N.I.

FACILITY FORM 602

N 69-17911	
(ACCESSION NUMBER)	(THRU)
30	1
(PAGES)	(CODE)
CR-98330	28
(NASA CR OR TMX OR AD NUMBER)	(CATEGORY)

LMSC/HREC A784665

LOCKHEED MISSILES & SPACE COMPANY
HUNTSVILLE RESEARCH & ENGINEERING CENTER
HUNTSVILLE RESEARCH PARK
4800 BRADFORD DRIVE, HUNTSVILLE, ALABAMA

LOW DENSITY PLUME IMPINGEMENT STUDY

FIRST QUARTERLY PROGRESS REPORT

8 September 1967

Contract NAS8-21150

by
A. W. Ratliff
Project Engineer

APPROVED BY: J W Benefield
for D. C. Shea, Manager
Aero-Mechanics Dept.

FOREWORD

This document is the first quarterly report describing the work being performed under contract NAS8-21150 by personnel of Lockheed Missiles & Space Company, Huntsville Research & Engineering Center, Huntsville, Alabama. The performance period covered is from 22 May 1967 through 25 August 1967.

The NASA Technical Monitor for this contract is W. O. Randolph, R-P&VE-PT.

SUMMARY

Study effort is being directed toward the development of engineering methods and computer programs for predicting convective heat flux and pressure forces in the free molecular, transition and slip flow regimes, as well as in the continuum flow regime, for low density plume impingement problems. The scope of this effort encompasses solid, monopropellant and bipropellant liquid rocket motors. Part of the total effort is being expended to improve noncontinuum plume prediction techniques and to obtain and learn to utilize existing programs for the prediction of radiant heating from both gaseous and solid particles in exhaust plumes.

During this quarter, a comprehensive literature search concerning the aerodynamics of free jets expanding into a vacuum was carried out. This survey revealed a large amount of existing literature. Several of the papers available were examined in detail to determine the most appropriate approach for the present investigation. From the study thus far, several important particulars should be mentioned. There exist methods, readily adaptable to the flow field program, for the analytical treatment of noncontinuum plumes. These methods are currently being included in the flow field program. Criteria have been established for continuing flow field calculations through transition and into free molecular flow.

A stagnation point convective heating technique, which is valid in a large region of the low density regime, was selected from several candidate solutions. The method selected is that of H. K. Cheng, and is valid in the range from continuum flow to full transition flow. Most of Cheng's analysis has been verified by a comprehensive study of his solution and other articles in the literature which discuss his solution.

A series of investigations was recently concluded using a modified method of characteristics program combined with a normal shock program which gives a good analytic description of flow fields. The blunt body program has been used to correlate several sets of test data proving its accuracy.

The streamline divergence method for off-windward streamlines has been programmed and is currently being checked out. A variety of hemisphere-nosecap configurations have been analyzed and the results are included herein.

A series of computer programs which calculate radiation from a particle laden rocket exhaust plume were obtained from Aeronutronics. These programs comprise a set of 3 codes which are used sequentially to solve a given problem. These programs have all been operated successfully and are considered checked out. They are currently being processed for transmittal to the customer.

CONTENTS

Section 1
INTRODUCTION

The flow of exhaust gases from rocket nozzles can cause a variety of complex design problems. Depending on vehicle altitude and the proximity of a rocket nozzle to adjacent surfaces, many problems can arise if the exhaust gases impinge on these surfaces. Such problems are especially acute in quasi-vacuum conditions which cause large billowing plumes. During separation of vehicle stages, rocket exhaust plume impingement may induce forces and pressures on the vehicle which must be evaluated. Attitude control rockets, as well as retrorocket and ullage motors, may cause direct impingement of exhaust gases on vehicle structure.

Because of the many problem areas associated with plume impingement, it is necessary to have adequate engineering methods and computer programs for predicting heat flux and pressures in low density plume impingement areas. It is the purpose of this study to provide such methods and programs so that these problems can be analyzed adequately.

The present effort is being expended in three primary areas. The first area involves the improvement of techniques for predicting noncontinuum exhaust plume flow fields, i.e., the slip flow, transition, and free molecular regimes. The second area is concerned with the development of techniques to evaluate continuum heating due to plume impingement on bodies immersed in the flow field. The third major area of investigation is concerned with developing engineering methods for analyzing convective heating in the noncontinuum flow regimes.

A relatively minor area of effort is that of obtaining and learning to utilize existing programs for the prediction of radiant heating from gaseous and solid particle plumes.

Section 2
NONCONTINUUM PLUME PREDICTION TECHNIQUES

2.1 LITERATURE SURVEY

A survey of the literature was made to determine the existing state of the art in noncontinuum plume prediction techniques. It was found that most previous studies of jets exhausting into vacuums have been directed to the development of supersonic molecular beams. Owen and Thornhill (Reference 1) and Sherman (Reference 2) used the method of characteristics to calculate centerline Mach numbers as a function of distance from the nozzle. Sherman noted in his investigation that a free jet would become inertia dominated at some distance from the nozzle so that the stream lines would become straight and would strongly resemble source flow.

Vick, et al., (Reference 3) and Cassanova and Stephenson (Reference 4) used the method of characteristics to calculate the flow field properties of jet exhaust plumes from highly underexpanded nozzles in a near vacuum. These calculated properties were found to be in good agreement with experimentally observed properties in the near flow field.

The above findings indicate that the method of characteristics is suitable for calculating flow field properties in the near flow regime. As the jet expands to low densities, however, the distance between intermolecular collisions increases to the point that the gas can no longer be treated as a continuous fluid. Moreover, since intermolecular collisions are the means for maintaining thermodynamic equilibrium between the various energy modes (vibration, rotation, translation), a rapid expansion will result in a nonequilibrium condition in the temperature of the gas. The vibrational temperature will "freeze" first because of the large number of collisions required to maintain equilibrium. The rotational temperature will freeze next, and the translational temperature will freeze last. The freezing of the translational temperature means that the flow has become free molecular.

Although there is in reality a continuous transition from equilibrium to frozen flow for each of the temperatures, a "sudden freeze" approximation may be made with reasonable accuracy. Knuth (References 5 and 6) defined criteria for both rotational and translational freezing in jets based on the following equation:

$$\left|\frac{DT}{Dt}\right| = \frac{T}{\tau} \tag{1}$$

where D/Dt is the hydrodynamic derivative, T is temperature (vibrational, rotational, or translational), and τ is the relaxation time for the temperature to reach equilibrium after a step change. If the magnitude of DT/Dt is smaller than T/τ, the temperature is considered to be in equilibrium; if DT/Dt is greater than T/τ, it is considered to be frozen. This criteria is analogous to previously investigated nonequilibrium effects, such as dissociation or chemical reaction (Bray, Reference 7).

The physical meaning of Equation (1) may be seen by observing that $T/\left|DT/Dt\right|$ is the time involved in an appreciable change in temperature in the flow field assuming continuum flow. Since τ is the relaxation time required to reach equilibrium after a step change, T will depart from equilibrium when $T/\left|DT/Dt\right|$ is smaller than τ.

For steady flow, Equation (1) may be written:

$$V\left|dT/ds\right| = T/\tau, \tag{2}$$

where V is the flow velocity and s is the distance along a streamline. The relaxation time τ may be expressed in terms of a collision number N as follows:

$$\tau = N/\dot{N}, \tag{3}$$

where $\dot{N}$ is the local collision frequency. N is simply the number of collisions required to achieve relaxation. The collision frequency $\dot{N}$ may be expressed in terms of the mean thermal velocity $\overline{V}$ and the Lagrangian (relative to moving gas) mean free path λ as follows:

$$\dot{N} = \overline{V}/\lambda . \tag{4}$$

Rearranging Equation (2), using Equations (3) and (4), yields the freezing point criterion:

$$Kn' = \left(\frac{V}{\overline{V}}\lambda\right)\left(\frac{1}{T}\left|\frac{dT}{ds}\right|\right) = \frac{1}{N} \tag{5}$$

The dimensionless parameter Kn' on the left hand side of Equation (5) is a local Knudsen number, which is a ratio of a mean free path to a characteristic length. The mean free path in this case is the Eulerian (relative to fixed coordinate system) mean free path $(V/\overline{V})\lambda$; and the characteristic length is $T/\left|dT/ds\right|$, the distance over which an appreciable change in temperature occurs.

Hamel and Willis (Reference 8) developed a moment solution of the Boltzman equation for spherical source flow. As was brought out in the preceding discussions, at large distances from the nozzle the flow of a free jet into a vacuum is approximated by spherical source flow. In their solution, the translational temperature was resolved into components parallel to and perpendicular to the streamline. An interesting finding in their analysis is that the perpendicular temperature initially decreases as $r^{-4/3}$ (r is distance from source), as in the isentropic case, and then abruptly changes to a r^{-1} dependency in the asymptotic limit. Since a collisionless flow should have a r^{-2} dependency, this indicates that the source flow expansion never really reaches free molecular flow. The parallel temperature, however, does approach a finite limiting value, and therefore, freezes.

Edwards and Cheng (Reference 9) independently obtained the same results as Hamel and Willis by using the B-G-K kinetic model (Reference 10).

Abuaf, et al.,(Reference 11) made experimental measurements of the perpendicular temperature in free jet expansions. They noted an $r^{-4/3}$ relationship in the near flow region and an r^{-2} relationship in the asymptotic limit. These results are in contradiction to the prediction of Hamel and Willis in the asymptotic limit and cast at least some doubt on the validity of their theory.

2.2 METHOD OF APPROACH

The method of approach selected for development in this study is to use the method of characteristics, in conjunction with the "sudden freeze" criteria of Knuth (References 5 and 6), up to the freezing point for translational temperature. From this point on, the mass flow velocity and temperature will be held constant and the streamlines straight, i.e., the flow will be considered free molecular.

A local Knudsen number Kn' [Equation (5)] will be calculated at each point in the characteristic net:

$$Kn' = \left(\frac{V}{\bar{V}} \lambda\right) \left(\frac{1}{T} \; \frac{dT}{ds}\right) = \sqrt{\frac{\pi \gamma}{8}} \; M \; \frac{\lambda}{R_o} \left| \frac{d(\ln T)}{d\bar{s}} \right| \qquad (6)$$

where γ is the isentropic exponent, M is the local Mach number, R_o is the nozzle exit radius, and $\bar{s}$ is the distance along streamline divided by R_o.

For the special case of a non-reacting, constant collision cross-section hard sphere gas, the mean free path λ is inversely proportional to density, and Equation (6) may be expressed:

$$\mathrm{Kn}' = \sqrt{\frac{\pi\gamma}{8}}\ \frac{\mathrm{Kn}_c}{\bar{\rho}}\ M \left|\frac{d(\ln T)}{d\bar{s}}\right| \qquad (7)$$

where $\mathrm{Kn}_c = \lambda c/R_o$ is the chamber Knudsen number, and $\bar{\rho}$ is the ratio of local density to chamber density.

In real gases, the molecular interactions are more complex than that predicted by the simple hard sphere model. A more realistic determination of the local mean free path λ can be obtained through the viscosity μ by the following relation (Reference 12):

$$\lambda = \frac{\mu}{0.499\rho\bar{V}} \quad , \qquad (8)$$

where ρ is the local density. Equation (8) is exact only for the case of hard spheres; however, it is nearly the same for all inverse power law repulsions, with the numerical factor in the denominator being 0.491 for Maxwell molecules (inverse fifth power law repulsion). The nature of the molecular interaction is accounted for by the variation of the effective collision cross-section and hence, the viscosity with temperature. A number of empirical formulae (Reference 12) have been devised for accounting for the variation of viscosity with temperature.

Using Equation (8), Equation (6) may now be expressed:

$$\mathrm{Kn}' = 2.51\pi\gamma\ \frac{M^2}{\mathrm{Re}} \left|\frac{d(\ln T)}{d\bar{s}}\right| \qquad (9)$$

where Re is the local Reynolds number:

$$\mathrm{Re} = \frac{\rho V R_o}{\mu} \qquad (10)$$

When the local Knudsen number Kn' becomes equal to the inverse of the collision number N for a particular energy mode, the temperature corresponding to that particular energy mode is considered to freeze and remain constant thereafter. The isentropic exponent γ, used in the method of characteristics flow field calculations, then changes accordingly. New stagnation values of temperature, density, and pressure are then calculated such that the static values are preserved across the freezing front.

When vibrational freezing occurs, the gas takes on the value of γ corresponding to its rotational and translational degrees of freedom. For a diatomic molecule such as nitrogen or oxygen, γ becomes 7/5. For a nonsymmetrical molecule such as water vapor or carbon dioxide, γ becomes 4/3.

The vibrational collision number N_v is highly temperature dependent and varies greatly depending on the kind of gas under consideration. Reference 13 provides a large amount of data on vibrational collision numbers and relaxation times for various gases at various temperatures.

After rotational freezing occurs, the gas is treated as a monatomic gas with γ equal to 5/3. The rotational collision number N_r is only a weak function of temperature (Reference 5) and may be treated as a constant for a given gas. Rotational collision numbers are given in Reference 14 for nitrogen, oxygen and air as 5.26, 4.09 and 4.82, respectively. Rotational collision number data is also provided in Reference 13.

When translational freezing occurs, the gas may be considered in free molecular flow. The streamlines remain straight thereafter, and the molecular velocities are all in the direction of stream flow. There is a distribution of velocities in the direction of flow corresponding to the frozen translational temperature, but there are no random velocities with components perpendicular to the streamline.

Knuth (Reference 5) used a translational collision number N_t of 5/4 which was based on Maxwell's (Reference 15) calculations for pressure inequality relaxations. This is equivalent to a local Knudsen number Kn' of 0.8 [Equation (5)] which is of the same order of magnitude as the Knudsen number specified for transition to free molecular flow in other rarefied gas flow studies.

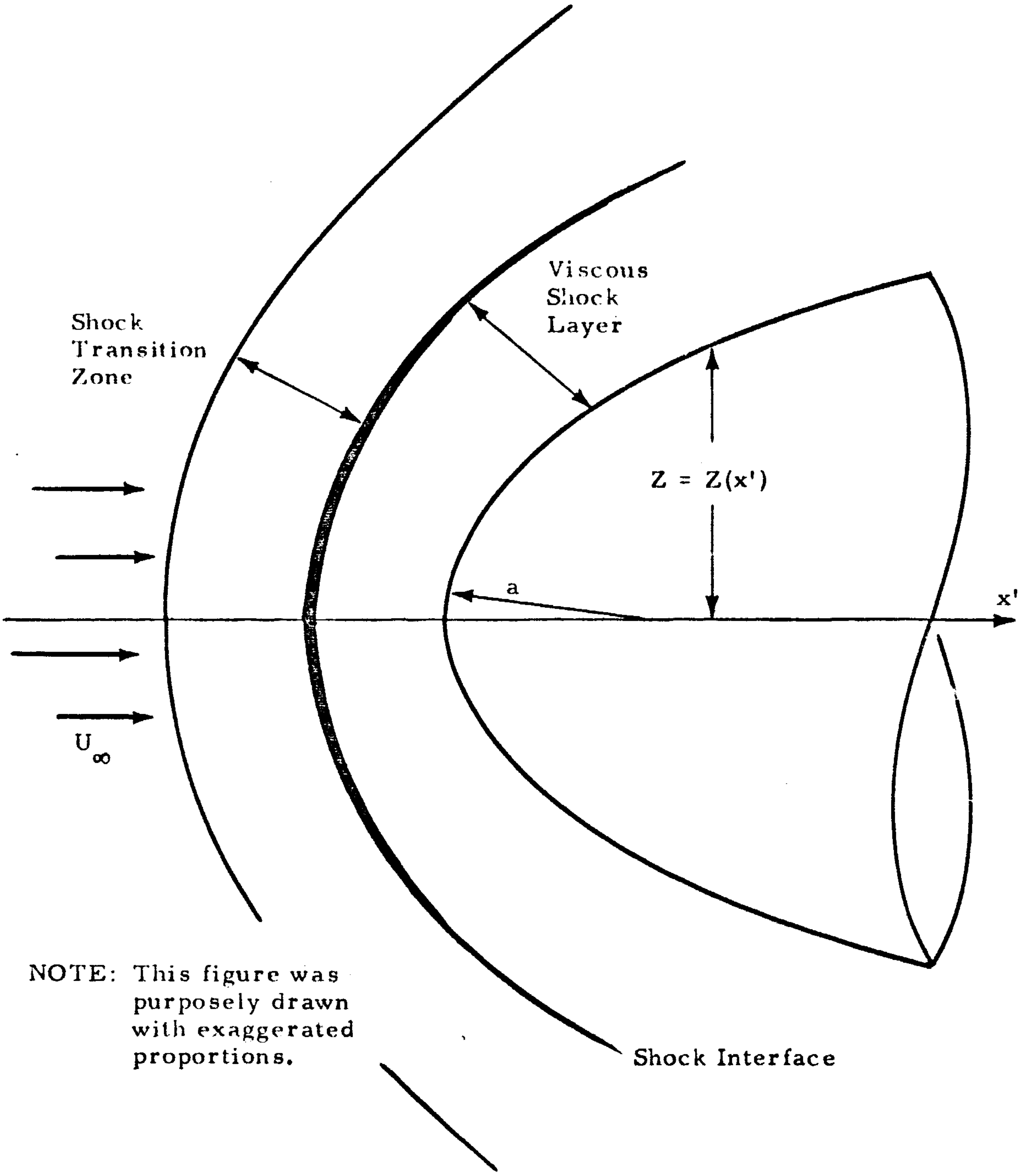
In the free molecular flow region, the stream velocity is constant, and the density varies according to the spreading of the straight streamlines, with the density being inversely proportional to the cross-sectional area of a stream tube. This model is currently being incorporated into the flow field program. Results computed by this model will be included in future progress reports.

Section 3
NONCONTINUUM CONVECTIVE HEATING

A body of arbitrary size immersed in a high altitude rocket exhaust plume may experience convective heating in one or all of the low density flow regimes, depending on the body's position in the exhaust plume and its relative size compared to that of the plume. Since the most severe heating rates will occur at the point where the flow stagnates on the body, it was felt the initial effort should be directed toward development of a stagnation point heating technique which would be valid in a large region of the low density flow regimes. Several methods of predicting stagnation heat transfer to blunt-nosed bodies in low density hypersonic flow were studied. The criteria for judging these methods, in addition to the accuracy of predicted values, also included economy of computer time required to obtain the answers. The thin shock layer method due to H.K. Cheng (Reference 16) was determined to be the best.

Cheng's low density blunt body solution is valid in the range from continuum flow to full transition flow, which includes the vorticity-interaction regime, the viscous shock layer regime, the incipient-merged layer regime, and the fully-merged layer regime as defined by Probstein (Reference 17). The blunt-body flow field, under the assumption of a uniform hypersonic low density approach flow, has been divided into two regions: (1) a shock transition zone which contains all the effects of the shock wave, and (2) a viscous shock layer (see Figure 1).

It is assumed that these two layers are thin with respect to the local nose radius and that gradients in the direction normal to the body surface are large in comparison to gradients along the body. The Navier-Stokes equations, along with the above two assumptions, are applied to both the shock transition zone and the viscous shock layer. The result of this application in the shock transition zone is a set of modified Rankine-Hugoniot relations



NOTE: This figure was purposely drawn with exaggerated proportions.

Figure 1

which show that tangential momentum and total enthalpy are no longer conserved across the shock wave due to the presence of viscous forces. These modified Rankine-Hugoniot relations define the boundary conditions which the shock layer equations must satisfy at the shock interface (see Figure 1).

An analogous treatment in the viscous shock layer results in a set of equations which are more difficult to solve. These complex equations, however, are valid over the entire shock layer around the body. Since the region of interest is the stagnation region, it is possible to reduce these equations to a much simpler form by setting up a perturbation solution about the stagnation streamline in the shock layer. The solution, to the zeroth order set of equations, can be divided into two types based on the order of magnitude of two very important parameters. Define:

$$\epsilon \equiv \frac{\gamma - 1}{2\gamma}$$

$$K^2 \equiv \epsilon \, \frac{\rho_\infty U_\infty a}{\mu_o} \left(\frac{T^* \mu_o}{T_o \mu^*} \right) ,$$

where

γ = ratio of specific heats
ρ_∞ = freestream density
U_∞ = freestream velocity
μ_o = freestream stagnation value of viscosity
T_o = freestream stagnation value of temperature
$( )^*$ = evaluated at reference temperature T^*
a = local nose radius

The parameter K^2 is essentially a modified Reynolds number and the parameter ϵ is a measure of the compression across the shock wave. If

$$O(1) \leq \epsilon K^2 \leq \infty \qquad \text{(Regime I)} ,$$

then the solution of the zeroth order set of perturbation equations can be found by a local similarity solution which is familiar in boundary layer theory. If

$$O(\epsilon) \leq \epsilon K^2 \leq O(1) \qquad \text{(Regime II)} \quad ,$$

then the solution to the set of equations can be found analytically by a direct integration procedure.

Based on the comprehensive study of Cheng's solution and other articles in the literature which discuss his solution, it is reasonable to assume that the solution of the equations in both Regimes I and II will give accurate values of stagnation point heating rates with a minimum amount of computer time. Thus, a two-fold approach will be followed during the next work period. The mathematical derivation of the entire blunt-body solution will continue until all the equations have been verified. Approximately one-half of the full solution has been verified at this time, and no serious difficulties are foreseen.

In addition to the derivation, however, work will begin on programming the solutions in both Regimes I and II as they appear in Cheng's paper. Thus, a headstart will be realized in setting up the final computer program, and any problems associated with obtaining final answers will be uncovered as early as possible. Of course, if the mathematical derivation brings any errors to light, these changes can be made quickly in the computer program.

Heating analysis of large bodies immersed in a low density rocket exhaust plume will also require a flat-plate type boundary layer solution which will be valid in the same flow regimes as the blunt-body stagnation point solution discussed above. From the information available at the present time, it appears reasonable to assume that a boundary layer growing over a flat-plate type surface in this environment will be laminar.

The only low density boundary layer solution presently available is due to Maslen (Reference 18). Maslen's solution predicts correction terms to the ordinary laminar boundary layer solution. This accounts for the low density effects of a slip velocity and temperature jump at the surface. Note that the low density effects which are dominant in a stagnation point solution for a blunt-body are not important for flow over a flat-plate type boundary, e.g., the vorticity generated by shock wave curvature. Maslen (Reference 18) obtains his solution using a perturbation technique on the laminar boundary layer equations where flow variables are expanded in terms of a small parameter proportional to the Knudsen number. Obviously the first order solution is the usual continuum laminar boundary layer solution. The higher order solutions contain the low density correction terms which are superposed on the continuum solution. Work has started on the complete derivation of this solution and verification of all equations.

Of equal importance but much greater difficulty is a solution for heat transfer in the full transition flow regime. Since the continuum-type perturbation methods (such as those in References 16 and 19) have been extended as far as is mathematically possible, any solution in transition flow must be based on the Boltzmann equation. In transition flow, however, there are too many intermolecular collisions taking place to permit setting the collision integrals equal to zero (i.e., free molecular flow). On the other hand, a solution to the full Boltzmann equation is not feasible.

The only method of calculating flow fields which looks promising is a solution of the BGK (Reference 20) equation, which is the Boltzmann equation with the collision integrals replaced by an approximate and mathematically simpler term representing the results of collisions. The solution of a flow field in the full transitional regime over a given body, even assuming uniform approach flow of a "cold" gas, may require a tremendous effort. On the basis of time limitations alone, it appears that a workable solution of the BGK equation is not possible. Since the lack of a heating prediction method in the transition flow regime does not leave a tremendous void between the other low density prediction method and free molecular flow methods, a curve-fit equation could easily be generated which would link the two known prediction methods across this flow regime. Very little, if any, accuracy will be lost by doing so.

Section 4
CONTINUUM CONVECTIVE HEATING

4.1 COMPUTER PROGRAM DEVELOPMENT

The convective heating methods chosen for the low density plume impingement study have been defined during this reporting period. They can basically be divided into the three following cases which will be analyzed by three distinct computer programs:

- Small plume - large surface
- Large plume - small body
- Master program - streamline divergence.

The first group of heat transfer problems include the effects of relatively small exhaust plumes impinging on large surfaces, such as during retro motor plume and staging interactions. In these cases, hypersonic assumptions cannot be applied to the calculation of the local flow properties over the large surfaces being analyzed; other methods must be used to obtain realistic heating rates to these surfaces.

Lockheed/Huntsville has currently concluded a series of investigations using a modified method of characteristics program in conjunction with a normal shock computer program, which provides a good analytic description of the above described flow field. This technique, which is essentially complete, gives good data correlation for large surfaces parallel to the centerline of the exhaust plume. Additional work on this program is planned which will extend present capabilities to include heat transfer calculations for large skewed surfaces in the exhaust plume.

A second grouping of convective heat transfer problems are those associated with relatively small bodies immersed in a large exhaust plume flow field. In these cases, a uniform approach flow may be assumed and rather conventional means may be used to obtain heat transfer over these bodies. In this respect, a blunt-body program capability has been included in the low density plume impingement study. This program is presently being used to correlate test data, and has been modified for use in the low density plume real gas environment. Primary additional work remaining in this area is in simplifying the data input required to run the computer program.

The final area of heat transfer problems will be analyzed through use of the "Master Program" in which the following heat transfer methods are being determined. The "streamline divergent" method will provide heating rates along streamlines as calculated over shapes immersed in a rocket exhaust plume. This method is the more general of the three separate methods described here and enables the analysis of a variety of plume body sizes. The most windward streamline heating rate calculation procedure has been checked out and is providing data for a variety of cases under investigation at Lockheed. A method of tracing the different streamlines off the windward streamline has been programmed and is currently being checked for errors. The remaining work on this program is to finish the off-windward streamline calculation procedures and to provide a real gas transport property subroutine to the main program. Also, an option for calculating the local pressures on the immersed bodies will be included in the main program.

4.2 DATA CORRELATION

Both the small plume-large surface and the large plume-small body computer programs have been used to successfully correlate test data. Results of an analysis of a test series in which an RPI retro engine (Centaur test series at MSFC) exhaust impinging on a flat plate parallel to the nozzle centerline are shown on Figure 2. Several skin friction coefficients were used with the method of Reference 21. This provided the most exact data-theory match. The heating rates as measured agree quite well with the results of the computer program.

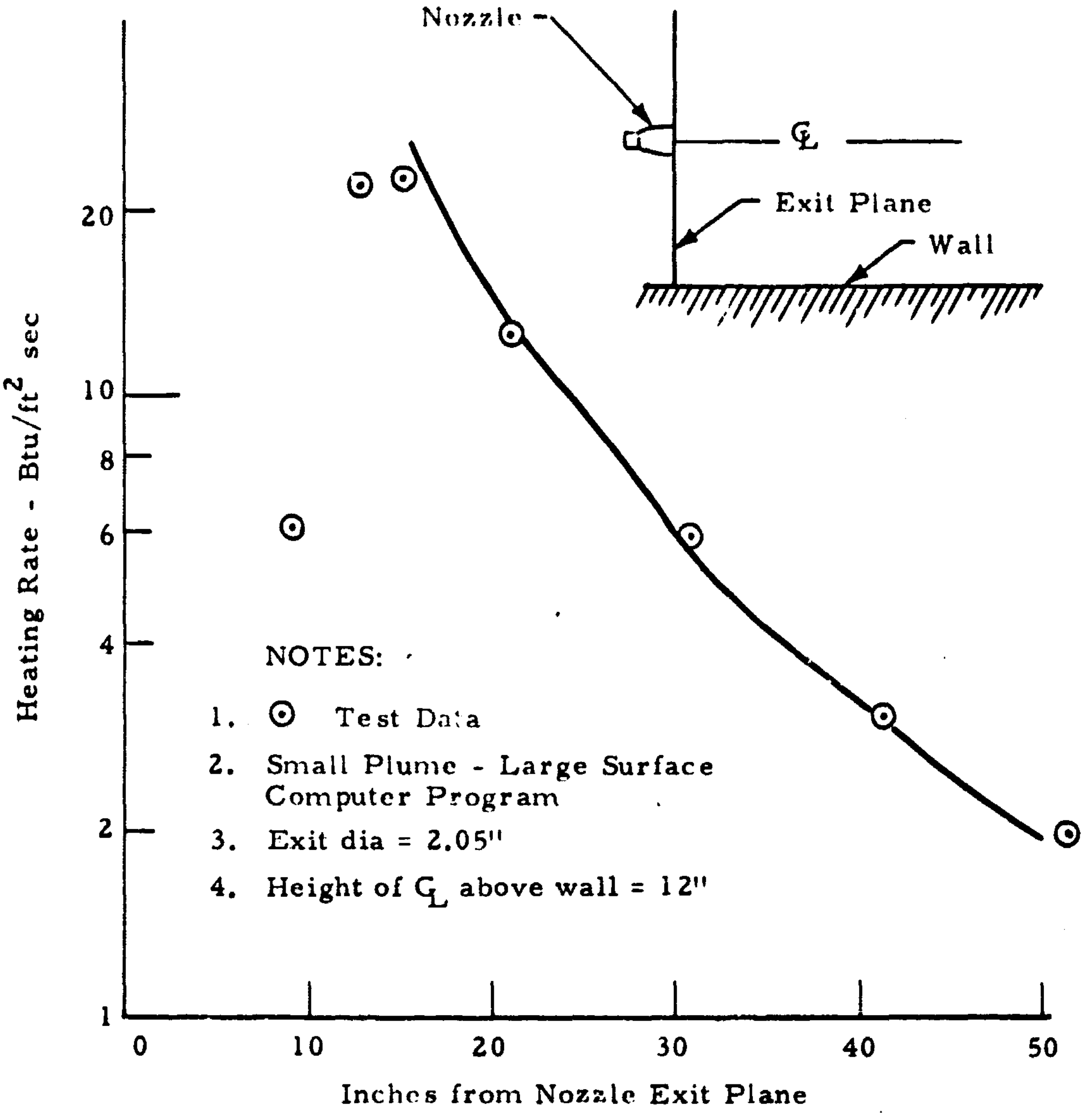


Figure 2 - Analytic Results as Compared to RPI Plume Impingement Experimental Data

The blunt-body program has also been used to evaluate rocket exhaust plume test data. A variety of hemisphere nosecap configurations have been analyzed using the program. The results of heating rate data taken from a blunt body test for the following three cases are shown on Figures 3 through 5:

- Agena Nozzle with Blunt-Body No. 1
- Malta Pit Four Nozzle with Blunt-Body No. 1
- Malta Pit Four Nozzle with Blunt-Body No. 2.

Blunt-Body No. 1 is approximately six inches in diameter and Blunt-Body No. 2 is 12 inches in diameter. The results of each analysis agree with the test data which show the boundary layers to be almost completely turbulent in nature.

The convective streamline divergence program, currently being checked out, is being used to evaluate data taken from the Douglas test series (unpublished data obtained from R-P&VE-PT). Both the O_2H_2 burner and the ullage motor configurations are being analyzed. No data correlation has as yet been completed. Work in this area will continue.

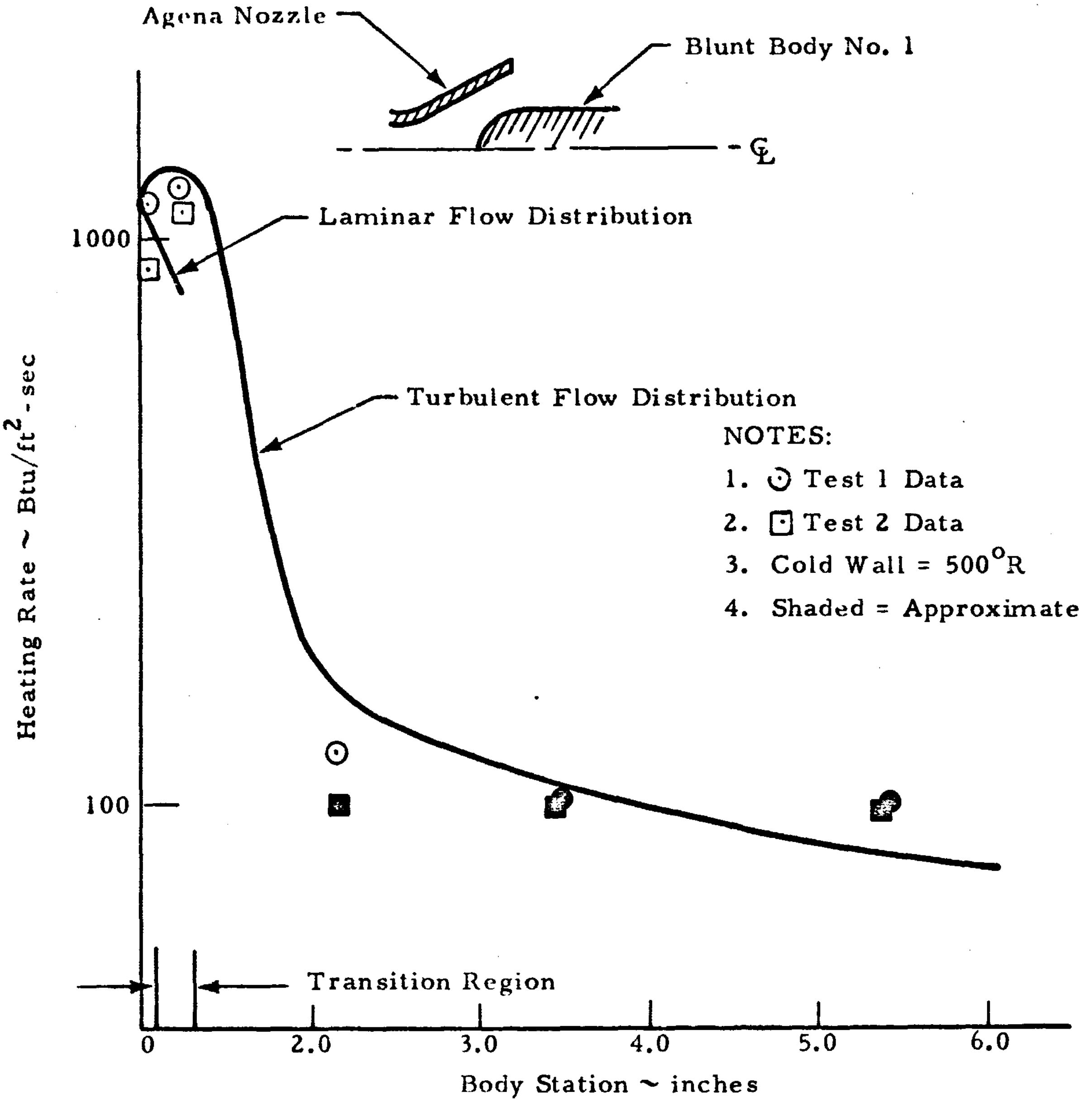


Figure 3 - Analytic Results of Agena Santa Cruz Induced Heating Rates over Small Reentry Body as Compared to Test Data

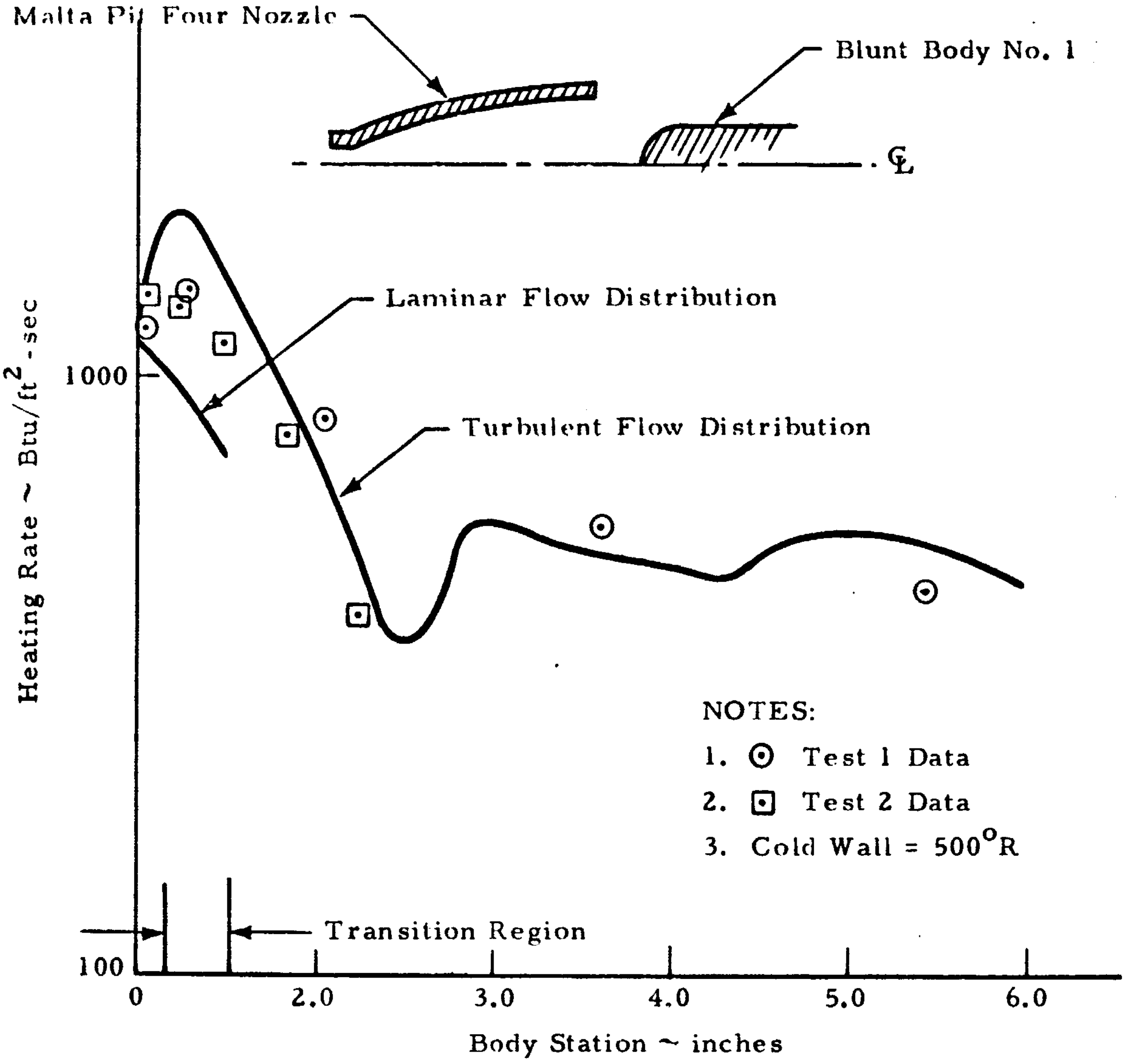


Figure 4 - Analytic Results of Malta Pit Four Induced Heating Rates Over Small Reentry Body as Compared to Test Data

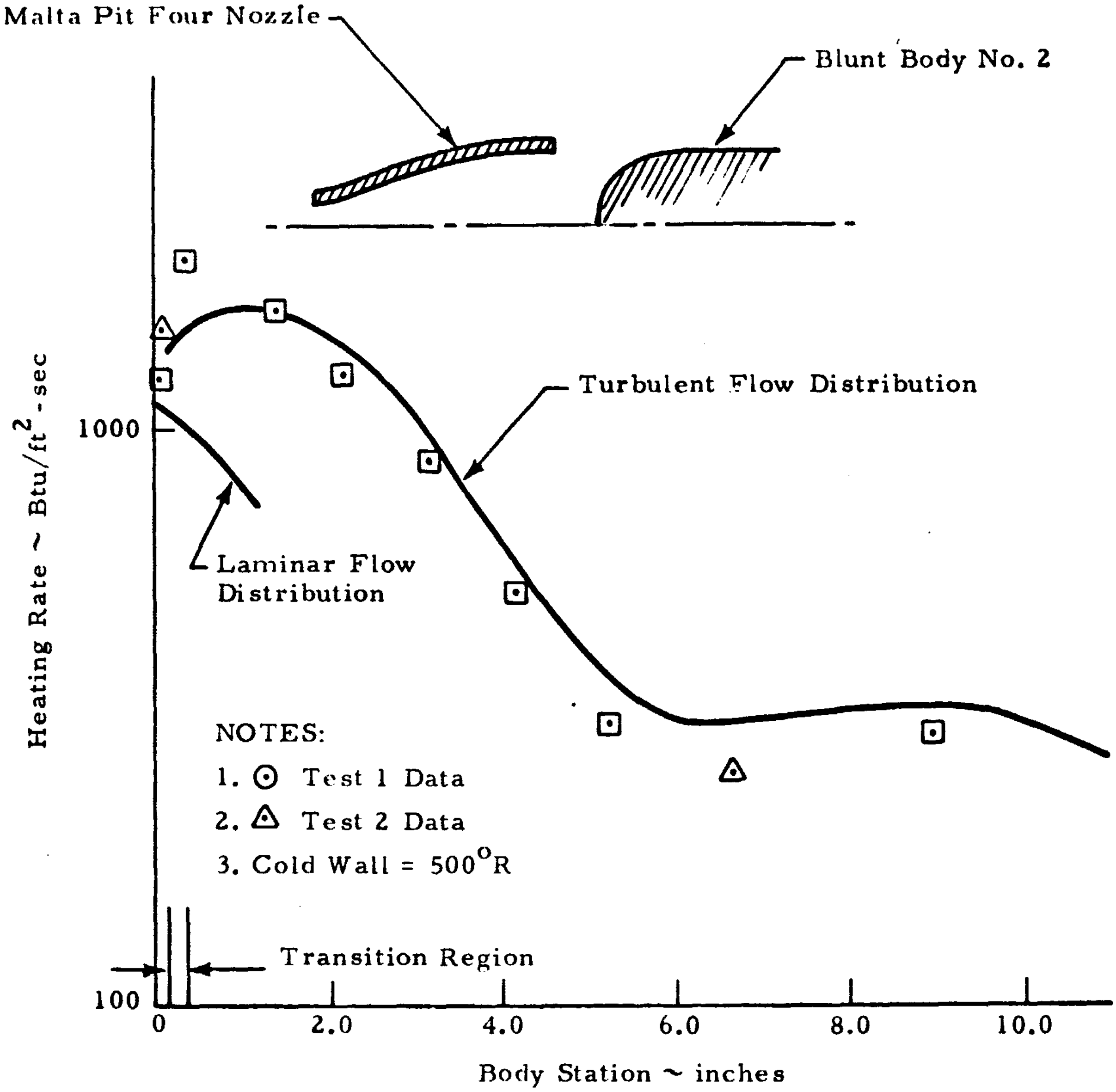


Figure 5 - Analytic Results of Malta Pit Four Induced Heating Rates over Large Reentry Body as Compared to Test Data

Section 5
RADIATIVE HEAT TRANSFER

A series of computer programs which calculate radiation from a particle-laden rocket exhaust plume was developed by Aeronutronics under contract to NASA/MSFC (Reference 22). The programs (Programs A, B and C) are used sequentially to solve a given problem.

Program A computes the centerline and limiting streamline trajectories for a given particle size. The calculation is started in the rocket combustion chamber where the particle velocity is assumed to be equal to the gas velocity, and proceeds through the nozzle and into the plume. The gas flow field in the nozzle and plume is calculated with the assumption that the effects of the particles can be uncoupled. A one-dimensional transonic solution is included in Program A as a subroutine,while the supersonic flow field can be calculated in advance by Lockheed's Method of Characteristics Computer Program, and the necessary flow field properties placed on a tape which is read by Program A. Program A punches out the particle velocity and temperature along the centerline and limiting streamlines for each particle size input. This punched output is used as input to Program B.

Program B computes the average radiative cross-sections, effective black body function, temperature, particle number density, and particle thermal and kinetic energy fluxes at specified locations within the two-phase plume. Input required includes the punched output from Program A plus Mie scattering theory tables for particle sizes comparable to the wavelength of the radiation. The scattering tables presently incorporated in Program B are particularized for aluminum oxide particles of radii between 0.1 and 20.0 microns. The particle size distribution is also input to Program B in the form of a skew-symmetric formula. Output includes punched cards with the average scattering and absorption cross-sections and back-scatter ratio, the effective spectral block body function, and the total particle number density throughout the plume. These cards are used as input to Program C.

Program C computes the radiation from the particle cloud to a target with arbitrary location along a specified line-of-sight. Multiple lines-of-sight may be selected to give the total hemispherical radiation to a given target. The radiative properties of the particle cloud are obtained from the punched output from Program B. The program prints out the radiative intensity to the target for each of a series of specified wavelengths.

Programs A, B and C have been fully checked out for a sample case based on the exhaust plume of an S-II ullage motor at an altitude of 120,000 feet. These programs are available for use by the customer.

Section 6

PLANNED ACTIVITIES

The methods developed for use in predicting the noncontinuum region of a plume flow field will be included in the flow field program, and results of calculations will be presented in the next progress report.

A two-fold approach will be followed in the development of the noncontinuum convective heating equations. Cheng's final results will be programmed so that numbers can be generated and checkout work continued. In addition, Cheng's analysis will be verified by continuing the development of the equations. Thus a headstart will be realized in setting up the final computer solution, and any problems associated with obtaining final answers will be uncovered as early as possible.

The convective heating rate computer program development will continue. The methods of approach have been determined, and the remaining effort will be in evaluating the available test data and ensuring that the programs will operate for the greatest variety of conditions possible.

The completion of the streamline divergence master program will receive major emphasis during the next report period. Continuous application of the program to evaluation of test data is planned with necessary program revisions to adequately match the test data.

The next task concerning the radiative heating facet of this study is to obtain and check out the MSFC Gaseous Radiation Computer Program.

REFERENCES

1. Owen, P. L. and G. K. Thornhill, "The Flow of an Axially-Symmetric Supersonic Jet From a Nearly-Sonic Orifice into a Vacuum," RMC RM 2616, Ministry of Supply (United Kingdom), Aeronautical Research Council, September 1948.

2. Sherman, F. S., "Self-Similar Development of Inviscid Hypersonic Free-Jet Flows," Technical Report: Fluid Mechanics 6-90-63-61, Lockheed Missiles & Space Company, Sunnyvale, California, 23 May 1963.

3. Vick, A. R., E. H. Andrews, J. S. Dennard and C. B. Craidon, "Comparisons of Experimental Jet Boundaries with Theoretical Results Obtained with the Method of Characteristics," NASA TN D-2327, June 1964.

4. Cassanova, R. A. and W. B. Stephenson, "Expansion of a Jet into Near Vacuum," AEDC-TR-65-151, August 1965.

5. Knuth, E. L., "Supersonic Molecular Beams," Applied Mechanics, Rev. 17, 751, 1964.

6. Knuth, E. L., "Rotational and Translational Relaxation Effects in Low-Density Hypersonic Free Jets," Report No. 64-53, Department of Engineering, University of California, Los Angeles, California, November 1964.

7. Bray, K. N. C., "Departure from Dissociation Equilibrium in a Hypersonic Nozzle," J. Fluid Mech., 6, 1959.

8. Hamel, B. B. and D. R. Willis, "Kinetic Theory of Source Flow Expansion with Application to the Free Jet," Phys. Fluids 9, 829, 1966.

9. Edwards, R. H. and H. K. Cheng, "Steady Expansion of a Gas Into a Vacuum," AIAA J., 4, 558, 1966.

10. Bhatnagar, P. L., E. P. Gross and M. Krook, "A Model for Collision Processes in Gases. I. Small Amplitude Processes in Charged and Neutral One-Component Systems," Phys. Rev. 94, 511, 1954.

11. Abuaf, N., J. B. Anderson, R. P. Andres, J. B. Fenn and D. R. Miller, "Studies of Low Density Supersonic Jets," Rarefied Gas Dynamics, Vol. II, C. L. Brundin, Ed., Academic Press, New York, 1967, p. 1317.

12. Kennard, E. H., Kinetic Theory of Gases, McGraw-Hill Book Company, New York, 1938.

13. Herzfeld, K. F. and T. A. Litovitz, Absorption and Dispersion of Ultrasonic Waves, Academic Press, New York, 1959.

14. Greenspan, M., "Rotational Relaxation in Nitrogen, Oxygen and Air," J. Acoust. Soc. Am., 31, 155, 1959.

15. Maxwell, J. C., "On the Dynamical Theory of Gases," The Scientific Papers of James Clerk Maxwell, Cambridge University Press, Cambridge, 1890.

16. Cheng, H. K., "The Blunt-Body Problem in Hypersonic Flow at Low Reynolds Number," CAL Report No. AF-1285-A-10, June 1963.

17. Probstein, R. F., "Shock-Wave and Flow Field Development in Hypersonic Reentry," ARS J., Vol, 31, No. 2, February 1961, p. 185.

18. Maslen, S. H., "Second Approximation to Laminar Compressible Boundary Layer on a Flat Plate in Slip Flow," NACA TN-2818.

19. Van Dyke, M., "Higher Approximations in Boundary Layer Theory," Part 1 - General Analysis, J. Fluid Mech., Vol. 14, 1962, pp. 161 - 177.

20. Bhatnagar, P. L., E. P. Gross and M. Krook, "A Model for Collision Processes in Gases," Physical Review, Vol. 94, No. 3, 1954, p. 511.

21. Spalding, D. B. and S. W. Chi, "The Drag of a Compressible Turbulent Boundary Layer on a Smooth Flat Plate with and without Heat Transfer," J. Fluid Mech., Vol. 18, January 1964, pp. 117 - 143.

22. Laderman, A. J., et al., "Study of Thermal Radiation, Particle Impingement Heating and Flow Field Analysis of Solid Propellant Rocket Exhausts," Publication No. U-4045, Aeronutronic Division of Philco-Ford, Newport Beach, California, 19 April 1967.