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Roy J. Schulz

Dr. Roy J. Schulz, Major Professor

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Carroll E. Peloubet

Roger Crawford

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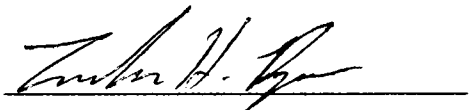
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PRESSURE RECOVERY IN TEST FACILITY DIFFUSERS: AN ENGINEERING ANALYSIS INCLUDING THE EFFECTS OF AFTERBURNING HEAT RELEASE, AERODYNAMIC BLOCKAGE, AND DUCT EXPANSION

A Thesis

Presented for the

Master of Science

Degree

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Luke Harley Rogers

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ABSTRACT

As engineers design new aircraft engine test facilities to accommodate new technologies such as hydrogen burning variable-cycle engines, they will need methods to easily evaluate diffuser duct performance. In this thesis, a simple control-volume analysis of engine test facility diffuser performance has been embodied in a computer program to predict basic flow conditions such as diffuser exit Mach number, temperature, and pressure, subject to such effects as heat release from afterburning, aerodynamic blockage from flameholding bars, and sudden-expansion of the flow. It was found that straight diffuser ducts result in serious limitations on the Mach number and mass flow rate of the facility bypass air flow, especially when the diffuser flow is partially blocked. The sudden-expansion duct, on the other hand, exhibited superior performance with better static pressure recovery at most conditions and lower exit Mach numbers. Its performance was not seriously degraded by either aerodynamic blockage or heat release in the diffuser.

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LIST OF SYMBOLS

SYMBOLS			UNITS
A	=	cross sectional area	ft^2
a	=	speed of sound	ft/sec
C_d	=	coefficient of drag	
c_p	=	specific heat at constant pressure	Btu/(lbf °R)
c_v	=	specific heat at constant volume	Btu/(lbf °R)
d	=	density	lbm/ft^3
d_b	=	diameter of flameholding bars	ft
D_b	=	drag due to flameholding bars	lbf
F	=	heat release rate	Btu/sec
F_t	=	thrust force	lbf
g	=	ratio of specific heats (gamma)	
g_c	=	gravitational constant	$(ft\ lbm)/(s^2\ lbf)$
J	=	conversion factor	Btu/(ft lbf)
M	=	Mach number	
m	=	molecular weight	
n_i	=	engine inlet efficiency	
P	=	static pressure	lbf/ft^2
q	=	dynamic pressure	lbf/ft^2
Q	=	wall heat loss rate	Btu/sec
r	=	duct radius	ft
R	=	gas constant	(ft lbf)/(°R lbm)
Re	=	Reynolds number	

S	=	bar spacing	ft
T	=	static temperature	°R
t	=	subscript indicates total conditions	
V	=	velocity	ft/sec
W	=	mass flow rate	lbm/sec
X	=	coefficient constants	
Y	=	stream mass function	
Z	=	constants of convenience	
ß	=	blockage ratio	
ø	=	operating equivalence ratio	

SUBSCRIPTS

1	=	indicates engine exhaust flow
2	=	indicates test cell bypass flow
3	=	indicates fully mixed diffuser flow before any blockage
3'	=	indicates fully mixed diffuser flow at the flameholder bars
4	=	indicates fully mixed diffuser at the diffuser exit
a	=	indicates ambient atmospheric conditions
B	=	indicates annular expansion base
b	=	refers to flameholding bars

CHAPTER I

BACKGROUND AND INTRODUCTION

Introduction

The pressure recovery performance of diffuser ducts has long been a study of great importance to engineers involved in ground testing of aircraft engines. As new approaches to exhaust handling such as afterburning in the diffuser are considered, it will be necessary to be able to estimate the conditions of the facility flow downstream of the test cell. This thesis presents a straight-forward method of approximating these flow conditions that designers of new facilities can use to evaluate the relative advantages or disadvantages of various exhaust handling techniques.

Hypersonic Propulsion Challenge

Phenomenal advances have been made in aircraft technology during the century since manned, powered flight was first attempted, resulting in many sophisticated, reliable, and practical aircraft. But, so far, useful designs have only been achieved that operate in the subsonic ($0<M<1$) and supersonic ($1<M<3$) flight regimes. While some research on the hypersonic ($M>5$) flight regime has been done, it has not resulted in a practical design, either military or commercial.

Several areas have been pinpointed as technological bottlenecks in hypersonic propulsion--disciplines in which great advances are

necessary. These include the use of hydrogen fuel, the development of variable cycle engines, including the scramjet, and thermal management techniques to withstand very high temperatures.

A great deal of ground testing will be required for breakthroughs to occur, and this testing will require test cell flows of high dynamic pressure and high enthalpy. The complexity of the advanced engine cycles will require that the test article be carefully integrated into the test cell environment to ensure proper simulation of the actual flight environment.

Ground Test Facilities for Propulsion

Ground test facilities for propulsion systems are a critical component of any aerospace development program and will be particularly important for the NASP and other new aerospace technologies. Hypersonic flight speeds will introduce design complications that can only be resolved by physical testing, despite the advanced abilities of Computational Fluid Dynamic Methods.

For propulsion testing it is necessary that test facilities accurately simulate flight conditions in parameters such as Mach number, total pressure, and total temperature, and that the engine be tested full-scale (Smith, Keel, and Boudreau, 1987). Unfortunately, as the flight Mach number increases the reservoir demands required to simulate such flow increase dramatically. Although some test facilities can simulate flight conditions up to Mach 7, the largest scale clean air propulsion facilities generally operate below a Mach number of 4,

with total temperatures and pressures on the order of 1000°R and 1000 psi, respectively. While advanced propulsion cycle aircraft may cruise at speeds up to Mach 25 and altitudes up to 200,000 feet, an important part of the envelope will be the take-off and landing. Thus, there will be a need for testing variable cycle hydrogen burning engines at lower altitudes and Mach numbers of 0 to 4, which is within the capability of current large propulsion test facilities (Zonars, 1985).

Test Techniques for Airbreathing Engines

Two different methods, direct-connect testing and free-jet testing (see Fig. 1)[1], are used in existing propulsion testing. In direct-connect testing all of the test facility air flow is input directly into the engine inlet. Conversely, in free-jet testing the engine is placed in the facility airstream, allowing air to flow into and around the engine.

The two testing techniques both have distinct advantages and drawbacks. Free-jet testing is the more comprehensive of the two methods since it can test the operation of the entire engine, including the effect of the surrounding flow on the inlet system and the exhaust nozzle performance. For example, the high level of interaction between the propulsion system and the aircraft aerodynamics envisioned for NASP makes the inclusion of the bypass flow critical for many tests (Hunt, Talcott, and Cubbage, 1977). Direct-connect testing offers the advantage of reduced facility flow requirements when only the engine

[1] All figures are included in Appendix A.

itself is being tested. For example, if the compression inlet is removed, the air flowing into the engine compressor should be at a much lower Mach number to account for the diffusion of the airflow that would occur in the inlet.

Disposing Hazardous Exhaust

An important consideration in the design of test facilities for variable cycle hydrogen fueled engines will be how the engine exhaust flow is handled. First, the velocity and temperature of the exhaust flow will be high and (for high altitude simulations) the pressure will be low, so the flow must be slowed, cooled, and repressurized before it is released to the atmosphere. Also, if the engine operates in a fuel rich condition, or if--because of a failure--combustion is not established, highly flammable hydrogen gas will remain in the exhaust flow. It is very important that some method of ensuring that any fuel remaining in the exhaust flow does not explode or burn in an uncontrolled fashion in the test facility exhaust ducting be developed for the propulsion tests of interest (Smith, et al, 1987).

These problems have previously been encountered in rocket engine testing where complex systems of diffusers, pumps, and coolers are now used in high Mach number facilities to lower the flow temperature and Mach number and raise the pressure. An accepted method for handling fuel in the exhaust has been to dump large quantities of inert nitrogen gas into the flow, but this technique may not be feasible for airbreathing engines (Stephens, Jordan, and Schulz, 1988).

Afterburning the excess fuel in the exhaust has occasionally been used and may be more desirable for airbreathing engines, so the diffuser duct should be compatible with this approach.

CHAPTER II

STATEMENT OF THE PROBLEM

Purpose of the Study

The purpose of this thesis is twofold. The first part is the development of an engineering analysis to predict the performance of the diffuser for either direct-connect or free-jet testing of airbreathing engines. The analysis will be capable of including the effects of heat release from afterburning, aerodynamic blockage due to imbedded flameholders, and sudden-expansion of the diffuser duct. The second part is to apply the analysis to representative test cases and draw conclusions about the diffuser performance results, including the quantitative effects of the afterburning, blockage, and expansion.

Diffuser Performance

The purpose of a diffuser in ground testing is to decrease the Mach number and increase the pressure of the exhaust flow, thus reducing the demands on test facility pumping machinery. Since it is cheaper to allow nature to do her own work, it would be desirable to design the diffuser duct to maximize pressure recovery, and thus place the minimum demands on the facility pumping system. The complication of afterburning in the diffuser is that it adds energy to the flow, increasing the total temperature and lowering the total pressure, thus causing the opposite of the desired result.

The method in which diffusers work to change the flow properties of supersonic streams is a complex combination of viscous shock-recompression processes, so complete theoretical prediction of diffuser performance is a formidable computational task. But, with certain simplifying assumptions, overall diffuser performance can be modelled by basic equations to arrive at approximations that are often satisfactory for initial engineering design work, in order to determine diffuser sizes, allowable inlet flow rates, and so forth. The effects of exhaust gas afterburning can be incorporated in a simplified analysis of the diffuser performance, allowing the advantage of eliminating the fuel in the flow to be roughly compared with the disadvantage of worsened diffuser performance.

Research Objective

This thesis presents a simple procedure that the test engineer can use to partially evaluate the performance of a diffuser duct for either free-jet or dirrect-connect testing, in terms of pressure recovery, exit temperature, and exit Mach number of the flow in the diffuser. A computer program has been developed--based on the global, control-volume conservation principles of mass, momentum, and energy--that provides a simple evaluation of the afterburning process in a free-jet cell (the more demanding of the two techniques). It uses input properties for the engine exhaust and the bypass flow and creates output properties for the fully mixed and burned flow leaving the diffuser. This analysis can be done for more complex diffuser

geometries, but in the present case a basic straight duct and a sudden-expansion duct are analyzed for different levels of blockage with and without heat release.

CHAPTER III

DIFFUSER SYSTEMS PERFORMANCE ANALYSIS

Simplifications and Assumptions

Fluid flow analysis is often a science of simplification. The governing equations for most flow problems can be complicated and unwieldy if details of mixing and burning must be accounted for. But fortunately, the governing equations can be greatly simplified by treating the flow with a global control-volume analysis. Analyses of this type have been used for many years by propulsion engineers to analyze duct flow and even to design and evaluate propulsion engines (see Shapiro, 1953, Hill and Peterson, 1965, and Oates, 1988).

In this analysis of the mixing of an engine exhaust stream and its bypass flow, the following assumptions were made to simplify the problem to one that has an algebraic solution:

1) the two streams are axial
2) there are no chemical reactions
3) the two streams mix completely
4) the flows are steady
5) internal wall shear stress is ignored
6) diffuser exit flow is compatible with down-stream conditions

The second assumption implies that the molecular weights, the

specific heats, and the gas constants of the two streams all remain constant. While this neglects the variation of these properties with temperature and chemical reaction, this simplification is in line with the rough nature of this analysis (further study is suggested to see whether this simplification significantly alters the results). The thermodynamic properties of the mixed flow can then be calculated from the mass-weighted properties of the input streams.

The effects of the wall shear stress are not included because it is expected that they will be small compared to the drag produced by the internal blockage. The wall stress becomes more important when the diffuser exit Mach number approaches unity, but, as will be seen this value is usually low in this study (Peters and Wehofer, 1962).

Analysis for a Constant Area Duct With No Blockage

In the first part of the development of the analysis, it is assumed that there are no internal blockages in the flow, and that the diffuser duct has a constant diameter (the area of the mixed flow equals the sum of the areas of the input flows).

Four fundamental equations (eqs. 1-4), conservation of mass, conservation of momentum, conservation of energy, and the equation of state are the foundation of this approach. These are given as follows for the case of a straight duct:

$$W_1 + W_2 = W_3 \tag{1}$$

$$P_1A_1 + W_1V_1/g_c + P_2A_2 + W_2V_2/g_c = P_3A_3 + W_3V_3/g_c \quad (2)$$

$$W_1 [C_{p1}T_1 + V_1^2/(2g_cJ)] + W_2 [C_{p2}T_2 + V_2^2/(2g_cJ)] = W_3 [C_{p3}T_3 + V_3^2/(2g_cJ)] + F - Q \quad (3)$$

$$Pm/(RT) = d \quad (4)$$

The subscripts 1 and 2 refer to the engine exhaust stream and the bypass flow, respectively, and subscript 3 refers to the mixed flow (Fig. 2). The conditions of streams 1 and 2 are assumed to be known, and the conditions of stream 3 are desired. The heat release rate, F, and the wall heat loss rate, Q, are heat source and sink terms that can be used to model the heat release due to afterburning and heat loss through wall heat transfer.

The first objective is to obtain an expression for the velocity of stream 3 in terms of properties of the other two streams and the physical restraints of stream 3 (such as area). As a part of this goal, five important constants, Z1 to Z5, will be defined from the manipulation of the above equations. Then the velocity will be used in conjunction with the constants to arrive at other important flow parameters.

To begin the derivation, the mass flow rate can be written as the sum of the density, area, and velocity, so equation 1 can be written:

$$W_3 = d_3A_3V_3 \quad (5)$$

and using equation 4 to eliminate density,

$$W_3 = A_3 V_3 P_3 m_3 / (T_3 R) \tag{6}$$

Solving for T_3 gives an expression for the temperature of stream 3 as a function of the pressure and velocity:

$$T_3 = Z_1 P_3 V_3 \tag{7}$$

where Z_1 is a constant defined, for convenience, as,

$$Z_1 = m_3 A_3 / (W_3 R) \tag{8}$$

Now, taking the second fundamental equation, conservation of momentum, and dividing by A_3 gives,

$$(P_1 A_1 + W_1 V_1 / g_c + P_2 A_2 + W_2 V_2 / g_c) / A_3 = P_3 + W_3 V_3 / (A_3 g_c) \tag{9}$$

Since the conditions of stream 3 are of primary interest, This can be rewritten as,

$$P_3 + Z_2 V_3 = Z_3 \tag{10}$$

where the constants Z_2 and Z_3 are defined by,

$$Z_2 = W_3/(A_3 g_c) \tag{11}$$

$$Z_3 = P_1A_1/A_3 + W_1V_1/(A_3 g_c) + P_2A_2/A_3 + W_2V_2/(A_3 g_c) \tag{12}$$

Now the stream 3 pressure has been reduced to a function of the velocity.

The conservation of energy equation (eq. 3) can be rewritten as,

$$W_3 [C_{p3}T_3 + V_3^2/(2g_cJ)] = W_1 [c_pT_1 + V_1^2/(2g_cJ)] + W_2 [c_pT_2 + V_2^2/(2g_cJ)] + F - Q \tag{13}$$

Dividing by the combined mass flow rate gives the following equation:

$$C_{p3}T_3 + V_3^2/(2g_cJ) = W_1/W_3 [c_pT_1 + V_1^2/(2g_cJ)] + W_2/W_3 [c_pT_2 + V_2^2/(2g_cJ)] + (F - Q)/W_3 \tag{14}$$

It is convenient to define stream mass fractions, Y_1 and Y_2, as the ratios of the inlet mass flows to the total mass flow:

$$Y_1 = W_1/W_3 \quad \text{and} \quad Y_2 = W_2/W_3 \tag{15}$$

Using these definitions, and multiplying through by the left-hand denominator, the energy equation becomes,

$$2Jg_cC_{p3}T_3 + V_3^2 = 2Jg_cY_1\ [c_pT_1 + V_1^2/(2g_cJ)] + 2Jg_cY_2\ [c_pT_2 + V_2^2/(2g_cJ)] + 2Jg_c(F-Q)/W_3 \quad (16)$$

If Z_4 and Z_5 are defined as,

$$Z_4 = 2Jg_cC_{p3} \quad (17)$$

$$Z_5 = 2Jg_c\ \{Y_1\ [c_pT_1 + V_1^2/(2g_cJ)] + Y_2\ [c_pT_2 + V_2^2/(2g_cJ)]\} + 2Jg_c(F-Q)/W_3 \quad (18)$$

then equation 16 can be written,

$$Z_4T_3 + V_3^2 = Z_5 \quad (19)$$

This gives a direct relation between the temperature and velocity of stream 3. Now there are three equations, 7, 10, and 19, defining three unknowns, T_3, P_3, and V_3. We can solve for V_3 by using equation 7 to eliminate T_3 from equation 19:

$$Z_4Z_1P_3V_3 + V_3^2 = Z_5 \quad (20)$$

Equation 10 can be used to replace P_3 giving,

$$Z_4Z_1\ (Z_3 - Z_2V_3)\ V_3 + V_3^2 = Z_5 \quad (21)$$

This expression can be arranged into a quadratic in V_3:

$$V_3^2 (1 - Z_1Z_2Z_4) + Z_1Z_3Z_4 V_3 - Z_5 = 0 \quad (22)$$

To solve equation 22 for V_3, it is helpful to define three coefficient constants:

$$X_a = 1 - Z_1Z_2Z_4 \quad (23)$$

$$X_b = Z_1Z_3Z_4 \quad (24)$$

$$X_c = -Z_5 \quad (25)$$

Now the quadratic in V_3 becomes,

$$X_a V_3^2 + X_b V_3 + X_c = 0 \quad (26)$$

If the energy added to the flow (F-Q) is not so great as to prevent a solution, then equation 26 gives the following results:

$$V_3 = [-X_b + (X_b^2 - 4X_aX_c)\cdot^5]/2X_a \quad (27)$$

$$V_3 = [-X_b - (X_b^2 - 4X_aX_c)\cdot^5]/2X_a \quad (28)$$

Equation 27 gives the subsonic solution for the mixed flow, while

equation 28 gives the supersonic solution. Either the subsonic or supersonic solution may occur, but from a pressure recovery viewpoint, only the subsonic operation is desirable, so the remainder of this thesis will focus on the subsonic solution.

Going back to the definition of the Z constants, the pressure and temperature can be now written as follows:

$$P_3 = Z_3 - Z_2 V_3 \tag{29}$$

$$T_3 = Z_1 P_3 V_3 \tag{30}$$

Now that the pressure, temperature, and velocity of stream 3 have been determined, only a few steps remain to completely describe the flow. As stated above, the thermodynamic properties of the mixed flow can be obtained from the mass weighted properties of the input flows. Thus,

$$c_{p3} = Y_1 c_{p1} + Y_2 c_{p2} \tag{31}$$

The molecular weight, m_3, was determined from,

$$1/m_3 = Y_1/m_1 + Y_2/m_2 \tag{32}$$

since the molecular weights of the input streams are known.

Other gas dynamic properties such as the speed of sound (a_3), the

specific heats ratio (g_3), and the Mach number (M_3) can be easily obtained from the basic relations,

$$g = c_{p3} / c_{v3} = c_{p3} / (c_{p3} - R/m_3) \tag{33}$$

$$a_3 = (g_c\, g\, R\, T_3 / m_3)^{.5} \tag{34}$$

$$M = V_3 / a_3 \tag{35}$$

Last, the net thrust force of the mixed flow on the duct, F, can be determined by,

$$F_3 = P_3A_3 + W_3V_3/g_c - Z_3A_3 \tag{36}$$

Extension of the Analysis to Duct Expansion and Internal Drag

Next the analysis is extended to include the effects of sudden expansion of the diffuser duct and the inclusion of flameholding bars.

The momentum equation can be written to include a drag term due to internal blockage from the bars and the force from the pressure on the base of the sudden-expansion:

$$P_1A_1+W_1V_1/g_c + P_2A_2+W_2V_2/g_c +P_BA_B = P_3A_3+W_3V_3/g_c + D_b \tag{37}$$

where the subscript B refers to the annular base of the sudden expansion (Fig. 3).

The base pressure coefficient, c_{pB}, is defined as,

$$c_{pB} = (P_B - P_2) / q_2 \tag{38}$$

where q_2 is the dynamic pressure of the bypass flow at the diffuser entrance. Now P_B can be written as,

$$P_B = P_2 + c_{pB}\, q_2 \tag{39}$$

Using the equation for dynamic pressure,

$$q_2 = .5\, g\, P_2\, M_2^2 \tag{40}$$

equation 39 becomes,

$$P_B = P_2\, (1 + .5\, c_{pB}\, g\, P_2\, M_2^2) \tag{41}$$

Now values for each term on the right hand side of equation 41 are known except for c_{pB}, which can be estimated from previous base pressure studies (Roberds, et al, 1989).

Since the blockage ratio of the bars with respect to the diffuser area (ß) multiplied by the duct area (A_3) gives the frontal area of the bars, the drag term can be written,

$$D_b = c_d q ß A_3 \tag{42}$$

where q is a representative dynamic pressure, and c_d is the coefficient of drag for an array of bars.

One study of a group of cylindrical bars in a flow (Dalton, 1977) has shown that typical drag coefficients for Reynolds numbers on the order of 10^4 are between .94 and 1.07. A drag coefficient of 1.0 was therefore chosen as a representative figure for arrayed blockage elements in subsonic flows.

The aerodynamic blockage area ratio caused by blockage elements in the difusser flow, such as flameholding bars, is approximated by,

$$\beta = A_B / A_3 = d_b(1 + .25\ S/r_3 - .25\ d_b/r_3)/S \qquad (43)$$

where S is the spacing between the bars, d_b is the bar diameter, and r_3 is the radius of the duct. Several simplifications are necessary to apply this theory to the previous analysis.

There is no existing "accepted" approach to representing the system, including the blockage elements, so a trial and error approach will be used. We will assume a representation, calculate the results, and then check the results to see whether they are reasonable. As a straight-forward approach, assume that the conditions at the blockage elements represents the fully-mixed outlet conditions. The area at the bars now redefines the stream 3 area as (1-ß) times the old area. The representative dynamic pressure used in the definition of the drag term (eq. 42) now becomes,

$$q = .5 d_3 V_3^2 / g_c \tag{44}$$

so that the drag due to aerodynamic blockage is now given by,

$$D_b = c_d \beta A_3 (.5 d_3 V_3^2 / g_c) \tag{45}$$

Now the effect of the drag due to blockage can be incorporated into the momentum equation as,

$$P_1 A_1 + W_1 V_1 / g_c + P_2 A_2 + W_2 V_2 / g_c + P_B A_A = (1-\beta) P_3 A_3 + W_3 V_3 / g_c + c_d \beta A_3 (.5 d_3 V_3^2 / g_c) \tag{46}$$

Using the same procedure as before to solve for V_3 will leave the V_3 dependency in the drag term. At this point, the solution can be found by either rederiving a relation for V_3, or by iterating. Since this theory lends itself to solution by computer program, iteration is the more attractive alternative. Briefly, this process is the following:

$$P_3 + W_3 V_3 / [g_c (1-\beta) A_3] + .5\, d_3 c_d A_3 / g_c\, \beta/(1-\beta) = [P_1 A_1 + W_1 V_1 / g_c + P_2 A_2 + W_2 V_2 / g_c + P_B A_A] / [(1-\beta) A_3] \tag{47}$$

Or, as before,

$$P_3 + Z_2V_3 = Z_3 \tag{48}$$

where the constants Z_2 and Z_3 are redefined as,

$$Z_2 = W_3 / [(1-\beta)g_cA_3] \tag{49}$$

$$Z_3 = [P_1A_1 + W_1V_1/g_c + P_2A_2 + W_2V_2/g_c + P_BA_A] / [(1-\beta)A_3] - .5\ d_3c_dA_3/g_c\ \beta/(1-\beta) \tag{50}$$

This is solved exactly as before, neglecting the drag term for the first iteration. Then the V_3 calculated is plugged into the drag term and V_3 is recalculated and this process is repeated until the value for V_3 converges.

Using the results determined for the mixed flow at 3, this process can be repeated with very little modification to calculate the conditions at 4.

CHAPTER IV

ESTIMATION OF DIFFUSER INLET CONDITIONS

Test Flight Conditions

Some reasonable input data was needed to allow tests of the computer code and to show trends in diffuser performance, so three test conditions were selected as representative of flight conditions that an advanced cycle engine may experience. The three altitude-Mach number combinations used are:

1) altitude = 20,000 ft., Mach number = 1.0
2) altitude = 30,000 ft., Mach number = 2.0
3) altitude = 40,000 ft., Mach number = 3.0.

For these three test conditions, temperature and pressure are defined by NASA standard day conditions.

Engine Exhaust Conditions

Starting with these ambient conditions, a simplified analysis was applied to obtain representative engine exhaust conditions for a hydrogen fueled engine. The exhaust conditions were estimated as follows.

The enthalpy of a gas depends on its kinetic energy, temperature, and heat of formation. The flow entering the engine combustor was

assumed to be composed of air at the total conditions of the representative flight trajectory and hydrogen fuel at room temperature. This leaves the total temperature of the exhaust a function only of the relative amounts of fuel and air, which have different total enthalpies. The operating equivalence ratio, ø, is defined as $(f/A)/(f/A)_s$, where (f/A) is the fuel-air ratio by mass, and $(f/A)_s$ is the stoichiometric fuel-air ratio. So then, the total temperature of the exhaust flow at a given flight condition depends only on ø:

$$T_{t1} = f(\text{ø})$$

Given ø, a NASA program (Gordon and McBride, 1973) can be used to find the exhaust stream total temperature. An operating equivalence ratio of 1 was used for all calculations that did not include afterburning in the diffuser.

The total pressure of the exhaust flow depends on both the flight velocity and the engine design. It can be reasonably assumed that for a well designed engine diffuser, the static pressure of the exhaust will not differ greatly from the static pressure of the surrounding air, so that the exhaust plume will not induce external flow separation. If the engine nozzle exit static pressure is taken to be equal to the ambient static pressure, then only a representative exhaust flow Mach number is needed to give the total pressure in the engine exhaust, since the exhaust gas properties gamma, m, and c_p are known. An engine exhaust nozzle exit Mach number of 2.15 was chosen as

a reasonable value for variable-cycle engines during flight between Mach 1 and 3.

The thrust produced by a jet engine is defined by:

$$T = W_1 (V_1 - V_a) + (P_1 - P_a) * A_1$$

This neglects the mass flow of the fuel, which for hydrogen is small compared to the mass flow of the air (the stoichiometric flow rate ratio is 3%); this admittedly rough generalization is consistent with the other approximations used in this thesis. Since $P_1 = P_a$ was chosen, the last term is zero, and the thrust varies only with the engine mass flow (V_1 and V_a are determined by M_1 and M_a). A set of test cases can be set up by varying the mass flow, which amounts to changing the size of the engine.

This process was used to calculated the exhaust conditions at the three simulated flight conditions given above. The results are tabulated at the end of this chapter.

To check that the approximation for the exit Mach number was valid a different approach was used to recalculate the exhaust properties at the third flight condition. First, a standard inlet pressure loss can be approximated by:

$$n_i = P_{t1} / P_{ta} = 1 - .075 (M_a - 1)^{1.35}$$

for flight Mach numbers up to about 3.0 (Shepherd, 1972). Since the

ambient pressure and the flight Mach number are given, the total pressure of the flow can be easily determined. Next a 25% total pressure loss was assumed for the fuel injection and combustion process at stoichiometric conditions (ø=1). This level of losses may be excessive for the actual engines, but was chosen as a conservative simplification for this analysis. If the exhaust static pressure is assumed to be twice the ambient pressure (an upper limit for exit pressure ratio in airbreathing engines), then the nozzle exit Mach number can be calculated.

Using this method, the exit Mach number was calculated to be 2.26. The alternative method did not result in a value for M_1 significantly different from the value of 2.15 that was assumed earlier, so that assumption was deemed valid. Complete calculations--to be explained below--were performed for all four test conditions, but the results for M_1=2.26 were not significantly different from those of the third condition (with M_1=2.15), so they are not presented.

Heat Release Due to Afterburning

To obtain a rough estimate of the heat released by afterburning, some simple calculations were performed for an engine operating equivalence ratio of 1.32, a fuel-rich condition. For a total exhaust flow rate of 50 lbm/sec, this gave an unburned hydrogen flow rate of 0.45 lbm/sec. The heat release rate, F, is simply the flow rate multiplied by the heat of combustion, which, for a lower heat of combustion of hydrogen of 51600 Btu/lbm, gives: F = 23000 Btu/sec.

This value for heat release rate was used for a select number of cases to evaluate the effect of heat release on diffuser performance.

Summary of Exhaust and Freestream Conditions

As stated earlier, the three representative flight conditions are the following:

A) altitude = 20,000 ft., Mach number = 1.0

B) altitude = 30,000 ft., Mach number = 2.0

C) altitude = 40,000 ft., Mach number = 3.0

Using the approach outlined above, the following test condition data was obtained for these three flight conditions:

Table 1. Summary of Bypass Flow and Engine Exhaust Conditions at the Diffuser Inlet.

	P_{t1} (psi)	T_{t1} (°R)	g_1	m_1	P_1 (psi)	T_{t2} (°R)	P_2 (psi)	M_1
A)	66.14	4290	1.27	25.4	6.76	537	6.76	2.15
B)	42.79	4290	1.27	25.4	4.37	741.4	4.37	2.15
C)	26.7	4612	1.24	24.6	2.73	1092	2.73	2.15

For every test condition, the ratio of specific heats for stream 2 (g_2) equals 1.4 and the stream 2 molecular weight (m_2) equals 28.9. Certainly many guesses and approximations were used to arrive at these conditions, but since only rough representations of the engine exhaust

conditions were needed as input for the analysis, and actual engine operating data for variable cycle engines is not available, this rough approach is justified.

Test Cases Evaluated

At each condition, A through C, calculations were made for five different engine mass flows. For conditions A and B these were W_1 = 50, 100, 150, 200, and 250 lbm/sec, while for condition C, W_1 = 50, 150, 250, 350, and 450 lbm/sec were used. Smaller mass flow rate increments were used for conditions A and B to generate a smoother data set, while larger flow rates were used for condition C to investigate whether diffuser performance trends would be consistent at these rather large engine sizes. At every mass flow, the Mach number of the bypass flow (M_2) was increased from zero in increments of .1 until the flow in the diffuser choked or until a Mach number of 1 was reached at the blockage (or at the exit if there is no blockage). Calculations were first performed for every engine mass flow at every test condition for blockage ratios from 0.0 to 0.5, for a straight diffuser duct with no heat release or wall friction.

Only subsonic bypass flows were investigated for two reasons. First, it was suggested that the bypass flow in a test cell may actually be subsonic in some tests due to engine installation configurations (Roy J. Schulz, private communication, 1990). Also this study was initially intended to look at straight duct configurations, for which the results of the analysis consistently showed choking at

subsonic bypass flow diffuser inlet Mach numbers. The sudden-expansion duct was analyzed to investigate whether this choking could be eliminated and to investigate the resulting diffuser performance. These and other results will be discussed later. For a theoretical and experimental investigation of diffuser performance with a supersonic bypass flow, see Peters and Wehofer, 1962. The previous analysis is still valid for a supersonic bypass flow if certain parameters such as the base pressure coefficient and the bar drag coefficient are modified.

The diffuser ducts studied were chosen to be axisymmetric in cross-section, as shown in Figures 2 and 3. The test cell bypass flow was treated as a flow passing through an annular area around the outside of the engine exhaust flow, and both flows fed directly into the diffuser. The outer diameter of the ducts with and without expansion was held fixed to reflect nominal test facility constraints. A constant diameter of 12 feet was chosen for the straight diffuser, while the sudden-expansion diffuser was chosen to be 12 feet in diameter before the expansion, and 24 feet diameter after, giving an area expansion ratio of 4:1. The areas of the engine exhaust flow and the surrounding annular bypass flow were allowed to vary to match the proscribed inlet mass flow conditions, but the total outer diameter enclosing both flows was fixed at 12 feet. The areas of the bypass flow at each flight condition and engine mass flow rate are tabulated below in square feet (the mass flow rates are given in lbm/sec).

Table 2. Summary of Bypass Flow Areas for Different Engine Exhaust Mass Flow Rates.

	W_1 = 50	W_1 = 100	W_1 = 150	W_1 = 200	W_1 = 250
Condition 1	111.59	110.10	108.60	107.10	105.60
Condition 2	110.78	108.46	106.15	103.83	101.52
	W_1 = 50	W_1 = 150	W_1 = 250	W_1 = 350	W_1 = 450
Condition 3	109.06	100.97	92.89	84.81	76.72

The calculations were repeated at select conditions to include a sudden expansion duct and heat release in the flow. Sudden expansion was investigated for the highest mass flow and blockage case (the condition most likely to exhibit choking) at conditions A, B, and C. Calculations were made for three straight diffuser duct cases with constant heat release: condition A with blockages of 0%, 30%, and 50%. These heat release calculations were then repeated to include sudden expansion at the same three blockages for condition A. The majority of the work was performed on the straight (constant area) duct since this geometry was most sensitive to bypass flow inlet conditions, engine conditions, and flameholder blockage. Due to the magnitude of data generated, only a selected number of the above cases are presented in the next section to show general trends and quantitative effects. As an example of the program output, the complete data calculated for a straight diffuser at the 10,000 ft. test case with no heat release is included in Appendix C.

CHAPTER V

RESULTS AND DISCUSSION

Summary of the Results

Several important results of the investigations performed with the computer program will be briefly summarized before a more complete explanation is given in the discussion of the figures created from the data.

It was determined that the straight diffuser duct is very susceptible to choking at the blockage (or at the exit if there is no blockage), even at low subsonic bypass flow diffuser inlet Mach numbers. Increasing simulated altitude, blockage, or engine mass flow rate all served to hasten choking, as also did the addition of heat release to the diffuser flow. A sudden-expansion in the diffuser was found to alleviate the choking problem, but at the cost of decreased pressure recovery at the lowest bypass flow Mach numbers.

Explanation of the Figures

The results of the computational study are presented in Figures 4 through 21 of Appendix A. A complete listing of the program used to generate this data is included in Appendix B, and a sample of the complete program output comprises Appendix C.

Figures 4-6 show the bypass flow diffuser inlet Mach number, M_2, at which choking occurs in the diffuser (afterwards called the critical

bypass Mach number) as a function of engine (stream 1) mass flow, for the straight duct, with no heat release for the 10, 20, and 30 kft. static pressure conditions in the diffuser inlet, respectively. Figures 7-9 show the effect of diffuser blockage on the diffuser flow exit Mach number, static pressure, and static temperature, respectively, as these are plotted versus M_2 for a fixed engine mass flow of 50 lbm/sec. The following three figures (10-12) show the effect of varying engine exhaust stream mass flow rate on the same three parameters, as diffuser exit Mach number, static pressure, and static temperature are plotted versus M_2 for two blockage ratios.

The effect of varying the simulated altitude at which the tests are performed is shown in the figures 13-15, again in terms of diffuser exit flow Mach number, static pressure, and static temperature respectively, plotted versus the bypass flow diffuser inlet Mach number; this time for a constant engine mass flow rate of 50 lbm/sec and at 0% and 50% blockage. The performance of a sudden-expansion diffuser is compared with that of a straight diffuser in the next three figures (16-18), in which both total and static conditions are plotted for a blockage of 50% and an engine mass flow rate of 250 lbm/sec. Figure 16 shows diffuser exit Mach number versus M_2, figure 17 shows diffuser exit static and total pressures versus M_2, and figure 18 shows static and total temperatures plotted versus M_2, the bypass flow Mach number at the diffuser inlet.

Last, the effect of heat release on diffuser exit Mach number, static pressure, and static temperature are shown in Figures 19, 20,

and 21, respectively. The three diffuser exit flow parameters are each plotted versus M2 for a constant engine mass flow of 50 lbm/sec and at blockage ratios of 0% and 50%.

Choking in the Diffuser

For every set of inlet conditions studied using a straight diffuser duct, choking occurred in the diffuser at some subsonic bypass flow inlet Mach number. Figure 4 shows that for no internal blockage at the lowest simulated altitude (10,000 ft.), the bypass flow reached Mach .72 at the diffuser inlet for the lowest engine exhaust mass flow rate (50 lbm/sec) before choking occurred. As the engine mass flow rate was increased up to 250 lbm/sec, the critical bypass flow Mach number naturally decreased since the diffuser was unable to pass any more mass flow. Increasing the internal blockage in the diffuser is seen to hasten choking since blockage elements such as flameholding bars reduce the effective cross-sectional area of the diffuser.

Figure 5 shows the same trends as Figure 4 for the second altitude condition, 20,000 feet. Again, both increasing engine exhaust mass flow rate and increasing blockage serve to lower the critical bypass Mach number.

Although it was expected that these trends would continue unchanged for the third altitude condition, Figure 6 shows an increase in critical Mach number with exhaust mass flow rate for W_1=350 to 450 lbm/sec, at the lowest blockage. At this point it will be helpful to develop a relationship between the bypass flow Mach number and mass

flow rate. The Mach number, speed of sound, and mass flow rate can be written as,

$$M = V / a$$

$$a = (g\ g_c\ R\ T / m)^{.5}$$

$$W = d\ V\ A$$

Solving the third equation for velocity and substituting these relations for speed of sound and velocity into the first equation gives,

$$M = W / [d\ A\ (g\ g_c\ R\ T / m)^{.5}]$$

Using the equation of state to eliminate density (d),

$$M = (W\ R\ T) / [A\ (g\ g_c\ R\ T / m)^{.5}] = W\ (R\ m\ T)^{.5} / A\ (g_c\ g)^{.5}$$

Solving this equation for the mass flow rate and defining a constant, $K = [(g\ g_c / (R\ m)]^{.5}$ gives the following equation for mass flow rate:

$$W = M\ A\ K/T^{.5}$$

Since variation of the square root of bypass flow temperature is relatively small, the mass flow rate is roughly proportional to the product of the Mach number and the area.

Now the reason for the behavior of the critical Mach number can be understood by referring back to the table of exhaust and bypass flow areas. For the first two altitude conditions (A and B) the variation in the engine mass flow rate is small enough to keep the bypass flow area rather constant (the maximum difference is 8%), so the mass flow rate is roughly proportional to the Mach number. For the much larger engine mass flow rates in condition C, the bypass area change becomes great enough (up to 30% difference) to change this relation.

In Figure 6, the bypass flow critical Mach number increases with engine mass flow rate for the lowest blockages. The bypass mass flow rate is decreasing (because of the diffuser choking) but the bypass flow area is decreasing even faster, driving the Mach number higher with increasing engine exhaust flow rate (see the last equation).

Effect of Varying Blockage on Diffuser Performance

Figure 7 shows the effects of varying the blockage ratio while holding the engine mass flow rate and the simulated altitude constant. As was mentioned above, increasing the blockage decreases the bypass flow critical Mach number (hastens diffuser choking), and it is also seen to increase the Mach number at the diffuser exit. This is because the blockage bars produce a drag force on the flow, decreasing the flow impulse which drives the Mach number up, similar to Fanno flow.

The effect of blockage on pressure recovery in the diffuser is shown in Figure 8. As mentioned above, the decrease in total pressure caused by increasing blockages reduces the static pressure at the

diffuser exit, as expected. The effect of blockage on diffuser exit temperature shown in Figure 9 is less dramatic: increasing internal blockage decreases the static temperature at the exit because blockage drives up the diffuser exit flow Mach number.

Changes in Diffuser Performance with Engine Flow Rate

Variation of diffuser exit Mach number with bypass flow diffuser inlet Mach number is shown in Figure 10 for different engine exhaust mass flow rates and two blockage ratios. The end point of each curve in Figure 10 shows the last bypass flow diffuser inlet Mach number (M_2) calculated before diffuser choking occurred. It can be seen that increased blockage causes diffuser choking at lower values of M_2, as does higher engine exhaust mass flow rates. Also, before choking occurs, the Mach numbers at the diffuser exit are higher for lower engine exhaust mass flow rates at the same bypass flow diffuser inlet Mach number.

Figure 11 reveals somewhat peculiar static pressure recovery performance for varying engine mass flow rates, for cases with and without internal blockage. At low bypass flow Mach numbers, pressure recovery is greater for higher engine exhaust flow rates, while just before choking occurs in the diffuser, pressure recovery is greater for lower engine exhaust flow rates. While this behavior is interesting, it is not seen as critical from a test facility design viewpoint. It simply reflects the fact that the pressure losses are greatest for the highest total mass flows. That is, at the lowest bypass flow Mach

numbers (and mass flow rates), the total diffuser mass flow rate is higher for higher engine exhaust flow rates, while at high values of M_2 (as the choking condition is approached), the total mass flow rate is lower for higher engine exhaust flow rates.

Figure 12 simply shows that as more hot exhaust gas is added to the flow, the diffuser exit temperature increases (from curve to curve); and, as more cool bypass flow is added, the exit temperature decreases (along a single curve).

Diffuser Performance Variation with Simulated Altitude

From Figure 13 it was seen that as the simulated flight altitude increases (decreasing the pressures of the inlet flows) and the flight Mach number increases (increasing bypass flow total temperature), the diffuser exit Mach number increases at each bypass flow diffuser inlet Mach number. The final expression for diffuser velocity derived in the analysis (eq. 27) shows that diffuser velocity changes roughly with the square root of inlet temperature and increases with decreasing inlet pressure. The definition for Mach number, $M = V / (g\ g_c\ R\ T / m)^{.5}$, serves to minimize the effect of changing temperatures, but the diffuser Mach number still increases with decreasing inlet pressure. Figure 13 also shows that the bypass flow diffuser inlet Mach number at choking decreases slightly with increasing altitude, largely due to decreasing bypass flow pressure.

The effect of altitude on pressure recovery shown in Figure 14 reflects the inlet pressure changes mentioned above. As the ambient

(and therefore diffuser inlet flow) pressure decreases, the diffuser exit pressure also decreases for cases with and without blockage. Figure 15 shows the increase in diffuser exit temperature as altitude, and inlet temperatures, increase. The static temperature versus mass flow plot also shows that at higher altitudes choking occurs in the diffuser at much lower bypass flow mass flow rates. This contrasts with Figure 13, which showed that the bypass flow Mach number at choking decreased only slightly with increasing altitude. This shows that while the bypass flow Mach number only decreased slightly, the bypass mass flow rate decreased more rapidly because of decreasing density.

Sudden-Expansion Diffuser Performance

Several cases with a sudden expansion diffuser were studied to investigate whether the choking exhibited in the straight diffuser could be eliminated. Figure 16 shows that the diffuser flow does not approach choking conditions for subsonic bypass flow diffuser inlet Mach numbers. The Mach numbers are lower at the diffuser exit because of the increase in the diffuser area, compared with the straight duct.

Figure 17 shows the important effect of sudden-expansion on pressure recovery. At the lowest bypass flow diffuser inlet Mach numbers (where choking is not imminent), the pressure recovery is significantly better for the straight diffuser. This is especially true for the total pressure, which is of greater significance to the test facility designer. Conversely, as choking occurs in the diffuser,

the straight duct pressure recovery is degraded far below the expanded duct pressure recovery. This indicates that the smaller area duct gives better pressure recovery if choking is not imminent, therefore, to maximize diffuser pressure recovery, the duct expansion should be carefully sized to avoid choking with the smallest possible area increase.

Total temperature at the diffuser exit for the two diffuser geometries is identical, as is shown in Figure 18. The diffuser exit static temperature is slightly lower for the straight duct because the exit Mach number is higher, and again, the sudden-expansion geometry does not experience choking.

Effect of Heat Release on Diffuser Performance

Figure 19 shows that as heat is added to the diffuser flow, choking is more likely. This is the familiar behavior of Rayleigh flow in straight ducts: the addition of energy to the flow drives the flow toward its choking condition. Note that because the energy sorce for the afterburning heat was included as a lumped heat release term in the energy equation, the calculations represent physical flows which have afterburned upstream of any blockage elements.

Diffuser pressure recovery is decreased by heat release into the flow, as shown in Figure 20, and Figure 21 shows the increase in temperature from heat release. These trends are valid in all three figures for flows with and without blockage. The effects of heat release shown in these figures are not nearly great enough to cause

choking in the sudden-expansion duct discussed above. This was verified by running the program for several cases with both a sudden-expansion and heat release, but the data resulting did not show sufficient variation from Figures 16-18 to merit inclusion in this thesis.

CHAPTER VI

CONCLUSIONS AND RECOMMENDATIONS

Summary of the Research

The results discussed in the previous section show that a simplified control volume analysis of complex fluid flow in diffuser systems can provide useful information about the flow. Data on the performance of the system in terms of diffuser exit Mach number, static pressure and static temperature were obtained using this analysis, and the results appear to be reasonable.

The control-volume analysis was applied to a diffuser system for use in a hypothetical free-jet engine test with subsonic bypass flow entering the diffuser, in which blockage elements (flame-holders) may be installed in the diffuser to initiate and stabilize exhaust afterburning. The results of this analysis show that if a straight diffuser duct, that is, one with no expansion or contraction of cross-sectional area, was used, the combined engine exhaust flow and free-jet bypass flow was restricted to relatively low mass flow rates to prevent choking at the diffuser exit. This problem was exacerbated by the inclusion of diffuser blockage or heat release in the analysis.

With no blockage or heat release in the flow in the straight diffuser, the bypass flow Mach number at the diffuser inlet was restricted to a maximum of about 0.7 for the lowest engine exhaust mass flow rates investigated. At higher exhaust flow rates corresponding to

cases of more interest in propulsion testing, the bypass flow Mach number was limited to a maximum of around 0.5. This restriction is rather severe, and would be prohibitive in many engine test scenarios.

To illustrate the performance degradation effect of blockage and heat release, fifty percent blockage of the flow by flame-holding elements further reduced the allowable Mach numbers of the bypass flow at the diffuser inlet by nearly half, and a small constant heat release reduced the allowable bypass flow Mach numbers by approximately 10%. For this reason, use of flameholders in a constant area diffuser is not recommended.

A sudden-expansion diffuser geometry was investigated at several of the worst performance cases for the straight duct, to determine whether choking could be prevented. An expansion ratio of four to one was chosen, which meant a doubling of the diameter of the axisymmetric diffuser. The performance of this diffuser proved to be superior, as bypass flow Mach numbers at the diffuser inlet of near unity did not choke the flow at the diffuser exit. Pressure recovery was lower at the lowest bypass flow Mach numbers, compared with the straight duct, but was greater at bypass flow Mach numbers that approached choking conditions. The sudden-expansion geometry decreased the diffuser exit Mach numbers even at bypass flow Mach numbers approaching unity, and the effect of heat release on the diffuser performance was minimal. The use of a sudden-expansion diffuser geometry is recommended, especially if the presence of flame-holders in the diffuser duct is required. Using this analysis, the minimum expansion required to

prevent diffuser choking can be estimated for a set of inlet conditions, thus giving maximum pressure recovery.

Conclusions

The conclusions of this study are summarized as follows:

1) The control-volume analysis method is a useful technique for investigating flows in diffuser ducts.

2) The constant area diffuser is a poor choice for use in free-jet testing of airbreathing propulsion engines, for the conditions described in this study.

3) The sudden-expansion diffuser of area ratio 4 exhibits superior performance that is not seriously degraded by the presence of blockage or heat release in the flow.

4) The expansion ratio should be minimized to maximize pressure recovery while still preventing choking.

Recommendations for Future Research

As information becomes available on the test condition requirements for new engines, this analysis can be used to estimate the adequacy of various diffuser systems. Since the effects of heat release and blockage elements are included, this process particularly lends itself to approximation of diffuser performance when afterburning is used to handle engine exhaust flows.

Three areas of this analysis are thought to merit further

investigation. First, since the effects of wall friction were not included, it is suggested that they be investigated to see whether diffuser performance would be significantly affected. The diffuser systems were assumed in the analysis to be low length-to-diameter ratio designs typical of many propulsion test facilities. If, however, length-to-diameter ratios over 10 are used, wall-friction will become an increasingly important factor. Second, the analysis was based on constant constituent gas properties, such as specific heats. If systems with very high temperature exhausts are investigated, the process should be modified to incorporate variable gas properties and variable composition for cases with afterburning. And last, the analysis should be applied to cases in which the free-jet flow entering the diffuser is supersonic, a test condition that is also expected to be encountered in future engine test programs.

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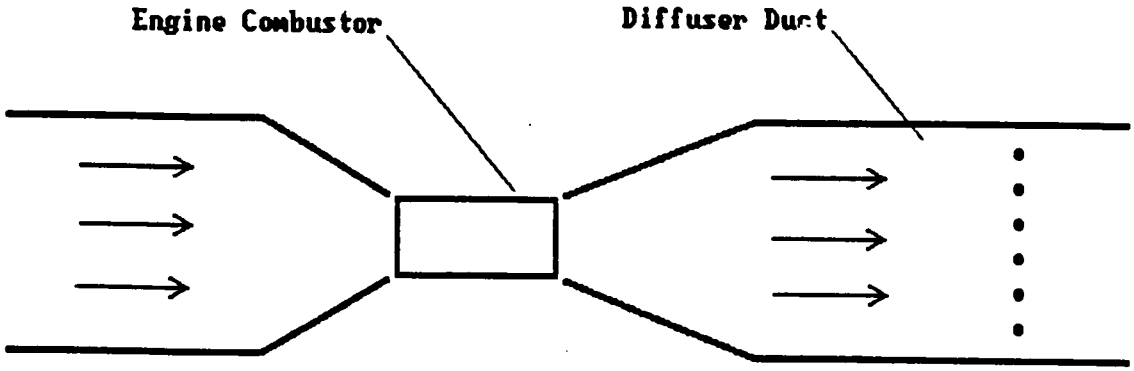
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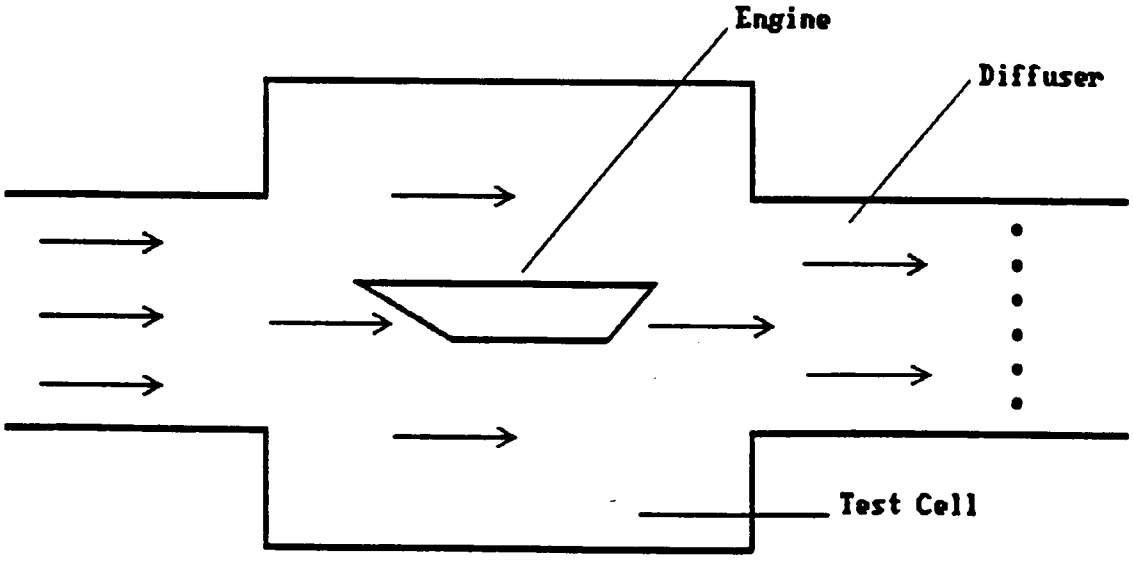
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APPENDICES

APPENDIX A: Figures



a) Direct-Connect Propulsion Testing,



b) Free-Jet Propulsion Testing.

Figure 1. Ground Facility Testing Techniques

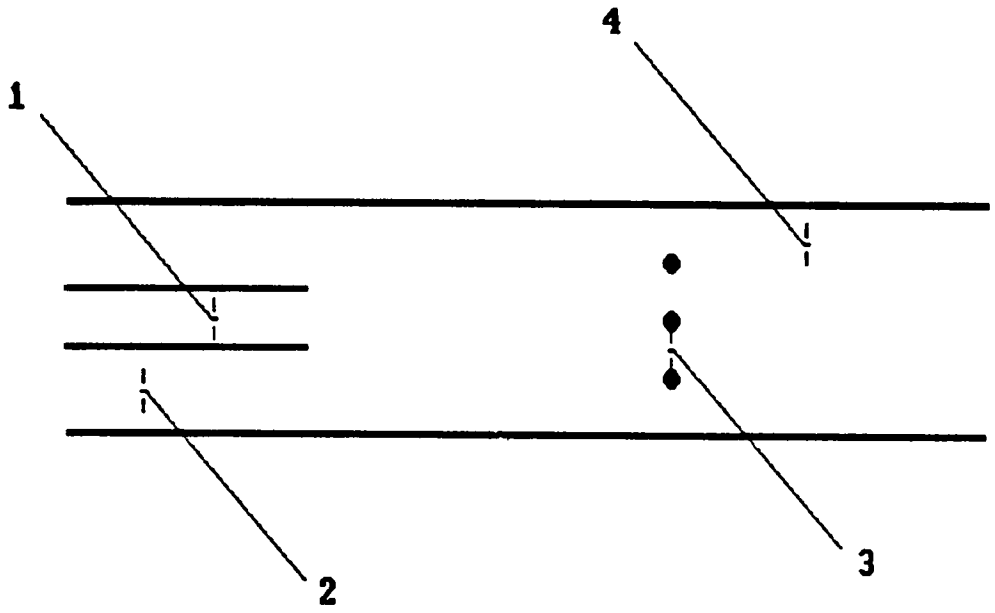


Figure 2. Straight Diffuser Duct Flow Parameter Locations.

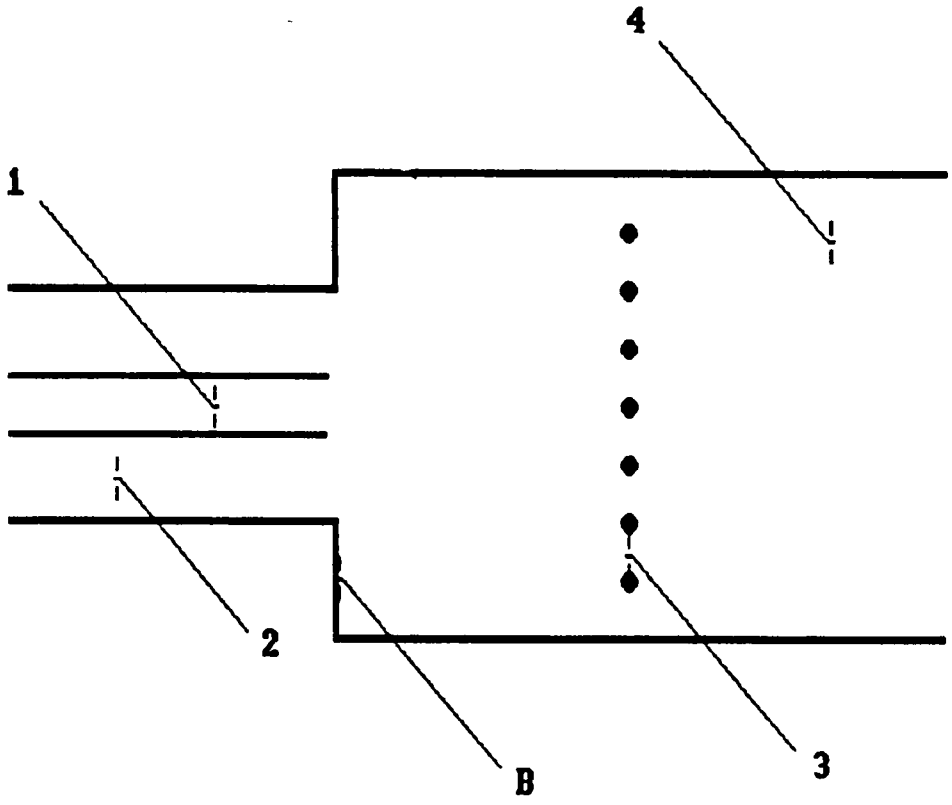


Figure 3. Sudden-Expansion Diffuser Duct Flow Parameter Locations.

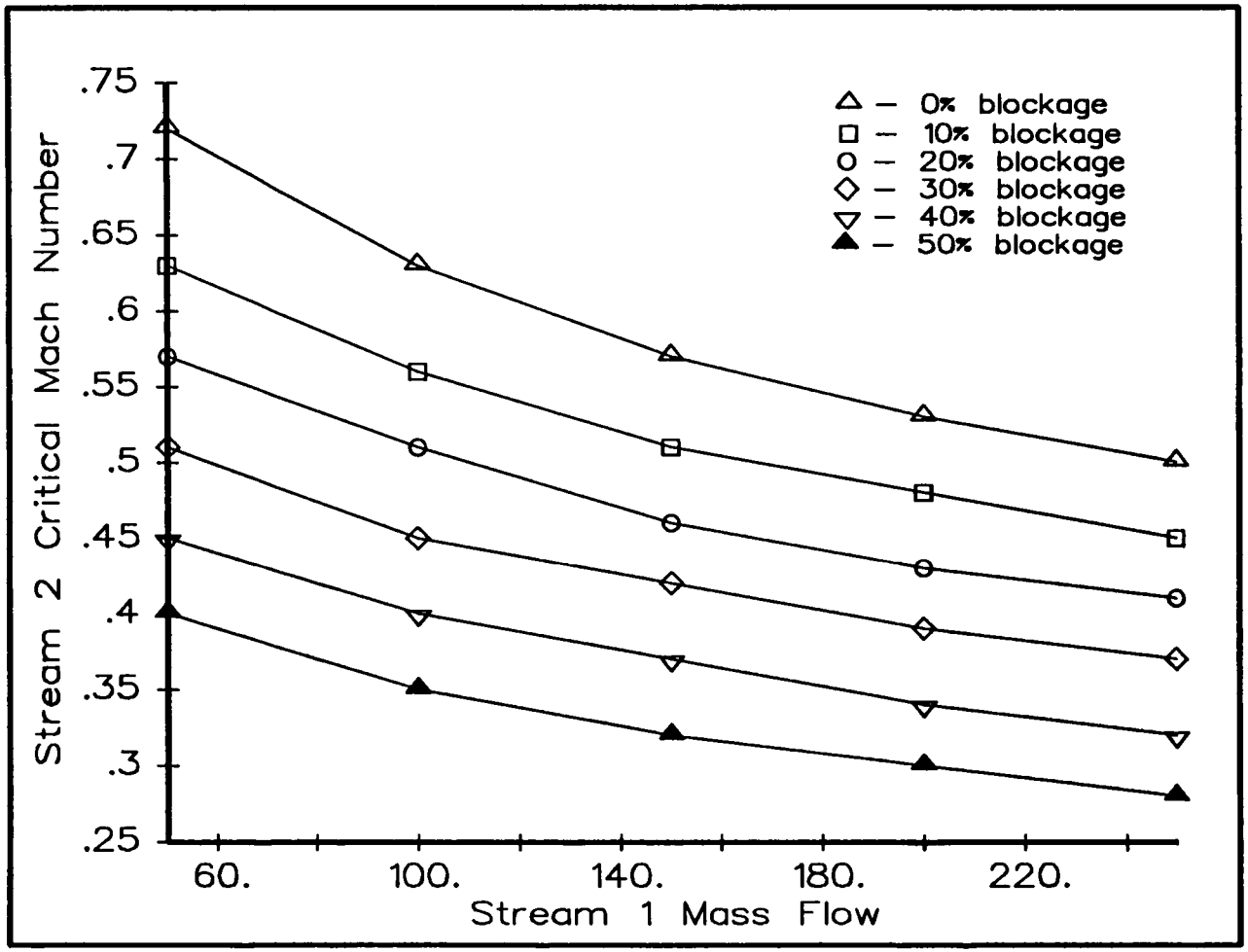


Figure 4. Bypass Flow Diffuser Inlet Mach Number at Choking vs. Engine Exhaust Stream Mass Flow Rate for Various Blockages at 10,000 ft. Test Condition.

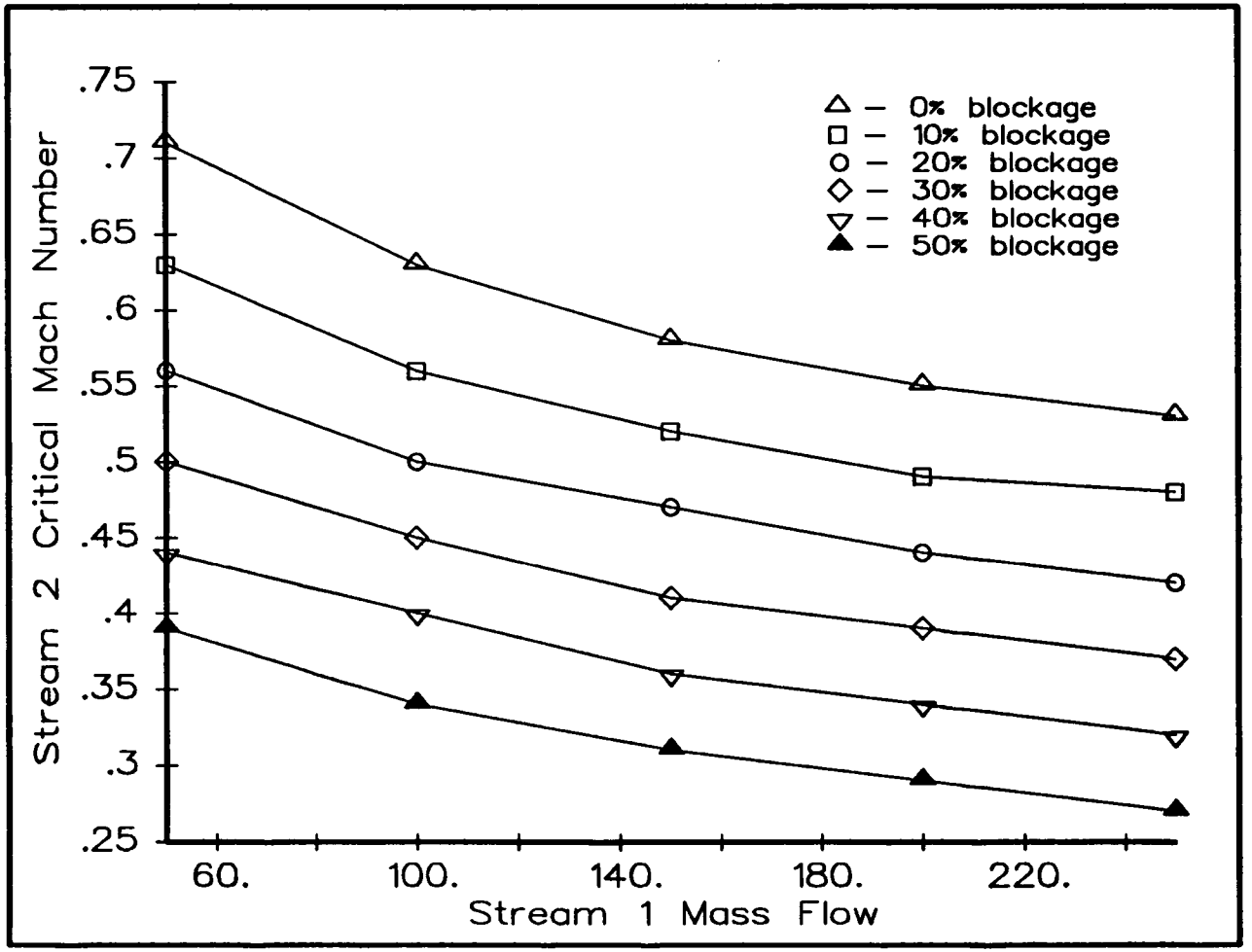


Figure 5. Bypass Flow Diffuser Inlet Mach Number at Choking vs. Engine Exhaust Stream Mass Flow Rate for Various Blockages at 20,000 ft. Test Condition.

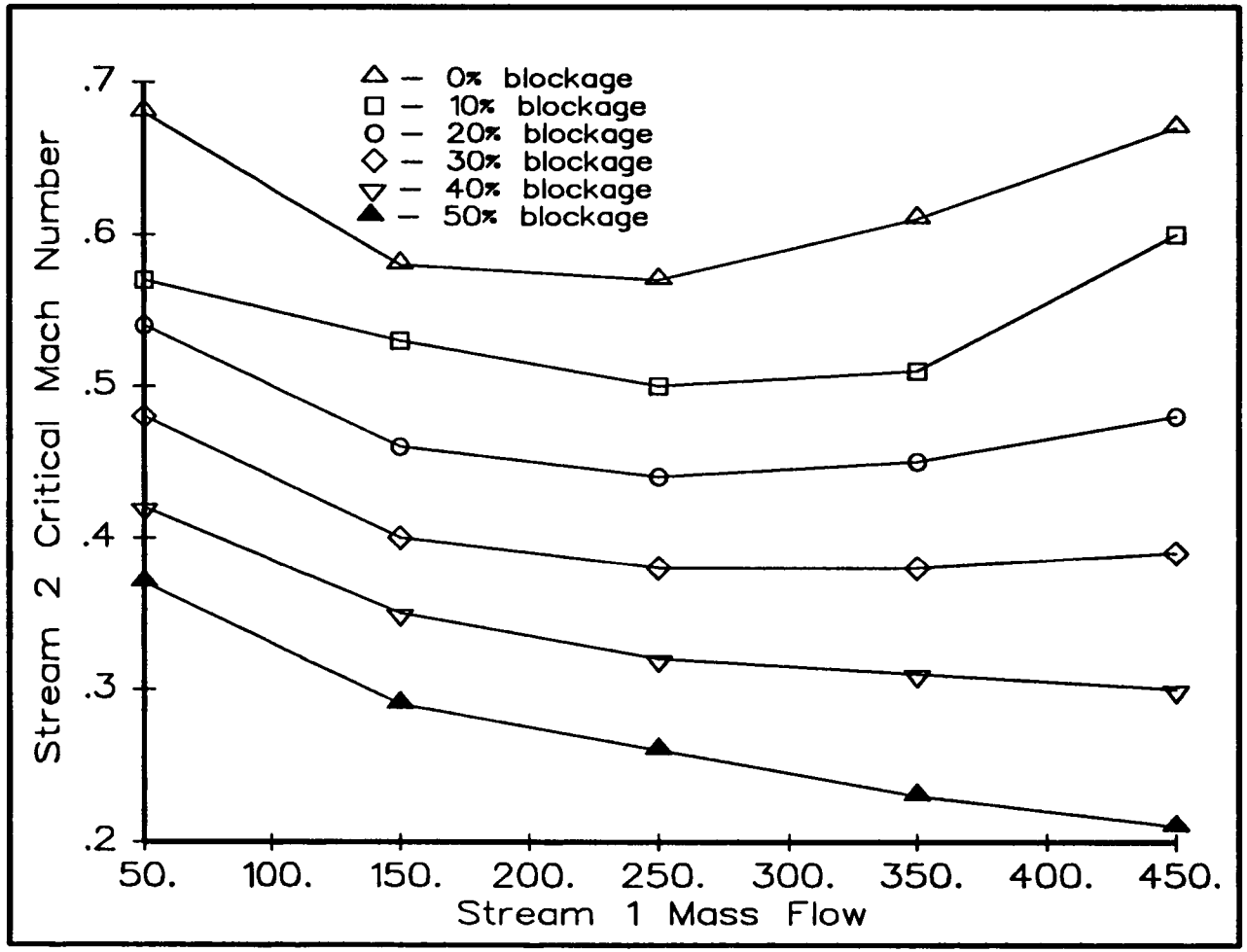


Figure 6. Bypass Flow Diffuser Inlet Mach Number at Choking vs. Engine Exhaust Stream Mass Flow Rate for Various Blockages at 30,000 ft. Test Condition.

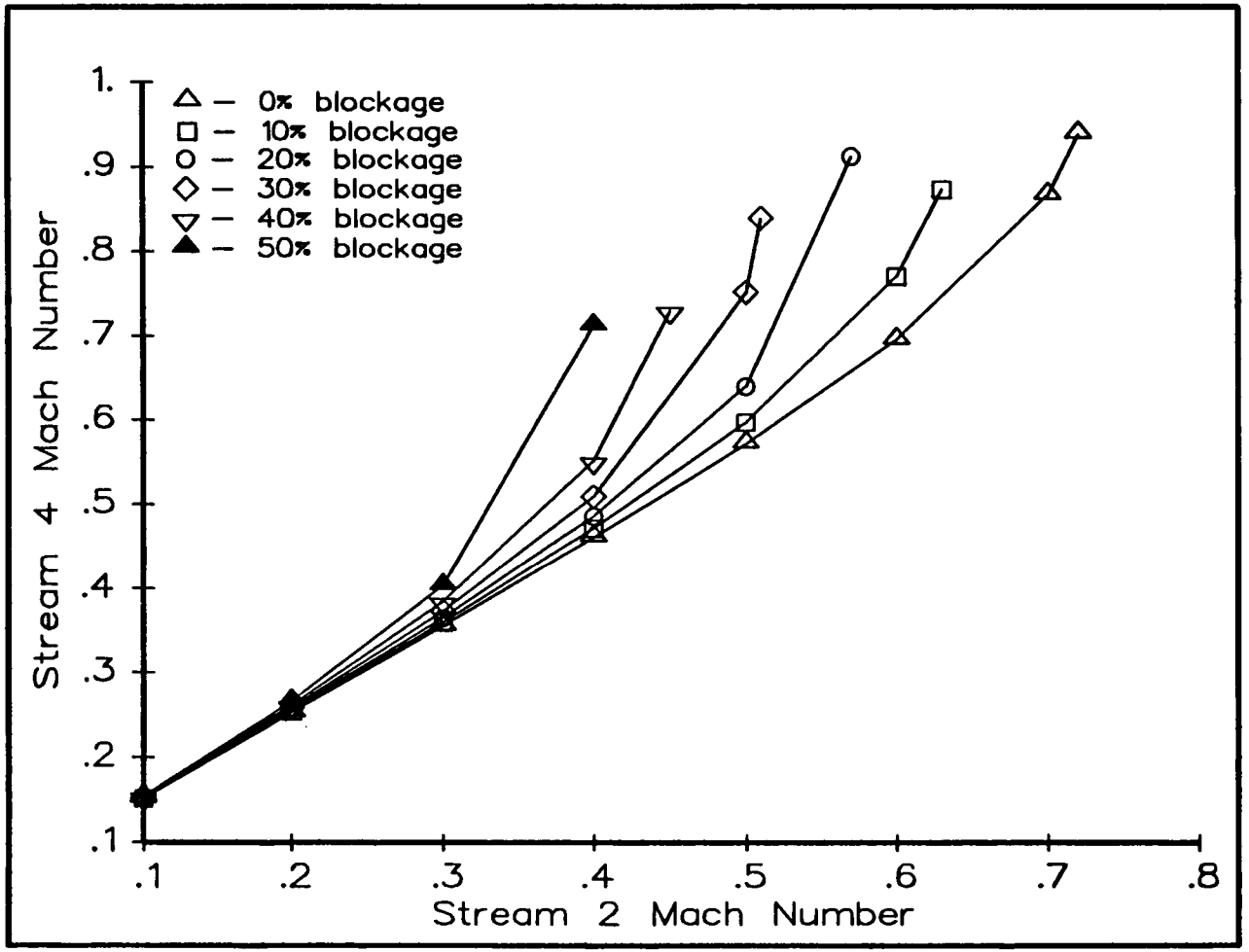


Figure 7. Diffuser Exit Mach Number vs. Bypass Flow Diffuser Inlet Mach Number for Various Blockages; 50 lbm/sec Engine Mass Flow Rate at 10,000 ft. Test Condition.

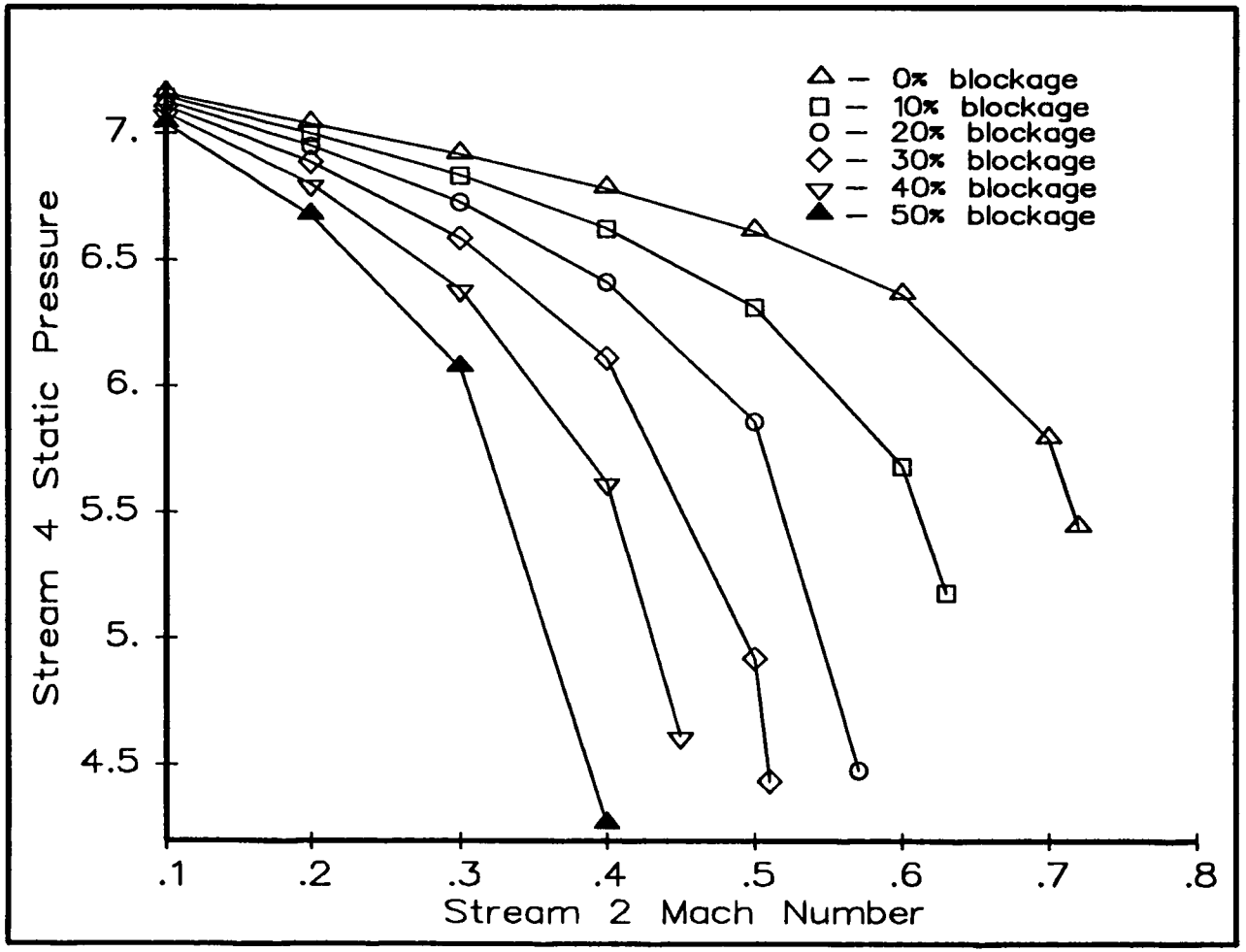


Figure 8. Diffuser Exit Static Pressure vs. Bypass Flow Diffuser Inlet Mach Number for Various Blockages; 50 lbm/sec Engine Mass Flow Rate at 10,000 ft. Test Condition.

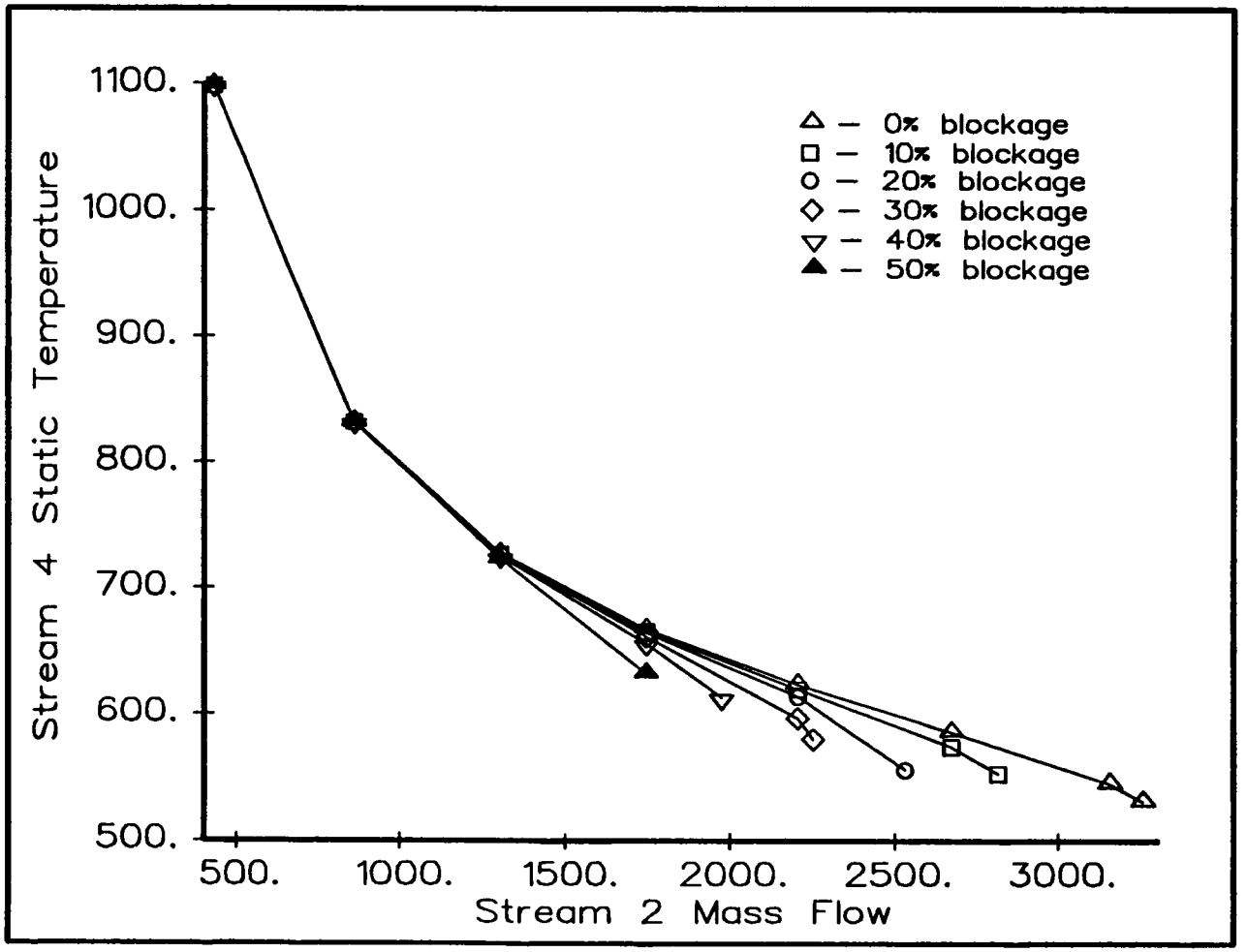


Figure 9. Diffuser Exit Static Temperature vs. Bypass Flow Diffuser Inlet Mach Number for Various Blockages; 50 lbm/sec Engine Mass Flow Rate at 10,000 ft. Test Condition.

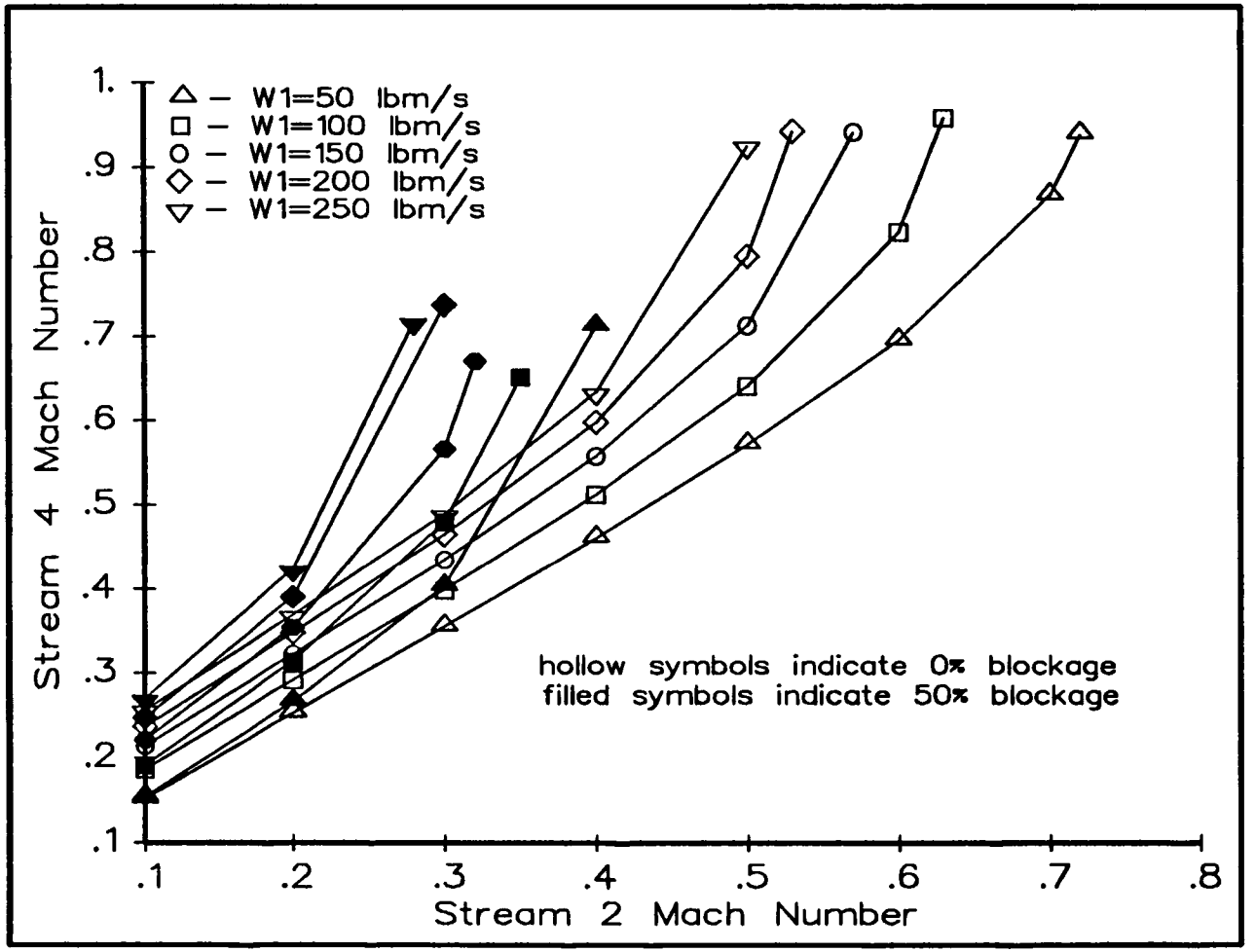


Figure 10. Diffuser Exit Mach Number vs. Bypass Flow Diffuser Inlet Mach Number for Various Engine Exhaust Stream Mass Flow Rates with 0% and 50% Blockage; 10,000 ft. Test Condition.

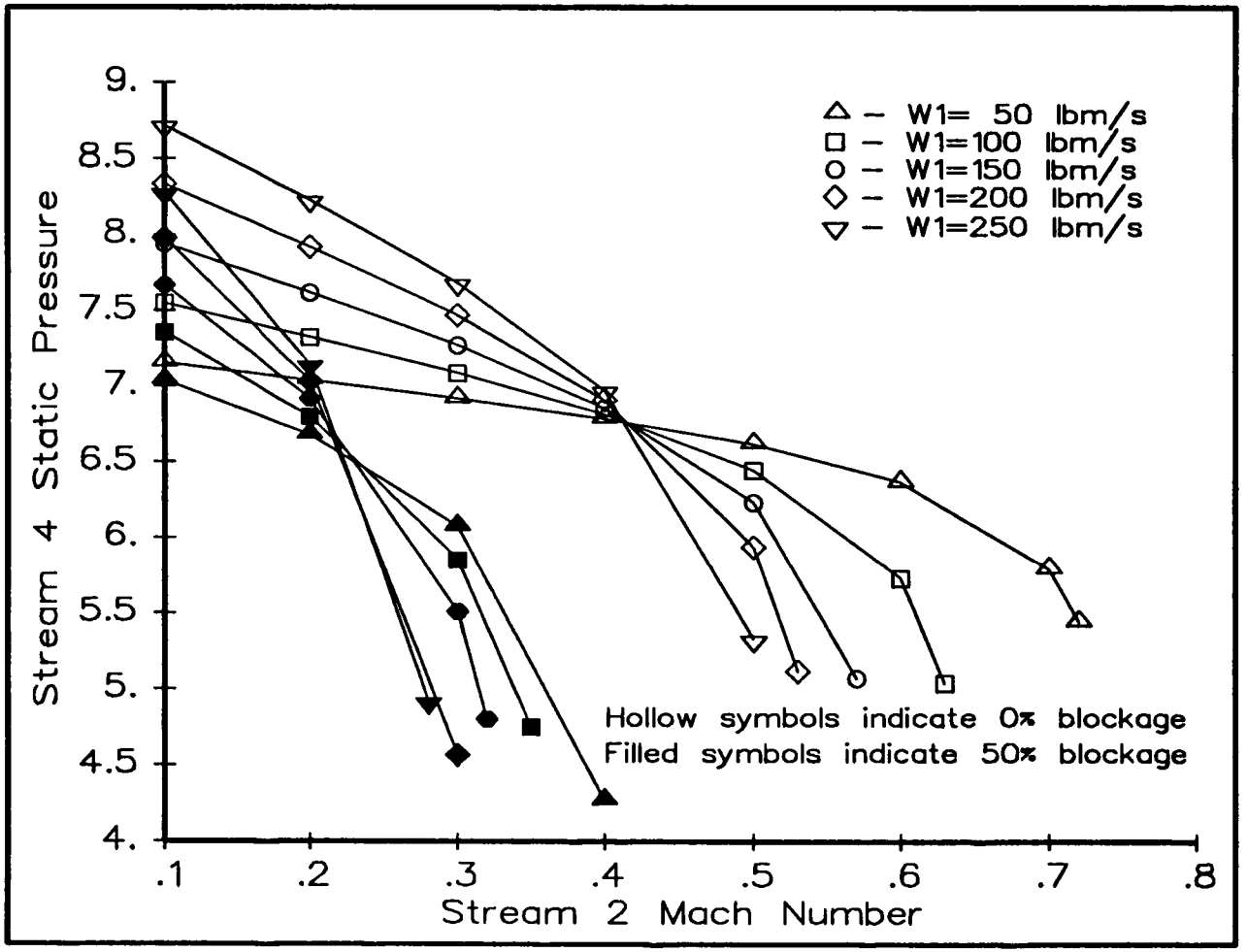


Figure 11. Diffuser Exit Static Pressure vs. Bypass Flow Diffuser Inlet Mach Number for Various Engine Exhaust Stream Mass Flow Rates with 0% and 50% Blockage; 10,000 ft. Test Condition.

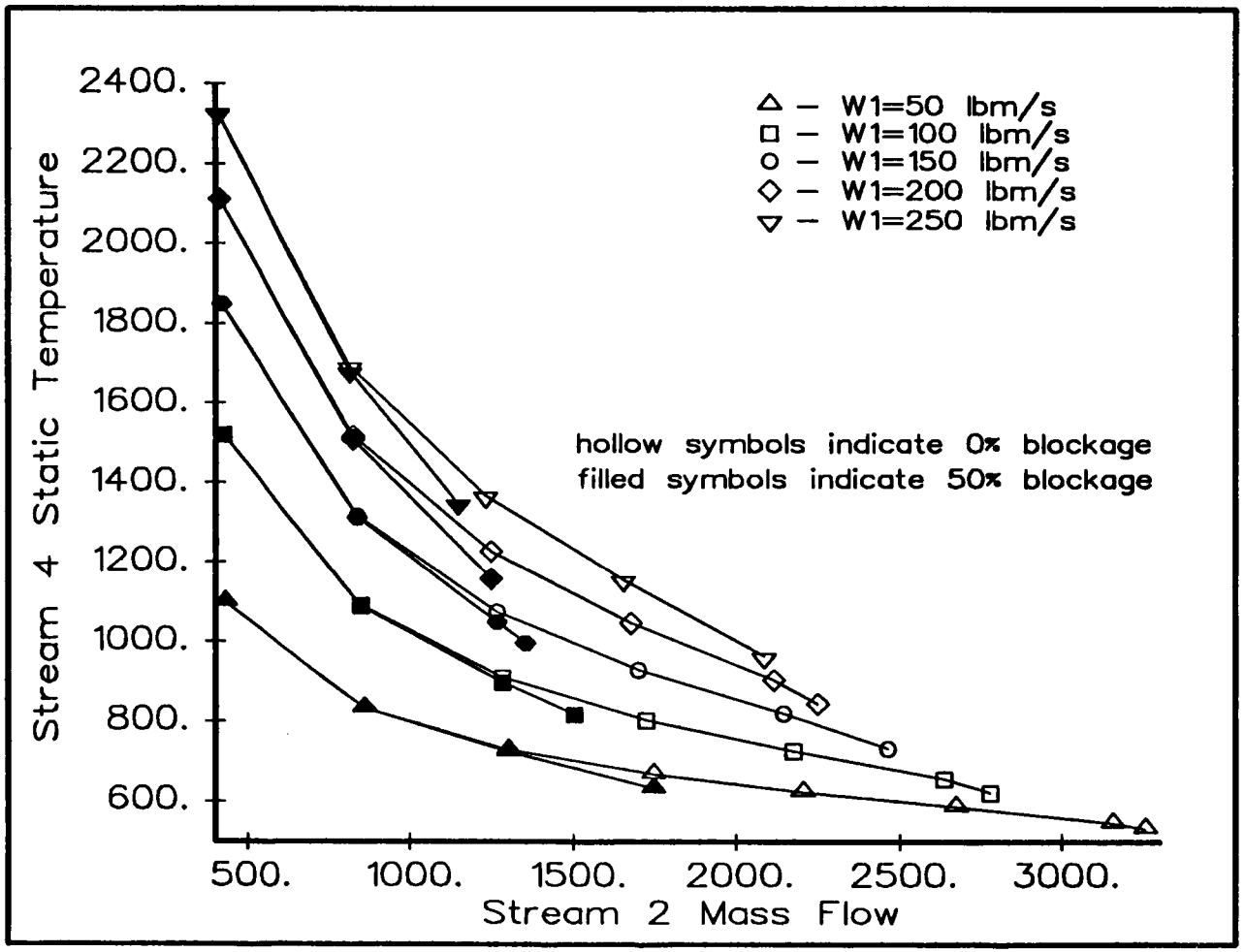


Figure 12. Diffuser Exit Static Temperature vs. Bypass Flow Diffuser Inlet Mach Number for Various Engine Exhaust Stream Mass Flow Rates with 0% and 50% Blockage; 10,000 ft. Test Condition.

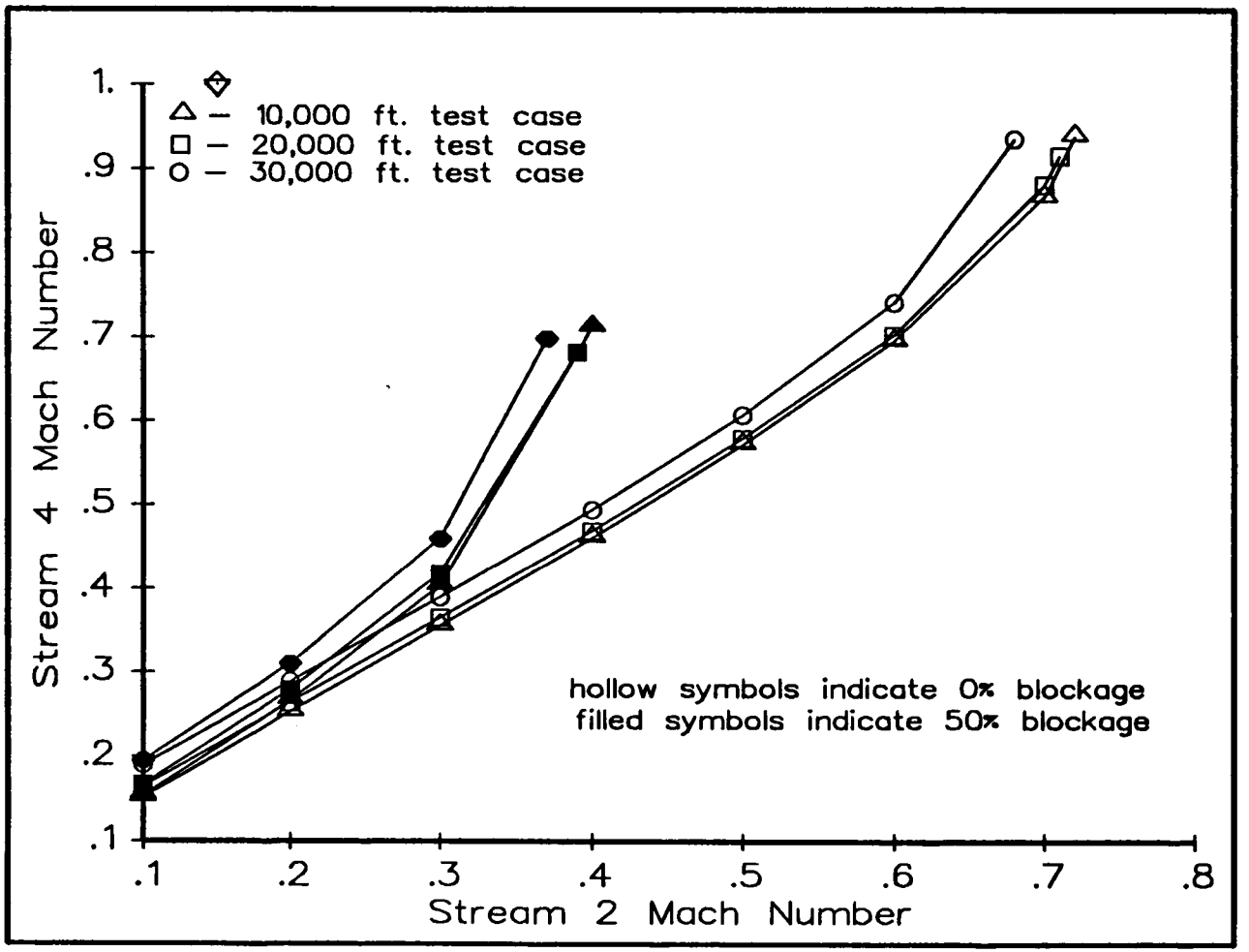


Figure 13. Diffuser Exit Mach Number vs. Bypass Flow Diffuser Inlet Mach Number for Various Simulated Altitudes with 0% and 50% Blockage; 50 lbm/sec Engine Mass Flow Rate.

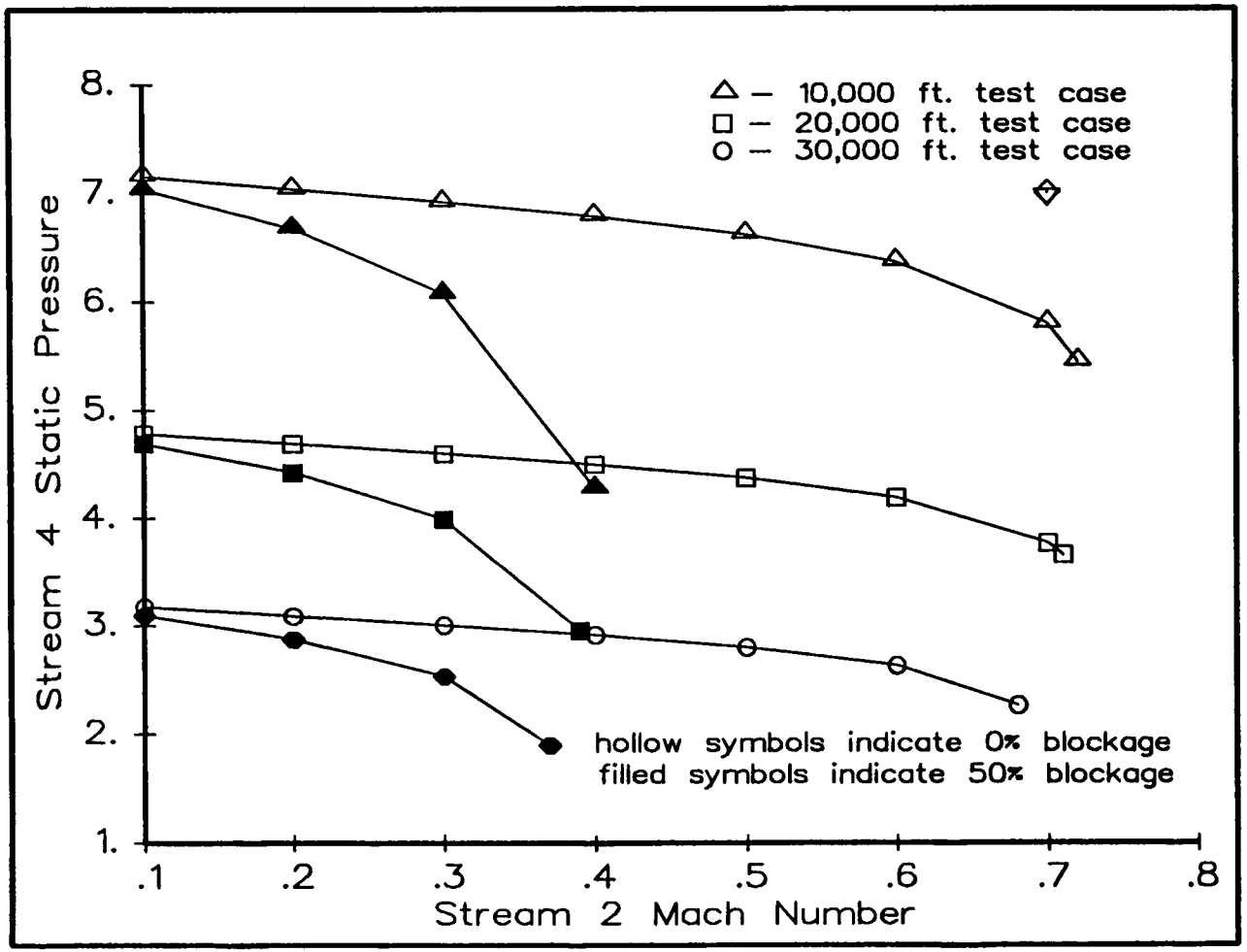


Figure 14. Diffuser Exit Static Pressure vs. Bypass Flow Diffuser Inlet Mach Number for Various Simulated Altitudes with 0% and 50% Blockage; 50 lbm/sec Engine Mass Flow Rate.

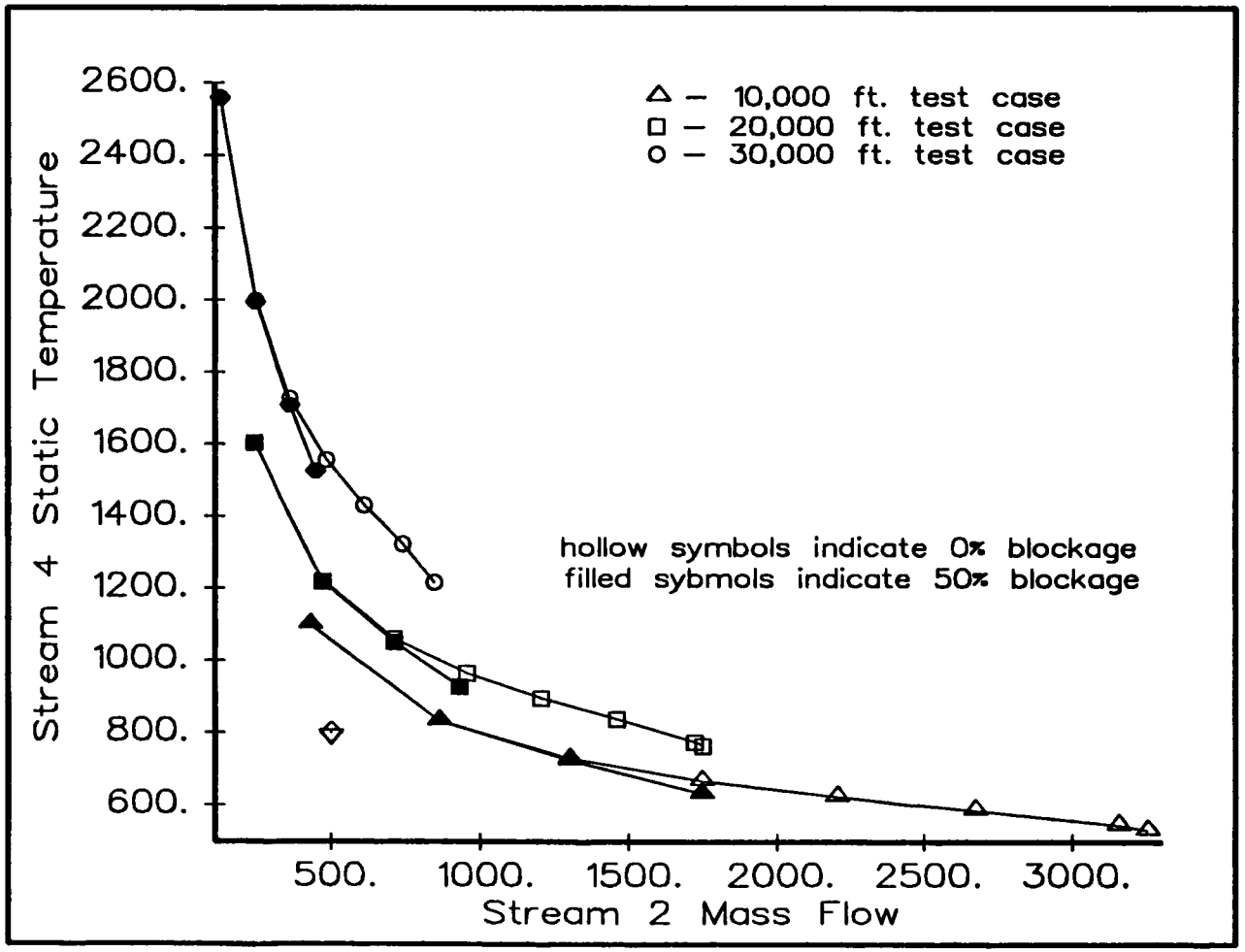


Figure 15. Diffuser Exit Static Temperature vs. Bypass Flow Diffuser Inlet Mach Number for Various Simulated Altitudes with 0% and 50% Blockage; 50 lbm/sec Engine Mass Flow Rate.

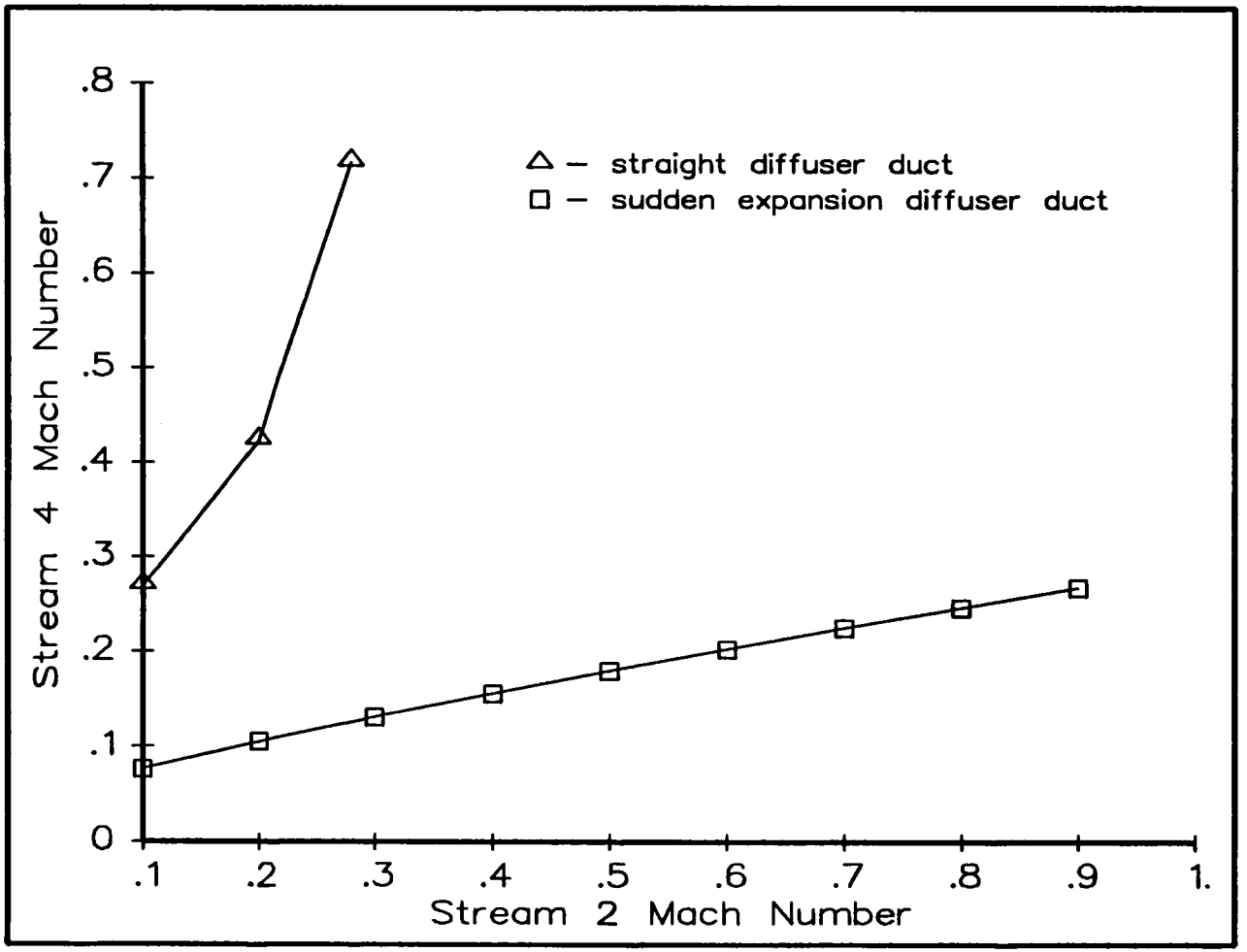


Figure 16. Diffuser Exit Mach Number vs. Bypass Flow Diffuser Inlet Mach Number for Straight and Sudden-Expansion Diffusers; 250 lbm/sec Engine Mass Flow Rate with 50% Blockage at 10,000 ft. Test Condition.

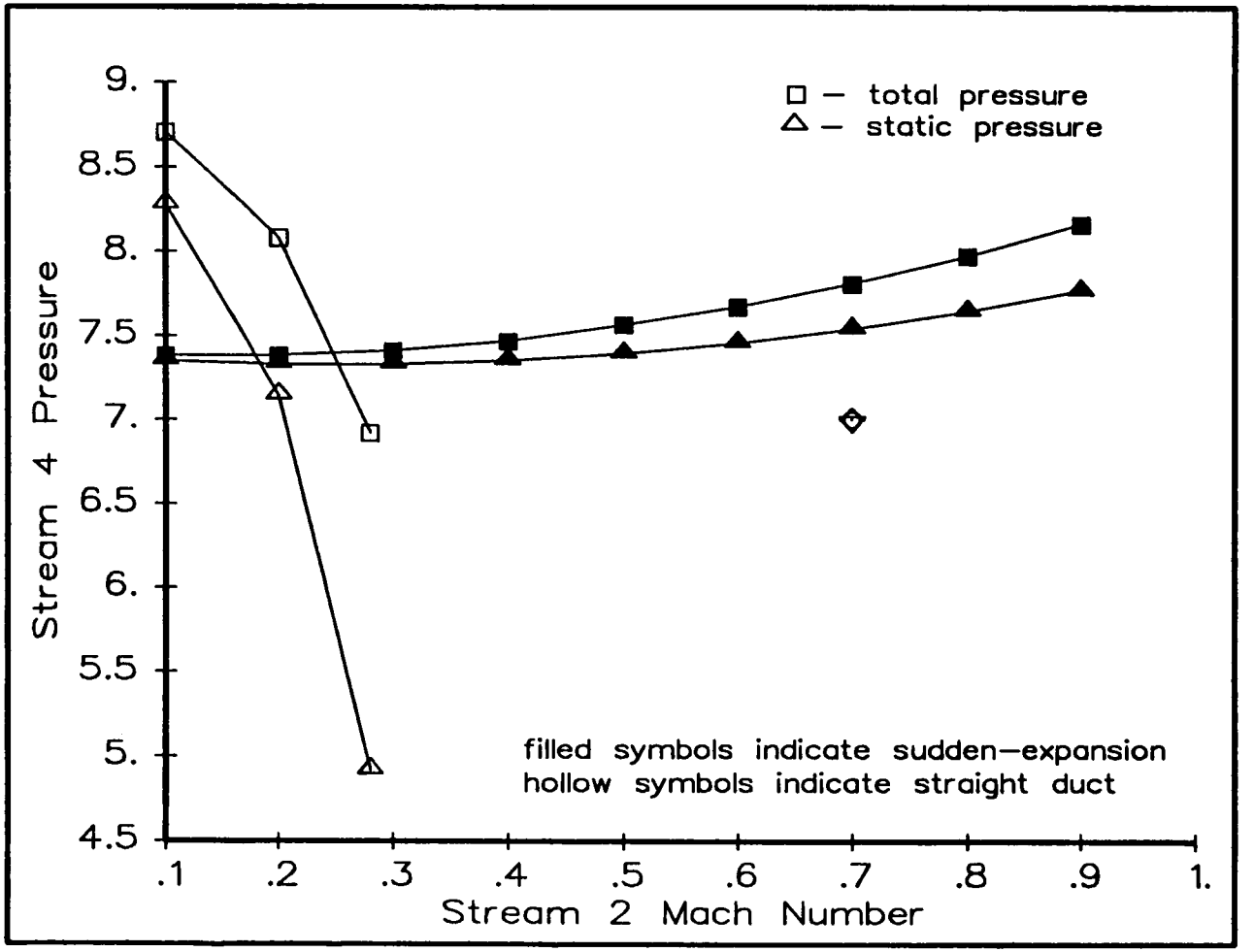


Figure 17. Diffuser Exit Static and Total Pressures vs. Bypass Flow Diffuser Inlet Mach Number for Straight and Sudden-Expansion Diffusers; 250 lbm/sec Engine Mass Flow Rate with 50% Blockage at 10,000 ft. Test Condition.

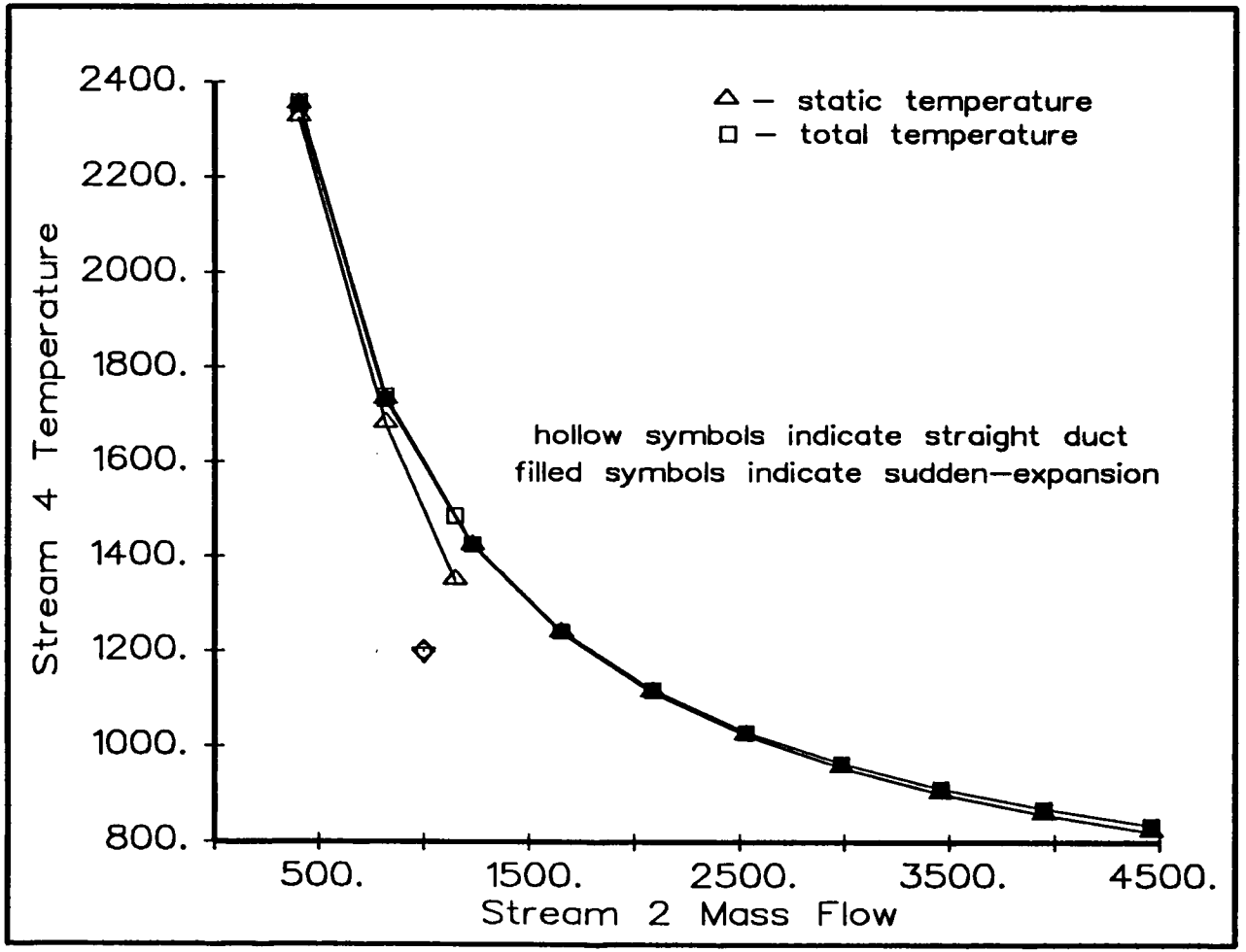


Figure 18. Diffuser Exit Static and Total Temperatures vs. Bypass Flow Diffuser Inlet Mach Number for Straight and Sudden-Expansion Diffusers; 250 lbm/sec Engine Mass Flow Rate with 50% Blockage at 10,000 ft. Test Condition.

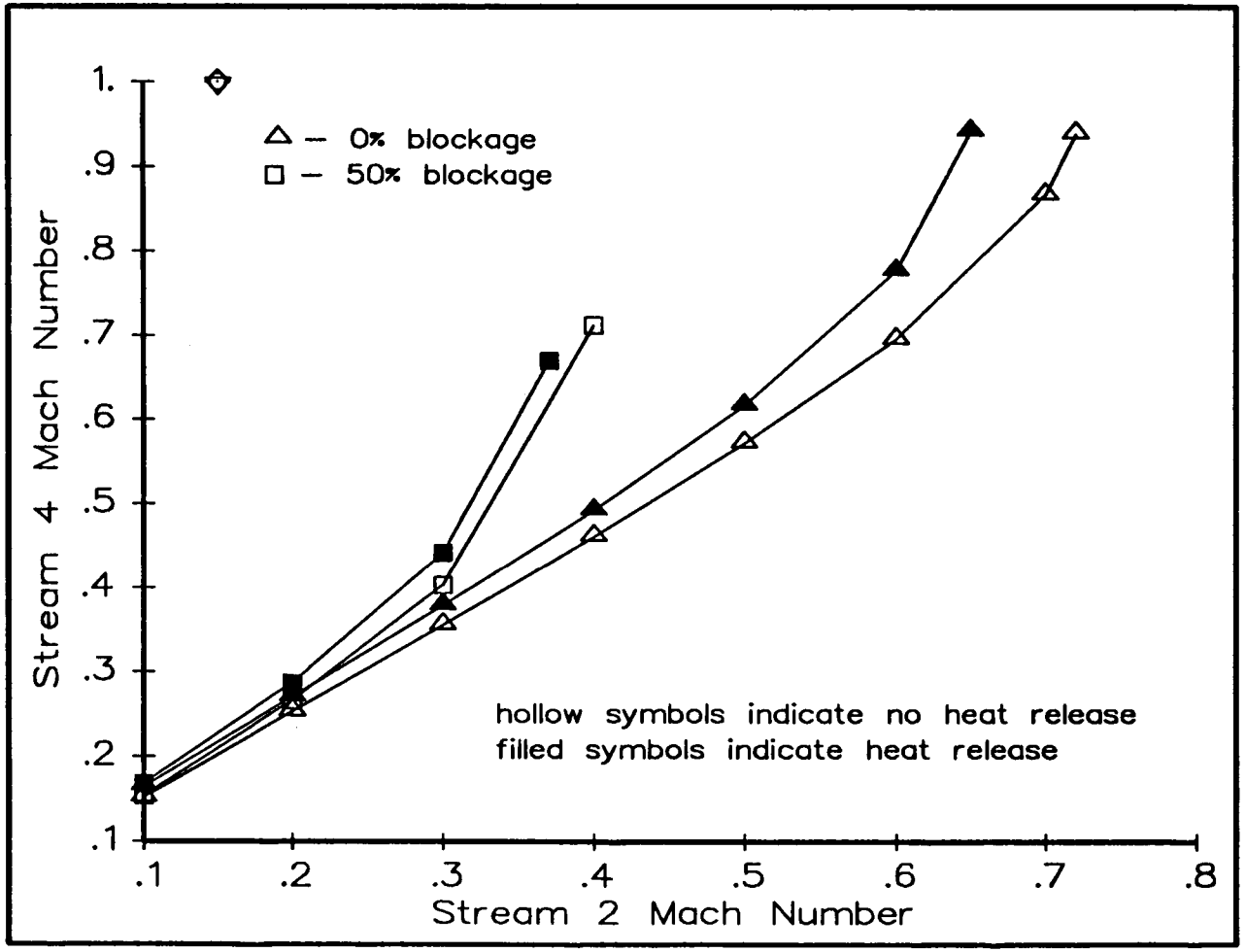


Figure 19. Diffuser Exit Mach Number vs. Bypass Flow Diffuser Inlet Mach Number With and Without Heat Release for 0% and 50% Blockages; 50 lbm/sec Engine Mass Flow Rate at 10,000 ft. Test Condition.

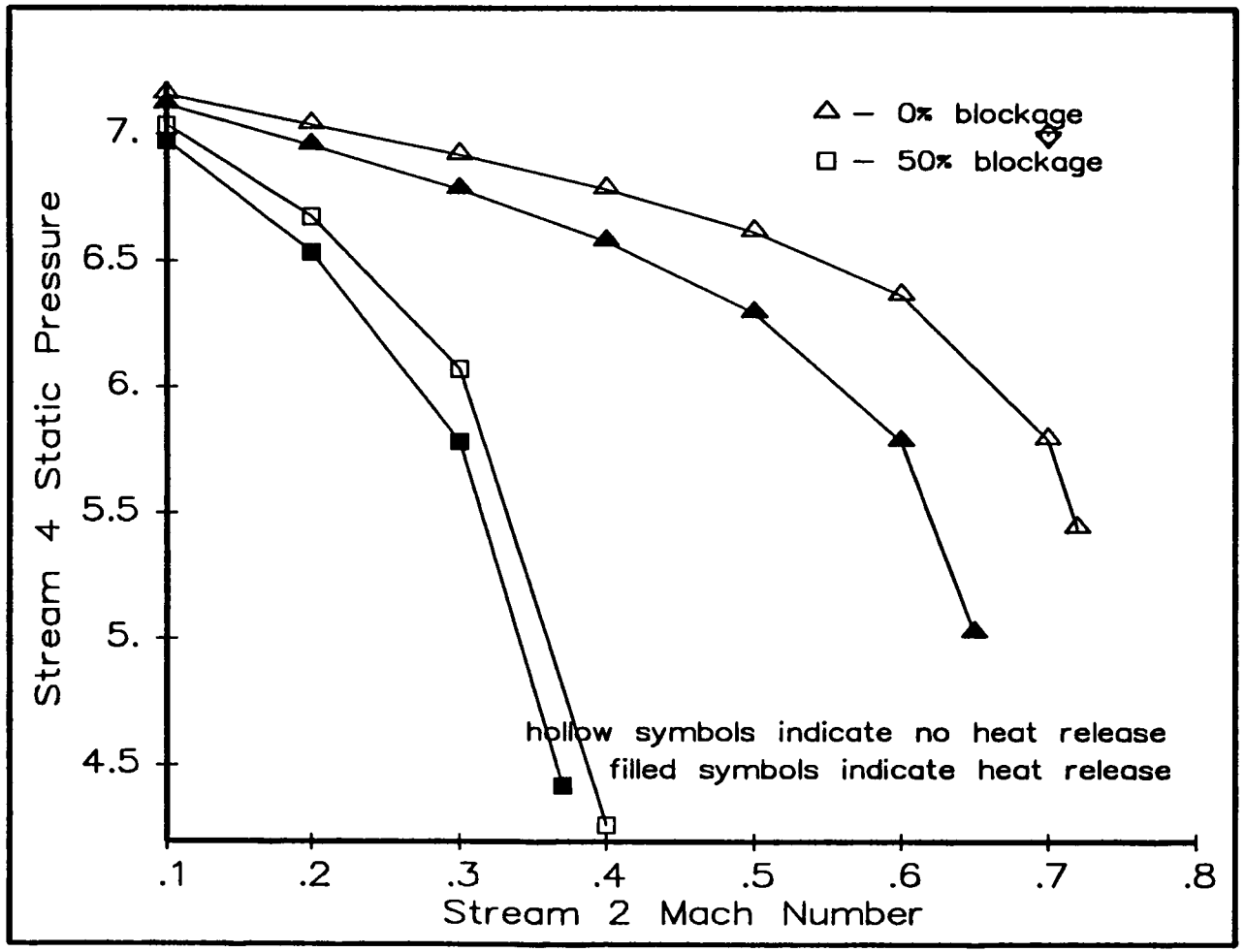


Figure 20. Diffuser Exit Static Pressure vs. Bypass Flow Diffuser Inlet Mach Number With and Without Heat Release for 0% and 50% Blockages; 50 lbm/sec Engine Mass Flow Rate at 10,000 ft. Test Condition.

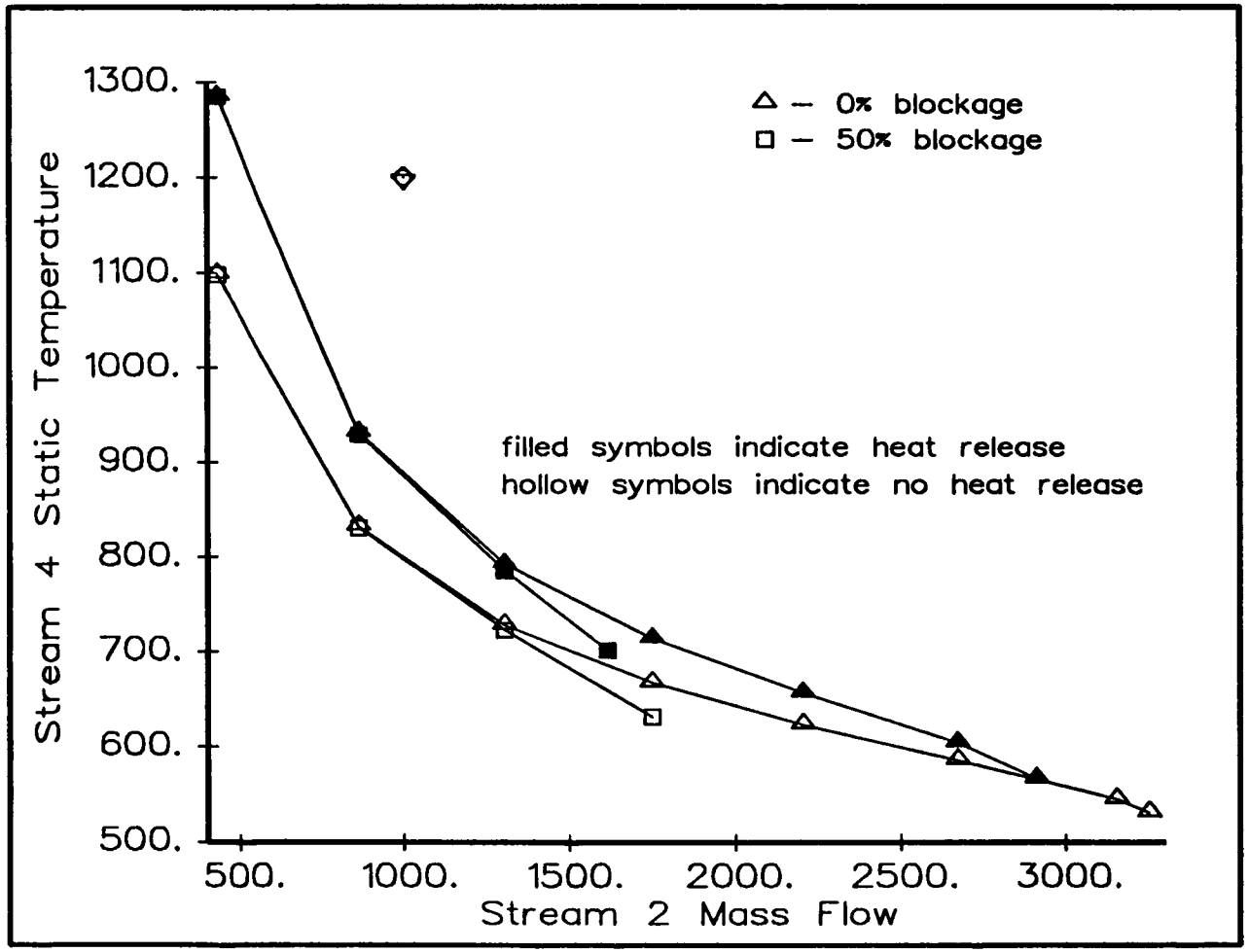


Figure 21. Diffuser Exit Static Temperature vs. Bypass Flow Diffuser Inlet Mach Number With and Without Heat Release for 0% and 50% Blockages; 50 lbm/sec Engine Mass Flow Rate at 10,000 ft. Test Condition.

APPENDIX B: Program Listing

```
'  Two-Stream Mixing Analysis
'  Written by R.J. Schulz and Luke H. Rogers.
'  University of Tennessee Space Institute
'  January 24, 1987 - October 31 1990
'
'
'
'
'     list of variables
'    -----------------
'
'(1) - inner stream variables
'(2) - outer stream variables
'(3) - mixed stream variables at flameholder bars
'(4) - mixed stream variables at exit
'aa - duct area, ft^2
'aforce - thrust force of exit stream, lbf
'aj - Btu to ft-lbf conversion factor, ft-lbf/Btu
'amach - Mach number
'amasck - mixed stream mass flow recalculated by rho*aa*u, lbm/sec
'amass - mass flow rate, lbm/sec
'amlos - percent difference between amasck and the sum of
'  the inner and outer stream mass flows
'ar - duct area ratio
'cd - coefficient of drag for flameholder bars
'cp - specific heat at constant pressure, Btu/lbm-R
'cpb - pressure coefficient at base for expanded duct
'fbase - pressure force on base of expanded duct, lbf
'fdot - heat release, Btu/sec
'gam - ratio of specific heats
'gc - gravitational acceleration constant, ft/sec^2
'p - static pressure, input in psi then changed to lbf/ft^2
'pb - static pressure at the step in an expanded duct, lbf/ft^2
'pt - total pressure, input in psi then changed to lbf/ft^2
'qdot - wall heat loss, Btu/sec
'r - duct radius, input in inches then changed to feet
'rg - universal gas constant
'rho - static density, lbm/ft^3
'rthom - total mixed stream density, lbm/ft^3
'sig - flameholder bars flow blockage factor
't - static temperature, degrees Rankine
'tt - total temperature, degrees Rankine
'u - velocity, ft/sec
'unir - universal gas constant
'w - molecular weight, lbm/lbmol
'xa,xb,xc - cofficient constants
'y - mass ratio
'z1,z2,z3,z4,z5 - constants defined for convenience
'
'
'
```

```
'
'
'
'
DIM pt(4),tt(4),amach(4),gam(4),w(4),r(4),P(4)
DIM rg(4),cp(4),t(4),rho(4),u(4),amass(4),aa(4),y(4)
'
OPEN "RAM:data" FOR OUTPUT AS #2
OPEN "test" FOR INPUT AS #3
'
GOSUB beggin
GOSUB innputt
GOSUB maine
'
CLOSE #2
CLOSE #3
END
'
'
beggin:
  gc=32.174
  pi=3.141593
  aj=778.16
  unir=1545.4
  cpb=0.10
RETURN
'
'
innputt:
' ----- input data from the file "test"
  INPUT #3, pt(1),tt(1),amach(1),gam(1),w(1)
  INPUT #3, P(2),tt(2),gam(2),w(2),r(3)
  INPUT #3, fdot,qdot,cd,ar,stepmass
'
  INPUT "Current date (d,m,y)";d$
  INPUT "                    ";m$
  INPUT "                    ";y$
  PRINT #2,"                Two Stream Mixing Analysis"
  PRINT #2,"                        ";d$;"-";m$",";y$
  PRINT #2,:  PRINT
'
' ----- allow user to check and change input data
  INPUT "Check input data";y$
  IF y$="y" OR y$="yes" OR y$="Y" OR y$="YES" THEN
1   PRINT "Stream 1:"
    IF pt(1)<>0 THEN PRINT ,"total pressure =",pt(1),"psi"
    IF tt(1)<>0 THEN PRINT ,"total temperature =",tt(1),"deg-R"
    IF amach(1)<>0 THEN PRINT ,"Mach number =",,amach(1)
    IF gam(1)<>0 THEN PRINT ,"specific heats ratio =",gam(1)
    IF w(1)<>0 THEN PRINT ,"molecular weight =",w(1),"lbm/lbmol"
    PRINT "Stream 2:"
```

```
    IF P(2)<>0 THEN PRINT ,"static pressure =",P(2),"psi"
    IF tt(2)<>0 THEN PRINT ,"total temperature =",tt(2),"deg-R"
    IF gam(2)<>0 THEN PRINT ,"specific heats ratio =",gam(2)
    IF w(2)<>0 THEN PRINT ,"molecular weight =",w(2),"lbm/lbmol"
    PRINT
    IF r(3)<>0 THEN PRINT "stream 3 radius =",r(3),"in."
    IF cd<>0 THEN PRINT "drag coefficient =",cd
    IF ar<>0 THEN PRINT "area ratio =",,ar
    IF fdot<>0 THEN PRINT "heat release =",fdot,"btu/sec"
    IF qdot<>0 THEN PRINT "wall heat loss =",qdot,"btu/sec"
    PRINT: PRINT
'
    INPUT "Change input data";z$
    IF z$="y" OR z$="yes" OR z$="Y" OR z$="YES" THEN
      PRINT
      FOR m=1 TO 2
        PRINT "Stream";m;":"
        INPUT "   total pressure (psi)";pt(m)
        INPUT "   static pressure (psi)";P(m)
        INPUT "   total temperature (deg-R)";tt(m)
        INPUT "   Mach number";amach(m)
        INPUT "   specific heats ratio";gam(m)
        INPUT "   molecular weight (lbm/lbmol)";w(m)
        PRINT
        NEXT m
      INPUT "   stream 3 radius (in.)";r(3)
      INPUT "   drag coefficient";cd
      INPUT "   area ratio";ar
      INPUT "   heat release (btu/sec)";fdot
      INPUT "   wall heat loss (btu/sec)";qdot
      PRINT: PRINT
    END IF
    IF z$="y" OR z$="yes" OR z$="Y" OR z$="YES" THEN z$="a": GOTO 1
  END IF
'
' ----- change from inches to feet
  pt(1)=pt(1)*144!
  P(2)=P(2)*144!
  r(3)=r(3)/12!
'
' ----- print out input conditions
  PRINT #2,"     *     *     *     INPUT CONDITIONS     *     *     *"
  FOR m=1 TO 2
    GOSUB prince
    NEXT m
  PRINT #2,"   stream 3 radius (ft.)",r(3)
  PRINT #2,"   drag coefficient",cd
  PRINT #2,"   area ratio",,ar
  PRINT #2,"   heat release (btu/sec)",fdot
  PRINT #2,"   wall heat loss (btu/sec)",qdot
'
```

```
RETURN
'
'
maine:
PRINT #2,:PRINT #2,:PRINT #2,
PRINT #2,"     *     *     *     OUTPUT CONDITIONS     *     *     *"
' ----- repeat 11 times for sig's from .1 to 1.0
FOR l=1 TO 6
oldsig=(l-1)*.1
sig=oldsig
IF oldsig>=.99 THEN GOTO 10
' ----- repeat 5 times for 5 different stream 1 mass flows
  FOR i=1 TO 5
  amass(1)=50!+(i-1)*stepmass
     ns=0
     j=1
' ----- repeat for stream 2 Mach numbers from .1 until a solution is no
' -----  longer obtained; then work backwards in Mach number increments
' -----  of .01 until the last solution is reached
8     IF ns=0 THEN amach(2)=j*.1
      IF ns=1 THEN amach(2)=amach(2)-.01
      IF ns=1 AND amach(2)<.1 THEN GOTO 4
' ----- calculate core and outer stream conditions
      m=1
      GOSUB flo
      m=2
      GOSUB flo
      aa(3)=pi*r(3)^2
      aa(4)=aa(3)
      aa(1)=amass(1)/(rho(1)*u(1))
      aa(2)=aa(3)/ar-aa(1)
      amass(2)=rho(2)*u(2)*aa(2)
      r(1)=SQR(aa(1)/pi)
      r(2)=SQR(aa(3)/(pi*ar))
      r(4)=r(3)
' ----- calculate the base pressure and force for expanded duct
      IF ar<>1 THEN
        pb=P(2)*(1!-.5*cpb*gam(2)*amach(2)^2)
        fbase=pb*(aa(3)-aa(2)-aa(1))
      END IF
'
' ----- print core and outer stream conditions
      IF i=1 AND j=1 THEN
        PRINT:PRINT:PRINT

   PRINT"************************************************************"
   PRINT"     ******************** sig =";sig;"********************"
   PRINT #2,:PRINT #2,:PRINT #2,
   PRINT #2,"************************************************************"
   PRINT #2,"   ******************** sig =";sig;"********************"
        FOR m=1 TO 2
```

```
          GOSUB prince
          GOSUB dumpster
          NEXT m
       END IF
'
       IF j=1 THEN PRINT:PRINT:PRINT "     amass(1)=";amass(1)
       IF j=1 THEN PRINT #2,:PRINT #2,:PRINT #2,"    amass(1)=";amass(1)
' ----- calculate mixed stream conditions at flameholders and at exit
       amass(3)=amass(1)+amass(2)
       amass(4)=amass(3)
       y(1)=amass(1)/amass(3)
       y(2)=amass(2)/amass(3)
       wmm=y(1)/w(1)+y(2)/w(2)
       w(3)=1!/wmm
       w(4)=w(3)
       rg(3)=unir/w(3)
       rg(4)=rg(3)
       cp(3)=y(1)*cp(1)+y(2)*cp(2)
       cp(4)=cp(3)
       gam(3)=cp(3)/(cp(3)-rg(3)/aj)
       gam(4)=gam(3)
'
       FOR k=3 TO 4
' ----- set blockage equal to zero for exit conditions
         IF k=4 THEN sig=0!
         IF k=3 THEN sig=oldsig
         sigs=1!-sig
         rho(k)=0!
         u(k)=0!
         oldu=0!
3        z1=w(k)*sigs*aa(k)/(unir*amass(k))
         z2=amass(k)/(gc*sigs*aa(k))
         IF k=3 THEN
           aterm=amass(1)*u(1)/gc+amass(2)*u(2)/gc
           bterm=.5*cd*rho(3)*u(3)^2*sig/(gc*sigs)
           z3=(P(1)*aa(1)+P(2)*aa(2)+aterm+fbase)/(aa(3)*sigs)-bterm
         END IF
         IF k=4 THEN z3=(P(3)*aa(3)*(1!-oldsig)+amass(3)*u(3)/gc)/aa(4)
         z4=2!*gc*aj*cp(k)
         IF k=3 THEN
           term1=y(2)*(cp(2)*t(2)+u(2)^2/(2!*gc*aj))
           term2=2!*gc*aj*(fdot-qdot)/amass(3)
           z5=2!*gc*aj*(y(1)*(cp(1)*t(1)+u(1)^2/(2!*gc*aj))+term1)+term2
         END IF
         IF k=4 THEN z5=2!*gc*aj*cp(3)*t(3)+u(3)^2
         xa=1!-z1*z2*z4
         xb=z1*z3*z4
         xc=-z5
         rad=xb^2-4!*xa*xc
' ----- iterate to find solution because of drag terms
         IF k=3 AND rad<0! THEN
```

```
          ns=1
          GOTO 8
        END IF
        root=SQR(rad)
        oldu=u(k)
        u(k)=(-xb+root)/(2!*xa)
        GOSUB micksflo
        IF mo=1 AND j=1 GOTO 5
        IF mo=1 GOTO 4
        check=ABS((oldu-u(k))/u(k))
        IF check>.001 THEN GOTO 3
'
' ----- print out mixed stream conditions
        IF k=4 AND j=1 THEN GOSUB princechange:GOSUB dumpsterchange
        IF k=4 THEN GOSUB smalldumpster: GOSUB shortprince
6     NEXT k
    j=j+1
    IF ns=1 GOTO 4
' ----- make sure that calculations stop at stream 2 Mach number of one
    IF amach(2)>=1! THEN
      PRINT ">>>   Error: Mach number greater than 1"
      PRINT #2,">>>   Error: Mach number greater than 1"
      GOTO 5
    END IF
    GOTO 8
4   mo=0
  NEXT i
5 NEXT l
10 RETURN
'
'
flo:
' ----- calculate conditions for stream 1 and stream 2
  rg(m)=unir/(aj*w(m))
  cp(m)=gam(m)*rg(m)/(gam(m)-1!)
  bb=(1!+.5*(gam(m)-1!)*amach(m)^2)
  bbb=bb^((gam(m)/(gam(m)-1!)))
  t(m)=tt(m)/bb
  IF m=1 THEN P(m)=pt(m)/bbb
  IF m=2 THEN pt(m)=P(m)*bbb
  rho(m)=P(m)*w(m)/(unir*t(m))
  u(m)=amach(m)*SQR(gam(m)*gc*unir*t(m)/w(m))
RETURN
'
'
micksflo:
' ----- calculate mixed flow conditions at flameholders and exit
  P(k)=z3-z2*u(k)
' ----- program fails if a negative pressure is computed; check
' -----       compatibility of input conditions
  IF P(k)<0! THEN
```

```
    PRINT: PRINT "  ------>   Negative pressure computed"
    PRINT #2,: PRINT #2,"  ------>   Negative pressure computed"
    INPUT "Print results anyway";w$
    IF w$="y" OR w$="yes" OR w$="Y" OR w$="YES" THEN
      m=3
      GOSUB dumpster
      GOSUB prince
    END IF
    mo=1
    RETURN
  END IF
  t(k)=z1*P(k)*u(k)
  amach(k)=u(k)/SQR(gam(k)*gc*unir*t(k)/w(k))
  rho(k)=P(k)*w(k)/(unir*t(k))
  tt(k)=t(k)*(1!+.5*(gam(k)-1!)*amach(k)^2)
  pt(k)=P(k)*(tt(k)/t(k))^(gam(k)/(gam(k)-1!))
  rthom=pt(k)*w(k)/(unir*tt(k))
  amasck=rho(k)*u(k)*aa(k)
  aforce=P(k)*aa(k)+rho(k)*u(k)^2*aa(k)/gc
  amlos=(amasck-amass(k))/amass(k)*100!
RETURN
'
'
' ----- printing routines
dumpster:
  PRINT
  IF m=1 THEN PRINT "   *****  Core Stream Conditions  *****"
  IF m=2 THEN PRINT "   *****  Outer Stream Conditions  *****"
  IF m=3 THEN PRINT "   *****  Mixed Stream Conditions  *****"
  IF amach(m)<>0 THEN PRINT  "Mach number",,amach(m)
  IF u(m)<>0 THEN PRINT "velocity",,u(m);"   ft/sec"
  IF P(m)<>0 THEN PRINT "static pressure",P(m)/144!;"   psi"
  IF pt(m)<>0 THEN PRINT "total pressure",pt(m)/144!;"   psi"
  IF t(m)<>0 THEN PRINT "static temperature",t(m);"   deg-R"
  IF tt(m)<>0 THEN PRINT "total temperature",tt(m);"   deg-R"
  IF rho(m)<>0 THEN PRINT "static density",rho(m);"   lbm/ft**3"
  IF gam(m)<>0 THEN PRINT "specific heats ratio",gam(m)
  IF cp(m)<>0 THEN PRINT "specific heat (P const.)",cp(m);"   Btu/lbm-
   R"
  IF w(m)<>0 THEN PRINT "molecular weight",w(m);"   lbm/lbmol"
  PRINT
  IF r(m)<>0 THEN PRINT "stream radius",,r(m);"   ft."
  IF aa(m)<>0 THEN PRINT "stream area",,aa(m);"   sq.ft"
  IF pb<>0 AND m=2 THEN PRINT #2,"initial base pressure",pb;"   psi"
  PRINT
RETURN
'
'
smalldumpster:
IF j=1 THEN
PRINT
```

```
PRINT " mach(2)";" ";"pt(2)";"     ";"t(2)";"    ";" mass(2)";"  ";
PRINT " mach(4)";"     ";"p(4)";"    ";"t(4)";"   ";" mass(4)"
PRINT "-------------------------------------------------------------";
PRINT "------------"
END IF
PRINT USING "###.##";amach(2);
PRINT USING "###.#####";pt(2)/144!;
PRINT USING "######.###";t(2);
PRINT USING "#####.####";amass(2);
PRINT USING "###.######";amach(4);
PRINT USING "####.#####";P(4)/144!;
PRINT USING "######.##";t(4);
PRINT USING "#####.###";amass(4)
RETURN
'
'
dumpsterchange:
  PRINT "                          annular gap",,(r(2)-r(1));"   ft."
  PRINT "                          stream area",,aa(2);"   sq.ft"
RETURN
'
'
prince:
  PRINT #2,
  IF m=1 THEN PRINT #2,"   *****  Core Stream Conditions  *****"
  IF m=2 THEN PRINT #2,"   *****  Outer Stream Conditions  *****"
  IF m=3 THEN PRINT #2,"   *****  Mixed Stream Conditions  *****"
  IF m=2 THEN PRINT #2,"For the following Mach number, the conditions
   are:"
  IF amach(m)<>0 THEN PRINT #2,"Mach number",,amach(m)
  IF u(m)<>0 THEN PRINT #2,"velocity",,u(m);"   ft/sec"
  IF P(m)<>0 THEN PRINT #2,"static pressure",P(m)/144!;"   psi"
  IF pt(m)<>0 THEN PRINT #2,"total pressure",pt(m)/144!;"   psi"
  IF t(m)<>0 THEN PRINT #2,"static temperature",t(m);"   deg-R"
  IF tt(m)<>0 THEN PRINT #2,"total temperature",tt(m);"   deg-R"
  IF rho(m)<>0 THEN PRINT #2,"static density",rho(m);"   lbm/ft**3"
  IF gam(m)<>0 THEN PRINT #2,"specific heats ratio",gam(m)
  IF cp(m)<>0 THEN PRINT #2,"specific heat (P const.)",cp(m);"
   Btu/lbm-R"
  IF w(m)<>0 THEN PRINT #2,"molecular weight",w(m);"   lbm/lbmol"
  PRINT #2,
  IF r(m)<>0 THEN PRINT #2,"stream radius",,r(m);"   ft."
  IF aa(m)<>0 THEN PRINT #2,"stream area",,aa(m);"   sq.ft"
  IF pb<>0 AND m=2 THEN PRINT #2,"initial base pressure",pb;"   psi"
  PRINT #2,
RETURN
'
'
princechange:
  PRINT #2,"                       annular gap",(r(2)-r(1));"   ft."
  PRINT #2,"                       stream area",aa(2);"   sq.ft"
```

```
RETURN
'
'
shortprince:
IF j=1 THEN
PRINT #2,
PRINT #2, "mach(2)";" ";"pt(2)";"     ";"t(2)";"  ";"mass(2)";" ";
PRINT #2, "mach(4)";"  ";"p(4)";"    ";"t(4)";" ";"mass(4)"
PRINT #2, "-------------------------------------------------------------"
END IF
PRINT #2, USING "###.##";amach(2);
PRINT #2, USING "###.###";pt(2)/144!;
PRINT #2, USING "######.#";t(2);
PRINT #2, USING "######.#";amass(2);
PRINT #2, USING "###.####";amach(4);
PRINT #2, USING "###.###";P(4)/144!;
PRINT #2, USING "######.#";t(4);
PRINT #2, USING "######.";amass(4)
RETURN
```

APPENDIX C: Complete Program Output for Straight Diffuser with No Heat Release, 10,000 ft. Test Condition

Two Stream Mixing Analysis
28-Nov,90

* * * INPUT CONDITIONS * * *

***** Core Stream Conditions *****

Mach number	2.15	
total pressure	66.14	psi
total temperature	4290	deg-R
specific heats ratio	1.27	
molecular weight	25.4	lbm/lbmol

***** Outer Stream Conditions *****

static pressure	6.76	psi
total temperature	537	deg-R
specific heats ratio	1.4	
molecular weight	28.9	lbm/lbmol

stream 3 radius (ft.)	6
drag coefficient	1
area ratio	1
heat release (btu/sec)	0
wall heat loss (btu/sec)	0

* * * OUTPUT CONDITIONS * * *

****

********** sig = 0 **********

***** Core Stream Conditions *****

Mach number	2.15	
velocity	5509.689	ft/sec
static pressure	6.759005	psi
total pressure	66.14	psi
static temperature	2641.565	deg-R
total temperature	4290	deg-R
static density	6.055873E-03	lbm/ft**3
specific heats ratio	1.27	
specific heat (P const.)	.3677717	Btu/lbm-R
molecular weight	25.4	lbm/lbmol
stream radius	.6906502	ft.
stream area	1.498533	sq.ft

***** Outer Stream Conditions *****

For the following Mach number, the conditions are:

Mach number	.1	
velocity	113.6165	ft/sec
static pressure	6.76	psi
total pressure	6.807438	psi
static temperature	535.9282	deg-R
total temperature	537	deg-R
static density	3.396719E-02	lbm/ft**3
specific heats ratio	1.4	
specific heat (P const.)	.2405151	Btu/lbm-R
molecular weight	28.9	lbm/lbmol
stream radius	6	ft.
stream area	111.5988	sq.ft

amass(1)= 50

annular gap 5.30935 ft.
stream area 111.5988 sq.ft

mach(2)	pt(2)	t(2)	mass(2)	mach(4)	p(4)	t(4)	mass(4)
0.10	6.807	535.9	430.7	0.1512	7.154	1098.0	481.
0.20	6.951	532.7	863.9	0.2526	7.036	831.8	914.
0.30	7.196	527.5	1302.3	0.3547	6.915	727.2	1352.
0.40	7.548	520.3	1748.3	0.4599	6.780	666.5	1798.
0.50	8.019	511.4	2204.4	0.5710	6.612	622.7	2254.
0.60	8.622	500.9	2672.9	0.6947	6.362	585.4	2723.
0.70	9.377	489.1	3155.9	0.8664	5.790	544.7	3206.
0.72	9.548	486.6	3254.5	0.9382	5.439	530.5	3304.

amass(1)= 100

annular gap 5.023273 ft.
stream area 110.1003 sq.ft

mach(2)	pt(2)	t(2)	mass(2)	mach(4)	p(4)	t(4)	mass(4)
0.10	6.807	535.9	424.9	0.1863	7.547	1520.6	525.
0.20	6.951	532.7	852.3	0.2917	7.321	1090.3	952.
0.30	7.196	527.5	1284.8	0.3983	7.084	908.4	1385.
0.40	7.548	520.3	1724.9	0.5117	6.810	801.8	1825.
0.50	8.019	511.4	2174.8	0.6405	6.440	725.4	2275.
0.60	8.622	500.9	2637.0	0.8227	5.729	655.7	2737.
0.63	8.832	497.5	2778.3	0.9576	5.036	621.0	2878.

amass(1)= 150

annular gap 4.803759 ft.
stream area 108.6018 sq.ft

mach(2)	pt(2)	t(2)	mass(2)	mach(4)	p(4)	t(4)	mass(4)
0.10	6.807	535.9	419.1	0.2138	7.938	1849.6	569.
0.20	6.951	532.7	840.7	0.3225	7.616	1316.1	991.
0.30	7.196	527.5	1267.4	0.4340	7.268	1073.9	1417.
0.40	7.548	520.3	1701.4	0.5572	6.850	927.7	1851.
0.50	8.019	511.4	2145.2	0.7124	6.228	819.2	2295.
0.57	8.426	504.2	2462.9	0.9407	5.067	731.2	2613.

amass(1)= 200

annular gap 4.6187 ft.
stream area 107.103 sq.ft

mach(2)	pt(2)	t(2)	mass(2)	mach(4)	p(4)	t(4)	mass(4)
0.10	6.807	535.9	413.3	0.2365	8.328	2112.8	613.
0.20	6.951	532.7	829.1	0.3477	7.917	1515.1	1029.
0.30	7.196	527.5	1249.9	0.4638	7.466	1225.7	1450.
0.40	7.548	520.3	1677.9	0.5974	6.902	1045.0	1878.
0.50	8.019	511.4	2115.6	0.7941	5.933	902.3	2316.
0.53	8.185	508.4	2249.1	0.9416	5.112	843.1	2449.

amass(1)= 250

annular gap 4.455659 ft.
stream area 105.6047 sq.ft

mach(2)	pt(2)	t(2)	mass(2)	mach(4)	p(4)	t(4)	mass(4)
0.10	6.807	535.9	407.6	0.2560	8.715	2328.0	658.
0.20	6.951	532.7	817.5	0.3687	8.226	1691.8	1068.
0.30	7.196	527.5	1232.4	0.4887	7.678	1365.7	1482.
0.40	7.548	520.3	1654.4	0.6331	6.967	1154.9	1904.
0.50	8.019	511.4	2086.0	0.9245	5.325	962.7	2336.
0.50	8.019	511.4	2086.0	0.9245	5.325	962.7	2336.

****
********** sig = .1 **********

***** Core Stream Conditions *****

Mach number	2.15	
velocity	5509.689	ft/sec
static pressure	6.759005	psi
total pressure	66.14	psi

```
static temperature              2641.565    deg-R
total temperature               4290    deg-R
static density                  6.055873E-03    lbm/ft**3
specific heats ratio            1.27
specific heat (P const.)        .3677717    Btu/lbm-R
molecular weight                25.4    lbm/lbmol

stream radius                   .6906502    ft.
stream area                     1.498533    sq.ft


   *****  Outer Stream Conditions  *****
For the following Mach number, the conditions are:
Mach number                     .1
velocity                        113.6165    ft/sec
static pressure                 6.76    psi
total pressure                  6.807438    psi
static temperature              535.9282    deg-R
total temperature               537    deg-R
static density                  3.396719E-02    lbm/ft**3
specific heats ratio            1.4
specific heat (P const.)        .2405151    Btu/lbm-R
molecular weight                28.9    lbm/lbmol

stream radius                   6    ft.
stream area                     111.5988    sq.ft


     amass(1)= 50
                        annular gap             5.30935    ft.
                        stream area             111.5988   sq.ft

mach(2) pt(2)    t(2)  mass(2) mach(4)  p(4)   t(4) mass(4)
-------------------------------------------------------------
  0.10  6.807   535.9   430.7  0.1515  7.141  1098.0   481.
  0.20  6.951   532.7   863.9  0.2540  6.998   831.7   914.
  0.30  7.196   527.5  1302.3  0.3589  6.833   726.8  1352.
  0.40  7.548   520.3  1748.3  0.4704  6.623   665.2  1798.
  0.50  8.019   511.4  2204.4  0.5965  6.313   619.3  2254.
  0.60  8.622   500.9  2672.9  0.7702  5.681   573.9  2723.
  0.63  8.832   497.5  2816.1  0.8729  5.178   552.8  2866.


     amass(1)= 100
                        annular gap             5.023273   ft.
                        stream area             110.1003   sq.ft

mach(2) pt(2)    t(2)  mass(2) mach(4)  p(4)   t(4) mass(4)
-------------------------------------------------------------
  0.10  6.807   535.9   424.9  0.1868  7.526  1520.5   525.
```

0.20	6.951	532.7	852.3	0.2938	7.267	1090.1	952.
0.30	7.196	527.5	1284.8	0.4044	6.973	907.6	1385.
0.40	7.548	520.3	1724.9	0.5275	6.596	799.4	1825.
0.50	8.019	511.4	2174.8	0.6854	5.987	717.7	2275.
0.56	8.364	505.3	2450.5	0.8680	5.080	660.1	2550.

amass(1)= 150

annular gap 4.803759 ft.
stream area 108.6018 sq.ft

mach(2)	pt(2)	t(2)	mass(2)	mach(4)	p(4)	t(4)	mass(4)
0.10	6.807	535.9	419.1	0.2145	7.909	1849.5	569.
0.20	6.951	532.7	840.7	0.3255	7.545	1315.6	991.
0.30	7.196	527.5	1267.4	0.4423	7.126	1072.4	1417.
0.40	7.548	520.3	1701.4	0.5797	6.569	923.4	1851.
0.50	8.019	511.4	2145.2	0.8038	5.454	799.7	2295.
0.51	8.073	510.4	2190.2	0.8534	5.180	782.6	2340.

amass(1)= 200

annular gap 4.6187 ft.
stream area 107.1032 sq.ft

mach(2)	pt(2)	t(2)	mass(2)	mach(4)	p(4)	t(4)	mass(4)
0.10	6.807	535.9	413.3	0.2376	8.290	2112.6	613.
0.20	6.951	532.7	829.1	0.3515	7.830	1514.4	1029.
0.30	7.196	527.5	1249.9	0.4744	7.292	1223.5	1450.
0.40	7.548	520.3	1677.9	0.6283	6.540	1038.1	1878.
0.48	7.915	513.3	2027.2	0.8877	5.085	894.5	2227.

amass(1)= 250

annular gap 4.455659 ft.
stream area 105.6047 sq.ft

mach(2)	pt(2)	t(2)	mass(2)	mach(4)	p(4)	t(4)	mass(4)
0.10	6.807	535.9	407.6	0.2573	8.669	2327.7	658.
0.20	6.951	532.7	817.5	0.3733	8.122	1690.8	1068.
0.30	7.196	527.5	1232.4	0.5016	7.472	1362.6	1482.
0.40	7.548	520.3	1654.4	0.6744	6.510	1144.2	1904.
0.45	7.768	516.1	1868.9	0.8472	5.473	1034.7	2119.

```
************************************************************
   ******************** sig = .2 ********************

   *****  Core Stream Conditions  *****
Mach number                     2.15
velocity                        5509.689     ft/sec
static pressure                 6.759005     psi
total pressure                  66.14     psi
static temperature              2641.565     deg-R
total temperature               4290     deg-R
static density                  6.055873E-03     lbm/ft**3
specific heats ratio            1.27
specific heat (P const.)        .3677717     Btu/lbm-R
molecular weight                25.4     lbm/lbmol

stream radius                   .6906502     ft.
stream area                     1.498533     sq.ft


   *****  Outer Stream Conditions  *****
For the following Mach number, the conditions are:
Mach number                     .1
velocity                        113.6165     ft/sec
static pressure                 6.76     psi
total pressure                  6.807438     psi
static temperature              535.9282     deg-R
total temperature               537     deg-R
static density                  3.396719E-02     lbm/ft**3
specific heats ratio            1.4
specific heat (P const.)        .2405151     Btu/lbm-R
molecular weight                28.9     lbm/lbmol

stream radius                   6     ft.
stream area                     111.5988     sq.ft


     amass(1)= 50
                        annular gap             5.30935     ft.
                        stream area             111.5988    sq.ft

mach(2) pt(2)    t(2)  mass(2) mach(4)  p(4)   t(4) mass(4)
------------------------------------------------------------
  0.10  6.807   535.9   430.7  0.1518  7.124 1098.0   481.
  0.20  6.951   532.7   863.9  0.2557  6.949  831.6   914.
  0.30  7.196   527.5  1302.3  0.3644  6.728  726.2  1352.
  0.40  7.548   520.3  1748.3  0.4853  6.412  663.5  1798.
  0.50  8.019   511.4  2204.4  0.6395  5.859  613.2  2254.
  0.57  8.426   504.2  2530.9  0.9116  4.477  555.7  2581.
```

amass(1)= 100

annular gap 5.023273 ft.
stream area 110.1003 sq.ft

mach(2)	pt(2)	t(2)	mass(2)	mach(4)	p(4)	t(4)	mass(4)
0.10	6.807	535.9	424.9	0.1875	7.499	1520.5	525.
0.20	6.951	532.7	852.3	0.2966	7.198	1089.7	952.
0.30	7.196	527.5	1284.8	0.4128	6.828	906.4	1385.
0.40	7.548	520.3	1724.9	0.5512	6.297	795.7	1825.
0.50	8.019	511.4	2174.8	0.7974	5.071	697.0	2275.
0.51	8.073	510.4	2220.4	0.8874	4.574	674.9	2320.

amass(1)= 150

annular gap 4.803759 ft.
stream area 108.6018 sq.ft

mach(2)	pt(2)	t(2)	mass(2)	mach(4)	p(4)	t(4)	mass(4)
0.10	6.807	535.9	419.1	0.2155	7.872	1849.3	569.
0.20	6.951	532.7	840.7	0.3293	7.455	1315.0	991.
0.30	7.196	527.5	1267.4	0.4539	6.939	1070.4	1417.
0.40	7.548	520.3	1701.4	0.6163	6.154	916.2	1851.
0.46	7.815	515.2	1966.4	0.8073	5.091	825.4	2116.

amass(1)= 200

annular gap 4.6187 ft.
stream area 107.1032 sq.ft

mach(2)	pt(2)	t(2)	mass(2)	mach(4)	p(4)	t(4)	mass(4)
0.10	6.807	535.9	413.3	0.2389	8.242	2112.4	613.
0.20	6.951	532.7	829.1	0.3565	7.718	1513.4	1029.
0.30	7.196	527.5	1249.9	0.4894	7.059	1220.3	1450.
0.40	7.548	520.3	1677.9	0.6849	5.961	1024.7	1878.
0.43	7.676	517.8	1808.1	0.8112	5.205	960.1	2008.

amass(1)= 250

annular gap 4.455659 ft.
stream area 105.6047 sq.ft

mach(2)	pt(2)	t(2)	mass(2)	mach(4)	p(4)	t(4)	mass(4)
0.10	6.807	535.9	407.6	0.2591	8.610	2327.4	658.
0.20	6.951	532.7	817.5	0.3794	7.988	1689.5	1068.
0.30	7.196	527.5	1232.4	0.5204	7.190	1358.1	1482.
0.40	7.548	520.3	1654.4	0.7675	5.655	1118.3	1904.
0.41	7.589	519.5	1697.1	0.8348	5.235	1085.4	1947.

```
************************************************************
   ******************** sig = .3 ********************

   *****  Core Stream Conditions  *****
Mach number                     2.15
velocity                        5509.689     ft/sec
static pressure                 6.759005     psi
total pressure                  66.14     psi
static temperature              2641.565     deg-R
total temperature               4290     deg-R
static density                  6.055873E-03     lbm/ft**3
specific heats ratio            1.27
specific heat (P const.)        .3677717     Btu/lbm-R
molecular weight                25.4     lbm/lbmol

stream radius                   .6906502     ft.
stream area                     1.498533     sq.ft


   *****  Outer Stream Conditions  *****
For the following Mach number, the conditions are:
Mach number                     .1
velocity                        113.6165     ft/sec
static pressure                 6.76     psi
total pressure                  6.807438     psi
static temperature              535.9282     deg-R
total temperature               537     deg-R
static density                  3.396719E-02     lbm/ft**3
specific heats ratio            1.4
specific heat (P const.)        .2405151     Btu/lbm-R
molecular weight                28.9     lbm/lbmol

stream radius                   6     ft.
stream area                     111.5988     sq.ft


     amass(1)= 50
                        annular gap              5.30935     ft.
                        stream area              111.5988    sq.ft

mach(2) pt(2)    t(2)  mass(2) mach(4)  p(4)    t(4) mass(4)
------------------------------------------------------------
  0.10  6.807   535.9   430.7  0.1522  7.103  1098.0   481.
  0.20  6.951   532.7   863.9  0.2581  6.886   831.4   914.
  0.30  7.196   527.5  1302.3  0.3720  6.586   725.4  1352.
  0.40  7.548   520.3  1748.3  0.5082  6.109   660.6  1798.
  0.50  8.019   511.4  2204.4  0.7513  4.918   596.3  2254.
  0.51  8.073   510.4  2250.7  0.8387  4.433   579.7  2301.
```

amass(1)= 100

annular gap 5.023273 ft.
stream area 110.1003 sq.ft

mach(2)	pt(2)	t(2)	mass(2)	mach(4)	p(4)	t(4)	mass(4)
0.10	6.807	535.9	424.9	0.1883	7.465	1520.4	525.
0.20	6.951	532.7	852.3	0.3003	7.107	1089.3	952.
0.30	7.196	527.5	1284.8	0.4247	6.629	904.7	1385.
0.40	7.548	520.3	1724.9	0.5925	5.833	788.8	1825.
0.45	7.768	516.1	1948.4	0.7594	4.905	728.3	2048.

amass(1)= 150

annular gap 4.803759 ft.
stream area 108.6018 sq.ft

mach(2)	pt(2)	t(2)	mass(2)	mach(4)	p(4)	t(4)	mass(4)
0.10	6.807	535.9	419.1	0.2168	7.825	1849.2	569.
0.20	6.951	532.7	840.7	0.3346	7.335	1314.2	991.
0.30	7.196	527.5	1267.4	0.4711	6.676	1067.3	1417.
0.40	7.548	520.3	1701.4	0.6961	5.398	899.3	1851.
0.42	7.632	518.7	1789.3	0.8464	4.511	847.0	1939.

amass(1)= 200

annular gap 4.6187 ft.
stream area 107.1032 sq.ft

mach(2)	pt(2)	t(2)	mass(2)	mach(4)	p(4)	t(4)	mass(4)
0.10	6.807	535.9	413.3	0.2407	8.180	2112.1	613.
0.20	6.951	532.7	829.1	0.3634	7.568	1512.1	1029.
0.30	7.196	527.5	1249.9	0.5127	6.724	1215.3	1450.
0.39	7.508	521.1	1634.7	0.8132	4.855	1003.2	1835.

amass(1)= 250

annular gap 4.455659 ft.
stream area 105.6047 sq.ft

mach(2)	pt(2)	t(2)	mass(2)	mach(4)	p(4)	t(4)	mass(4)
0.10	6.807	535.9	407.6	0.2614	8.533	2326.9	658.
0.20	6.951	532.7	817.5	0.3880	7.807	1687.6	1068.
0.30	7.196	527.5	1232.4	0.5509	6.773	1350.4	1482.
0.37	7.430	522.7	1526.9	0.8369	4.892	1140.0	1777.

```
**********************************************************
   ******************** sig = .4 ********************

   *****  Core Stream Conditions  *****
Mach number                    2.15
velocity                       5509.689     ft/sec
static pressure                6.759005     psi
total pressure                 66.14     psi
static temperature             2641.565     deg-R
total temperature              4290     deg-R
static density                 6.055873E-03     lbm/ft**3
specific heats ratio           1.27
specific heat (P const.)       .3677717     Btu/lbm-R
molecular weight               25.4     lbm/lbmol



stream radius                  .6906502     ft.
stream area                    1.498533     sq.ft


   *****  Outer Stream Conditions  *****
For the following Mach number, the conditions are:
Mach number                    .1
velocity                       113.6165     ft/sec
static pressure                6.76     psi
total pressure                 6.807438     psi
static temperature             535.9282     deg-R
total temperature              537     deg-R
static density                 3.396719E-02     lbm/ft**3
specific heats ratio           1.4
specific heat (P const.)       .2405151     Btu/lbm-R
molecular weight               28.9     lbm/lbmol

stream radius                  6     ft.
stream area                    111.5988     sq.ft


     amass(1)= 50
                    annular gap              5.30935     ft.
                    stream area              111.5988    sq.ft

mach(2) pt(2)    t(2)  mass(2) mach(4)  p(4)   t(4) mass(4)
-----------------------------------------------------------
  0.10  6.807   535.9   430.7  0.1528  7.075 1097.9   481.
  0.20  6.951   532.7   863.9  0.2613  6.800  831.1   914.
  0.30  7.196   527.5  1302.3  0.3834  6.384  724.2  1352.
  0.40  7.548   520.3  1748.3  0.5504  5.617  655.1  1798.
  0.45  7.768   516.1  1975.0  0.7294  4.614  612.6  2025.
```

amass(1)= 100

annular gap 5.023273 ft.
stream area 110.1003 sq.ft

mach(2)	pt(2)	t(2)	mass(2)	mach(4)	p(4)	t(4)	mass(4)
0.10	6.807	535.9	424.9	0.1895	7.420	1520.3	525.
0.20	6.951	532.7	852.3	0.3056	6.981	1088.6	952.
0.30	7.196	527.5	1284.8	0.4436	6.338	902.0	1385.
0.40	7.548	520.3	1724.9	0.7074	4.821	768.0	1825.

amass(1)= 150

annular gap 4.803759 ft.
stream area 108.6018 sq.ft

mach(2)	pt(2)	t(2)	mass(2)	mach(4)	p(4)	t(4)	mass(4)
0.10	6.807	535.9	419.1	0.2186	7.760	1848.9	569.
0.20	6.951	532.7	840.7	0.3423	7.167	1313.0	991.
0.30	7.196	527.5	1267.4	0.5001	6.272	1061.9	1417.
0.37	7.430	522.7	1570.3	0.7485	4.715	917.2	1720.

amass(1)= 200

annular gap 4.6187 ft.
stream area 107.1032 sq.ft

mach(2)	pt(2)	t(2)	mass(2)	mach(4)	p(4)	t(4)	mass(4)
0.10	6.807	535.9	413.3	0.2432	8.096	2111.6	613.
0.20	6.951	532.7	829.1	0.3736	7.356	1510.1	1029.
0.30	7.196	527.5	1249.9	0.5558	6.177	1205.4	1450.
0.34	7.323	524.9	1420.1	0.7135	5.121	1097.3	1620.

amass(1)= 250

annular gap 4.455659 ft.
stream area 105.6047 sq.ft

mach(2)	pt(2)	t(2)	mass(2)	mach(4)	p(4)	t(4)	mass(4)
0.10	6.807	535.9	407.6	0.2646	8.428	2326.3	658.
0.20	6.951	532.7	817.5	0.4009	7.549	1684.6	1068.
0.30	7.196	527.5	1232.4	0.6144	6.034	1333.2	1482.
0.32	7.257	526.2	1316.1	0.7135	5.337	1263.2	1566.

```
************************************************************
   ******************** sig = .5 ********************

   *****  Core Stream Conditions  *****
Mach number                    2.15
velocity                       5509.689     ft/sec
static pressure                6.759005     psi
total pressure                 66.14     psi
static temperature             2641.565     deg-R
total temperature              4290     deg-R
static density                 6.055873E-03     lbm/ft**3
specific heats ratio           1.27
specific heat (P const.)       .3677717     Btu/lbm-R
molecular weight               25.4     lbm/lbmol

stream radius                  .6906502     ft.
stream area                    1.498533     sq.ft


   *****  Outer Stream Conditions  *****
For the following Mach number, the conditions are:
Mach number                    .1
velocity                       113.6165     ft/sec
static pressure                6.76     psi
total pressure                 6.807438     psi
static temperature             535.9282     deg-R
total temperature              537     deg-R
static density                 3.396719E-02     lbm/ft**3
specific heats ratio           1.4
specific heat (P const.)       .2405151     Btu/lbm-R
molecular weight               28.9     lbm/lbmol

stream radius                  6     ft.
stream area                    111.5988     sq.ft


     amass(1)= 50
                    annular gap              5.30935     ft.
                    stream area              111.5988    sq.ft

mach(2) pt(2)    t(2)   mass(2) mach(4)  p(4)    t(4) mass(4)
-------------------------------------------------------------
  0.10  6.807   535.9    430.7  0.1537  7.035  1097.9   481.
  0.20  6.951   532.7    863.9  0.2661  6.675   830.7   914.
  0.30  7.196   527.5   1302.3  0.4026  6.071   722.2  1352.
  0.40  7.548   520.3   1748.3  0.7117  4.265   631.3  1798.
```

amass(1)= 100

annular gap 5.023273 ft.
stream area 110.1003 sq.ft

mach(2)	pt(2)	t(2)	mass(2)	mach(4)	p(4)	t(4)	mass(4)
0.10	6.807	535.9	424.9	0.1911	7.354	1520.1	525.
0.20	6.951	532.7	852.3	0.3138	6.796	1087.6	952.
0.30	7.196	527.5	1284.8	0.4790	5.851	896.5	1385.
0.35	7.358	524.2	1503.8	0.6511	4.751	816.4	1604.

amass(1)= 150

annular gap 4.803759 ft.
stream area 108.6018 sq.ft

mach(2)	pt(2)	t(2)	mass(2)	mach(4)	p(4)	t(4)	mass(4)
0.10	6.807	535.9	419.1	0.2212	7.667	1848.5	569.
0.20	6.951	532.7	840.7	0.3544	6.916	1310.9	991.
0.30	7.196	527.5	1267.4	0.5658	5.509	1048.6	1417.
0.32	7.257	526.2	1353.5	0.6705	4.802	995.9	1503.

amass(1)= 200

annular gap 4.6187 ft.
stream area 107.1032 sq.ft

mach(2)	pt(2)	t(2)	mass(2)	mach(4)	p(4)	t(4)	mass(4)
0.10	6.807	535.9	413.3	0.2469	7.975	2111.0	613.
0.20	6.951	532.7	829.1	0.3904	7.031	1506.6	1029.
0.30	7.196	527.5	1249.9	0.7369	4.566	1157.7	1450.
0.30	7.196	527.5	1249.9	0.7369	4.566	1157.7	1450.

amass(1)= 250

annular gap 4.455659 ft.
stream area 105.6047 sq.ft

mach(2)	pt(2)	t(2)	mass(2)	mach(4)	p(4)	t(4)	mass(4)
0.10	6.807	535.9	407.6	0.2694	8.275	2325.3	658.
0.20	6.951	532.7	817.5	0.4230	7.143	1679.3	1068.
0.28	7.138	528.7	1148.9	0.7165	4.915	1347.7	1399.

VITA

Luke Harley Rogers is currently employed as a Project Manager with the Department of Energy's Morgantown Energy Technology Center. He is simultaneously pursuing a doctoral degree in Mechanical Engineering at Carnegie-Mellon University.

Born in Opelika, Alabama in 1967, he attended city of Auburn public and private schools, graduating valedictorian from Lee-Scott Academy in 1985. He graduated with highest honor from Auburn University in 1989 with a Bachelor of Science degree in Aerospace Engineering. This was followed by a Master of Science degree in the same field from the University of Tennessee Space Institute, from which he graduated in 1991.