM
AXIAL LOCATION, INITIAL JET DIAMETERS

CENTERLINE COMPOSITION
HEATED ARGON JETS IN COAXIALLY FLOWING NITROGEN

* COAXIAL HELIUM
CENTERLINE COMPOSITION
HEATED ARGON JETS IN COAXIALLY FLOWING NITROGEN

* COAXIAL HELIUM