SECA-TR-92-02

ORBITAL MANEUVERING VEHICLE (OMV) PLUME AND PLUME EFFECTS STUDY

FINAL REPORT

Contract No. NAS8-38243

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Foreword

This final report is submitted by SECA, Inc., to the National Aeronautics and Space Administration, George C. Marshall Space Flight Center, Alabama, for Contract NAS8-38243, entitled "Orbital Maneuvering Vehicle (OMV) Plume and Plume Effect Study". This report presents the results of work performed by SECA to fulfill the requirements of Contract NAS8-38243.

Two other documents already published which are summarized in this report also comprise part of the final report. These documents which are contained as appendices to this report are:

"Definition of the MRE15 Engine Exhaust Plume Flowfield", SECA-TR-90-03, 30 March 1990

"Definition of the OMV GN2 Thruster Exhaust Plume Flowfield", SECA TR-90-13, 15 August 1990.

Summary

The object of this contract was to characterize the Orbital Maneuvering Vehicle (OMV) propulsion and attitude control system engine exhaust plumes and predict the resultant plume impingement pressure, heat loads, forces and moments. The resultant environments could then be used by the designer to insure adequacy of the structural, attitude control and thermal control systems.

The original contract provided for two increments of funding for the entire study. However, late in the first year of this study the OMV project was terminated so that the second increment was not funded. As a result of the reduced funding, not all tasks were completed. The following studies were completed:

1. The MRE15 (main propulsion and primary attitude control thruster) axisymmetric exhaust plume was characterized.

2. The Gaseous Nitrogen (GN2) secondary attitude control thruster axisymmetric exhaust plume was characterized.

3. An axisymmetric Monte Carlo simulation of the MRE15 exhaust plume was performed.

4. Initial estimates of the base heating environments to the propulsion model were determined for an axisymmetric Monte Carlo MRE15 plume.

5. Plimp code modifications and input files for locating the 28 hydrazine attitude control thrusters, 24 GN2 attitude control thrusters, and four propulsion module thrusters were generated for input to the plume impingement program. These files could be used to perform the impingement environment prediction for the OMV.

The techniques, methods and models for predicting plume induced environments presented in this report can be applied to the Cargo Transfer Vehicle (CTV) which is presently being considered as part of the NLS vehicle.

Contents

1.0 Introduction

This final report describes the results of work performed by personnel of SECA, Inc. for the NASA/MSFC Induced Environments Branch (ED33) under Contract NAS8-38243. This incrementally funded contract entitled, "Orbital Maneuvering Vehicle (OMV) Plume and Plume Effects Study", contained three major tasks which were to be completed if the incrementally funded contract were fully funded.

Task 1 of the contract called for analyzing the Propulsion Model (PM) engine combustion chamber, nozzle and exhaust plume flowfield using continuous methodologies. This effort is described in Section 2.1 of this report.

Task 2 of this contract called for the analysis of the PM engine flowfields using axisymmetric and three dimensional Monte Carlo techniques. The axisymmetric Monte Carlo analysis was performed and is described in Section 2.2

Task 3 of the contract called for the analysis of the cold gas gaseous nitrogen (GN2) attitude control thruster, hydrazine attitude control thruster, exhaust plumes and the plume induced environments due to the attitude control thrusters. The plume analysis for this task was completed and part of the impingement analysis was performed. These results are presented in Section 2.3

2.0 Technical Discussion

2.1 Propulsion Module Axisymmetric Plume Model Development

The OMV base line design prior to and at the beginning of this contract utilized four Variable Thrust Bipropellant Engines (VTE) as the primary orbit change propulsion system on the Propulsion Module (PM). As the design matured the VTE engines were replaced with MRE15, 15 lbf Hydrazine Thrusters. These engines are the same engines which are used as part of the attitude control thrusters. The continuum analysis of this engine is discussed in Section 2.3 of this report. The continuum analysis of the PM engine/plume flowfield was necessary to provide the input data to perform the axisymmetric Monte Carlo analysis of the PM flowfield in order to calculate the base heating environment to the OMV. The axisymmetric Monte Carlo analysis and results are described in Section 2.2

2.2 Axisymmetric PM Plume Direct Simulation Monte Carlo (DSMC) Analysis

The object of this task was to provide an estimate of the OMV PM base environment due to a single engine plume. Figure 1 shows the PM engine layout for the OMV. There are four MRE15 engines located in the base as shown in Figure 1. When these engines fire the plumes interact and cause flow reversal into the base which results in heat and pressure loads which need to be accounted for. Due to the relatively low density of the flow the only way (lacking applicable experimental data) to predict the interaction of the flowfields is to perform a three dimensional analysis using Direct Simulation Monte Carlo (DSMC) techniques. The approach for performing this analysis required three steps. Step 1 requires performing a continuum analysis of the MRE15 engine and plume.

This analysis is described in Section 2.3. Step 2 uses the continuum analysis as input and performs an axisymmetric DSMC analysis. Finally, Step 3 uses the results of Step 2 to perform a full three dimensional Monte Carlo analysis to determine the base environment. Since the second increment was not funded, only the axisymmetric analysis was performed.

DSMC methods have become more and more popular for solving complex flowfields in low density flows where transitional non-equilibrium and specie diffusion are important. Three dimensional DSMC methods could be used to solve the entire 4 engine plume flowfield starting at the exit plane of the engine but the computer time necessary to do this would be excessive. To reduce the computer resource requirements an axisymmetric DSMC calculation of a single MRE15 engine was performed An axisymmetric DSMC MRE15 calculation was used to characterize the flowfield in the near region around the engine including the engine heat shield. The axisymmetric results were then used to calculate the heat loads to the engine heat shield region.

The basic code which was used to perform the axisymmetric DSMC MRE calculations was the GAPS code (Ref. 1). This model was developed to solve unique design problems for the Galileo Spacecraft.

The direct simulation Monte Carlo method was originated by G. A. Bird and has been developed by numerous modelers over the past decade. This method is a computational technique for the modeling of a real gas flow at a molecular level with several thousand simulated molecules. The velocity components and position coordinates of the simulated molecules are stored in the computer and these are modified with time as the molecules are followed through representative collisions and boundary interactions in the

simulated flowfield.

The initial state of the gas is specified and boundary conditions corresponding to the desired flow are applied at time zero. The flow is always unsteady, but the boundary conditions are generally such that a steady flow is obtained as the large-time state of the unsteady flow. Time is advanced by discrete steps of magnitude 10 Δt which is small compared with the mean free time between collisions. The simulated flowfield is divided into a network of spatial cells of such size that the change in flow properties across each cell is small. All macroscopic quantities of interest are obtained as averages of the randomly-fluctuating molecular states within the various cells.

The molecular motion and the collision processes are uncoupled over the time interval Δt by the repeated application of the following procedure:

(i)   All the molecules are moved through distances appropriate to their instantaneous velocity components and Δt.

(ii) A representative set of collisions, appropriate to Δt, is computed among the molecules, and the pre-collision velocity components of those molecules involved in the collisions are replaced by their post-collision values.

Therefore, along any molecular path, collisions can only occur at intervals that are integral multiples of Δt. Since Δt is small compared with the mean free time, the resulting distortion of the path is small.

The direct simulation procedure is equivalent to a numerical solution of the Boltzmann equation. The left hand side of that

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equation is represented directly by the process of following the trajectories of the individual molecules. The collision integral on the right hand side is properly represented by sampling collision partners from the collision probability appropriate to the particular molecular model, and by calculating collisions at a rate consistent with the local collision frequency. It can be shown that, as the uncoupling interval Δt and the cell size are made very small, and the number of molecules is made large, the Monte Carlo simulation differs from the Boltzmann equation only by random statistical fluctuations.

Since the conservation equations of continuum fluid mechanics are embodied in the Boltzmann equation, solution of the Boltzmann equation gives the proper description of gas flows at all density levels. Therefore, the direct simulation technique can, in principle, be used to describe the entire rarefaction spectrum from the collisionless to the continuum limit. The practical constraints for the application of this method to continuum flows are the limited computer resources; memory and time. For this reason, the GAPS program has been designed to only model the flow outside the "core" of the exhaust plume. The results of the continuum MRE15 analysis serve as the specified boundary for the GAPS code. Aerospace Corporation has performed DSMC studies (Ref. 2) using the basic GAPS code. Earlier studies (Ref. 3) identified some areas of improvement in the original Bird (Ref. 4) formulation which have been included in the version of the GAPS code which was used for this study. These differences are confined to inflow boundary conditions, spatial cell construction and the referencing of molecules to a particular cell.

Inflow boundaries must generally be located within a flow where continuum solutions are still valid. It is then possible to derive an explicit relation for the one-way flux of molecules

through an arbitrarily oriented plane element within this flow. The net inflow is the difference between the inward and outward one-way flows and can be expressed as

$$N_n = N^+ - N^-$$

Bird's approach is to calculate N^+ and to introduce an essentially fixed number of molecules per time step through the boundary element (fluctuations occur because only an integral number of molecules can be introduced in any one time increment). The outgoing flux at any element is then established by the collision processes within the cells adjacent to the boundary and this in turn also establishes the net flow. It was found that this approach did not reproduce the average net flow to the accuracy desired in the simulation of nozzle and plume flowfields. To overcome this a fixed net flow boundary condition is used and the number of inflow molecules is determined from

$$N^+ = N_n + N^-$$

This requires a small amount of additional storage because the value of N^- must be determined for every inflow element during a given time step. The procedure ensures that the various molecular fluxes at the boundary are matched to the continuum results.

The spatial structure of cells is based upon the construction of distinct regions each of which is further subdivided into computation cells. Each region allows independently selected time steps and molecular weighing factors. These features are crucial to simulations which involve as much as, or more than, ten order of magnitude variations in basic flow properties such as density or in controllable features such as cell dimensions.

The basic geometry of a region is a closed quadrilateral which

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can also take a triangular form if one side is collapsed to zero length. The geometric form refers to the region cross-section projected onto a plane passing through the axis of symmetry. Cells are constructed by dividing opposite pairs of region sides into integral numbers of segments. Endpoints of the segments are connected by straight lines and these form a network of quadrilateral cells within the region. The segment lengths can be made to vary in a power-law fashion, with stretching parameters which are independently adjustable for each side of the region. This allows an extremely flexible control of cell volumes, which is important to maintain an adequate sample of molecules within each cell. Solid bodies within or bounding the flow can be fitted by straight line segments, each of which is one side of a distinct region. Should this be inconvenient or undesirable, bodies which can be analytically described may be embedded in a rectangular cell network. Cells which are partially covered by the solid are then volume adjusted to exclude that occupied by the body. Some wasted storage is needed for those cells completely covered by the solid but this will generally be minor or can be made so by using many embedding regions rather than a single one.

To avoid all the inherent problems of a point reference system a special algorithm is used to rapidly determine cell number based upon a given region and molecular coordinates. Moreover indexing every time a molecule moves is avoided in favor of a procedure executed after all molecules move to new positions. This simplifies code structure and improves efficiency.

Figure 2 shows a typical flowfield geometry for the GAPS program. The lip region is broken into a separate region from the rest of the flowfield. Densities and gradients in the lip region are very high, so that more cells are necessary. The first step in the axisymmetric MRE15 DSMC calculation was to analyze the lip

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region. Then the results of the lip calculation were supplied to the complete axisymmetric DSMC model as input conditions much the same as the continuum plume source segments. By calculating the lip region alone, then patching it into the complete solution, considerable computer resources were saved.

The GAPS code has been used to model the Voyager spacecraft plumes. This model has been compared against flight calorimeter data with very good results.

Three DSMC cases were run for the single MRE15 axisymmetric plume. Case 1 was a free plume without an OMV base heat shield. Case 2 had a heat shield .375 inches ahead of the lip while case 3 had the heat shield 1 inch ahead of the heat shield. Cases 2 and 3 were calculated to provide a sensitivity of peak heat rate and distribution to the distance the engine projected out from the base.

Figure 3-6 present the DSMC results for the MRE15 case 1 that has no vehicle base. Figure 3 presents the velocity vectors, Figure 4 the density contours, Figure 5 rotational temperature contours and Figure 6 the translational temperatures. It is apparent that the plume goes out of continuum at relatively low angles off the starting surface by examining the rotational and translational temperatures.

Figures 7 and 8 present the results of case 2 where the base is .375 inches upstream of the nozzle exit. Figure 7 shows velocity vectors, and Figure 8 shows density contours. Figure 9 shows density contours for case 3 where the base is 1 inch upstream of the lip.

As was previously mentioned, the purpose of running cases 2

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and 3 was to get an estimate of the base heating environments for a single engine as a function of nozzle exit plane location with respect to the base. Figure 10 presents the heating rate distribution to the base for cases 2 and 3 as a function of distance from the nozzle centerline. By examining Figure 10, it is obvious that the closer the exit plane is to the base the higher the heating rate. The peak heating rate for the .375 inch spacing is .029 BTU/Ft^2/sec while the peak for the 1 inch separation plane is .01 BTU/Ft^2/sec. The location of the peak heating rates are at different positions on the base although in general fairly near the lip. These results are qualitatively the same as what would result from a continuum impingement analysis, although the continuum results would be two to three times higher.

A three dimensional analysis of the four engine thruster would produce higher peak heating rates than the single engine due to plume interaction and the reversal of more mass towards the base. An estimate of the peak heating on the order of .1 to .3 BTU/Ft^2/sec depending on the engine spacing and location of the exit plane.

The results of cases 1 - 3 and the program used to perform these calculations are resident on the MSFC EADS computer system. They can be obtained by contacting Y. C. Lee at ED33.

The three input files are contained on the first file of the magnetic tape that accompanies this final report (See Section 2.4). The files are: CASE1.INP, CASE2.INP and CASE3.INP. The magnetic tape was generated in a VAX/VMS Backup format at 6250 BPI.

2.3 Hydrazine and Cold Gas Thruster Plume and Plume Impingement Modeling for the OMV Vehicle.

This section describes the modeling of the MRE15 and cold gas nitrogen attitude control plume calculations. Additionally, the input data files that were generated for the plume impingement induced environments are described. Not all plume impingement input data were generated since the second contract increment was not funded. None of the plume impingement environments were generated. The plume impingement program (PLIMP-Ref. 5) which was to be used for performing this analysis is also described along with the modifications which were made to it to perform the OMV Plume Impingement Induced Environments.

2.3.1 MRE15 Hydrazine Plume

The MRE 15 is a 15 lbf hydrazine engine which was to be used as the primary engine for the Reaction Control System (RCS) as well as the thrusters for the Propulsion Module (PM) of the Orbital Maneuvering Vehicle (OMV). The MRE 15 plume characterization is required in order to predict the MRE 15 plume induced environments to the OMV itself, as well as to payloads it is retrieving or deploying.

The analysis of the MRE 15 nozzle and plume flowfields was performed using the Reacting and Multi-phase Computer Code RAMP2 (Ref. 9). RAMP2 is a method of characteristics based code used to solve inviscid supersonic flowfields.

The purpose of the RAMP2 code is to solve a rocket exhaust flowfield in sufficient detail so that the plume may be used to adequately specify design environments for systems which are influenced by the plume. For high altitude plumes, an adequate definition of the plume requires the inclusion of chemistry and nozzle boundary layer effects. The TRAN72 (Ref. 7) program and BLIMPJ (Ref. 8) codes are included in the RAMP2 code along with

the RAMP2F flowfield code to treat chemistry and boundary layer effects.

In order to use the original RAMP2 code (Ref. 9) to solve a high altitude plume, the following steps are required. First, the TRAN72 program input data is prepared and executed to generate a data tape describing the thermodynamic characteristics of the post-combustion gases. Next the RAMP2F flowfield data are prepared and the nozzle flowfield is solved using the TRAN72 program thermodynamic data tape as input. Then in order to adequately describe the nozzle boundary layer, the BLIMPJ code is executed using an input data file and flowfield tape generated by the RAMP2F nozzle solution. Finally, the exhaust plume is generated by using the nozzle solution and boundary layer solution to generate an exit plane start line that is used to initiate the plume solution. Thus, the generation of a high altitude plume could require up to four different executions of programs (TRAN72, RAMP2F, BLIMPJ, and RAMP2F) for the specification of the most detailed and accurate results. Physical input data are required only for the TRAN72 and first RAMP2F execution. All data required for the BLIMPJ code and second RAMP2F execution are generated internally to the program and/or communicated via temporary files.

Recently RAMP2 has been modified (Ref. 6) which will better handle nozzles which operate at a low chamber pressure and/or high area ratio. Motors of these types may have boundary layers which contain a significant percentage of the mass flow of the motor. Large boundary layers can interact with the inviscid portion of the flow and alter the flowfield from what would be calculated, assuming a pure inviscid calculation. The original version of RAMP2 which was mentioned above (Ref. 9) could not account for the interaction of the boundary layer and the

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inviscid flowfield. RAMP2 made a single pass through the nozzle and performed a single boundary layer solution using the BLIMPJ code. These solutions were then merged at the exit plane and plume solution was performed.

The latest version of RAMP2 (Ref. 6) was used to calculate the MRE 15 plume. This version allows a first order approximation of the interaction of the boundary layer and inviscid flowfield. The basic method involves making two passes through RAMP2 to calculate the nozzle flowfield and two passes through the BLIMPJ code to calculate the boundary layer. The first pass through the RAMP2 code calculates the nozzle flowfield using the original nozzle contour. After the first nozzle solution, the BLIMPJ code is executed using the conditions which exist at the nozzle wall (from the first nozzle solution) as the inviscid streamline boundary layer edge conditions. The results of this calculation including the boundary layer displacement thickness as a function of nozzle station are stored on FORTRAN Unit 2. RAMP2 is then executed again and the nozzle contour is modified using the displacement thickness information contained on Unit 2. After the modified contour flowfield solution is completed, BLIMPJ is again executed to calculate the nozzle boundary layer using edge conditions taken at the wall of the modified nozzle flowfield solution. While in the BLIMPJ solution, a check is made once the boundary layer calculations have been completed. If the pressure at the lip of the nozzle varies by more than 10% from the pressure at the inside edge of the boundary layer in the inviscid solution (modified contour) then another pass is made through BLIMPJ with the edge conditions interpolated from the nozzle solution based on the location of the boundary layer edge in the flowfield. These two passes are made within the last BLIMPJ execution and require no intervention by the user. This second pass is made to ensure that the

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boundary layer and inviscid flowfield properties match at the edge of the boundary layer. The RAMP2, TRAN72 and BLIMPJ versions which were used for this analysis are contained in File 2, 3 and 4 of the accompanying magnetic tape.

Recently, a model has been developed which fits the RAMP2 flowfield results using a source flow approximation. This model called SFPGEN (Ref. 10) was developed to support a Space Station Contamination Model developed by SEA, Inc. for NASA (Ref. 11).

The source flow plume model generator is a code which determines the flow properties from a RAMP2 flowfield and generates a formatted file that can be used by the PLIMP code to rapidly determine plume impingement pressures and heating rates out to large distances from the exit plane. This model was used to calculate the MRE15 source flow plume. A more detailed description of the source flow model can be found in Appendix A.

The source flow code and input files for the MRE15 source flow plume are on file 5 of the magnetic tape. The complete description of the MRE15 analysis and results can be found in Appendix A (Ref. 12). File 6 of the magnetic tape contains all MRE15 input/output files for the MRE15 RAMP2 analysis as well at the source flow plume file (MRE15UN16.DAT)

2.3.2 OMV GN2 Plume Analysis

The OMV GN2 RAMP2 flowfield analysis and source flow plume analysis were performed using the same tools that were described in Section 2.3.1. The only difference in the analysis was that only a single pass was made for the boundary layer analysis and ideal gas was assumed. The OMV GN2 nozzle has an area ratio of

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10 which does not require multiple passes through the RAMP nozzle and boundary layer calculations since boundary layer effects on the inviscid nozzle solution are minimal. Ideal gas was assumed since the specific heat ratio of nitrogen at low temperatures is constant at 1.4. The OMV GN2 RAMP2 input/output files and the source flow model (OMVGN2UN16.DAT) are contained on file 7 of the magnetic tape.

A detailed description of the OMVGN2 analysis and results can be found in Appendix B (Ref. 13).

2.3.3 OMV Plume Impingement Modeling

This section describes the plume impingement program which was modified for use in the OMV attitude control thruster plume impingement analysis. Also included in this section is a description of the OMV attitude control thruster layout and the input data generated for the PLIMP code for these thrusters.

2.3.3.1 Plume Impingement Modeling for the OMV

The Plume Impingement Program (PLIMP, Ref. 5) is utilized to calculate the majority of plume induced force, moment, heating rate and contamination environments for the OMV vehicle during this study. The development of this code has been supported by NASA beginning in the early 70's (Ref. 14) and more recently upgraded by SECA personnel to include the capability to predict contamination (Ref. 5). Under other programs SECA personnel have increased the capability of the code to handle flowfields from other flowfield computational models (source flow plume) as well as free molecular RAMP2 flowfields.

The PLIMP code utilizes the free body concept to calculate

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the resultant environments to an object immersed in the flowfield. The free body concept assumes that the flowfield can be precomputed and through the use of appropriate theory (based on local conditions at the impinged body) the resulting: forces, moments, heating rates and contamination fluxes are computed.

The body local impingement force and moment data are obtained by numerically integrating the local impact pressure distributions over the body surfaces. Plume flowfield data, to provide environmental data for the impact pressure and local heating calculations, are obtained from an output file generated by the Variable O/F Method-of-Characteristics Computer Program (MOC), (Ref. 15) or the RAMP2 code (Ref. 9).

The vehicle composite shape and the particular motor are located with respect to the reference coordinate system (Fig. 11). The composite shape is then represented by a series of geometrically simple subshapes (each in its own local coordinate system). These subshapes are further divided into smaller incremental areas as determined from the input information. Local flow conditions on a given body surface are obtained by locating the centroid of each elemental area in the free plume from a search of the plume flowfield data stored on a file. The flow properties thus obtained are assumed to act uniformly over each of the elemental area.

The body local flow regimes are determined by the value of the local Knudsen number (Kn). Continuum flow is assumed to exist for Kn <0.01, transitional flow exists for Kn between 0.01 and 10.0 and Kn> 10 defines the non-continuum (free molecule) flow regime. The characteristic lengths used in the Knudsen number calculations are a representative body dimension (i.e., plate dimensions, cylinder diameter and length, etc.) so that the

elemental area local flow regime is determined by comparing the mean free molecular path of the local plume to the projected body dimension. In the continuum flow regime, the local impact pressures are computed using modified Newtonian theory which includes a correction factor to account for the higher pressures noted experimentally for small incidence angles (Ref. 16). In the free molecular flow regime, the body local flow properties are assumed to depend only on collisions of the gas molecules with the body surface. Environmental equilibrium is assumed so that a Maxwellian-type flow exists and the body local flow properties are calculated from kinetic theory and Maxwell's law of distribution of molecular velocities. The local force is then computed from the sum of the forces produced by the incident and reflected molecules. In the transitional flow regime the local impact pressure is calculated empirically as a function of the local Mach number and Knudsen number to yield a smooth transition from the continuum to the free molecular flow regime.

This program contains several methods for calculating convective heat transfer rates to bodies immersed in rocket exhaust plumes. Each method is applicable to a particular situation, determined either by geometry or by the assumption made in obtaining the local flow properties. No single method currently will suffice for all shapes and flow conditions. In fact, a different method must be frequently used for the various subshapes of an impinged body. The method to be used on a given subshape must be specified in the input data.

Several options are also available to the user for obtaining the local flow properties for use in the heat transfer analysis. In all of the methods, the local pressure depends on the angle that the local surface makes with the free stream flow. Fortunately, this method is applicable to a majority of

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hypersonic flow problems. In the leading edge and corner regions, corrections have to be made to the pressure and heating values as calculated by the program. Free molecular heating rates are also calculated at each elemental area from an energy balance type equation and the decision of which flow regime to consider is simplified by a printout of the applicable flow regime based on the local Kn.

The program can currently analyze the impingement flow properties on six (6) basic subshapes. These are: 1) a surface described by a conical equation, i.e., cylinder, cone, etc.; 2) rectangular flat plate; 3) circular plate; 4) right triangle; 5) airfoil; and 6) a body of revolution in which the surface curvature as a function of the longitudinal axis is described by a polynomial equation. (A maximum of fourth-order curve can be used.)

The original version of the code will only handle up to 10 subshapes for a given engine impinging on a body. The OMV vehicle model requires using many more subshapes. While multiple computer runs could be made for each engine, to calculate the entire environment from a bookkeeping standpoint, it is much more convenient to perform the calculations in one computer run. The version of the PLIMP code which is being delivered with this report has been modified to treat 50 subshapes.

For free molecular impingement the subshape modeling as far as how to break it down into elemental areas is not important since only the location and impingement angle relative to the engine (along with plume mass flux, temperature and surface temperature) are important. The present version of the PLIMP code utilizes a model which treats the impingement of molecules in the free molecular regime utilizing a diffuse or cosine

scattering assumption. A very good description of the model can be found in Ref. 17. The following sketch depicts this type of scattering.

DIFFUSE OR COSINE SCATTERING
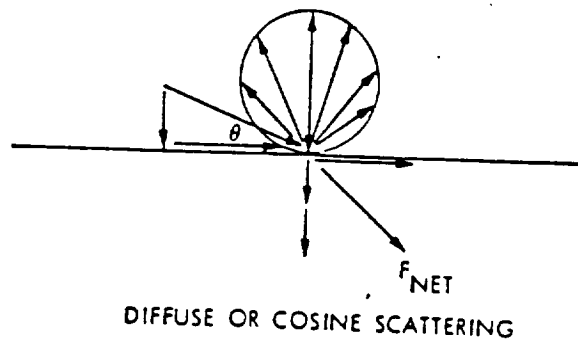
In the case of diffuse scattering, the incident gas molecules are absorbed by the surface and are subsequently reemitted at angles which are independent of the angle of incidence. This diffuse or cosine scattering is most typical of relatively low-energy gases incident upon amorphous surfaces. These surfaces may be clean in the spacecraft cleanliness sense, but have adsorbed gases or surface oxidation present. In this case, the normal and tangential components of the incident molecular momentum are transferred to the surface, and some additional amount, dependent upon the surface temperature, is imparted normal to the surface by the reemitted molecules.

Maxwell first proposed that some fraction f of the incident molecules is absorbed by the surface and is subsequently reemitted diffusely, with a distribution of velocities corresponding to that in a still gas at the temperature of the surface. The remaining fraction, 1 - f, is perfectly reflected. All of the incident normal momentum and a fraction f of the incident tangential momentum are assumed to be transferred to the surface. Additional momentum is imparted normal to the surface by the diffuse reemission of the f fraction and the specular

reflection of the 1 - f molecules. Knudsen, in an attempt to characterize the energy exchange between gas and surface, introduced a coefficient of accommodation to describe the degree to which the incident molecules were "accommodated" to the temperature of the surface. Expressed in terms of energy flux per unit of surface area, this energy accommodation coefficient α_e may be defined as

$$\alpha_e = \frac{E_i - E_r}{E_i - E_s}$$

where the subscript i refers to the incident energy flux, r denotes the energy flux carried away from the surface by the reflected molecules, and s refers to that flux which would be carried away from the surface if the reemitted gas molecules were in Maxwellian equilibrium at the temperature of the surface.

Expressing Maxwell's scattering characterization in similar fashion leads to an expression for what has commonly become known as the tangential momentum accommodation coefficient α_t (corresponding to f)

$$\alpha_t = \frac{\tau_i - \tau_r}{\tau_i - \tau_s}$$

where τ_i denotes that component of the incident momentum which is tangent to the surface, and τ_r is the tangential component of momentum imparted to the surface by the reemitted molecules; τ_s denotes the tangential momentum which is imparted to the surface by the reemission of molecules in Maxwellian equilibrium at the temperature of the surface, and is zero by symmetry.

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Believing that the momentum exchange process is yet more complex, Bell and Schaaf (Ref. 18) introduced what may be termed a normal momentum accommodation coefficient, α_n, defined by analogy to the first equation above as

$$\alpha_n = \frac{P_i - P_r}{P_i - P_s}$$

where P refers to the component of momentum imparted normal to the surface, and the subscripts are as defined above.

At the present time the PLIMP code assumes all accommodation coefficients are unity. The models for force and heating rate presently in the PLIMP code are identical to those presented in Ref. 17, however there presently is no tangential force calculation in PLIMP. Depending on orientation and size of a surface, the tangential component can significantly effect the forces and torques that the OMV could experience due to free molecular impingement. The PLIMP code was modified to include the tangential component of force. Making the same assumption that the incoming particles have a Maxwellian distribution of molecular velocities about the macroscopic gas velocity, the incident tangential momentum component may be written:

$$\tau_i = \gamma \rho U^2 \ X \ \cos\{\theta\}/(S\pi^{.5})$$

Here ρ and U are the incident gas density and velocity, θ is the impingement angle.

γ is the ratio of specific heats, and S is the molecular speed ratio, defined as the ratio of the macroscopic gas velocity

to the most probable molecular velocity:

$$S = U/(2RT)^{0.5}$$

Other quantities are defined as:

$$\eta = S \sin(\theta)$$
$$X = \exp(-\eta^2) + \pi^{0.5}\eta [1 + erf (\eta)]$$

Since all of the incident molecules are reemitted diffusely from the surface with a Maxwellian distribution of velocities corresponding to the temperature of the surface, the outgoing tangential component of momentum removed from the surface is zero. Thus only the incident tangential component was incorporated into PLIMP. This modification is included in the version of PLIMP which is contained on file 8 of the accompanying magnetic tape.

2.3.3.2   OMV Hydrazine/GN2 Thruster Location and PLIMP Input
           Files

This section describes the OMV attitude control thruster geometry and inputs to the PLIMP code. The plume impingement calculations were not performed since the second contract increment was not funded.

Figure 12 shows the OMV body fixed frame coordinate system which was used as the reference coordinate system for setting up the PLIMP code. Figure 13 shows a schematic of where the hydrazine thrusters are located on the OMV. The GN2 thrusters are not shown but are located adjacent to each hydrazine thruster except for hydrazine thruster A7, B7, C7, D7 for which there is no corresponding GN2 thruster. Figure 14 shows a typical layout

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of the OMV Orbital Replacement Unit (ORU) and the location of the thrusters. Table 1 shows the location and direction cosines of the hydrazine thrusters in the PLIMP coordinate system while Table 2 shows the same information for the GN2 thrusters.

The input files for all 28 hydrazine thrusters were generated for the PLIMP code. These data files are on file 9 of the accompanying magnetic tape. None of the GN2 input files were generated due to the previously mentioned funding limitations.

2.4 Summary of Data Contained on Magnetic Tape for OMV Plume and Plume Impingement Analyses

The programs used to perform this study as well as the input and output files for generating the results discussed in this report are contained on the accompanying magnetic tape. The tape was generated at 6250 BPI using a VAX/VMS format. Table 3 summarizes the contents of the magnetic tape.

3.0 Summary and Conclusions

This report presents the results of a study to characterize the OMV engine exhaust plume flowfields and predict the resultant plume induced pressure and heat loads to the vehicle structure. Continuum methodology was used to calculate the MRE15 and GN2 thruster plumes. Additionally DSMC axisymmetric calculations of the MRE15 exhaust plume were performed and resultant estimates of the expected base heating to the Propulsion Model from a single engine were presented. Modifications to the Plume Impingement Program were described as well as the input data to PLIMP for the OMV attitude control thrusters. A tape accompanies this report which contains the computer codes and input/output files which were used and generated during this study. All subtasks were not

completed due to program termination and the lack of the second funding increment.

The codes and methodology delivered and described in this report are directly applicable to calculating plume induced environments for the National Launch System Cargo Transfer Vehicle.

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Table 1. OMV Hydrazine Thruster Locations and Directions in Body Fixed Frame

Thruster	Location (in)			Direction Cosines (Thrust Vectors)		
	X	Y	Z	X	Y	Z
A1	-60.50	59.20	-63.44	1.000	0.000	0.000
A2	-1.74	54.16	-68.39	0.000	-0.985	0.174
A3	-1.74	68.39	-54.16	0.000	-0.174	0.985
A4	-36.74	61.69	-61.69	-0.707	-0.500	0.500
A5	-49.35	68.39	-54.16	0.000	-0.174	0.985
A6	-49.35	54.16	-68.39	0.000	-0.985	0.174
B1	-60.50	63.44	59.20	1.000	0.000	0.000
B2	-1.74	68.39	54.16	0.000	-0.174	-0.985
B3	-1.74	54.16	68.39	0.000	-0.985	-0.174
B4	-36.74	61.69	61.69	-0.707	-0.500	-0.500
B5	-49.35	54.16	68.39	0.000	-0.985	-0.174
B6	-49.35	68.39	54.16	0.000	-0.174	-0.985
C1	-60.50	-59.20	63.44	1.000	0.000	0.000
C2	-1.74	-54.16	68.39	0.000	0.985	-0.174
C3	-1.74	-68.39	54.16	0.000	0.174	-0.985
C4	-36.74	-61.69	61.69	-0.707	0.500	-0.500
C5	-49.35	-68.39	54.16	0.000	0.174	-0.985
C6	-49.35	-54.16	68.39	0.000	0.985	-0.174
D1	-60.50	-63.44	-59.20	1.000	0.000	0.000
D2	-1.74	-68.39	-54.16	0.000	0.174	0.985
D3	-1.74	-54.16	-68.39	0.000	0.985	0.174
D4	-36.74	-61.69	-61.69	-0.707	0.500	0.500
D5	-49.35	-54.16	-68.39	0.000	0.985	0.174
D6	-49.35	-68.39	-54.16	0.000	0.174	0.985
A7	-60.50	63.44	-59.20	1.000	0.000	0.000
B7	-60.50	59.20	63.44	1.000	0.000	0.000
C7	-60.50	-63.44	59.20	1.000	0.000	0.000
D7	-60.50	-59.20	-63.44	1.000	0.000	0.000

Table 2. OMV Cold Gas Thruster Locations and Directions in Body Fixed Frame

Thruster	Location (in)			Direction Cosines		
	X	Y	Z	X	Y	Z
A1	-60.50	61.45	-61.45	1.000	0.000	0.000
A2	-1.74	54.66	-65.83	0.000	-0.985	0.174
A3	-1.74	65.83	-54.66	0.000	-0.174	0.985
A4	-34.08	58.78	-63.02	-0.707	-0.482	0.517
A5	-49.35	65.83	-54.66	0.000	-0.174	0.985
A6	-49.35	54.66	-65.83	0.000	-0.985	0.174
B1	-60.50	61.45	61.45	1.000	0.000	0.000
B2	-1.74	65.83	54.66	0.000	-0.174	-0.985
B3	-1.74	54.66	65.83	0.000	-0.985	-0.174
B4	-34.08	63.02	58.78	-0.707	-0.517	-0.482
B5	-49.35	54.66	65.83	0.000	-0.985	-0.174
B6	-49.35	65.83	54.66	0.000	-0.174	-0.985
C1	-60.50	-61.45	61.45	1.000	0.000	0.000
C2	-1.74	-54.66	65.83	0.000	0.985	-0.174
C3	-1.74	-65.83	54.66	0.000	0.174	-0.985
C4	-34.08	-58.78	63.02	-0.707	0.482	-0.517
C5	-49.35	-65.83	54.66	0.000	0.174	-0.985
C6	-49.35	-54.66	65.83	0.000	0.985	-0.174
D1	-60.50	-61.45	-61.45	1.000	0.000	0.000
D2	-1.74	-65.83	-54.66	0.000	0.174	0.985
D3	-1.74	-54.66	-65.83	0.000	0.985	0.174
D4	-34.08	-63.02	-58.78	-0.707	0.517	0.482
D5	-49.35	-54.66	-65.83	0.000	0.985	0.174
D6	-49.35	-65.83	-54.66	0.000	0.174	0.985

Table 3. OMV Magnetic Tape Contents

DESCRIPTION OF FILE CONTENTS

FILE	SAVESET NAME	
1	FILE1	THREE MONTE CARLO INPUT FILES FOR THE MRE15 AXIYMMETRIC PLUME
2	FILE2	RAMP2 CODE
3	FILE3	TRAN72 CODE AND DATA FILE
4	FILE4	BLIMPJ CODE
5	FILE5	SFPGEN RAMP2 SOURCE FLOW PROGRAM, MRE15 AND OMVGN2 INPUT/COM FILES
6	FILE6	MRE15 RAMP INPUT/OUTPUT/COM FILES AND SOURCE FLOW PLUME (MRE15UN16.DAT)
7	FILE7	OMVGN2 RAMP INPUT/OUTPUT/COM FILES AND SOURCE FLOW PLUME (OMVGN2UN16.DAT)
8	FILE8	PLUME IMPINGEMENT PROGRAM
9	FILE9	OMV GN2 AND MRE15 ENGINE PLIMP INOUT FILES

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RCS THRUSTER
-ROTATED 90 DEG
-CANTED 10 DEG

Propulsion Module (PM)

Short Range Vehicle (SRV)

MOVED 3.5 INCH
IN +x
DIRECTION
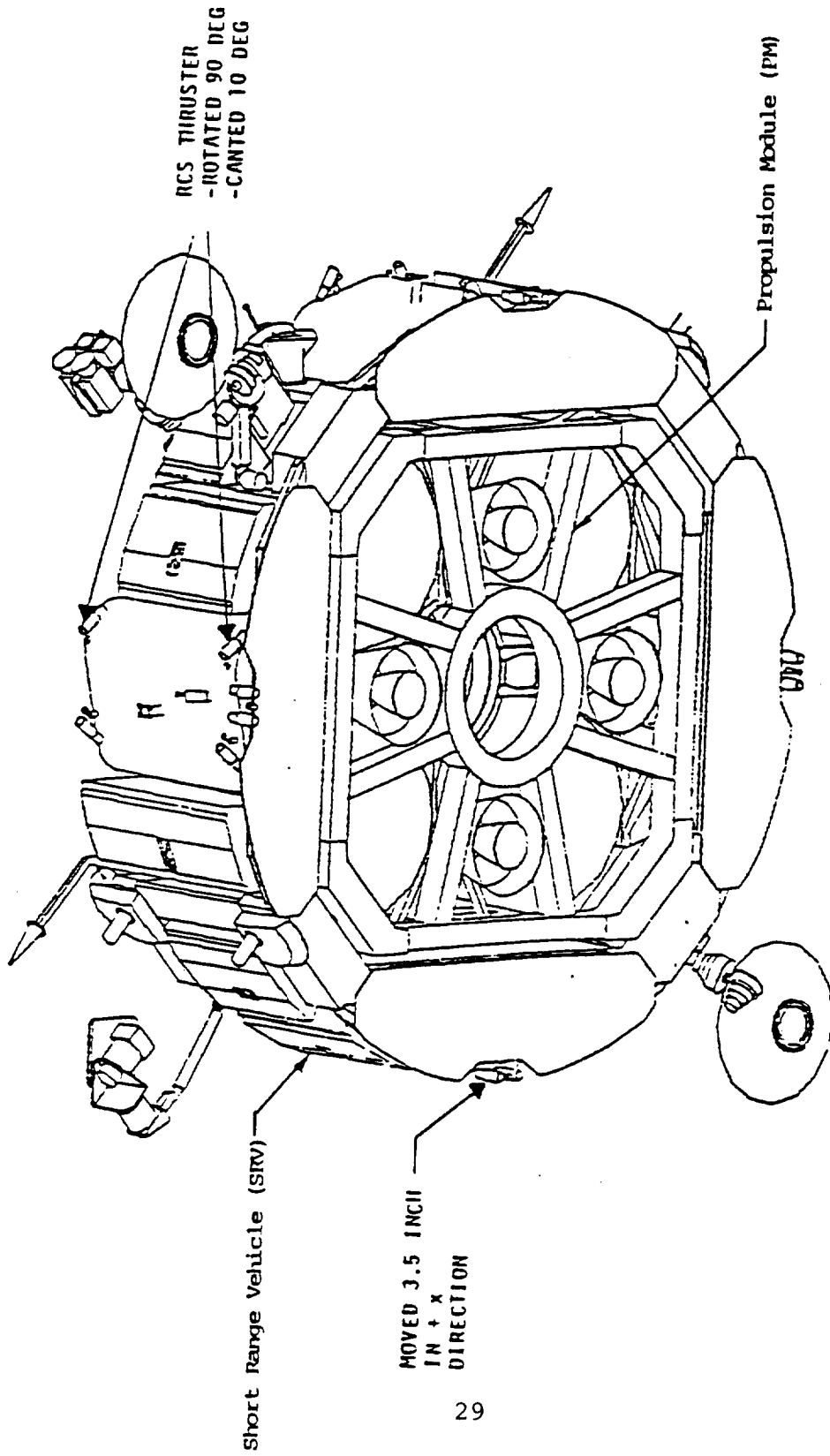
Fig. 1 OMV Configuration
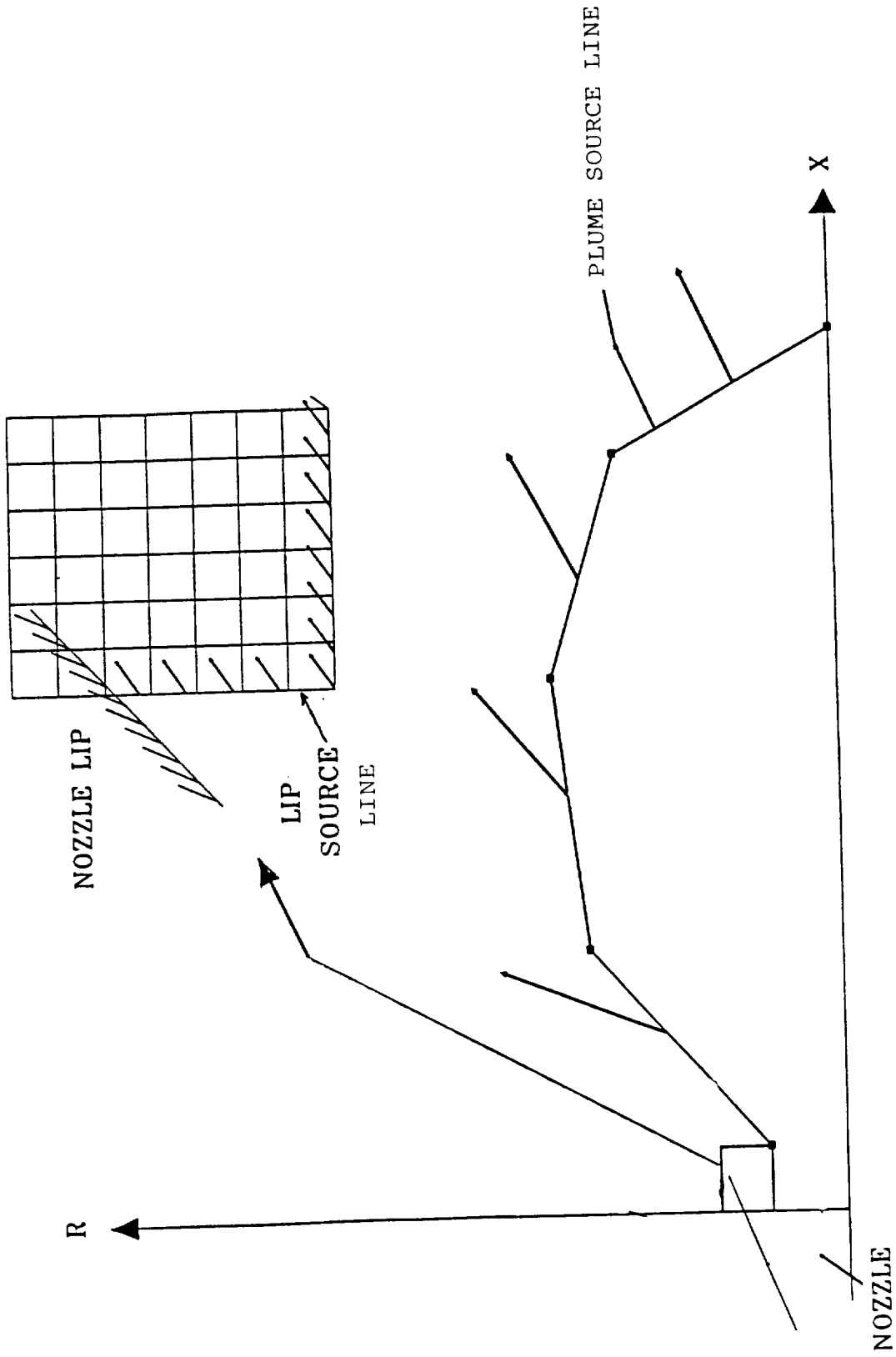
Fig. 2 Plume Domains and Source Lines for DSMC Analysis
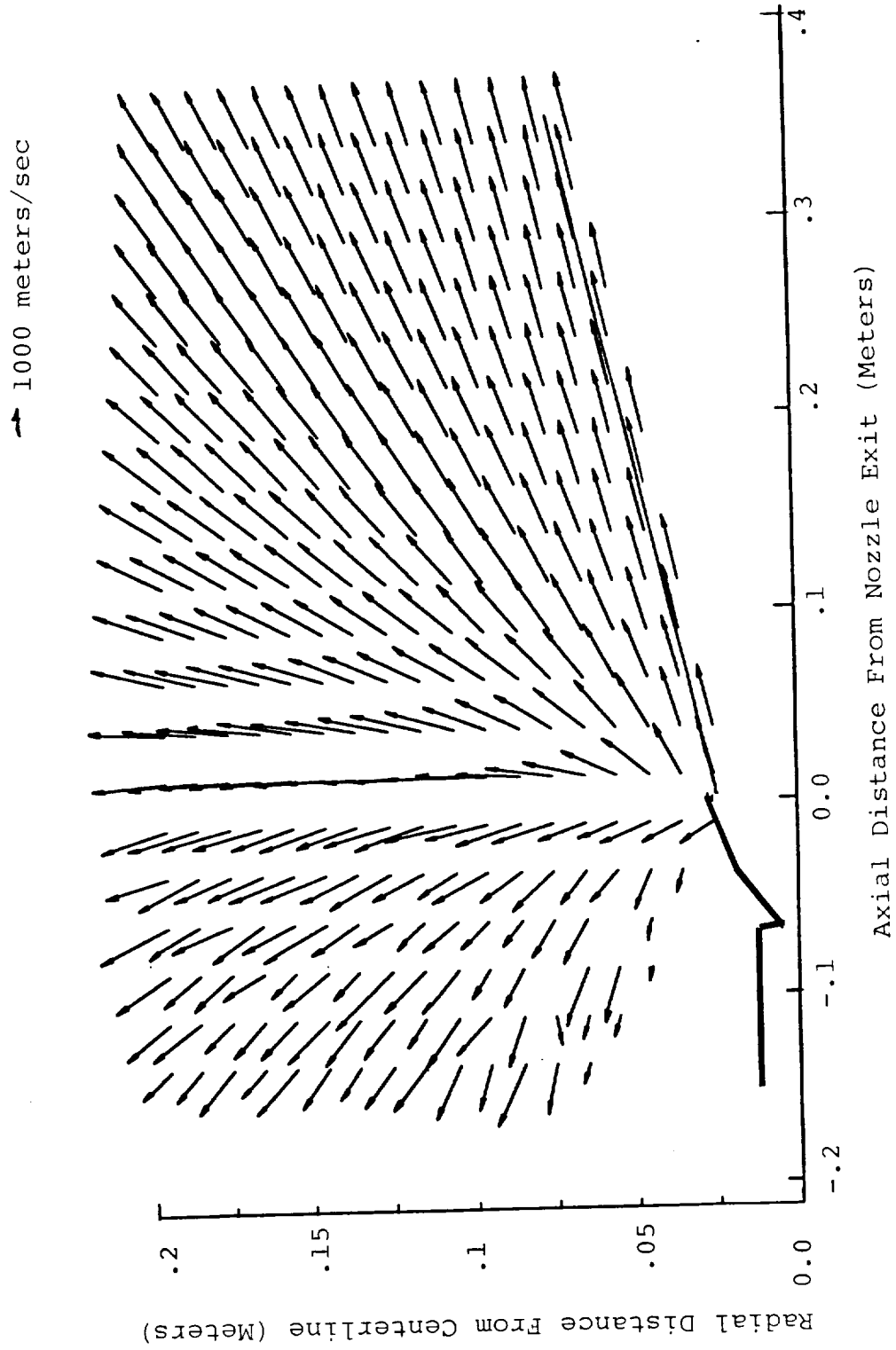
Fig. 3 Velocity Vector Distribution of MRE15 Flowfield Without a Base, Calculated Using DSMC Model
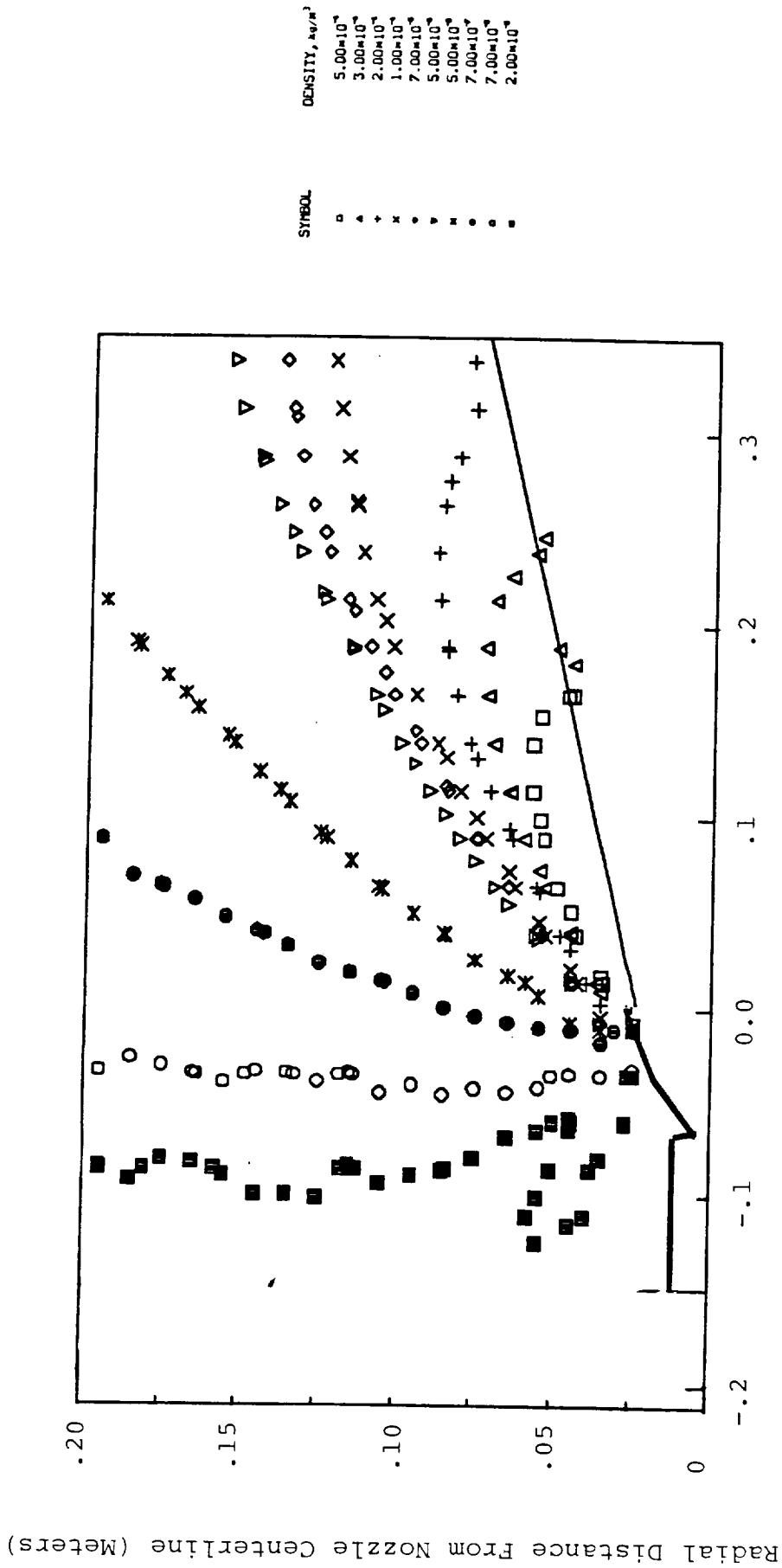
Fig. 4 Density Contours For MRE15 Flowfield Without a Base,
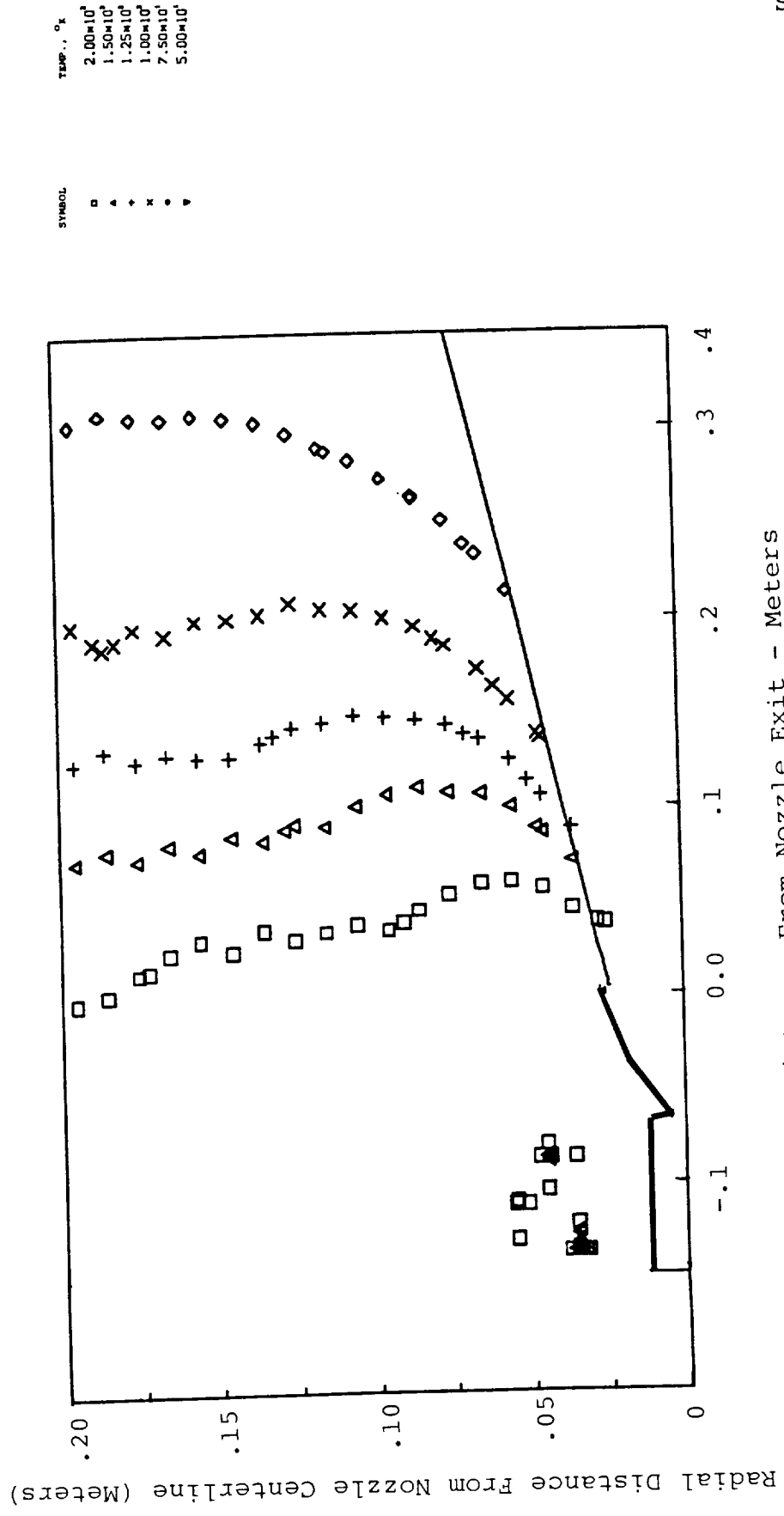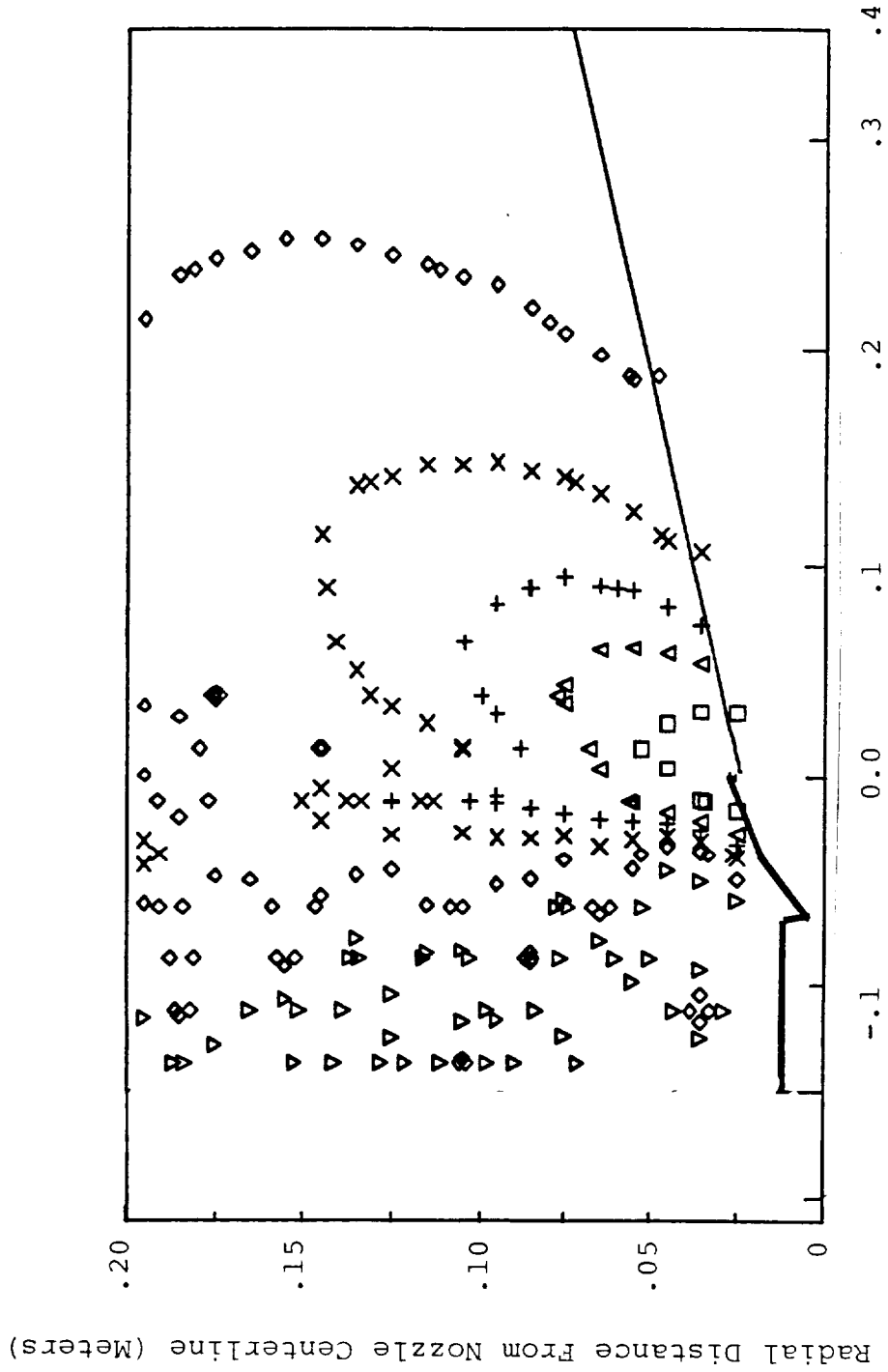Calculated Using DSMC Model

Fig. 5 Rotational Temperature Contours For MRE15 Engine,
Calculated Using DSMC Model

Fig. 6 Translational Temperature Contours For MRE15 Engine,
Calculated Using DSMC Model

Fig. 7 Velocity Vectors in DSMC MRE15 Plume with the OMV Base
.375 Inches Ahead of Lip

Axial Distance From Nozzle Exit Plane (Meters)

Radial Distance From Nozzle Centerline (Meters)
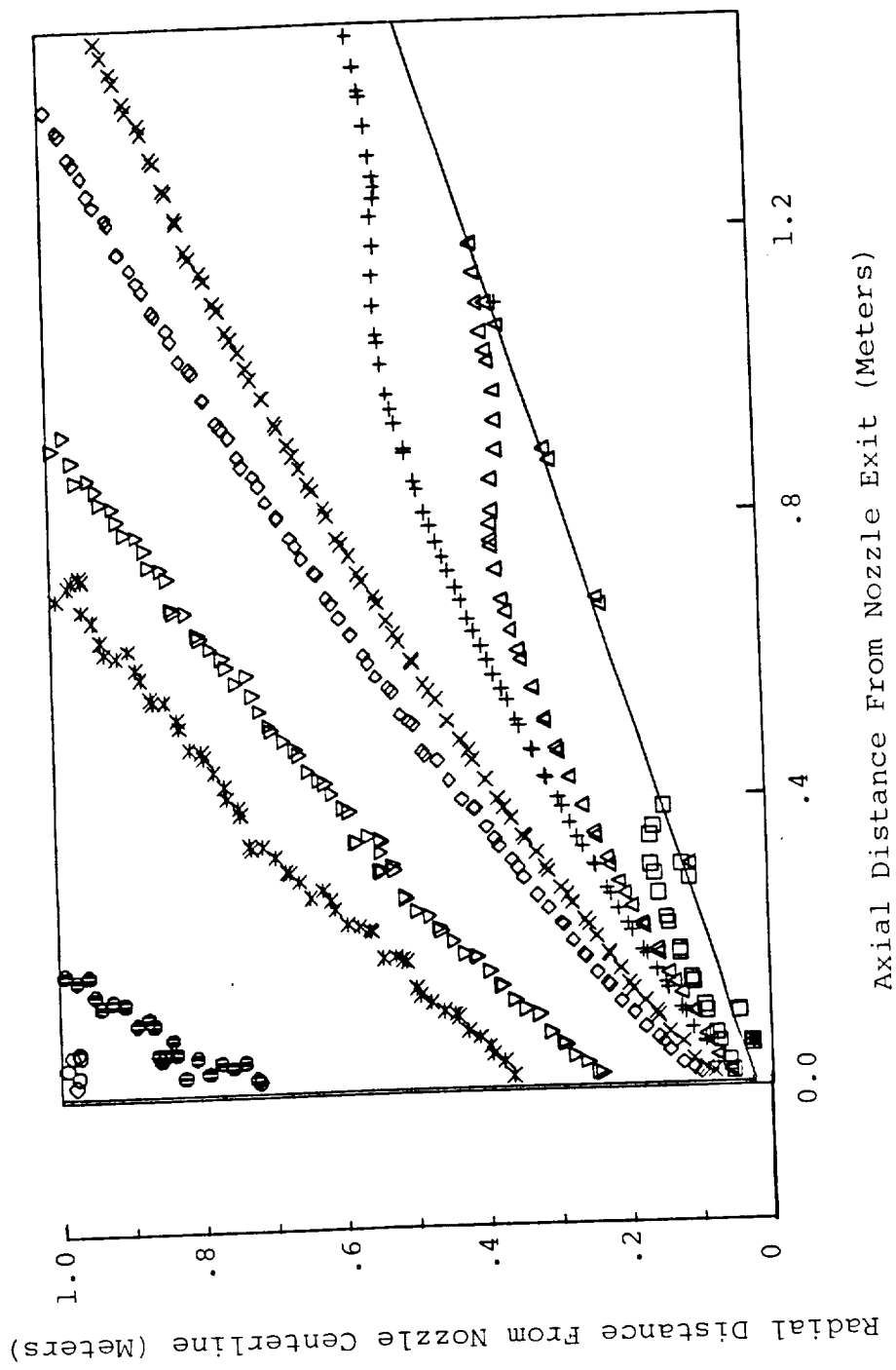
→ 1000 Meters

Fig. 8 Density Contours For DSMC MRE15 Plume With the OMV Base,
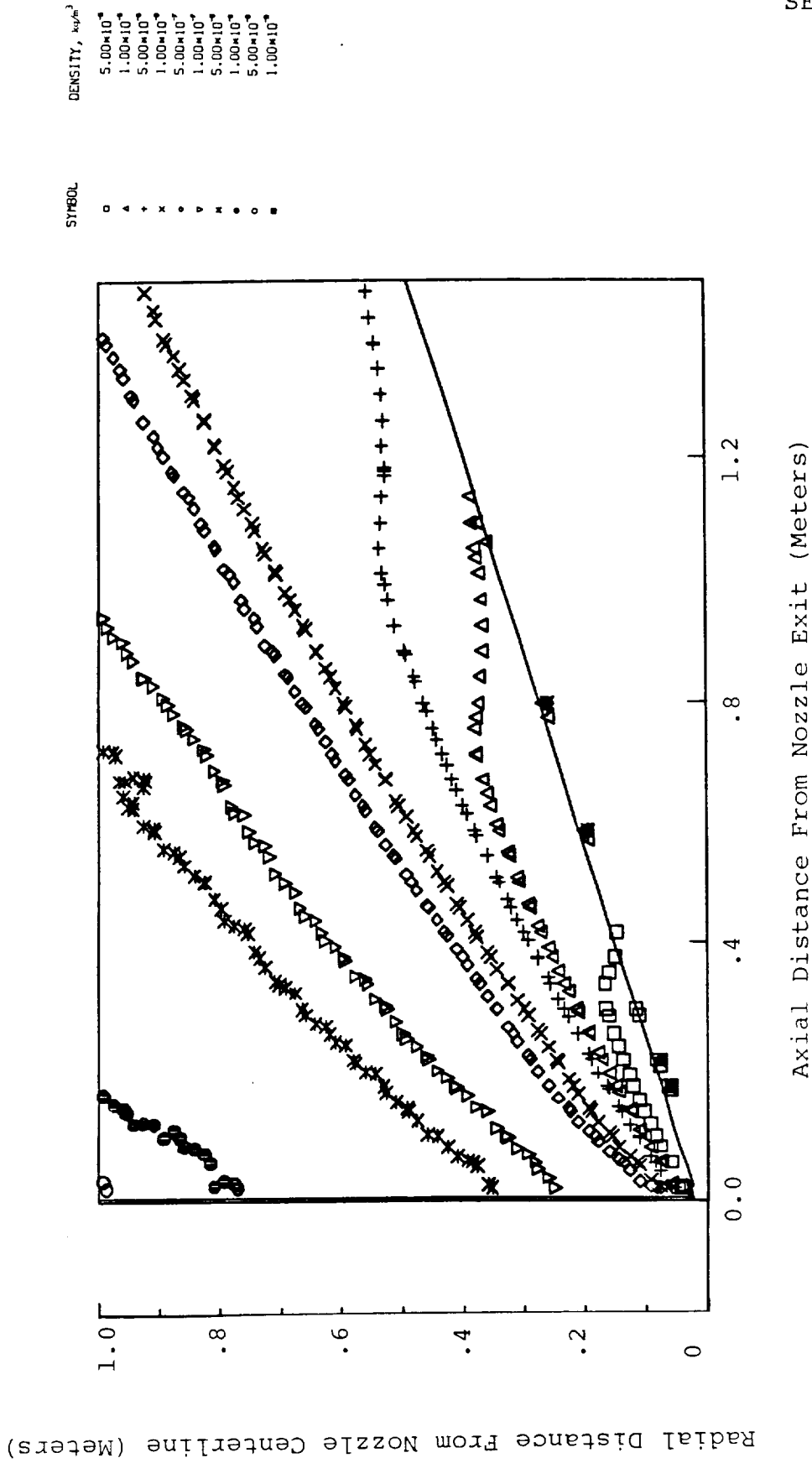.375 Inches Ahead of Lip

Fig. 9 Density Contours For DSMC MRE15 Plume With the OMV Base,
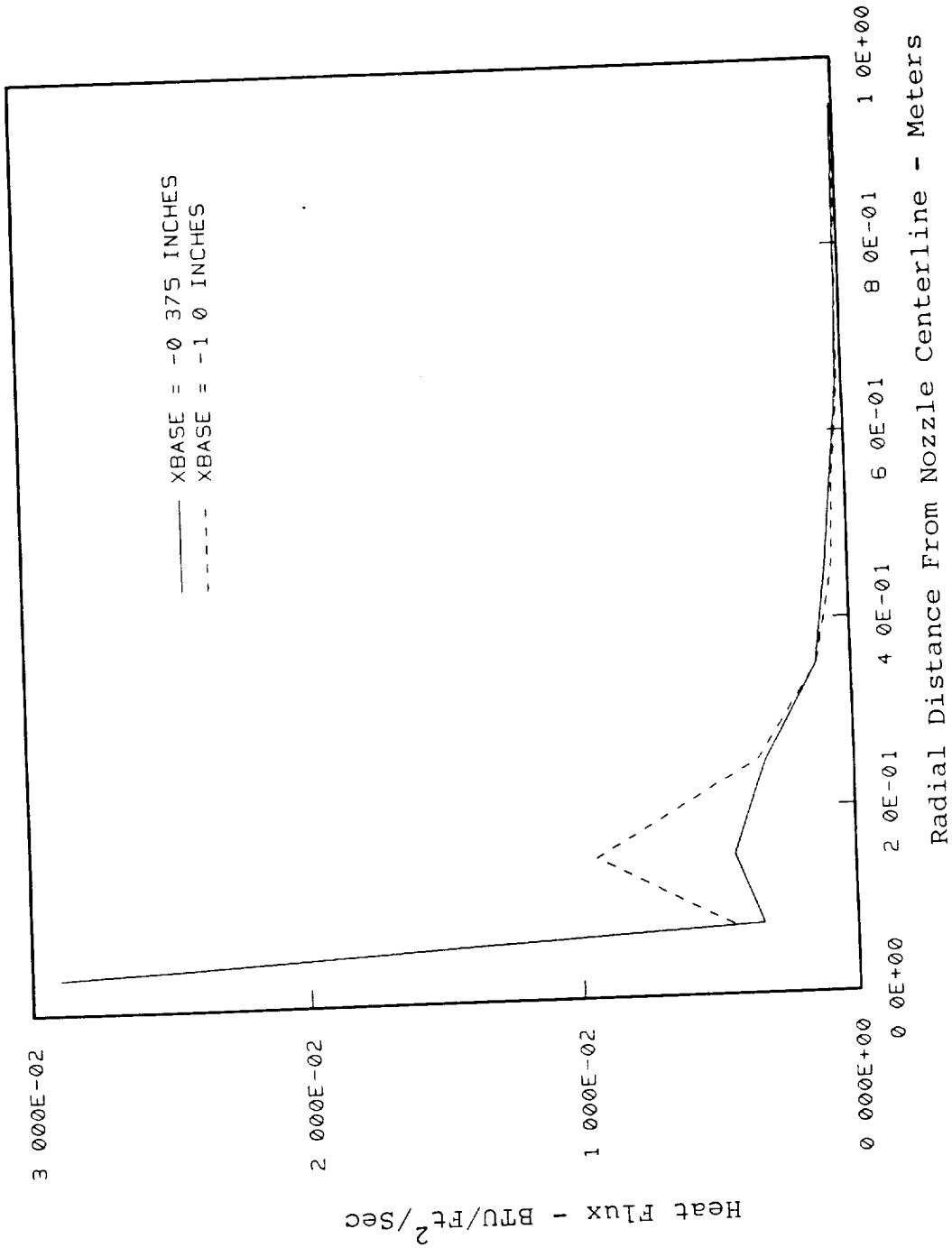1.0 Inches Ahead of Lip

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Fig. 10 OMV Base Heating Rate Distribution For Two Different Nozzle
Heights, Calculated For With A Single Axisymmetric MRE15
Nozzle Using a DSMC Model

NOTES: 1. Shuttle configuration used as example since representation of it requires use of many subshapes.

2. Wing subshapes are NACA airfoil 0012-64. This can easily be changed to another airfoil geometry.

3. Impingement data and heating rates obtained at centroid of each grid element.
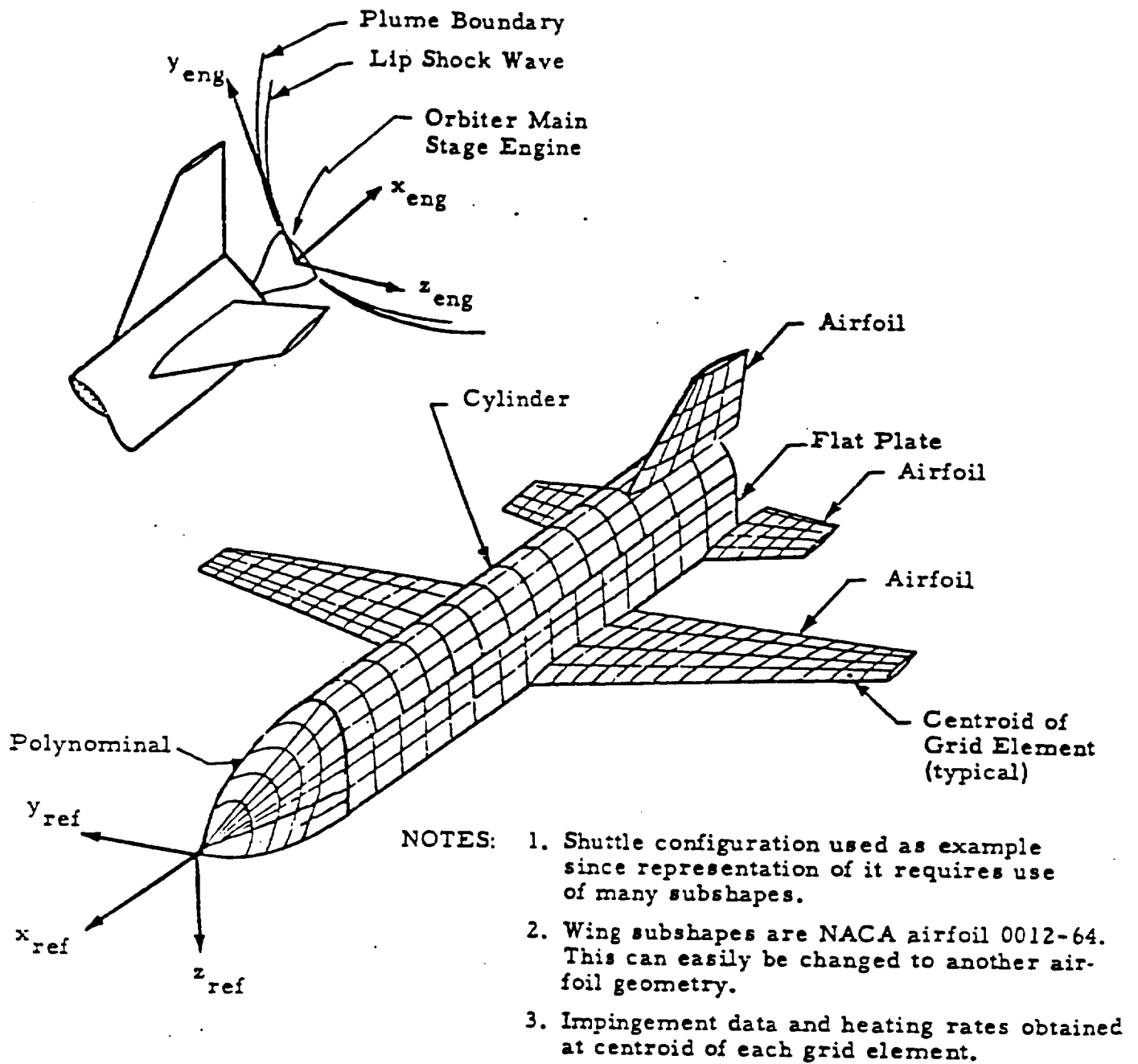
Fig. 11 - Sketch of Subshape System and Grid Scheme Used in Force, Moment, Contamination and Heating Analysis

Fig. 12   OMV Body Fixed Frame Reference System
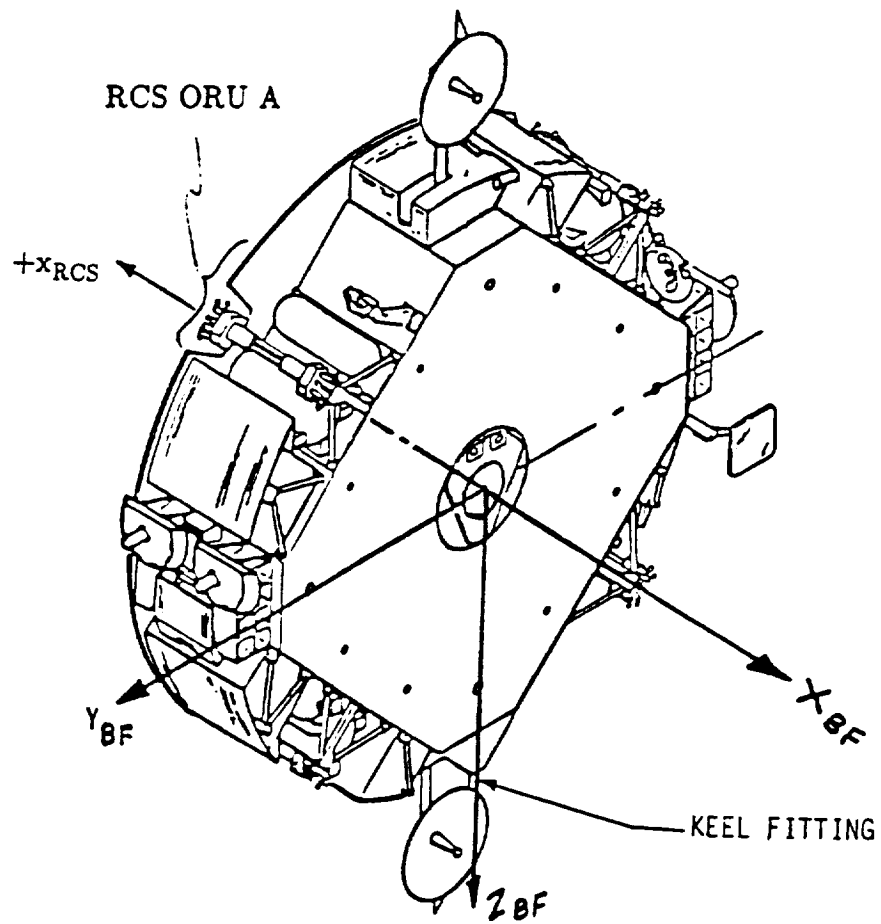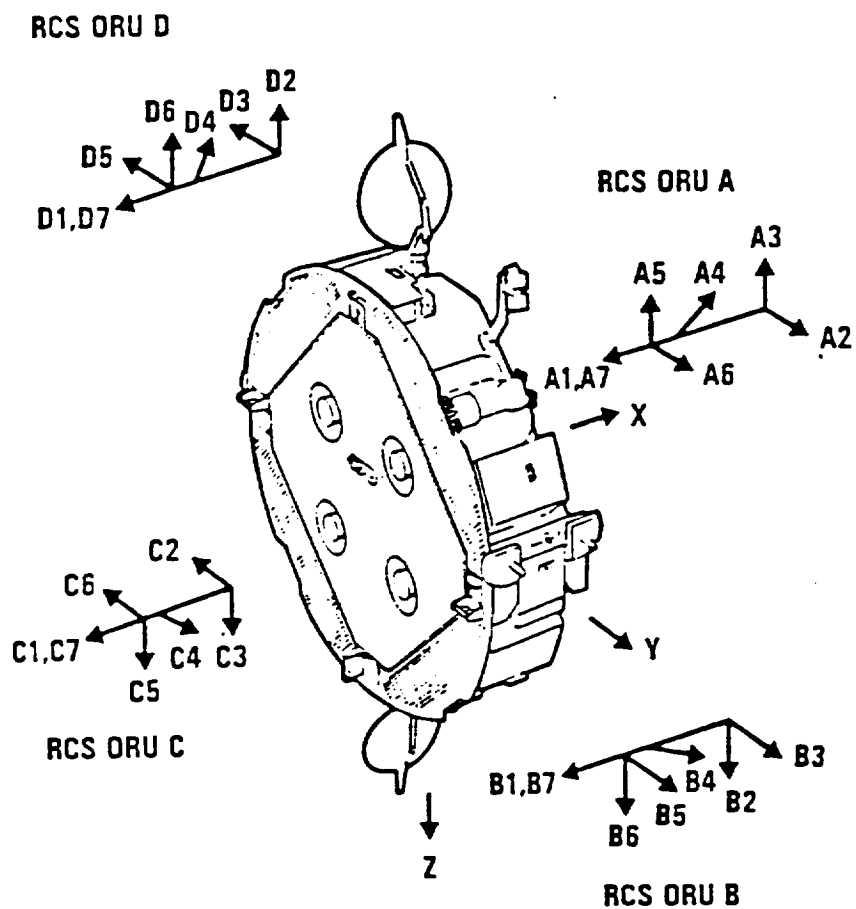(PLIMP Reference System)

RCS ORU D

RCS ORU A

RCS ORU C

RCS ORU B

Fig. 13 ORU Orientations and Thruster Locations

VIEW A-A

NEW THRUSTER LOCATIONS

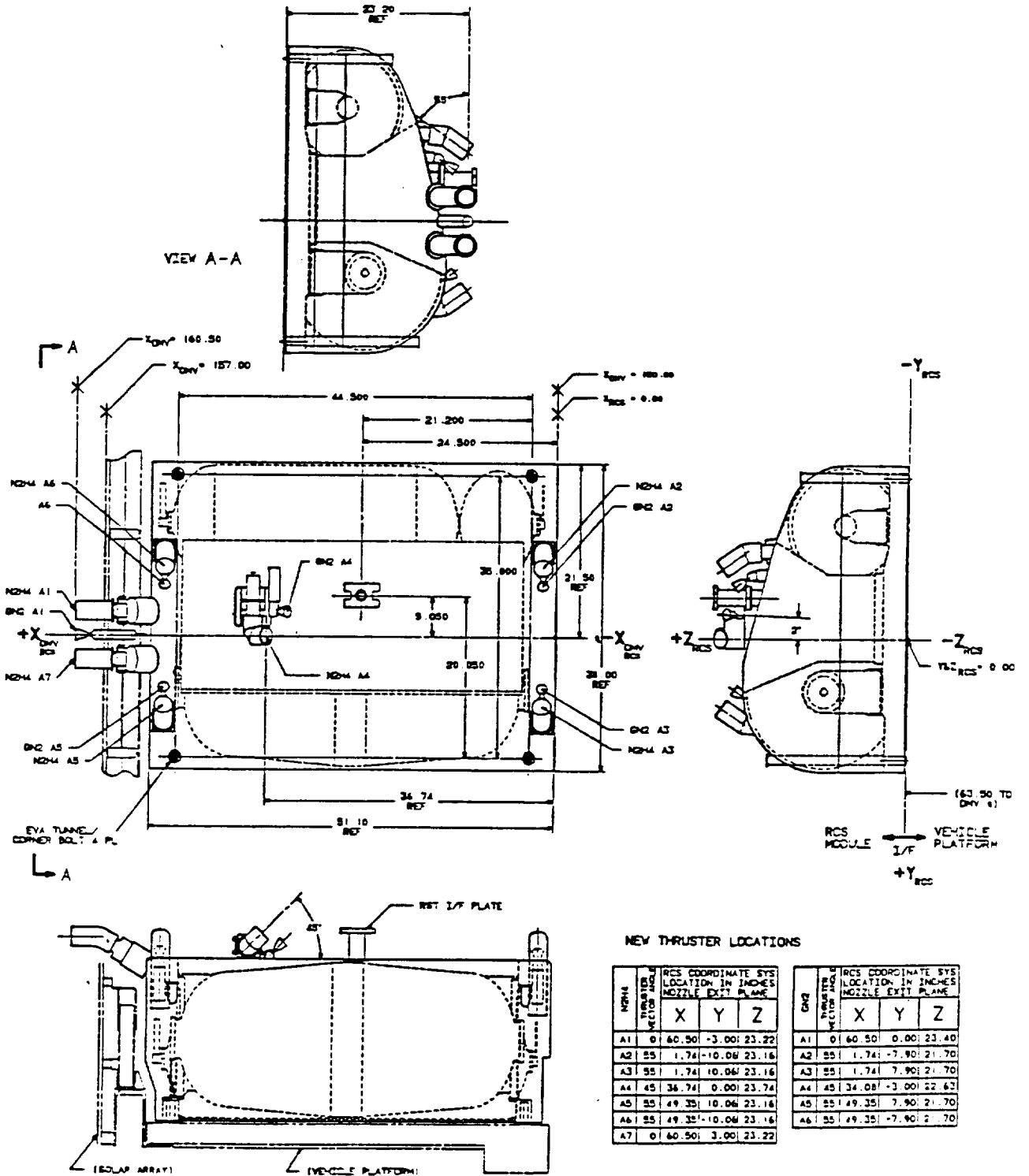| N2H4	THRUSTER VECTOR ANGLE	RCS COORDINATE SYS LOCATION IN INCHES NOZZLE EXIT PLANE			GN2	THRUSTER VECTOR ANGLE	RCS COORDINATE SYS LOCATION IN INCHES NOZZLE EXIT PLANE		
		X	Y	Z			X	Y	Z
A1	0	60.50	-3.00	23.22	A1	0	60.50	0.00	23.40
A2	55	1.74	-10.06	23.16	A2	55	1.74	-7.90	21.70
A3	55	1.74	10.06	23.16	A3	55	1.74	7.90	21.70
A4	45	36.74	0.00	23.74	A4	45	34.08	-3.00	22.63
A5	55	49.35	10.06	23.16	A5	55	49.35	7.90	21.70
A6	55	49.35	-10.06	23.16	A6	55	49.35	-7.90	21.70
A7	0	60.50	3.00	23.22					

Fig. 14 Typical OMV ORU Configuration Including Attitude Control Jet Locations

APPENDIX A

Definition of the MRE15 Engine Exhaust Plume Flowfield

DEFINITION OF THE MRE15 ENGINE EXHAUST
PLUME FLOWFIELD

30 March 1990

Contract NAS8-38243

Prepared For:

National Aeronautics and Space Administration
Marshall Space Flight Center, Alabama 35812

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1.0 Forward

This document presents the results of work performed by SECA, Inc. for NASA, Marshall Space Flight Center under Contract NAS8-38243. The NASA contracting officer representative for this study is Mr. P. R. Sulyma, ED33.

2.0 Introduction

This report presents the flowfield characteristics of the MRE 15 engine exhaust plume. The MRE 15 is a 15 lbf hydrazine engine which will be used as the primary engine for the Reaction Control System (RCS) as well as the thrusters for the Propulsion Module (PM) of the Orbital Maneuvering Vehicle (OMV). The MRE 15 plume characterization is required in order to predict the MRE 15 plume induced environments to the OMV itself, as well as to payloads it is retrieving or deploying. This report presents the MRE 15 flowfield characteristics and describes the methodology which was used to characterize the plume.

3.0 Discussion

This section describes the MRE 15 exhaust plume flowfield which was generated using the RAMP2 (Ref. 1) code and a new source flow model (Ref. 2).

3.1 RAMP2 MRE 15 Flowfield

The analysis of the MRE 15 nozzle and plume flowfields was performed using the Reacting and Multi-phase Computer Code (RAMP2 Ref. 1). RAMP2 is a method of characteristics based code used to solve inviscid supersonic flowfields.

The purpose of the RAMP2 code is to solve a rocket exhaust flowfield in sufficient detail so that the plume may be used to adequately specify some design environment for systems which are influenced by the plume. For high altitude plumes, an adequate definition of the plume requires the inclusion of chemistry and nozzle boundary layer effects. The TRAN72 (Ref. 3) program and BLIMPJ (Ref. 4) codes are included in the RAMP2 code along with the RAMP2F flowfield code to treat chemistry and boundary layer effects.

In order to use the original RAMP2 code (Ref. 5) to solve a high altitude plume, the following steps are required. First, the TRAN72 program input data is prepared and executed to generate a data tape describing the thermodynamic characteristics of the post-combustion gases. Next the RAMP2F flowfield data are prepared and the nozzle flowfield is solved using the TRAN72 program data tape as input. Then in order to adequately describe the nozzle boundary layer, the BLIMPJ code is executed using an

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input data file and flowfield tape generated by the RAMP2F nozzle solution. Finally, the exhaust plume is generated by using the nozzle solution and boundary layer solution to generate an exit plane start line that is used to initiate the plume solution. Thus, the generation of a high altitude plume could require up to four different executions of programs (TRAN72, RAMP2F, BLIMPJ, and RAMP2F) for the specification of the most detailed and accurate results. Physical input data are required only for the TRAN72 and first RAMP2F execution. All data required for the BLIMPJ code and second RAMP2F execution are generated internally to the program and/or communicated via temporary files.

Recently RAMP2 has been modified (Ref. 1) which will better handle nozzles which operate at a low chamber pressure and/or have high area ratio nozzles. Motors of these types may have boundary layers which contain a significant percentage of the mass flow of the motor. Large boundary layers can interact with the inviscid portion of the flow and alter the flowfield from what would be calculated, assuming a pure inviscid calculation. The original version of RAMP2 which was mentioned above (Ref. 5) could not account for the interaction of the boundary layer and the inviscid flowfield. RAMP2 made a single pass through the nozzle and performed a single boundary layer solution using the BLIMPJ code. These solutions were then merged at the exit plane and plume solution was performed.

The latest version of RAMP2 (Ref. 1) was used to calculate the MRE 15 plume. This version allows a first order approximation of the interaction of the boundary layer and inviscid flowfield. The basic method involves making two passes through RAMP2 to calculate the nozzle flowfield and two passes through the BLIMPJ code to calculate the boundary layer. The first pass through the RAMP2 code calculates the nozzle flowfield using the original nozzle contour. After the first nozzle solution, the BLIMPJ code is executed using the conditions which exist at the nozzle wall (from the first nozzle solution) as the inviscid streamline boundary layer edge conditions. The results of this calculation including the boundary layer displacement thickness as a function of nozzle station are stored on FORTRAN Unit 2. RAMP2 is then reexecuted and the nozzle contour is modified using the displacement thickness information contained on Unit 2. After the modified contour flowfield solution is completed, BLIMPJ is again executed to calculate the nozzle boundary layer using edge conditions taken at the wall of the modified nozzle flowfield solution. While in the BLIMPJ solution, a check is made once the boundary layer calculations have been completed. If the pressure at the lip of the nozzle varies by more than 10% from the pressure at the inside edge of the boundary layer in the inviscid solution (modified contour) then another pass is made through BLIMPJ with the edge conditions interpolated from the nozzle solution based on the location of

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the boundary layer edge in the flowfield. These two passes are made within the last BLIMPJ execution and require no intervention by the user. This second pass is made to ensure that the boundary layer and inviscid flowfield properties match at the edge of the boundary layer.

The MRE 15 engine specifications that were used as partial input for this analysis are contained in Table 1. Table 2 presents the TRAN72 input file for generating the thermodynamic data input file for RAMP2. Table 3 contains the input files for the RAMP2 code. The nozzle contour represented by a table of X, Y and flow angle values is contained in the RAMP2 input data shown in Table 3. The RAMP2 flowfield was calculated on the NASA/MSFC ED31 VAX. The VAX COM files for executing the codes are shown in Table 4 (TRAN72) and Table 5 (RAMP2).

The RAMP2 flowfield characteristics of the MRE 15 exhaust plume are shown in Figures 1-9. These figures present isovalue contours of Mach number, static pressure, temperature, pitot total pressures, density, velocity, mass flux, flow angle, and constant mass flow streamlines. The RAMP2 binary output file (Unit 3) is stored on the NASA/MSFC VAX and can be obtained by contacting the NASA COR for this study.

3.2 MRE15 Source Flow Plume Model

Recently, a model has been developed which fits the RAMP2 flowfield results using a source flow approximation. This model called SFPGEN (Ref. 2) was developed to support a Space Station Contamination Model developed by SEA, Inc. for NASA (Ref. 6).

The source flow plume model generator is a code which determines the flow properties in the RAMP2 flowfield. The SFPGEN code is based on the radial lookup code (Ref. 7, 8). Modifications have been made to this code to determine the local properties in the already computed RAMP2 flowfield and then output a formatted file of a simple representation of the RAMP2 flowfield. Properties are determined at constant distances from the exit plane as a function of angular distance from the plume axis. Ten of these source surfaces are determined at even increments of distance starting at the exit plane of the motor and terminating at the maximum distance on the axis in the RAMP2 plume. RAMP2 should be executed out to about 80-100 exit radii where all the gas streamlines no longer change slope. At each of the 10 data surfaces the local/centerline ratios of density, total enthalpy and temperature are determined as a function of angle off the axis, out to the maximum expansion angle. The maximum expansion angle is passed to the source flow module from RAMP2. In addition to the angular variation in properties, the code also generates an array which contains the flow property (density, velocity and total enthalpy) distribution along the

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axis. Twenty five points are used at even axial increments, starting at the exit plane and terminating at the last source station. A single set of mass flow averaged species distributions is also determined at the exit plane of the nozzle. A formatted output file (Unit 16) is then generated which can be passed on as input data to the Space Station Contamination Model or PLIMP code.

The source flow plume model has the advantage over other source models, in that it has the capability to include total temperature effects in the exhaust plume due to oxidizer/fuel distribution and nozzle wall boundary layer effects. This model does assume a constant specific heat ratio and molecular weight. The specific heat ratio and species distribution which is used are mass flow averaged values at the exit plane. Engines which are typically used for orbital application have high area ratios where the exit plane specific heat ratio is very close to what the specific heat ratios would be in the plume. Additionally (neglecting O/F ratio effects) the species at the exit plane are frozen and do not change in the plume. Previous comparisons of RAMP2 and SFPGEN show that SFPGEN results almost exactly match the RAMP2 calculations.

The baseline SFPGEN code used 10 radial distributions and 25 points on the axis to describe the flowfield. The radial distribution of flowfield properties is assumed constant from the nozzle exit plane up to the first source station. Therefore, in the near field (< 8 exit diameters), the SFPGEN flowfield properties can be in error due to the large gradients which are present near the exit plane.

Using this model during the checkout of PLIMP, the flowfield properties, as expected, in the near field differed enough to cause significant differences in predicted environments using the SFPGEN and RAMP2 plumes. To improve the near field results SFPGEN was modified to fit the plume with 25 source lines and up to 50 axis points. In addition, the source lines were made more concentrated in the near field through the use of a cosine distribution. The source lines also begin 1.5 exit radii from the exit plane. These modifications greatly increased the accuracy in the near field distribution while maintaining the fidelity in the far field. At high impingement angles, the boundary layer edge velocity (important for convective heating rate predictions) is very sensitive to local flow angle. The baseline SFPGEN code assumed that the local flow angle was the arctan (Y/X). For the far field, this assumption is valid. However, for the near field (< 10 diameters) and beyond 80 degrees where boundary layer effects are significant, this assumption can result in flow angles that are in error by as much as 7 degrees. To improve the flow angle prediction, flow angle was added to the local/centerline ratios at each source line.

This modification improved the flow angle prediction to $\pm$ 1.5 degrees. A detailed description of the SFPGEN program can be found in Reference 2.

The major advantages of using the SFPGEN code to produce a flowfield are: the flowfield is portable between different computers; the flowfield requires considerably less computer storage than the RAMP2 flowfield; auxiliary (induced environments) calculations are considerably faster using a source flow plume; the source flow plume can be extended to much larger distances than are practical for running the RAMP2 code; and the model can be easily used by other codes.

The RAMP2 flowfield description is stored on a binary file which requires that the same computer type be used to generate the plume and perform application calculations. The SFPGEN flowfield output is a formatted ASCII file that can be easily transported from computer to computer without rerunning the RAMP2 code. Thus, once a particular RAMP2 flowfield is generated, the SFPGEN flowfield can be transferred to other organizations very easily without the cost of rerunning the RAMP2 plume.

A typical RAMP2 binary flowfield file requires on the order of 4-5 megabytes of mass storage. The SFPGEN flowfield requires about .06 megabytes of storage. Thus, the computer resource requirements are significantly reduced.

Considerable time is spent by application codes (PLIMP, Ref. 9, 10) in looking up flowfield properties in a RAMP2 flowfield. Timing tests performed using RAMP2 and SFPGEN flowfields show that PLIMP runs 3-4 times faster using a SFPGEN flowfield. For applications which require significant PLIMP calculations, significant reductions in computer resources can be realized.

Reference 6 contains a description of the original routines which use this data file to determine local flow properties in the plume. These routines have been subsequently modified and copies of these routines, as well as the MRE 15 SFPGEN data file, are maintained on the NASA/MSFC VAX and can be obtained from the NASA - COR. These routines will be particularly useful to organizations that are interested in plume induced environments to payloads being deployed or retrieved by the OMV.

Figures 10 - 16 show the flowfield characteristics of the MRE 15 SFPGEN plume. These figures present isovalve contours of Mach number, static pressure, temperature, pitot total pressure, density, velocity and mass flux, respectively.

4.0 Conclusions

This report provides a detailed description of the OMV

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vehicle MRE 15 exhaust plume flowfield characteristics calculated with the RAMP2 and SFPGEN codes. Included in the report are brief descriptions of the two models, MRE 15 engine characteristics and RAMP2 input data files. The RAMP2 flowfield could be recalculated by other organizations using the information contained in this report. The MRE 15 SFPGEN flowfield can be readily used by other organizations who are interested in MRE 15 plume induced environments which require local flowfield properties which can be supplied using the SFPGEN MRE 15 model.

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9. Penny, M.M. and C.J. Wojciechowski, "User's Manual and Description of a Computer Program for Calculating Heating Rates, Forces and Moments Acting on Bodies immersed in Rocket Exhaust Plumes," LMSC-HREC D162867-II, Lockheed Missiles & Space Company, Huntsville, AL, March 1971.

10. Smith, S.D., "Development of a Nozzle/Plume and Plume Impingement Code," CIFR008, Continuum, Inc., Huntsville, AL, November 1986.

Table 1. MRE-15 Engine Specifications

Inlet Pressure (psia)	300
Nominal Thrust (lbf)	15
Area Ratio	50
Chamber Pressure (psia)	134.7
Chamber Temperature (°F)	1700
Throat Diameter (in)	.296 ± .005
Propellant	Hydrazine
Nozzle	Contoured
Nozzle Wall Temperature (Throat) (°F)	1700
Nozzle Wall Temperature (Lip) (°F)	1300

Table 2

TRAN72 Input Data For MRE15 Engine

```
REACTANTS
H 2.0                    00      .47  M 0.0    G 1200.  F
N 2.0                    00      .30  M 0.0    G 1200.  F
UA1.0                    00      .22  M 0.0    G 1200.  F
H 2.0       0 1.0        00      .01  M 0.0    G 1200.  F

NAMELISTS
$INPT2 KASE=1, RKT=T, PSIA=T, MOCTF=T, P=134.7, 1.0, FPCT=T, MIX(1)=100.,
       PARTHT=T, NQI=10, QDOTP=-200.,-175.,-150.,-125.,-100.,
-75.,-50.,-25.,0.0,100.$
$TAPGEN IREAD=1, IO=8, IN=10$
HYDRAZ 55  DISS
$RKTINP PCP=3.0, 5.0, 10.0, 50.0, 100., 200., 500., 1000., NFZ=2$
STOP
```

Table 3

RAMP2 Input Data Files For MRE15 Engine

```
MRE15UN5A.DAT
 0    3    2    1
A/A*=50, HYDRAZINE MOTOR, MODEL MRE15 PC=134.7 OMV RCS

 32      3020036   103502   11   203   0        0        12570
.01233

0.0000E+00 0.1233E-01 0.0000E+00      0.1291E-02 0.1237E-01 0.3000E+01
0.2578E-02 0.1247E-01 0.6000E+01      0.3859E-02 0.1264E-01 0.9000E+01
0.5128E-02 0.1287E-01 0.1200E+02      0.6384E-02 0.1317E-01 0.1500E+02
0.7622E-02 0.1354E-01 0.1800E+02      0.8840E-02 0.1397E-01 0.2100E+02
0.1003E-01 0.1447E-01 0.2400E+02      0.1120E-01 0.1502E-01 0.2700E+02
0.1233E-01 0.1564E-01 0.3000E+02      0.1263E-01 0.1581E-01 0.3080E+02
0.2500E-01 0.2319E-01 0.3080E+02      0.4167E-01 0.3285E-01 0.2940E+02
0.5000E-01 0.3738E-01 0.2770E+02      0.5833E-01 0.4157E-01 0.2570E+02
0.6667E-01 0.4542E-01 0.2390E+02      0.7500E-01 0.4899E-01 0.2240E+02
0.8333E-01 0.5227E-01 0.2060E+02      0.9167E-01 0.5532E-01 0.1960E+02
0.1000E+00 0.5820E-01 0.1860E+02      0.1083E+00 0.6096E-01 0.1800E+02
0.1167E+00 0.6360E-01 0.1720E+02      0.1250E+00 0.6610E-01 0.1620E+02
0.1333E+00 0.6846E-01 0.1540E+02      0.1417E+00 0.7071E-01 0.1475E+02
0.1500E+00 0.7285E-01 0.1415E+02      0.1583E+00 0.7490E-01 0.1340E+02
0.1667E+00 0.7683E-01 0.1270E+02      0.1750E+00 0.7867E-01 0.1220E+02
0.1833E+00 0.8042E-01 0.1160E+02      0.1917E+00 0.8209E-01 0.1105E+02
0.2000E+00 0.8369E-01 0.1065E+02      0.2083E+00 0.8522E-01 0.1015E+02
0.2212E+00 0.08720283 0.9400E+01

 1
 3   .3       -05         0.0    0.0    0.0    0.0
 2                        0.0    0.0    1000.  0.0
HYDRAZ 55  DISS       MKS 0.0    0.0    1000.  0.0
            0.0   0.0  1.02
0.6   -4.0   0.0   0.0  10.      90.0   0.0    0.0
.01   .003   100.  .005 5.       .95    .05
0     2      2     0    0.00500
2160. .2212  1760.
0.0

MRE15UN5B.DAT
 1   3   2   2

MRE15UN5C.DAT
 1   3   2   3
 1                 130
```

Table 4

Listing TRAN72 VAX COM File For MRE15 Engine

```
$ SET DEF [033013.RAMP]
$ ASSIGN CECMRE15.DAT  FOR005
$ ASSIGN MRE15UN10.DAT FOR010
$ ASSIGN CECTHERM.R2F FOR004
$ ASSIGN CEC.OUT FOR006
$ RUN [033013.RAMP]CECR2F
```

Table 5

Listing of RAMP2 VAX COM File For MRE15 Engine

```
$ SET DEF [033013.RAMP]
$ ASSIGN MRE15.OUT FOR006
$ ASSIGN MRE15UN7.DAT   FOR007
$ ASSIGN MRE15UN8.DAT   FOR008
$ ASSIGN MRE15UN9.DAT   FOR009
$ ASSIGN MRE15UN10.DAT  FOR010
$ ASSIGN MRE15UN3.DAT   FOR003
$ COPY CECTHERM.R2F MRE15UN4A.DAT
$ ASSIGN MRE15UN4A.DAT FOR004
$ ASSIGN MRE15UN5A.DAT     FOR005
$ ASSIGN MRE15UN1.DAT   FOR001
$ ASSIGN MRE15UN2.DAT   FOR002
$ ASSIGN MRE15UN12.DAT  FOR012
$ ASSIGN MRE15UN13.DAT  FOR013
$ ASSIGN MRE15UN14.DAT FOR014
$ ASSIGN MRE15UN17.DAT FOR017
$ ASSIGN MRE15UN11.DAT FOR011
$ RUN [033013.RAMP]RAMP2P
$ ASSIGN BLIMPJ.OUT FOR006
$ RUN [033013.RAMP]BLIMPJ
$ COPY MRE15UN2.DAT MRE15UN2A.DAT
$ ASSIGN MRE15.OUT1 FOR006
$ ASSIGN MRE15UN5B.DAT FOR005
$ ASSIGN MRE15UN1A.DAT FOR001
$ RUN [033013.RAMP]RAMP2P
$ COPY MRE15UN3.DAT MRE15UN3B.DAT
$ ASSIGN BLIMPJ.OUT1 FOR006
$ RUN [033013.RAMP]BLIMPJ
$ COPY MRE15UN1A.DAT MREUN1A.DAT1
$ ASSIGN FOR001.DAT FOR001
$ ASSIGN MRE15.OUT2 FOR006
$ ASSIGN MRE15UN5C.DAT FOR005
$ RUN [033013.RAMP]RAMP2P
```
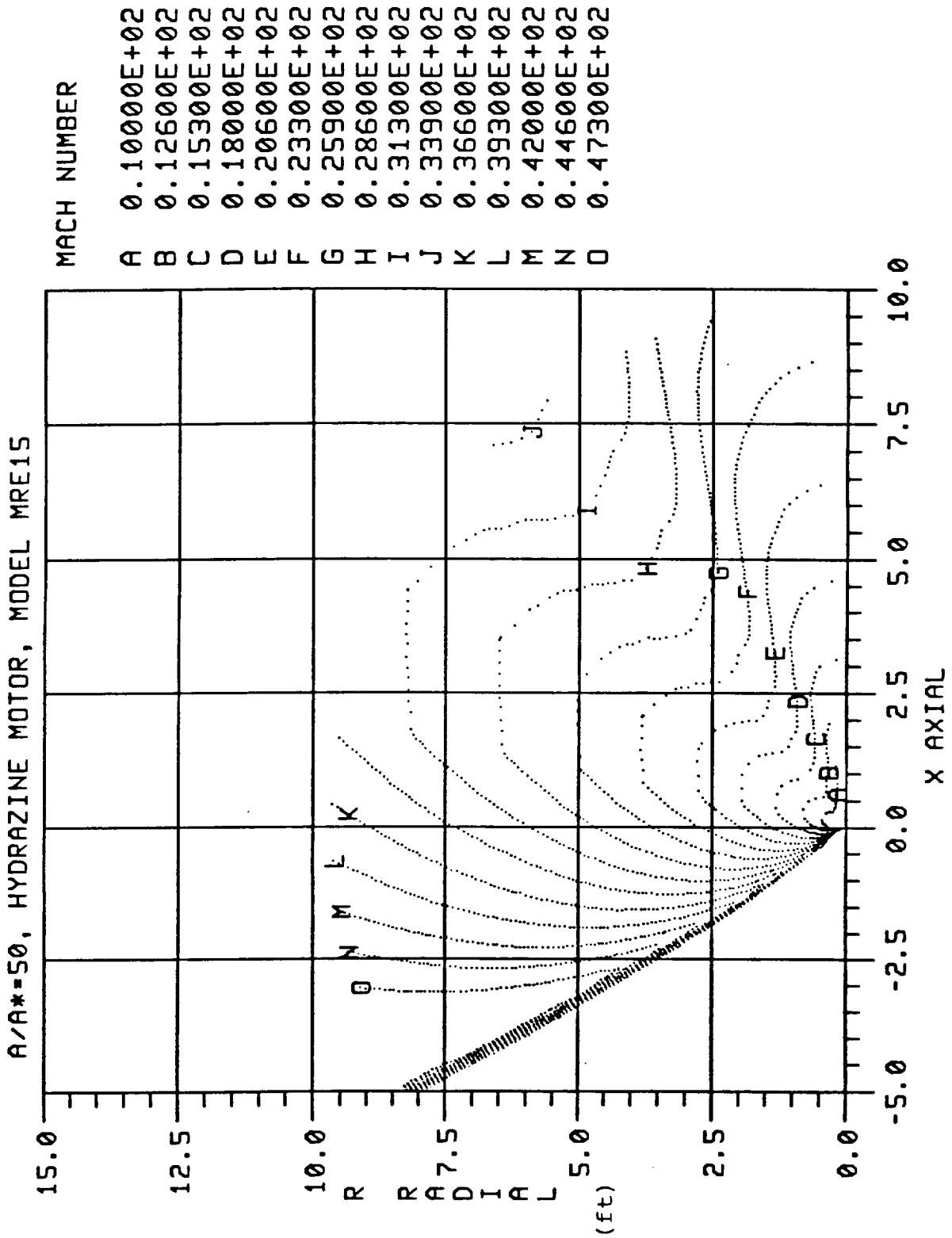
Figure 1. Mach Number Contours for MRE15 Engine Exhaust Plume
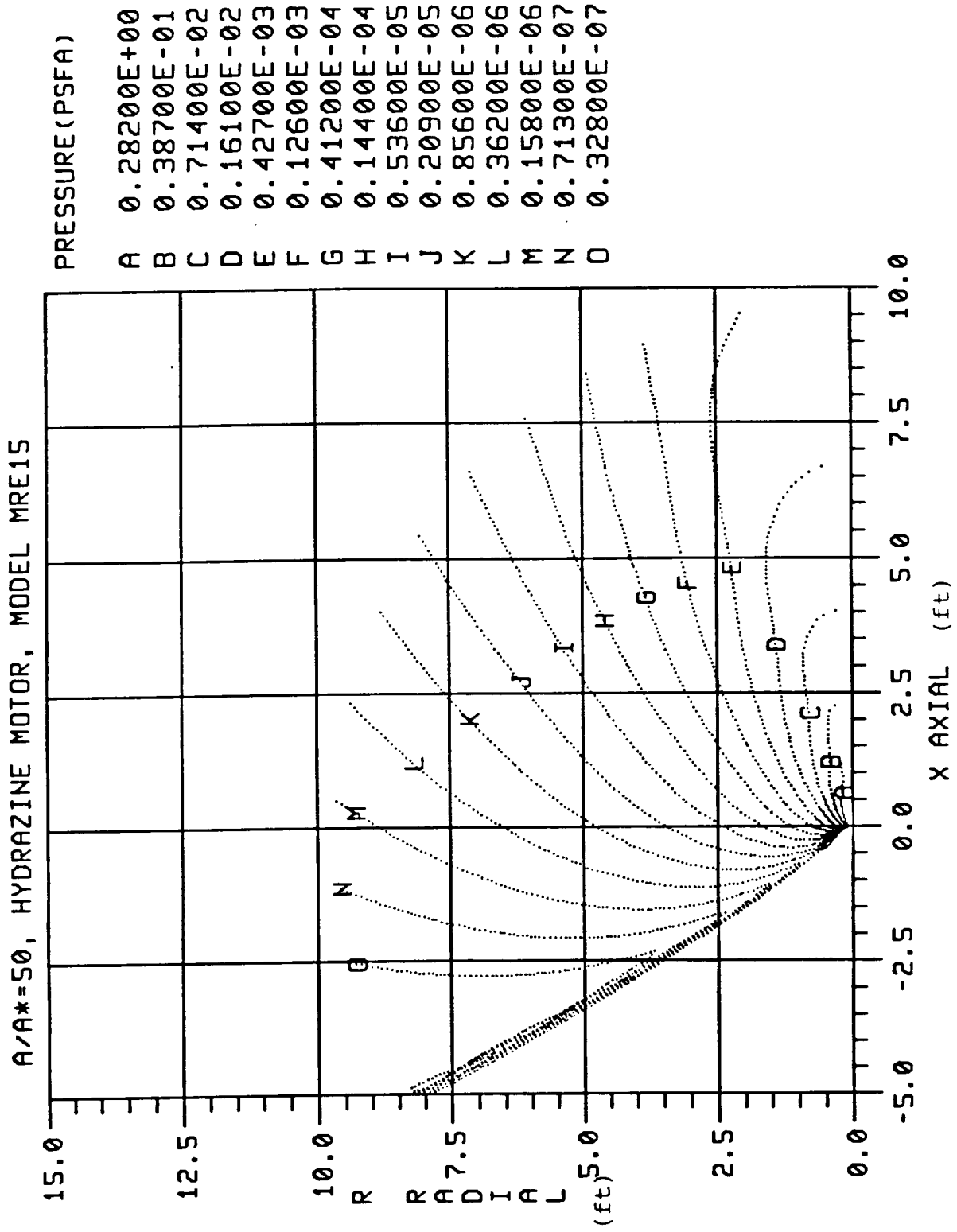Calculated Using RAMP2

Figure 2. Pressure Contours for MRE15 Engine Exhaust Plume
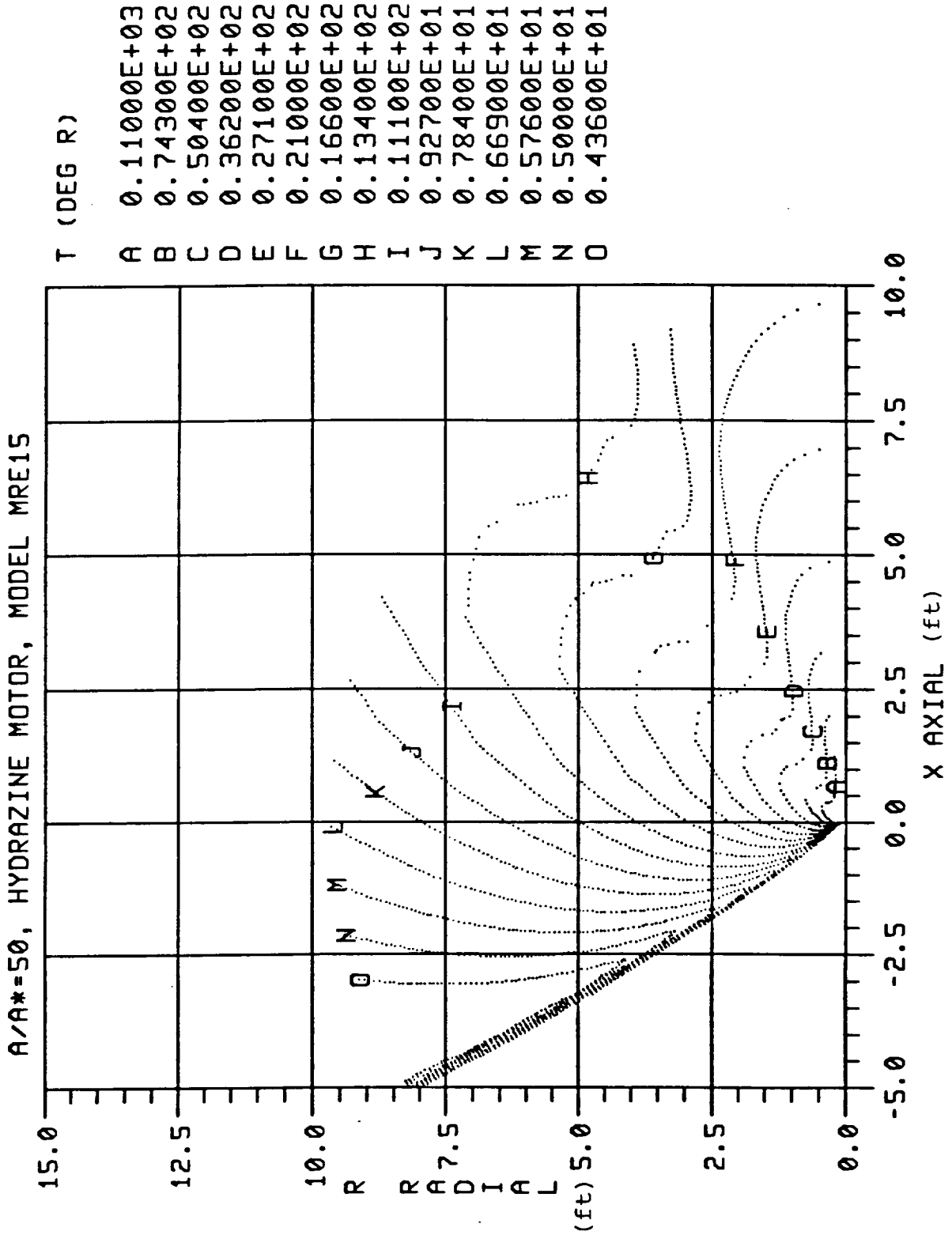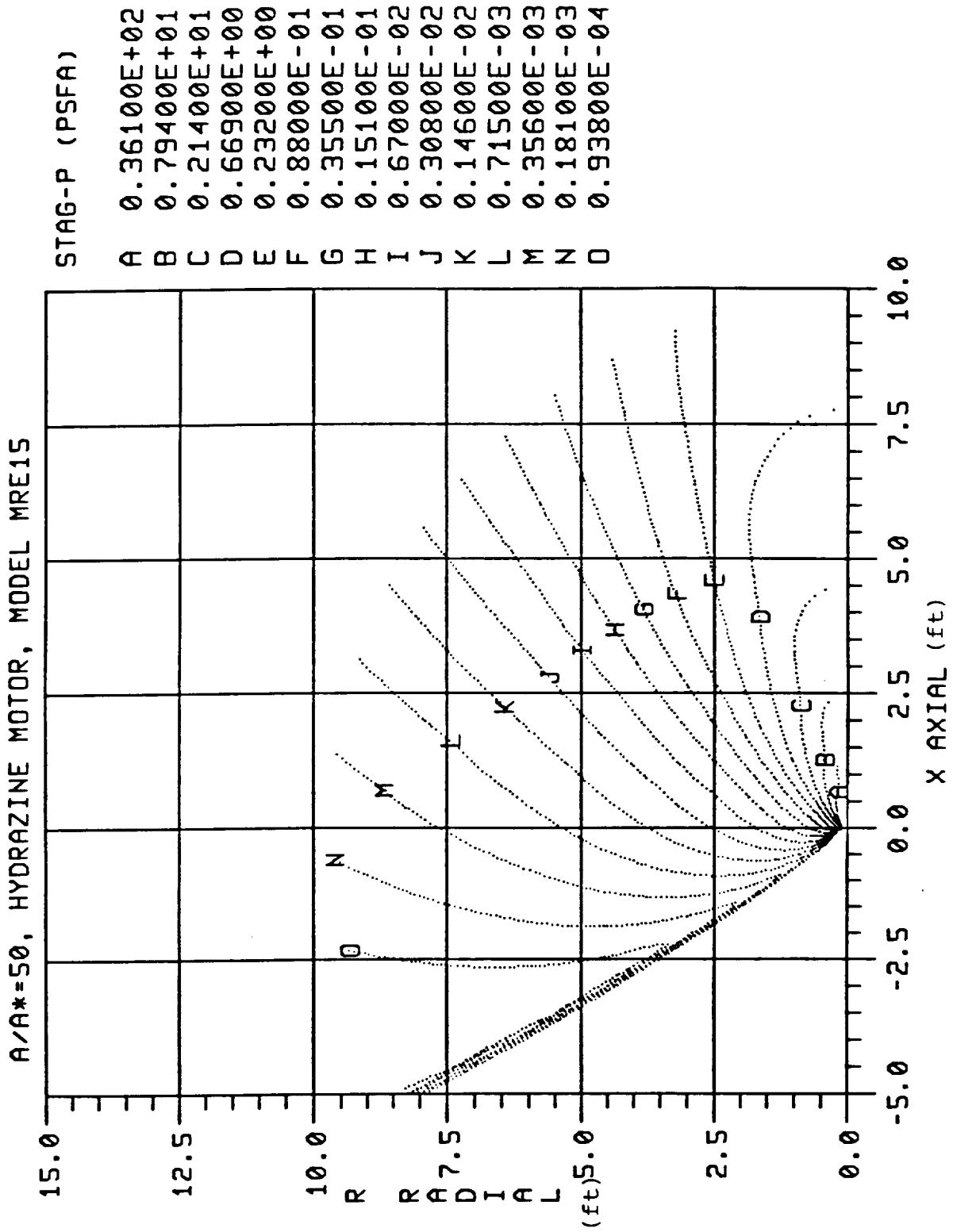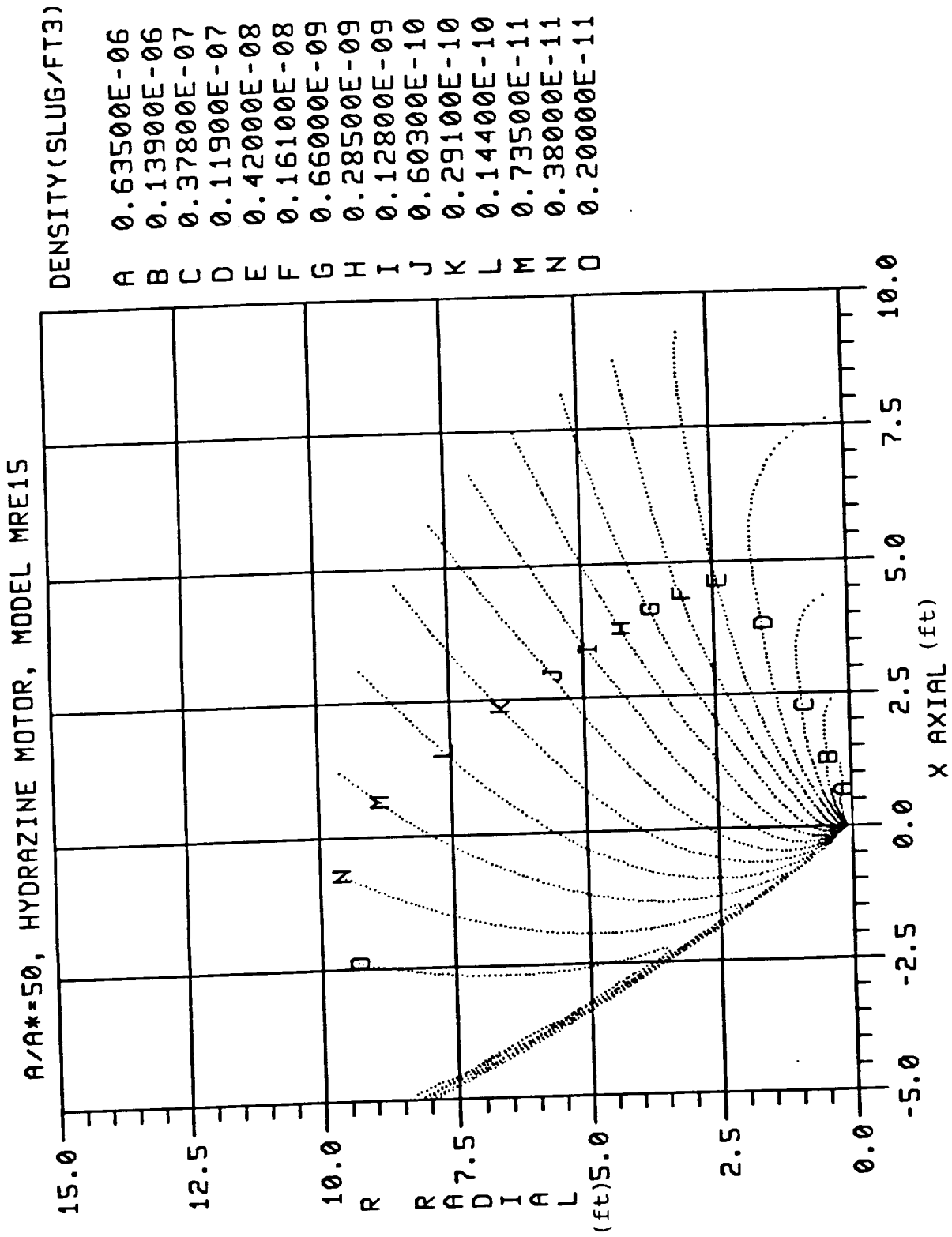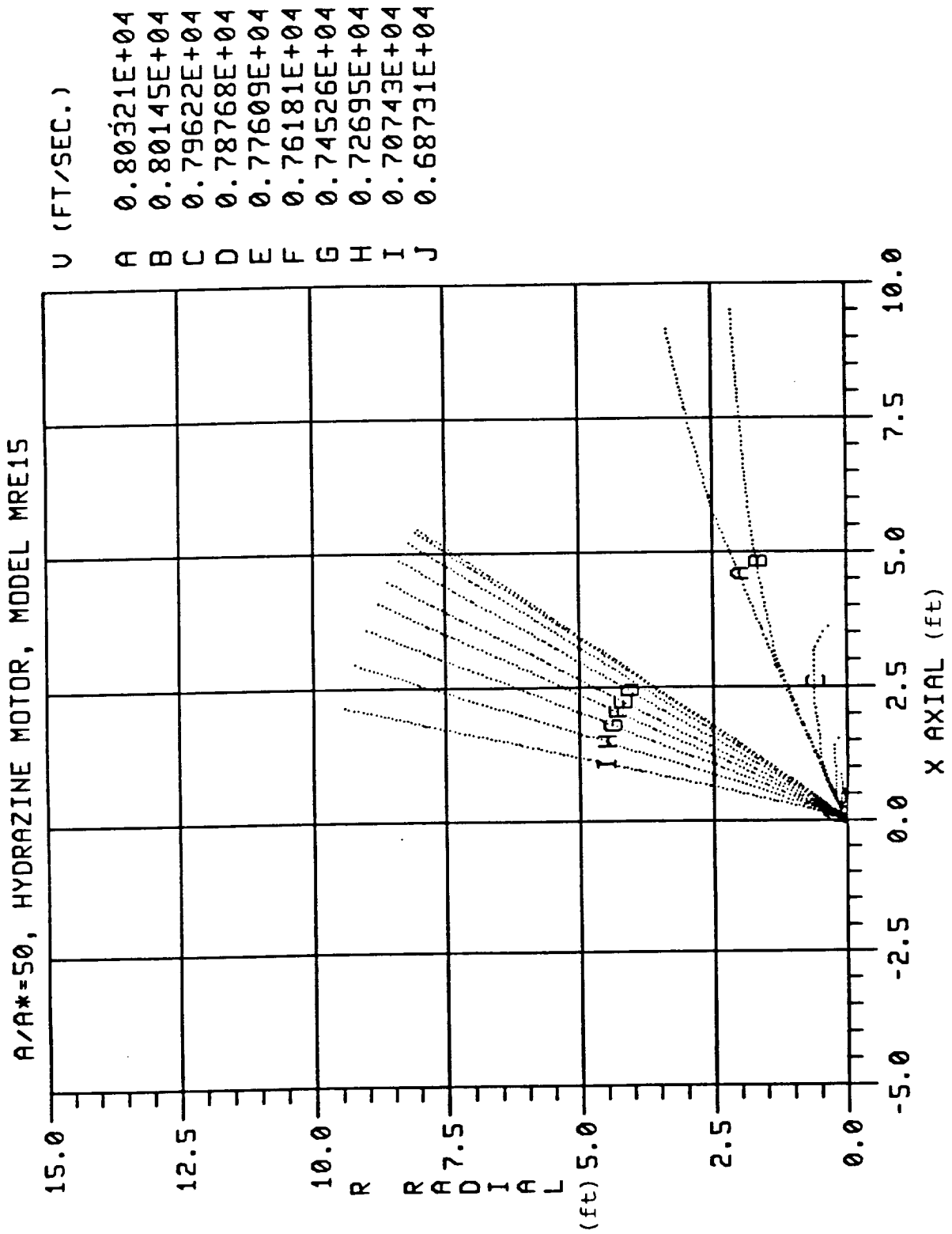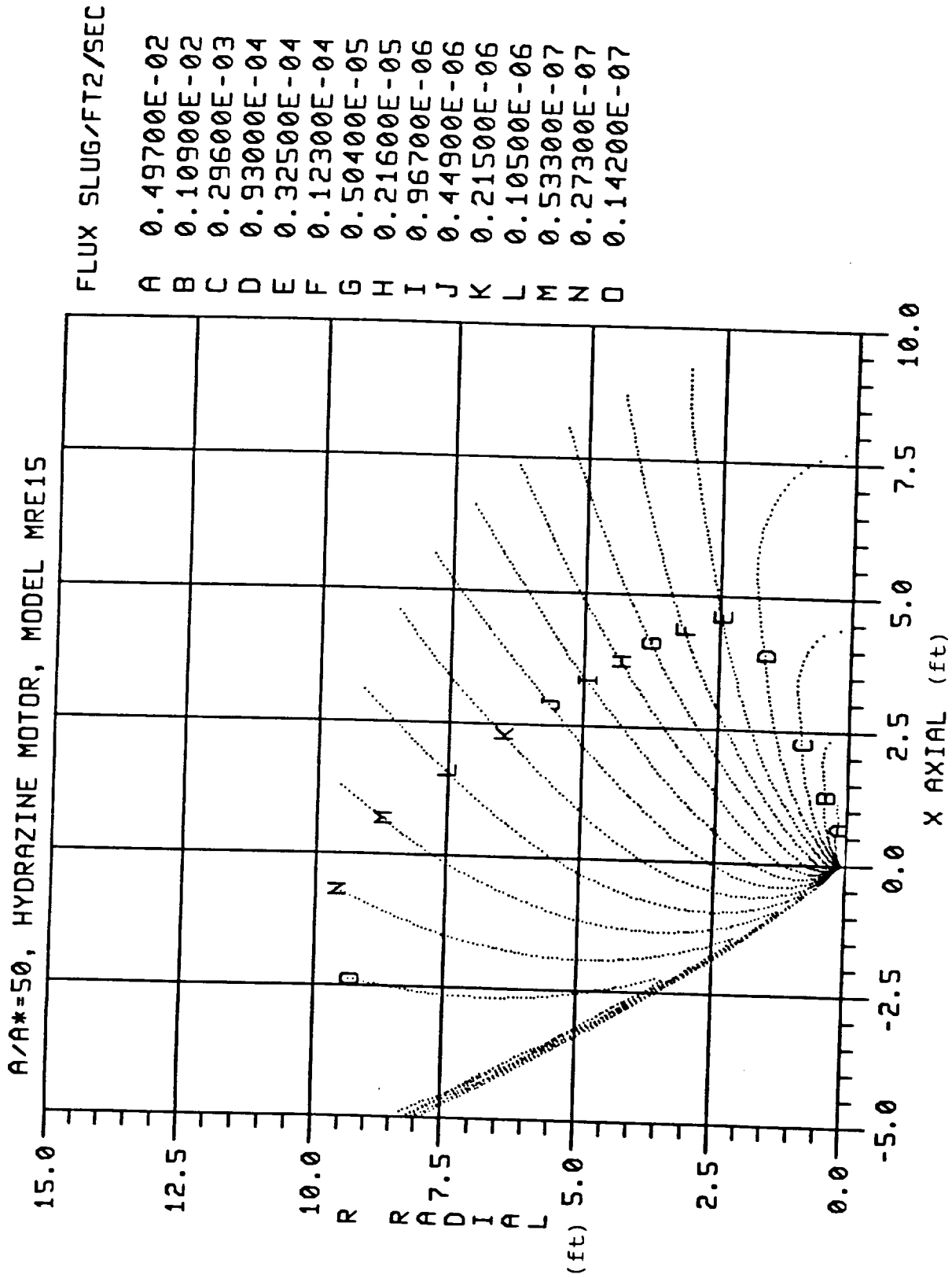Calculated Using RAMP2

A/A*=50, HYDRAZINE MOTOR, MODEL MRE15

T (DEG R)

A 0.11000E+03
B 0.74300E+02
C 0.50400E+02
D 0.36200E+02
E 0.27100E+02
F 0.21000E+02
G 0.16600E+02
H 0.13400E+02
I 0.11100E+02
J 0.92700E+01
K 0.78400E+01
L 0.66900E+01
M 0.57600E+01
N 0.50000E+01
O 0.43600E+01

Figure 3. Temperature Contours for MRE15 Engine Exhaust Plume
Calculated Using RAMP2

A/A*=50, HYDRAZINE MOTOR, MODEL MRE15

STAG-P (PSFA)

A	0.36100E+02
B	0.79400E+01
C	0.21400E+01
D	0.66900E+00
E	0.23200E+00
F	0.88000E-01
G	0.35500E-01
H	0.15100E-01
I	0.67000E-02
J	0.30800E-02
K	0.14600E-02
L	0.71500E-03
M	0.35600E-03
N	0.18100E-03
O	0.93800E-04

Figure 4. Pitot Total Pressure Contours for MRE15 Engine
Exhaust Plume Calculated Using RAMP2

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Figure 5. Density Contours for MRE15 Engine Exhaust Plume
Calculated Using RAMP2

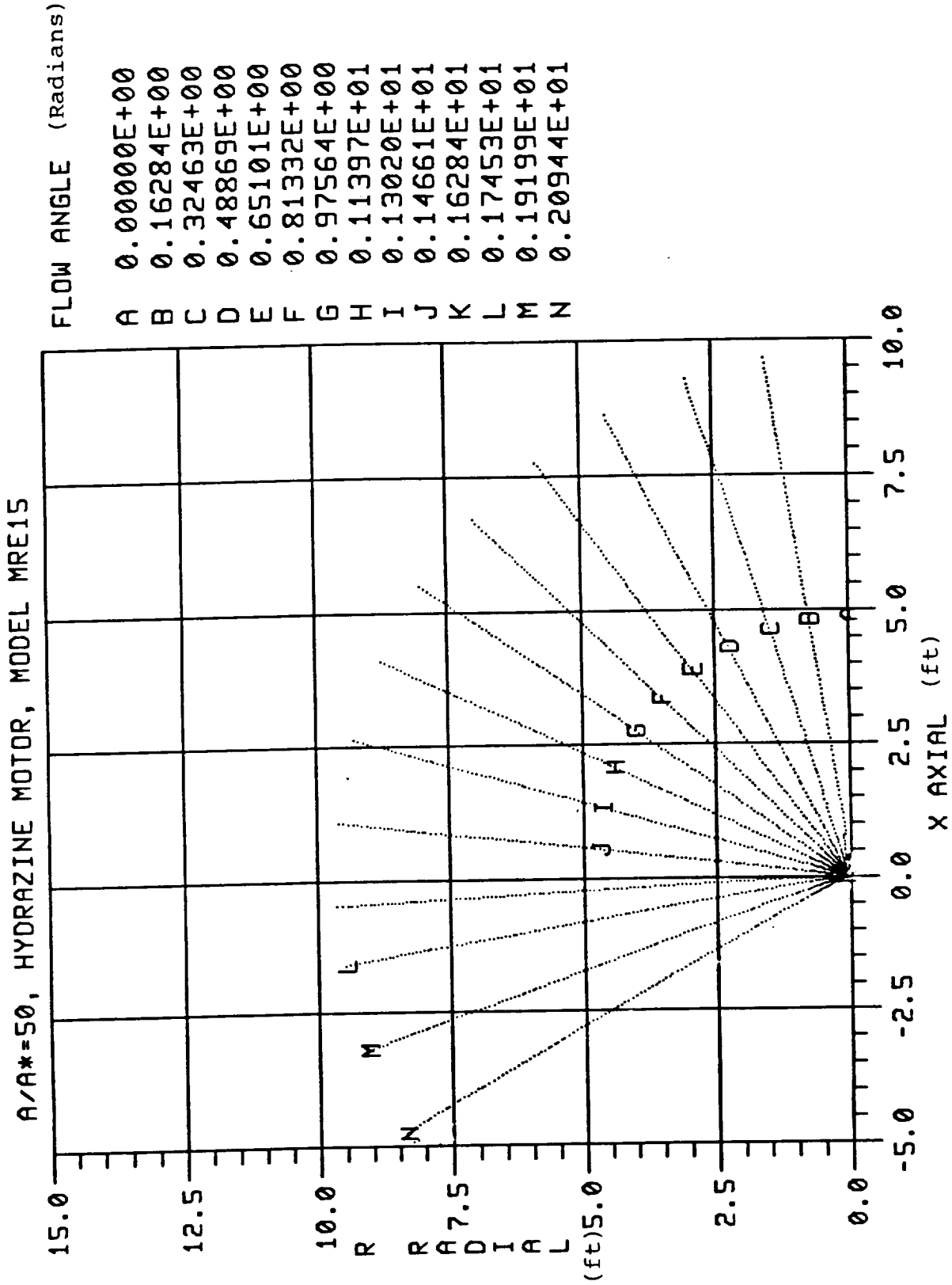Figure 6. Velocity Contours for MRE15 Engine Exhaust Plume
Calculated Using RAMP2

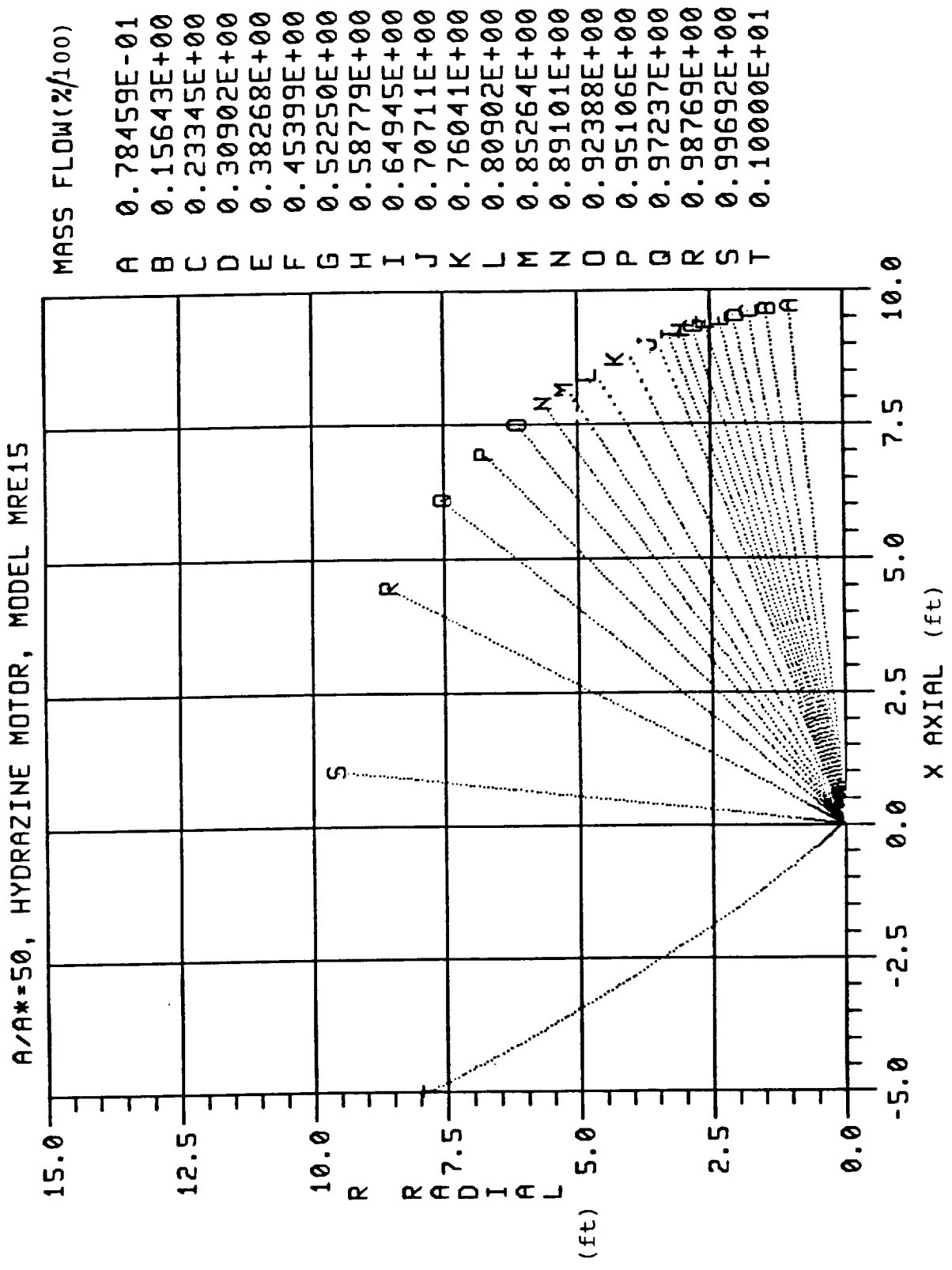A/A*=50, HYDRAZINE MOTOR, MODEL MRE15

	FLUX SLUG/FT2/SEC
A	0.49700E-02
B	0.10900E-02
C	0.29600E-03
D	0.93000E-04
E	0.32500E-04
F	0.12300E-04
G	0.50400E-05
H	0.21600E-05
I	0.96700E-06
J	0.44900E-06
K	0.21500E-06
L	0.10500E-06
M	0.53300E-07
N	0.27300E-07
O	0.14200E-07

Figure 7. Mass Flux Contours for MRE15 Engine Exhaust Plume Calculated Using RAMP2

Figure 8. Flow Angle Contours for MRE15 Engine Exhaust Plume
Calculated Using RAMP2

Figure 9. Mass Flow Contours for MRE15 Engine Exhaust Plume
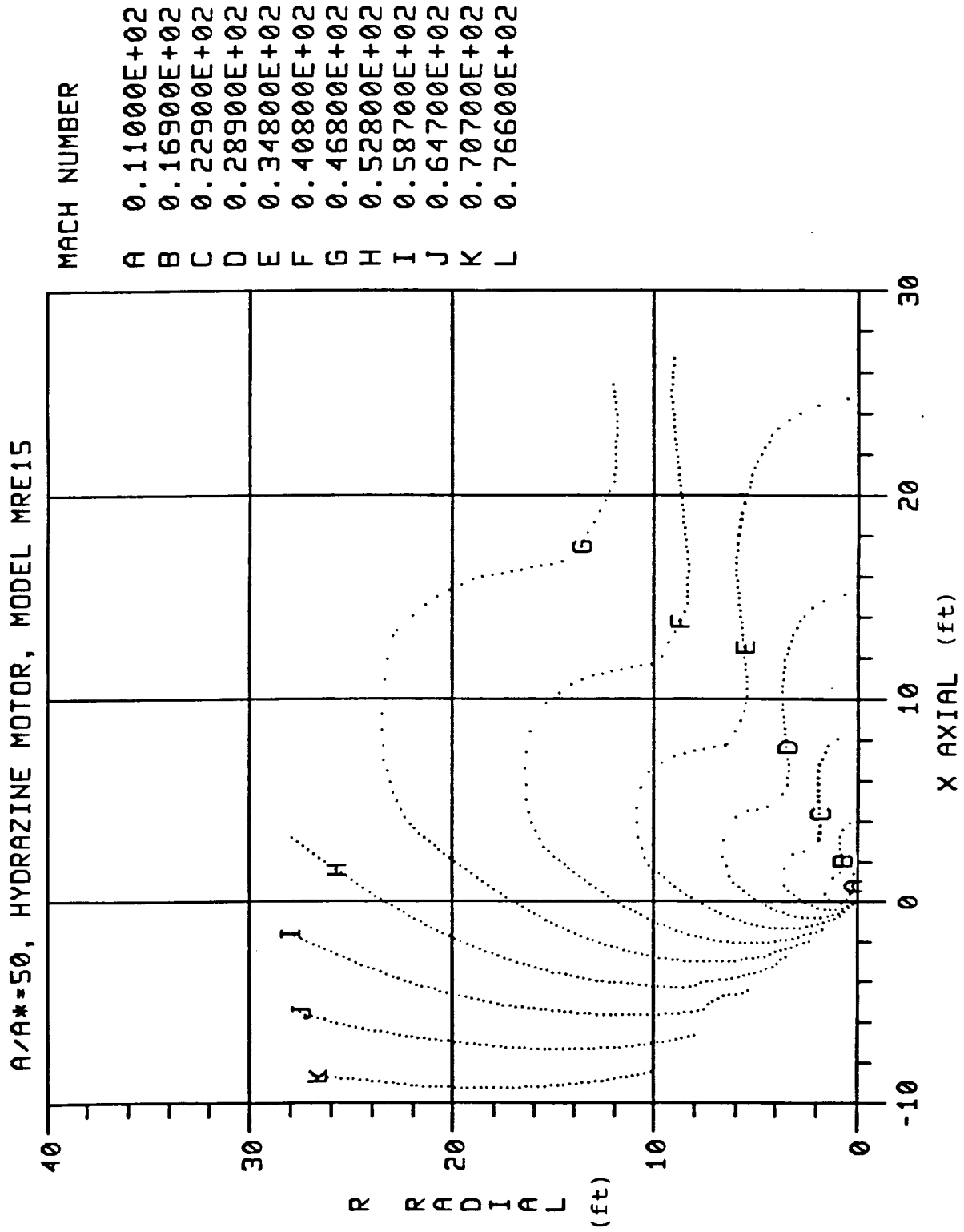Calculated Using RAMP2

Figure 10. Mach Number Contours for MRE15 Engine Exhaust Plume
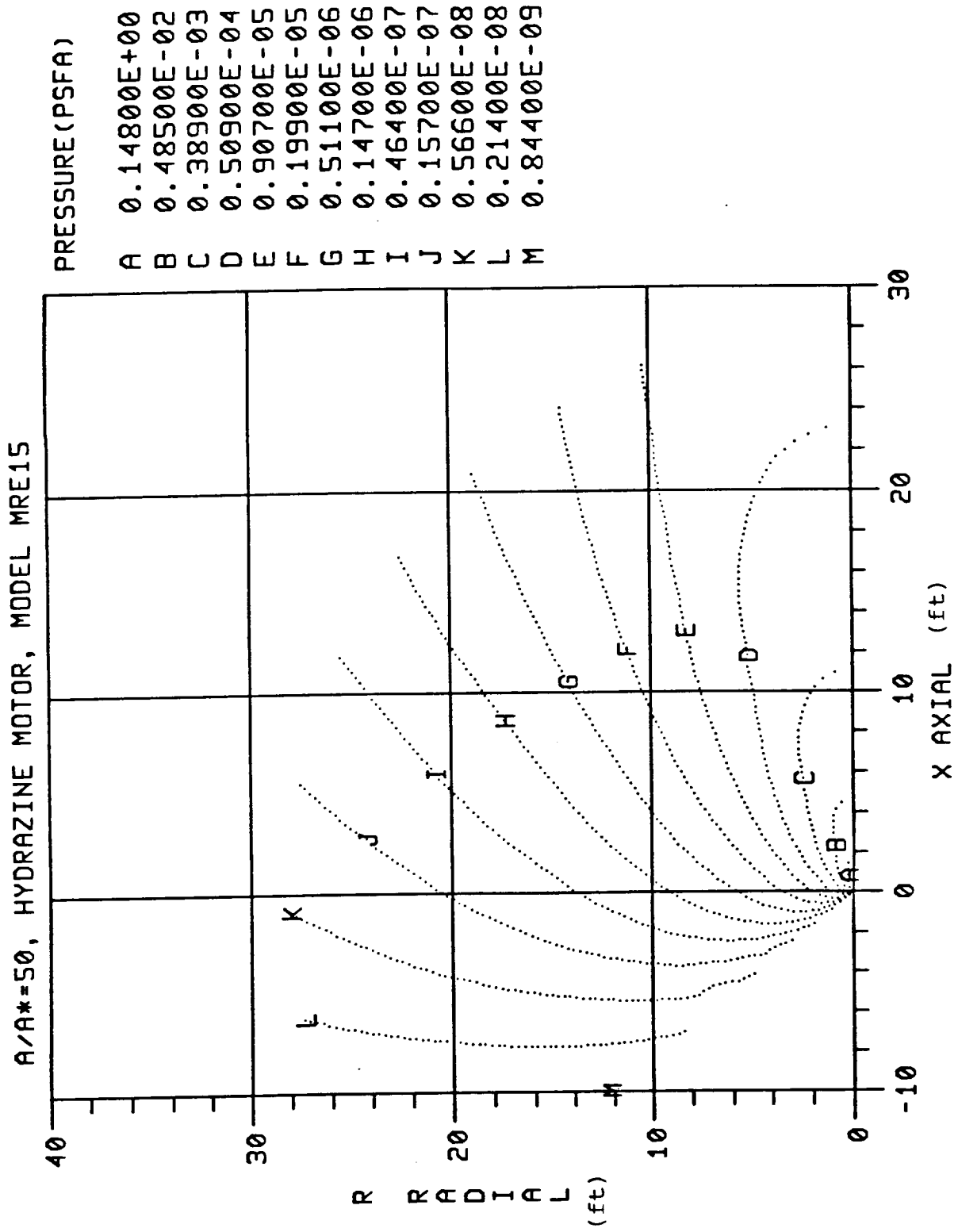Calculated Using SFPGEN

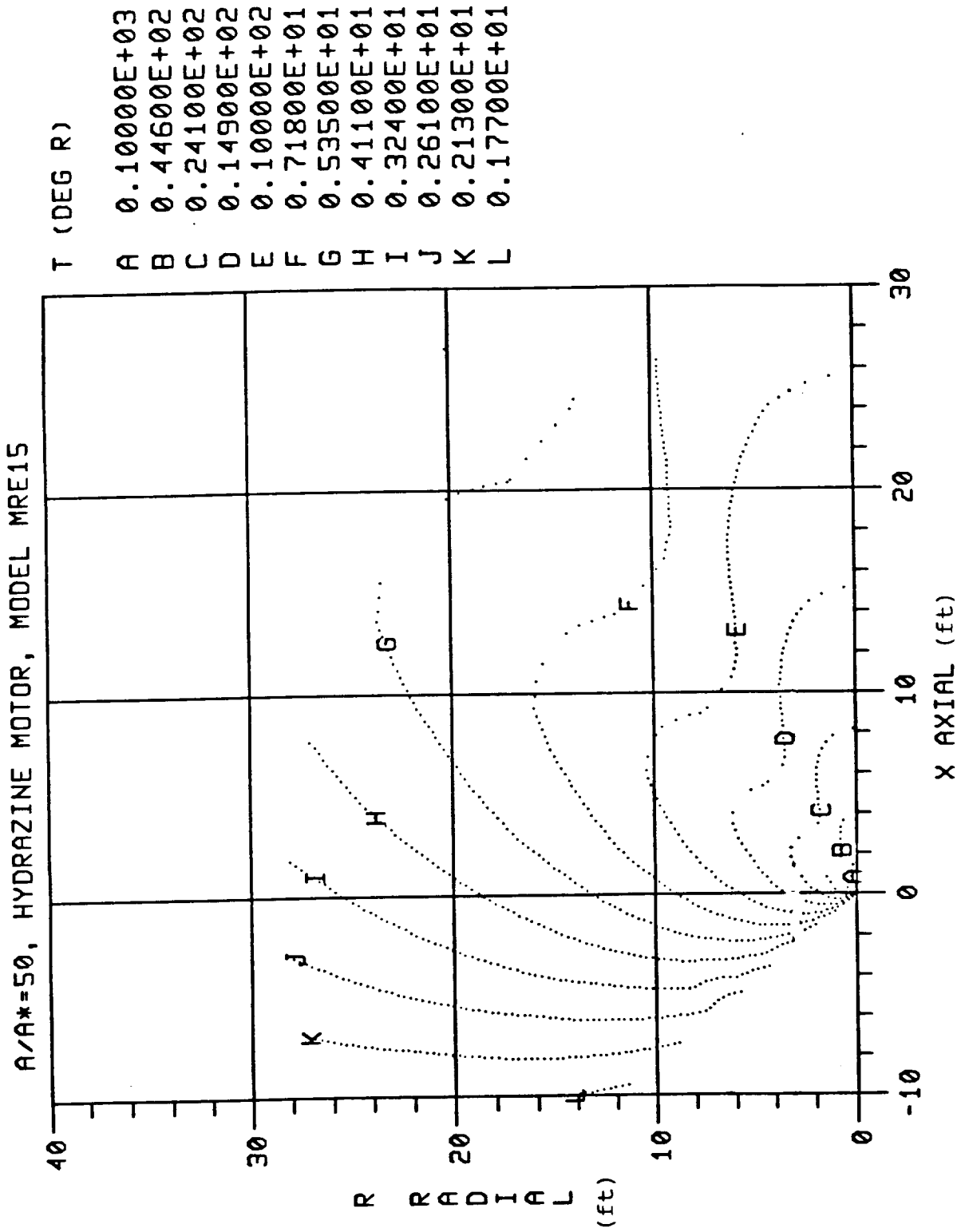Figure 11. Pressure Contours for MRE15 Engine Exhaust Plume
Calculated Using SFPGEN

A/A*=50, HYDRAZINE MOTOR, MODEL MRE15

T (DEG R)

A	0.10000E+03
B	0.44600E+02
C	0.24100E+02
D	0.14900E+02
E	0.10000E+02
F	0.71800E+01
G	0.53500E+01
H	0.41100E+01
I	0.32400E+01
J	0.26100E+01
K	0.21300E+01
L	0.17700E+01

Figure 12. Temperature Contours for MRE15 Engine Exhaust Plume
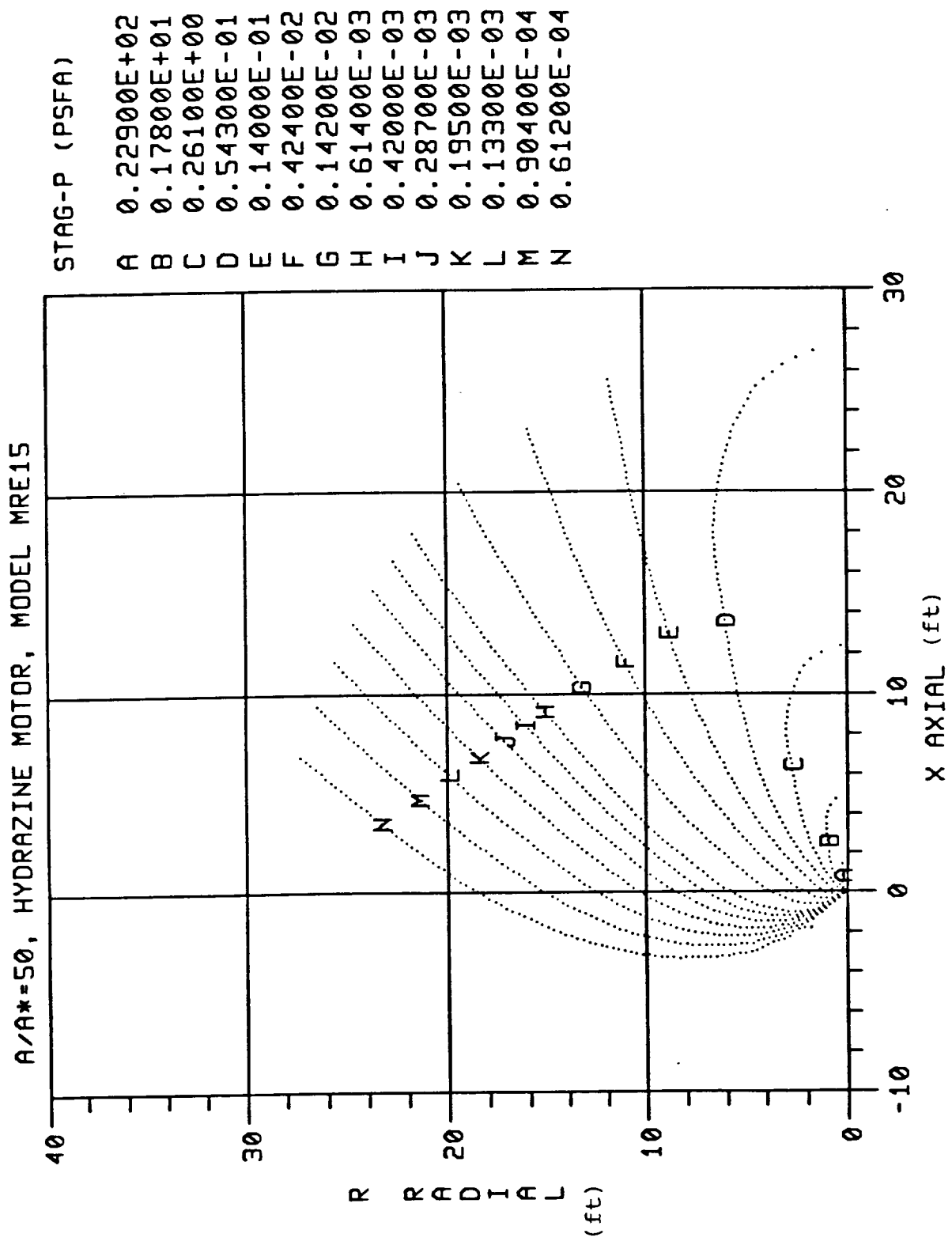Calculated Using SFPGEN

Figure 13. Pitot Total Pressure Contours for MRE15 Engine
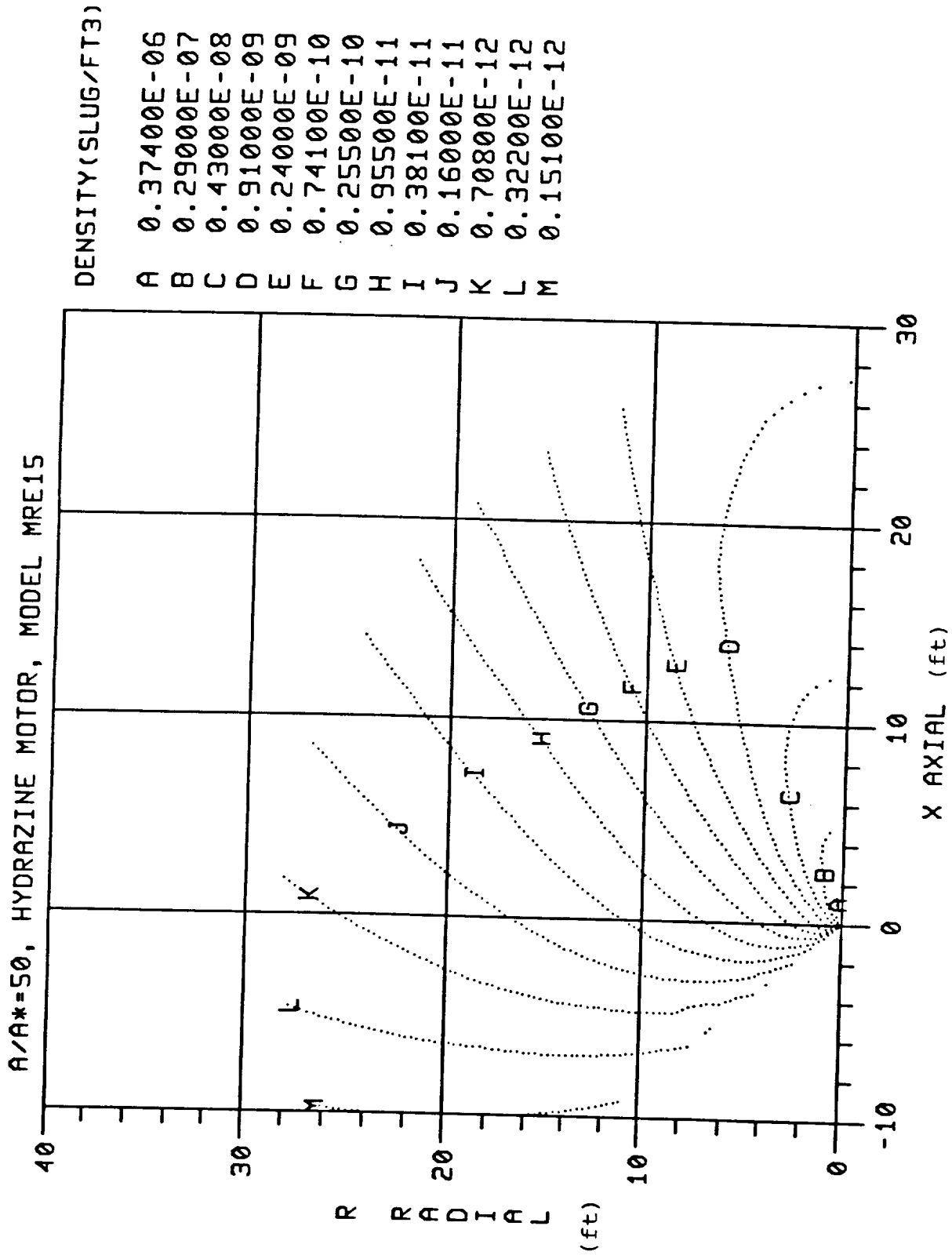Exhaust Plume Calculated Using SFPGEN

Figure 14. Density Contours for MRE15 Engine Exhaust Plume
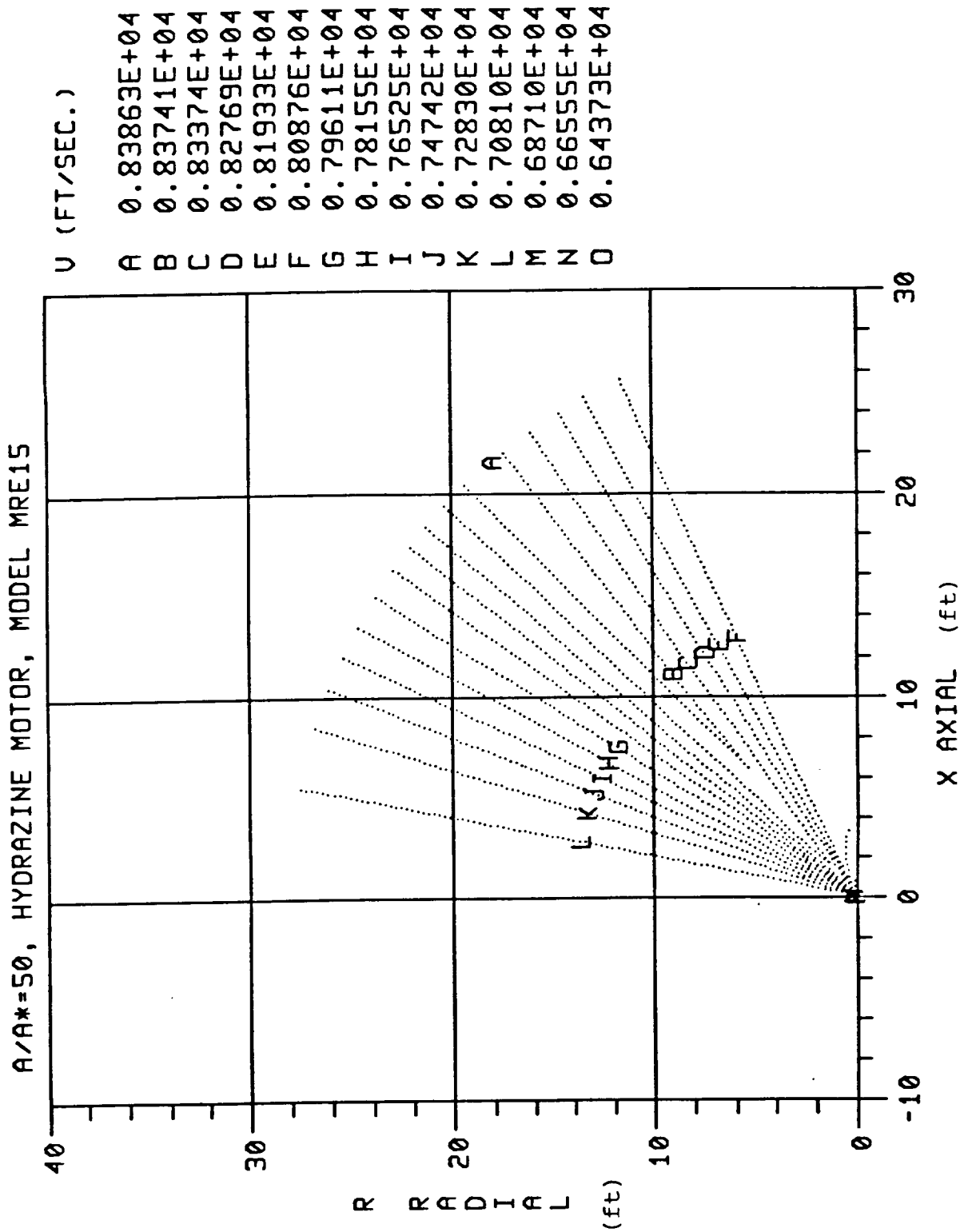Calculated Using SFPGEN

A/A*=50, HYDRAZINE MOTOR, MODEL MRE15

U (FT/SEC.)

A 0.83863E+04
B 0.83741E+04
C 0.83374E+04
D 0.82769E+04
E 0.81933E+04
F 0.80876E+04
G 0.79611E+04
H 0.78155E+04
I 0.76525E+04
J 0.74742E+04
K 0.72830E+04
L 0.70810E+04
M 0.68710E+04
N 0.66555E+04
O 0.64373E+04

X AXIAL (ft)

RADIAL (ft)

Figure 15. Velocity Contours for MRE15 Engine Exhaust Plume
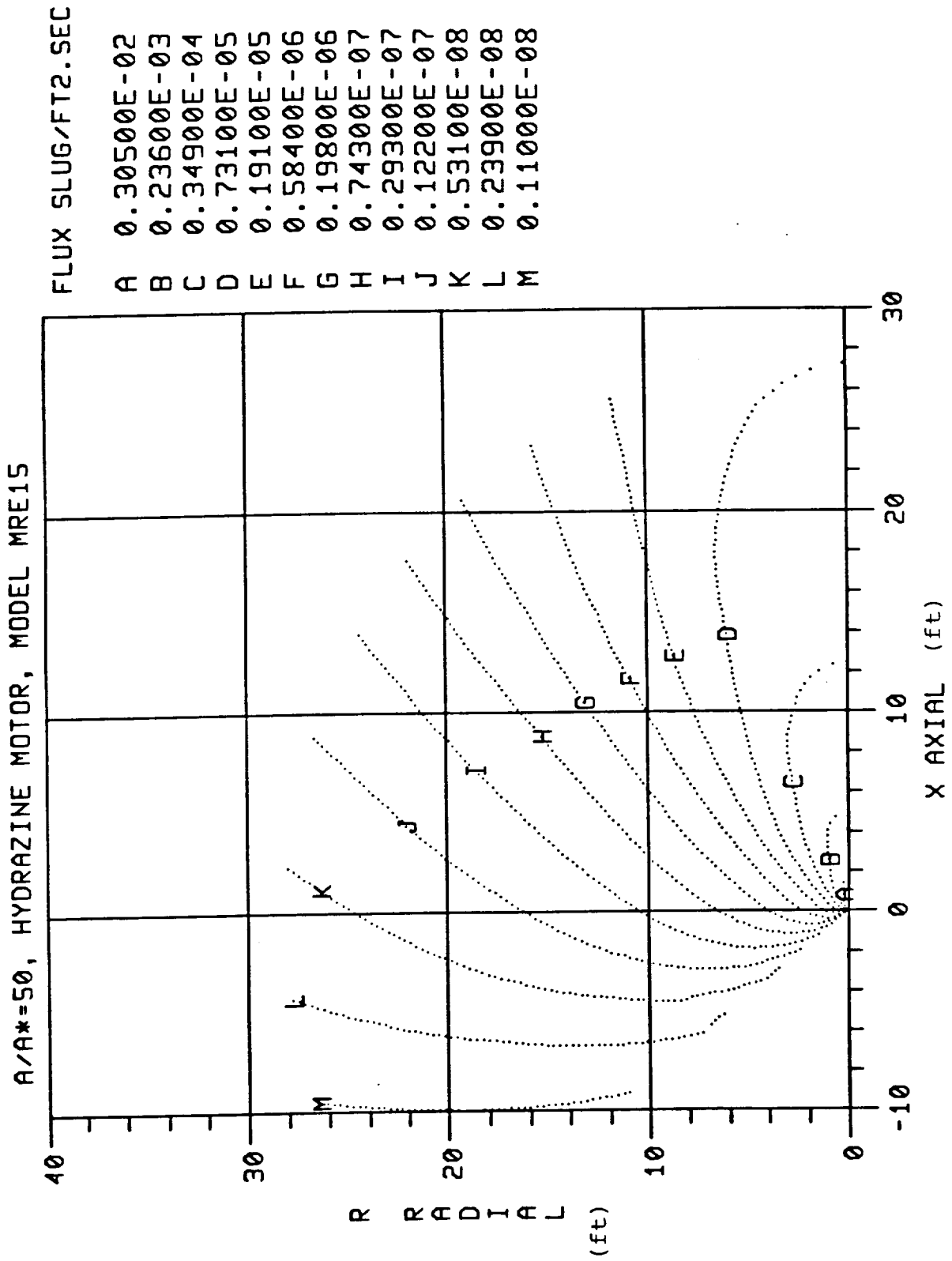Calculated Using SFPGEN

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Figure 16. Mass Flux Contours for MRE15 Engine Exhaust Plume
Calculated Using SFPGEN

APPENDIX B

Definition of the OMV GN2 Thruster Exhaust Plume Flowfield

DEFINITION OF THE OMV GN2 THRUSTER EXHAUST
PLUME FLOWFIELD

15 August 1990

Contract NAS8-38243

Prepared For:

National Aeronautics and Space Administration
Marshall Space Flight Center, Alabama 35812

by:

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1.0 Forward

This document presents the results of work performed by SECA, Inc. for NASA, Marshall Space Flight Center under Contract NAS8-38243. The NASA contracting officer representative for this study is Mr. P. R. Sulyma, ED33.

2.0 Introduction

This report presents the flowfield characteristics of the Orbital Maneuvering Vehicle (OMV), GN2 thruster exhaust plume. The GN2 thruster is a 5 lbf cold gas (Nitrogen) engine which will be used as the secondary engine for the Reaction Control System (RCS) of the OMV. The GN2 thruster plume characterization is required in order to predict the GN2 thruster plume induced environments to the OMV itself, as well as to payloads it is retrieving or deploying. This report presents the GN2 thruster flowfield characteristics and describes the methodology which was used to characterize the plume.

3.0 Discussion

This section describes the GN2 thruster exhaust plume flowfield which was generated using the RAMP2 (Ref. 1) code and a new source flow model (Ref. 2).

3.1 RAMP2 GN2 Thruster Flowfield

The analysis of the GN2 nozzle and plume flowfields was performed using the Reacting and Multi-phase Computer Code (RAMP2 Ref. 1). RAMP2 is a method of characteristics based code used to solve inviscid supersonic flowfields.

The purpose of the RAMP2 code is to solve a rocket exhaust flowfield in sufficient detail so that the plume may be used to adequately specify some design environment for systems which are influenced by the plume. For high altitude plumes, an adequate definition of the plume requires the inclusion of chemistry and nozzle boundary layer effects. The TRAN72 (Ref. 3) program and BLIMPJ (Ref. 4) codes are included in the RAMP2 code along with the RAMP2F flowfield code to treat chemistry and boundary layer effects.

In order to use the original RAMP2 code (Ref. 5) to solve a high altitude plume, the following steps are required. First, the TRAN72 program input data is prepared and executed to generate a data tape describing the thermodynamic characteristics of the post-combustion gases. Next the RAMP2F flowfield data are prepared and the nozzle flowfield is solved using the TRAN72

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program data tape as input. Then in order to adequately describe the nozzle boundary layer, the BLIMPJ code is executed using an input data file and flowfield tape generated by the RAMP2F nozzle solution. Finally, the exhaust plume is generated by using the nozzle solution and boundary layer solution to generate an exit plane start line that is used to initiate the plume solution. Thus, the generation of a high altitude plume could require up to four different executions of programs (TRAN72, RAMP2F, BLIMPJ, and RAMP2F) for the specification of the most detailed and accurate results. Physical input data are required only for the TRAN72 and first RAMP2F execution. All data required for the BLIMPJ code and second RAMP2F execution are generated internally to the program and/or communicated via temporary files.

Recently RAMP2 has been modified (Ref. 1) which will better handle nozzles which operate at a low chamber pressure and/or have high area ratio nozzles. Motors of these types may have boundary layers which contain a significant percentage of the mass flow of the motor. Large boundary layers can interact with the inviscid portion of the flow and alter the flowfield from what would be calculated, assuming a pure inviscid calculation. The original version of RAMP2 which was mentioned above (Ref. 5) could not account for the interaction of the boundary layer and the inviscid flowfield. RAMP2 made a single pass through the nozzle and performed a single boundary layer solution using the BLIMPJ code. These solutions were then merged at the exit plane and plume solution was performed.

The latest version of RAMP2 (Ref. 1) was used to calculate the GN2 thruster plume. This version allows a first order approximation of the interaction of the boundary layer and inviscid flowfield. The basic method involves making two passes through RAMP2 to calculate the nozzle flowfield and two passes through the BLIMPJ code to calculate the boundary layer. The first pass through the RAMP2 code calculates the nozzle flowfield using the original nozzle contour. After the first nozzle solution, the BLIMPJ code is executed using the conditions which exist at the nozzle wall (from the first nozzle solution) as the inviscid streamline boundary layer edge conditions. The results of this calculation including the boundary layer displacement thickness as a function of nozzle station are stored on FORTRAN Unit 2. RAMP2 is then reexecuted and the nozzle contour is modified using the displacement thickness information contained on Unit 2. After the modified contour flowfield solution is completed, BLIMPJ is again executed to calculate the nozzle boundary layer using edge conditions taken at the wall of the modified nozzle flowfield solution. While in the BLIMPJ solution, a check is made once the boundary layer calculations have been completed. If the pressure at the lip of the nozzle

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varies by more than 10% from the pressure at the inside edge of
the boundary layer in the inviscid solution (modified contour)
then another pass is made through BLIMPJ with the edge conditions
interpolated from the nozzle solution based on the location of
the boundary layer edge in the flowfield. These two passes are
made within the last BLIMPJ execution and require no intervention
by the user. This second pass is made to ensure that the
boundary layer and inviscid flowfield properties match at the
edge of the boundary layer.

While the latest version of the RAMP2 code was used to
calculate the OMV GN2 thruster nozzle/plume flowfield, the
multiple pass option was not utilized. The OMV GN2 nozzle has a
low area ratio (10) nozzle that will result in negligable
boundary layer effects on the inviscid flowfield. Additionally,
it was not necessary to use the TRAN72 program to calculate the
gas thermodynamics since the nitrogen gas can be treated as an
ideal gas having a constant molecular weight (28) and specific
heat ratio (1.4)

The GN2 engine specifications that were used as partial
input for this analysis are contained in Table 1. Table 2
contains the input files for the RAMP2 code. The RAMP2 flowfield
was calculated on the NASA/MSFC ED31 VAX. The VAX COM file for
executing the codes is shown in Table 3 (RAMP2).

The RAMP2 flowfield characteristics of the GN2 thruster
exhaust plume are shown in Figures 1-9. These figures present
isovalue contours of Mach number, static pressure, temperature,
pitot total pressures, density, velocity, mass flux, flow angle,
and constant mass flow streamlines. The RAMP2 binary output file
(Unit 3) is stored on the NASA/MSFC VAX and can be obtained by
contacting the NASA COR for this study.

3.2 GN2 Thruster Source Flow Plume Model

Recently, a model has been developed which fits the RAMP2
flowfield results using a source flow approximation. This model
called SFPGEN (Ref. 2) was developed to support a Space Station
Contamination Model developed by SEA, Inc. for NASA (Ref. 6).

The source flow plume model generator is a code which
determines the flow properties in the RAMP2 flowfield. The
SFPGEN code is based on the radial lookup code (Ref. 7, 8).
Modifications have been made to this code to determine the local
properties in the already computed RAMP2 flowfield and then
output a formatted file of a simple representation of the RAMP2
flowfield. Properties are determined at constant distances from
the exit plane as a function of angular distance from the plume

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axis. Ten of these source surfaces are determined at even increments of distance starting at the exit plane of the motor and terminating at the maximum distance on the axis in the RAMP2 plume. RAMP2 should be executed out to about 80-100 exit radii where all the gas streamlines no longer change slope. At each of the 10 data surfaces the local/centerline ratios of density, total enthalpy and temperature are determined as a function of angle off the axis, out to the maximum expansion angle. The maximum expansion angle is passed to the source flow module from RAMP2. In addition to the angular variation in properties, the code also generates an array which contains the flow property (density, velocity and total enthalpy) distribution along the axis. Twenty five points are used at even axial increments, starting at the exit plane and terminating at the last source station. A single set of mass flow averaged species distributions is also determined at the exit plane of the nozzle. A formatted output file (Unit 16) is then generated which can be passed on as input data to the Space Station Contamination Model or PLIMP code.

The source flow plume model has the advantage over other source models, in that it has the capability to include total temperature effects in the exhaust plume due to oxidizer/fuel distribution and nozzle wall boundary layer effects. This model does assume a constant specific heat ratio and molecular weight. The specific heat ratio and species distribution which is used are mass flow averaged values at the exit plane. Engines which are typically used for orbital application have high area ratios where the exit plane specific heat ratio is very close to what the specific heat ratios would be in the plume. Additionally (neglecting O/F ratio effects) the species at the exit plane are frozen and do not change in the plume. Previous comparisons of RAMP2 and SFPGEN show that SFPGEN results almost exactly match the RAMP2 calculations.

The baseline SFPGEN code used 10 radial distributions and 25 points on the axis to describe the flowfield. The radial distribution of flowfield properties is assumed constant from the nozzle exit plane up to the first source station. Therefore, in the near field (< 8 exit diameters), the SFPGEN flowfield properties can be in error due to the large gradients which are present near the exit plane.

Using this model during the checkout of PLIMP, the flowfield properties, as expected, in the near field differed enough to cause significant differences in predicted environments using the SFPGEN and RAMP2 plumes. To improve the near field results SFPGEN was modified to fit the plume with 25 source lines and up to 50 axis points. In addition, the source lines were made more

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concentrated in the near field through the use of a cosine distribution. The source lines also begin 1.5 exit radii from the exit plane. These modifications greatly increased the accuracy in the near field distribution while maintaining the fidelity in the far field. At high impingement angles, the boundary layer edge velocity (important for convective heating rate predictions) is very sensitive to local flow angle. The baseline SFPGEN code assumed that the local flow angle was the arctan (Y/X). For the far field, this assumption is valid. However, for the near field (< 10 diameters) and beyond 80 degrees where boundary layer effects are significant, this assumption can result in flow angles that are in error by as much as 7 degrees. To improve the flow angle prediction, flow angle was added to the local/centerline ratios at each source line. This modification improved the flow angle prediction to $\pm$ 1.5 degrees. A detailed description of the SFPGEN program can be found in Reference 2.

The major advantages of using the SFPGEN code to produce a flowfield are: the flowfield is portable between different computers; the flowfield requires considerably less computer storage than the RAMP2 flowfield; auxiliary (induced environments) calculations are considerably faster using a source flow plume; the source flow plume can be extended to much larger distances than are practical for running the RAMP2 code; and the model can be easily used by other codes.

The RAMP2 flowfield description is stored on a binary file which requires that the same computer type be used to generate the plume and perform application calculations. The SFPGEN flowfield output is a formatted ASCII file that can be easily transported from computer to computer without rerunning the RAMP2 code. Thus, once a particular RAMP2 flowfield is generated, the SFPGEN flowfield can be transferred to other organizations very easily without the cost of rerunning the RAMP2 plume.

A typical RAMP2 binary flowfield file requires on the order of 4-5 megabytes of mass storage. The SFPGEN flowfield requires about .06 megabytes of storage. Thus, the computer resource requirements are significantly reduced.

Considerable time is spent by application codes (PLIMP, Ref. 9, 10) in looking up flowfield properties in a RAMP2 flowfield. Timing tests performed using RAMP2 and SFPGEN flowfields show that PLIMP runs 3-4 times faster using a SFPGEN flowfield. For applications which require significant PLIMP calculations, significant reductions in computer resources can be realized.

Reference 6 contains a description of the original routines

which use this data file to determine local flow properties in the plume. These routines have been subsequently modified and copies of these routines, as well as the MRE 15 SFPGEN data file, are maintained on the NASA/MSFC VAX and can be obtained from the NASA - COR. These routines will be particularly useful to organizations that are interested in plume induced environments to payloads being deployed or retrieved by the OMV.

Figures 10 - 16 show the flowfield characteristics of the GN2 SFPGEN plume. These figures present isovalve contours of Mach number, static pressure, temperature, pitot total pressure, density, velocity and mass flux, respectively.

4.0 Conclusions

This report provides a detailed description of the Oribital Maneuvering Vehicle GN2 thruster exhaust plume flowfield characteristics calculated with the RAMP2 and SFPGEN codes. Included in the report are brief descriptions of the two models, GN2 thruster characteristics and RAMP2 input data files. The RAMP2 flowfield could be recalculated by other organizations using the information contained in this report. The GN2 flowfield can be readily used by other organizations who are interested in GN2 plume induced environments which require local flowfield properties which can be supplied using the SFPGEN GN2 model.

References

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5. Smith, S.D., "High Altitude Supersonic Flow of Chemically Reacting Gas-Particle Mixtures - Volume III - RAMP2 - Computer Code User's and Applications Manual," Lockheed Missiles & Space Co., Huntsville, AL, LMSC-HREC TR D867400-III, October 1984.

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7. Smith, S.D., "Description of a Computer Program to prepare an Axisymmetric Flowfield Tape for the Gaseous Radiation Program", LMSC-HREC D225753, Lockheed missiles & Space Co., Huntsville, AL, March 1972.

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9. Penny, M.M. and C.J. Wojciechowski, "User's Manual and Description of a Computer Program for Calculating Heating Rates, Forces and Moments Acting on Bodies immersed in Rocket Exhaust Plumes," LMSC-HREC D162867-II, Lockheed Missiles & Space Company, Huntsville, AL, March 1971.

10. Smith, S.D., "Development of a Nozzle/Plume and Plume Impingement Code," CIFR008, Continuum, Inc., Huntsville, AL, November 1986.

Table 1. GN2 Thruster Specifications

Inlet Pressure (psia)	276-315
Nominal Thrust (lbf)	5
Area Ratio	10
Chamber Pressure (psia)	63
Chamber Temperature (°F)	530
Throat Diameter (in)	.25 ± .001
Propellant	Nitrogen
Nozzle	15° Conical
Adiabatic Nozzle Wall	
Nozzle Length (Throat to Exit) (In)	1.0241

Table 2

RAMP 2 Input Data Files For GN2 Thruster

OMVGN2UN5A.DAT

```
    0    3    2    0
 OMV COLD GAS NOZZLE/PLUME GN2  PC=63 PSIA  TC=530 R
   31     3000003    100207   11  203            0                     12570
.01041667
1  0       -1.0      .108506-030.0        -1.0      -.02083333.002696031
2  1        0.0       0.0        0.0        .267949192.010049206.085342523
3          .73      -05                    0.0       0.0       0.0      1000.
2                     0.0        0.0       0.0       0.0       1000.       0.0
NITROGEN PC=63                  MKS        1         1         365.1067
365.1067
0.0                 1
0.0      28.1340    1.400      294.4       4.28688   .6667     .198  -03  .7
0.0       0.0       1.01        0.0        657.192095          0.0   0.0
0.6      -4.0       0.0         0.0        5.0       90.0       .04   0.0
.005      .0015     1000.       .005       5.        .95
          1
N2
1.        0    0     1    0              0.0300
   0
N2
```

OMVGN2UN5B.DAT

```
  1    3    2    0    000
```

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Table 3

Listing of RAMP2 VAX COM File for GN2 Thruster

```
$ SET DEF [033013.RAMP.OMVGN2]
$ ASSIGN OMVGN2.OUT FOR006
$ ASSIGN OMVGN2UN7.DAT  FOR007
$ ASSIGN OMVGN2UN8.DAT  FOR008
$ ASSIGN OMVGN2UN9.DAT  FOR009
$ ASSIGN OMVGN2UN3.DAT  FOR003
$ ASSIGN [033013.RAMP]CECTHERM.R2F FOR004
$ ASSIGN OMVGN2UN5A.DAT      FOR005
$ ASSIGN OMVGN2UN1.DAT  FOR001
$ ASSIGN OMVGN2UN2.DAT  FOR002
$ ASSIGN OMVGN2UN12.DAT FOR012
$ ASSIGN OMVGN2UN13.DAT FOR013
$ ASSIGN OMVGN2UN14.DAT FOR014
$ ASSIGN OMVGN2UN17.DAT FOR017
$ ASSIGN OMVGN2UN11.DAT FOR011
$ RUN [033013.RAMP.SOURCE]RAMP
$ ASSIGN BLIMPJ.OUT FOR006
$ RUN [033013.RAMP.SOURCE.BLIMPJ]BLIMPJ
$ ASSIGN OMVGN2UN20.DAT FOR020
$ ASSIGN OMVGN2UN5B.DAT FOR005
$ COPY OMV1GN2UN3A.DAT OMVGN2UN3.DAT
$ ASSIGN OMVGN2.OUT1 FOR006
```
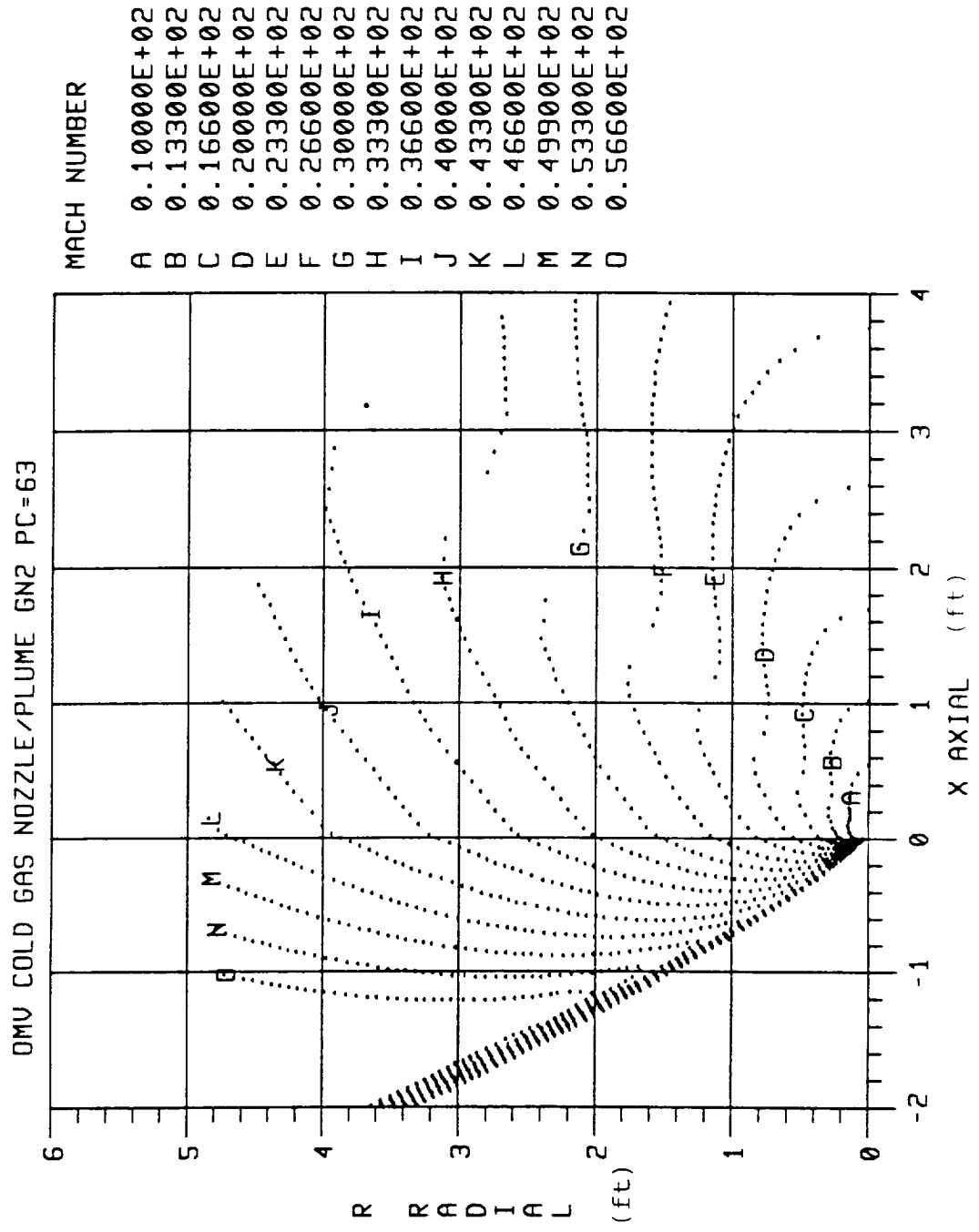
Figure 1. Mach Number Contours for GN2 Thruster Exhaust Plume
Calculated Using RAMP2
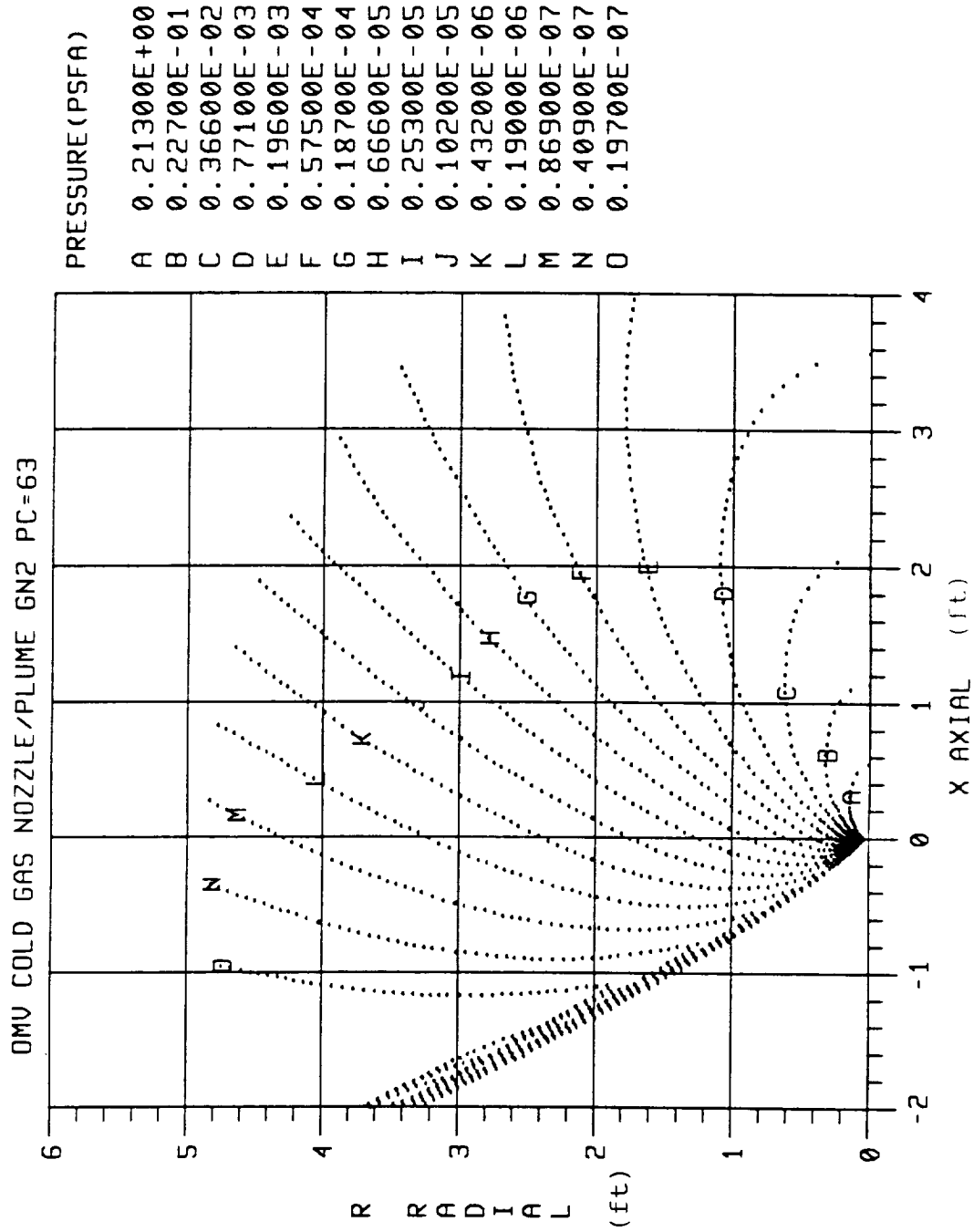
Figure 2. Pressure Contours for GN2 Thruster Exhaust Plume
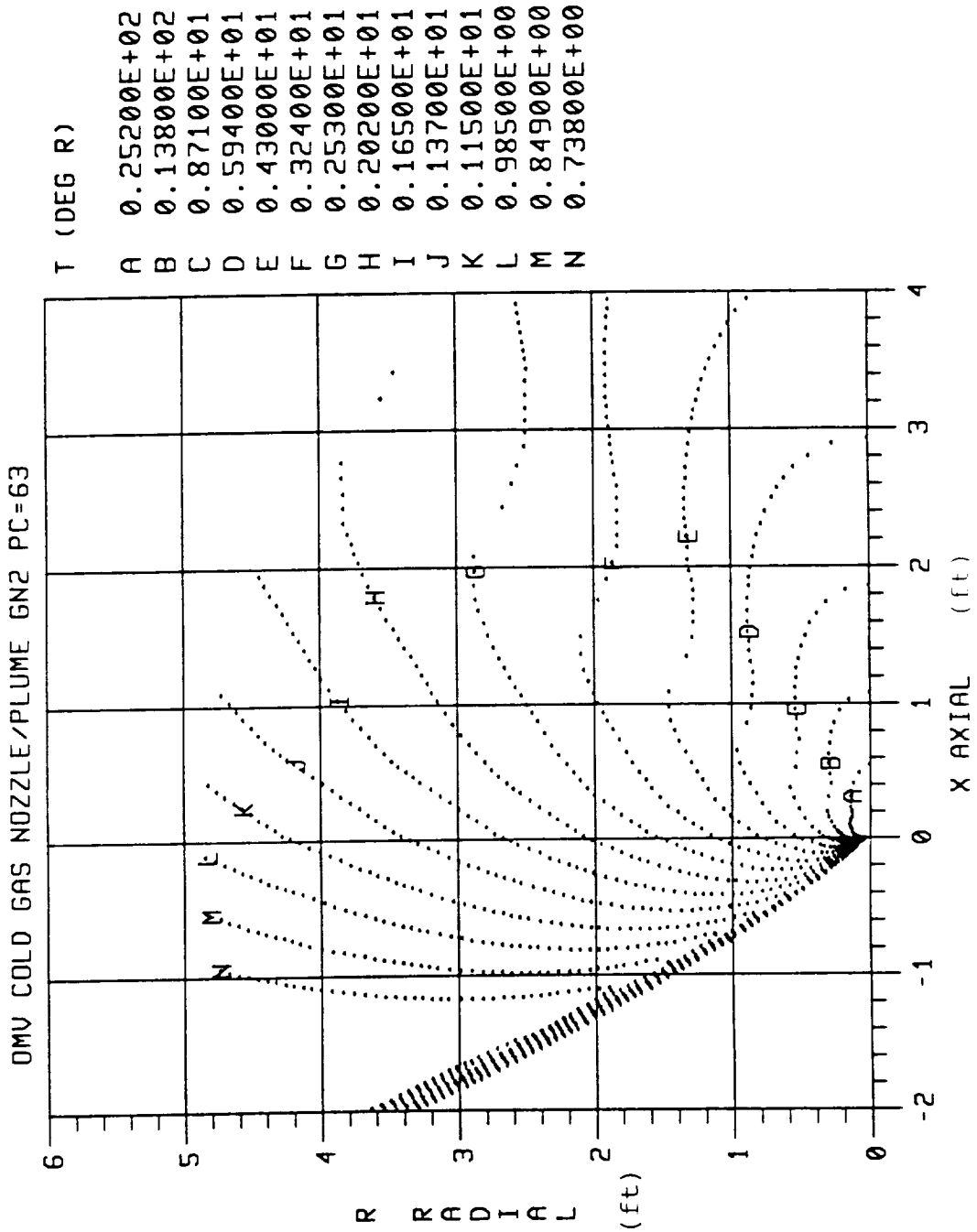Calculated Using RAMP2

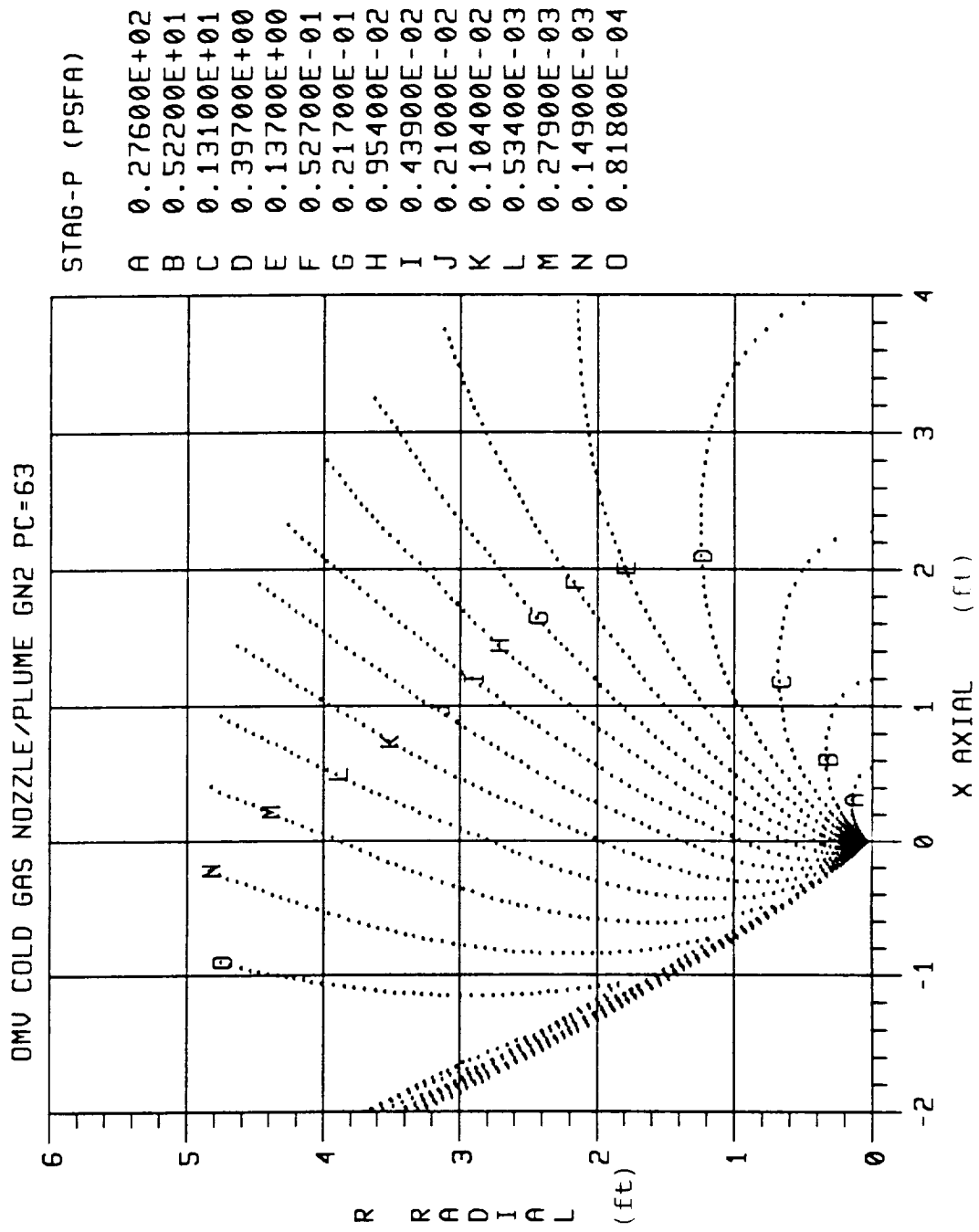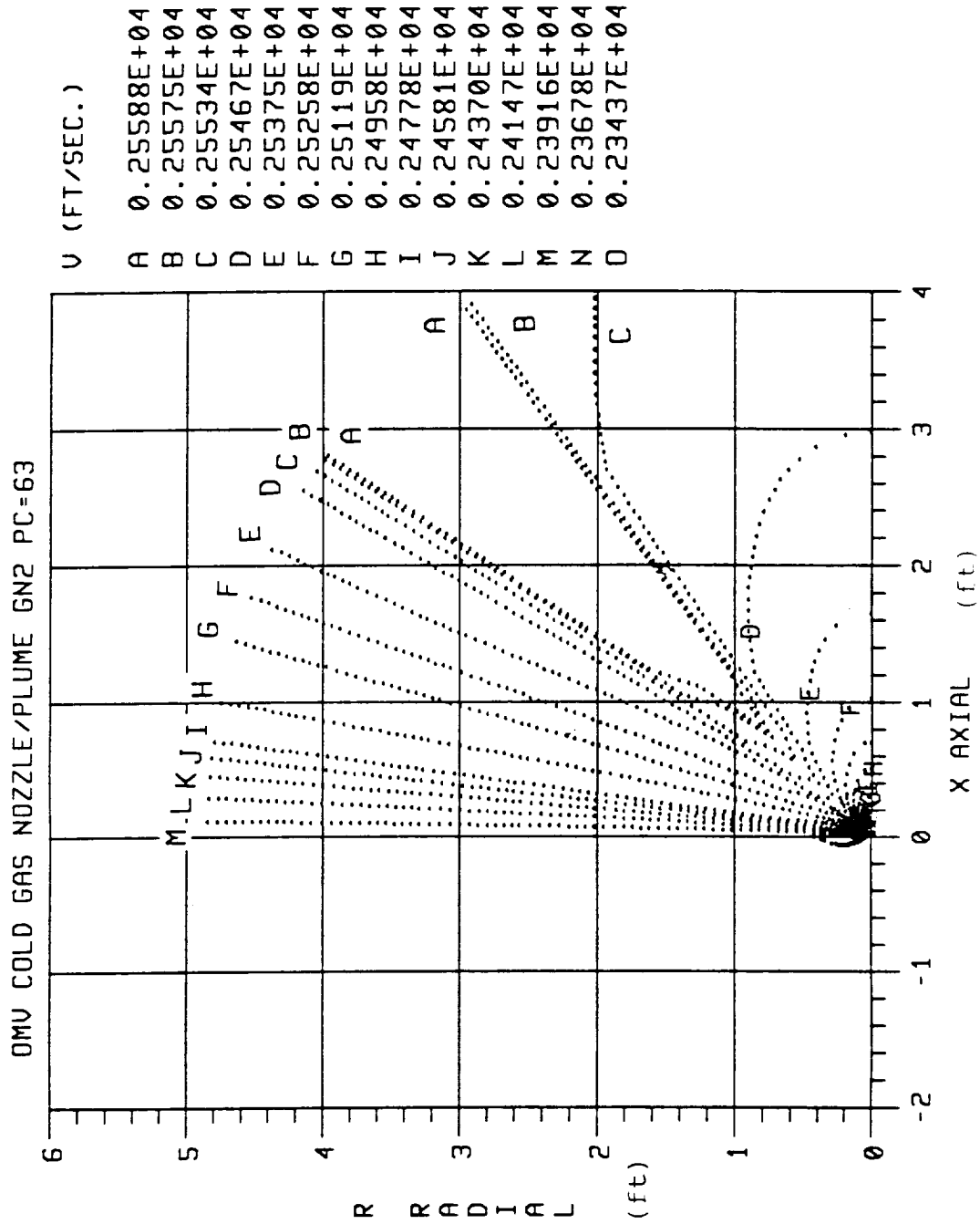Figure 3. Temperature Contours for GN2 Thruster Exhaust Plume Calculated Using RAMP2

OMV COLD GAS NOZZLE/PLUME GN2 PC=63

STAG-P (PSFA)

A 0.27600E+02
B 0.52200E+01
C 0.13100E+01
D 0.39700E+00
E 0.13700E+00
F 0.52700E-01
G 0.21700E-01
H 0.95400E-02
I 0.43900E-02
J 0.21000E-02
K 0.10400E-02
L 0.53400E-03
M 0.27900E-03
N 0.14900E-03
O 0.81800E-04

X AXIAL   (ft)

R R A D I A L   (ft)

Figure 4.   Pitot Total Pressure Contours for GN2 Thruster Exhaust Plume
Calculated Using RAMP2

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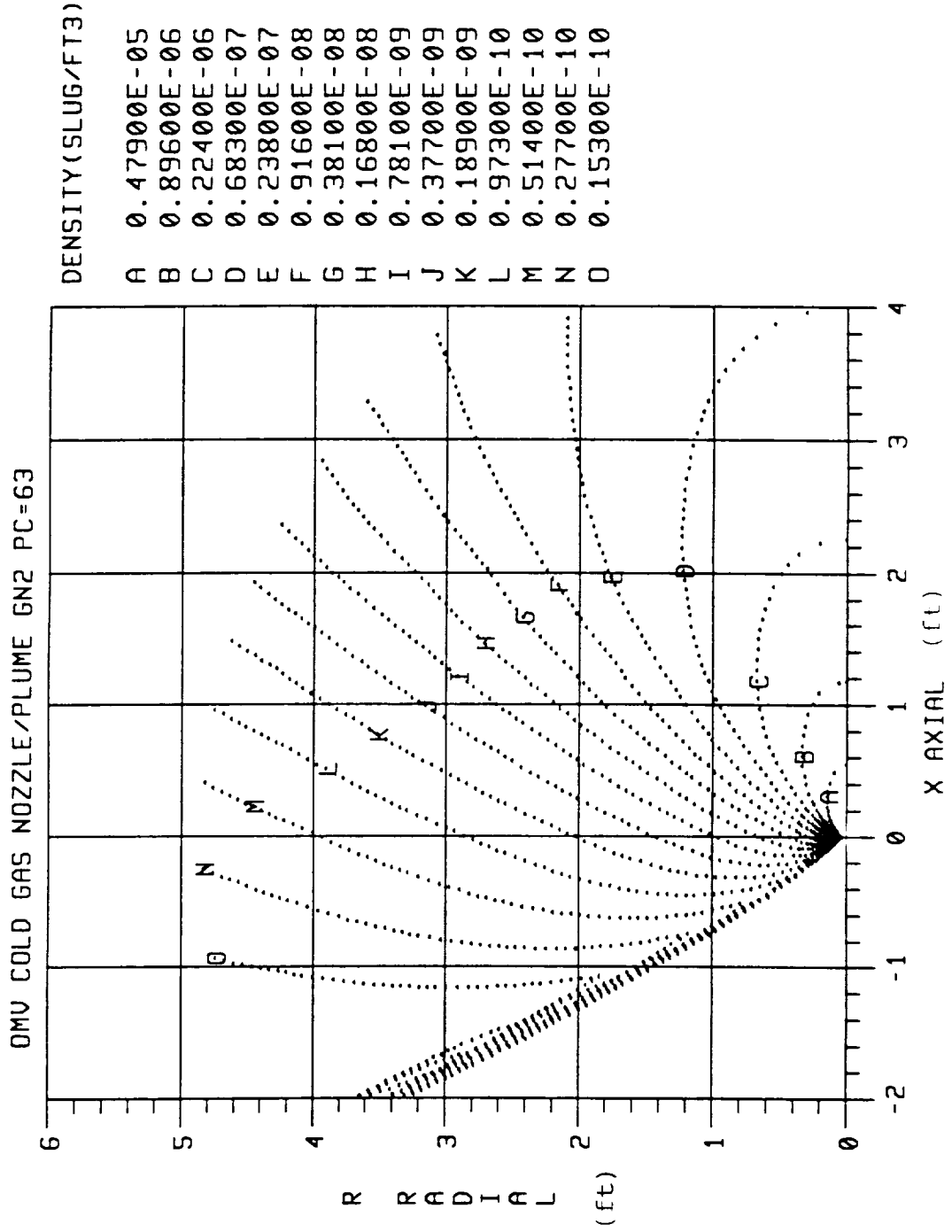
Figure 5. Density Contours for GN2 Thruster Exhaust Plume
Calculated Using RAMP2

Figure 6. Velocity Contours for GN2 Thruster Exhaust Plume
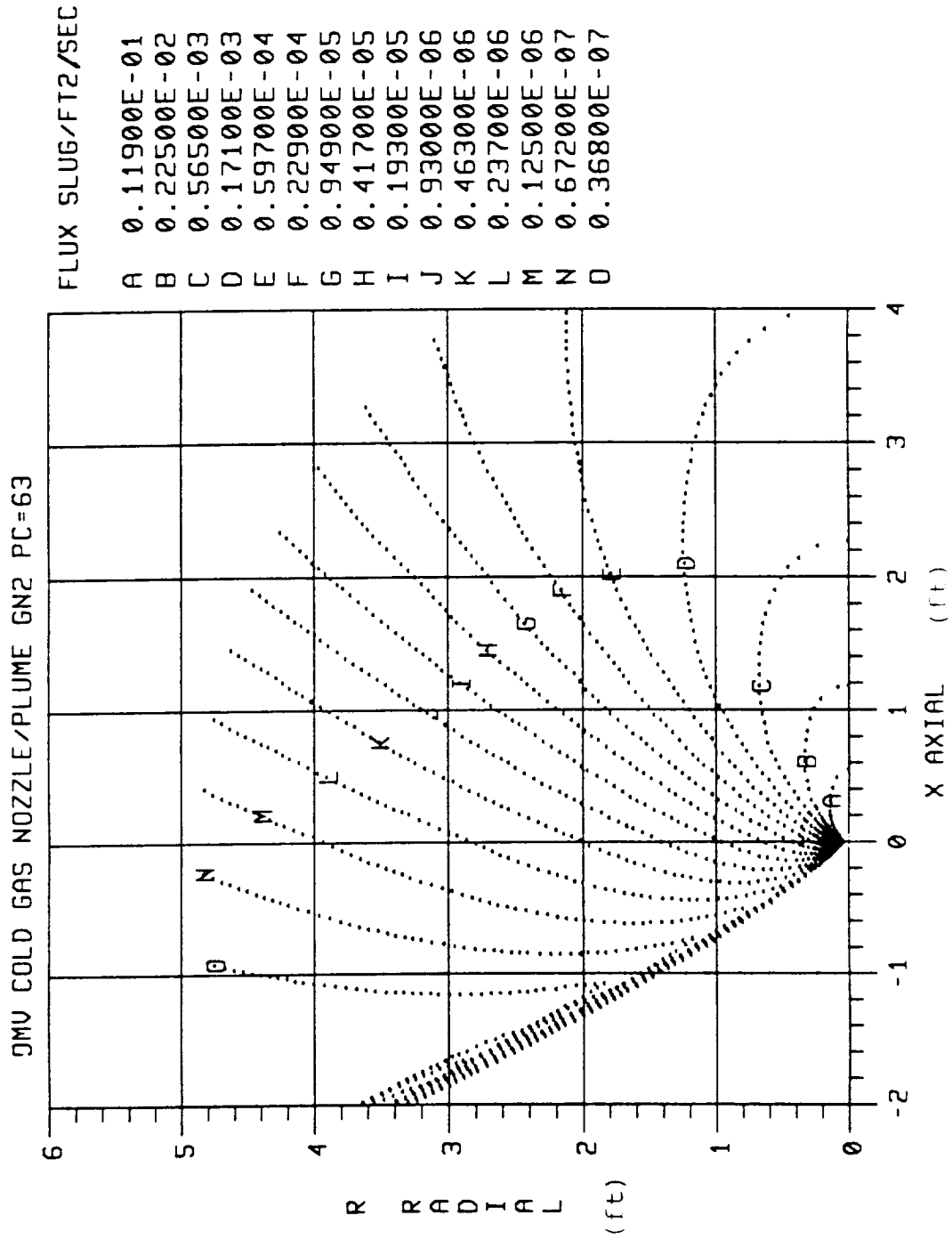Calculated Using RAMP2

Figure 7. Mass Flux Contours for GN2 Thruster Exhaust Plume
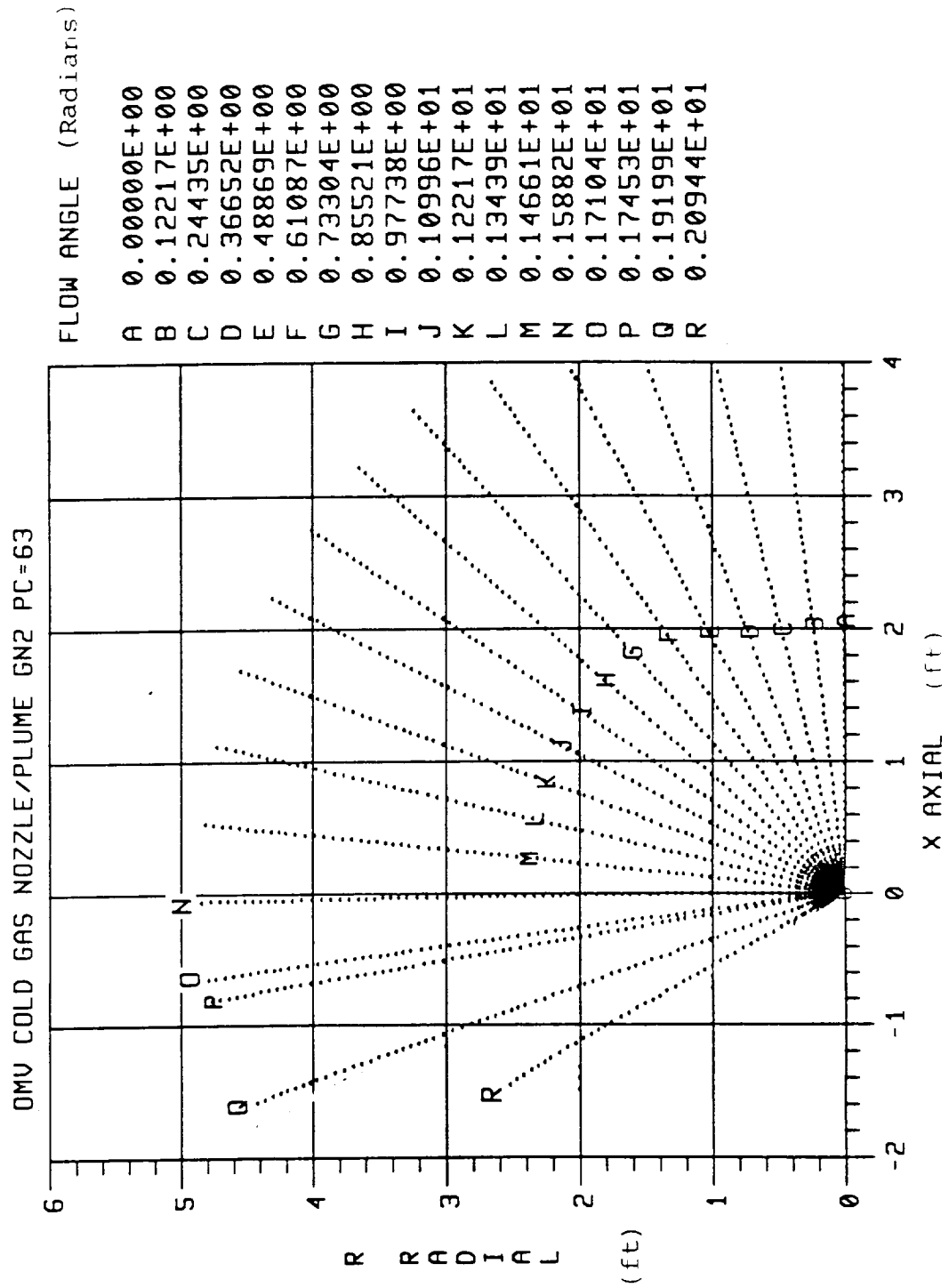Calculated Using RAMP2

Figure 8. Flow Angle Contours for GN2 Thruster Exhaust Plume Calculated Using RAMP2
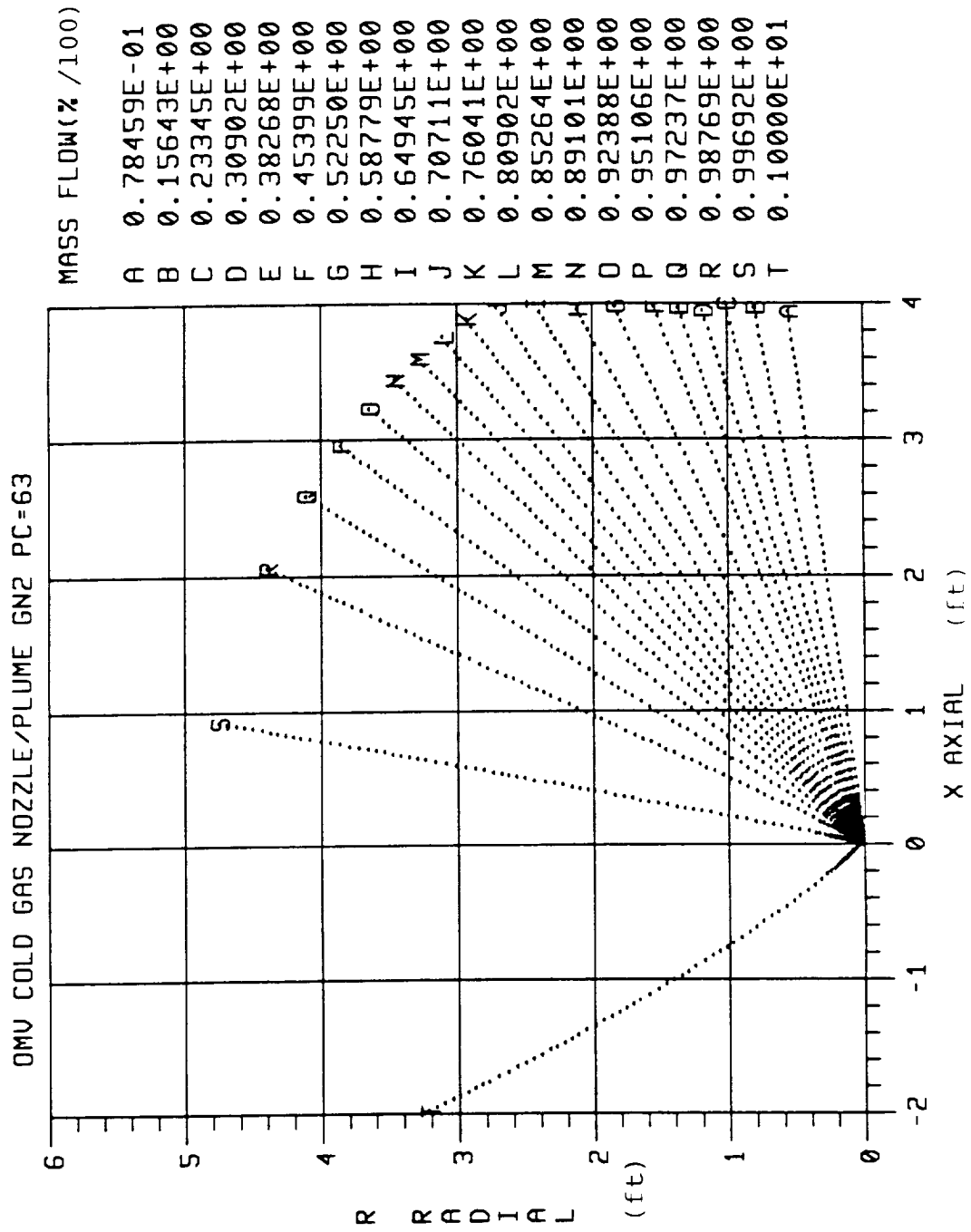
Figure 9. Mass Flow Contours for GN2 Thruster Exhaust Plume Calculated Using RAMP2
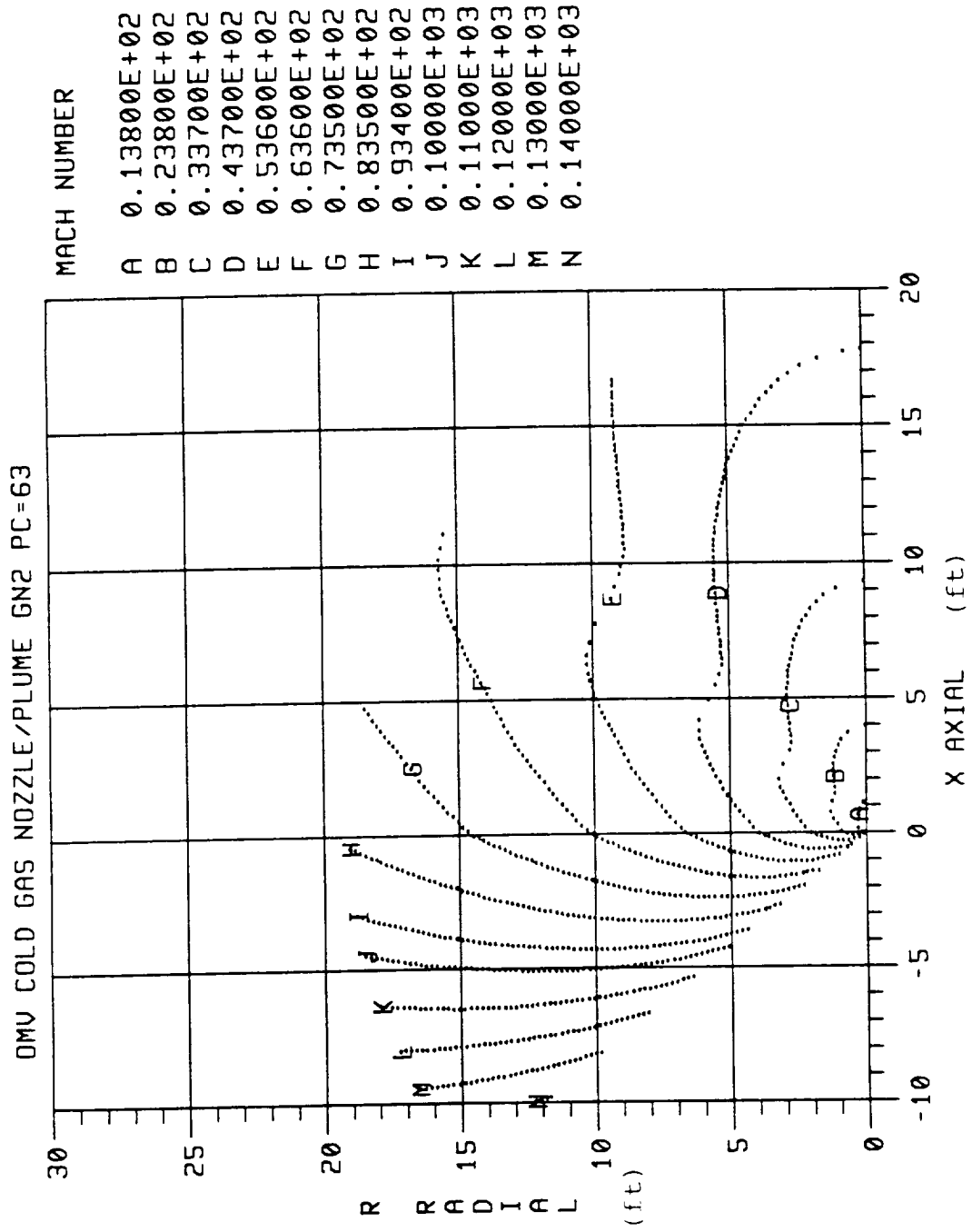
C 2

OMU COLD GAS NOZZLE/PLUME GN2 PC=63

MACH NUMBER

A 0.13800E+02
B 0.23800E+02
C 0.33700E+02
D 0.43700E+02
E 0.53600E+02
F 0.63600E+02
G 0.73500E+02
H 0.83500E+02
I 0.93400E+02
J 0.10000E+03
K 0.11000E+03
L 0.12000E+03
M 0.13000E+03
N 0.14000E+03

X AXIAL (ft)

RRADIAL (ft)

Figure 10.   Mach Number Contours for GN2 Thruster Exhaust Plume
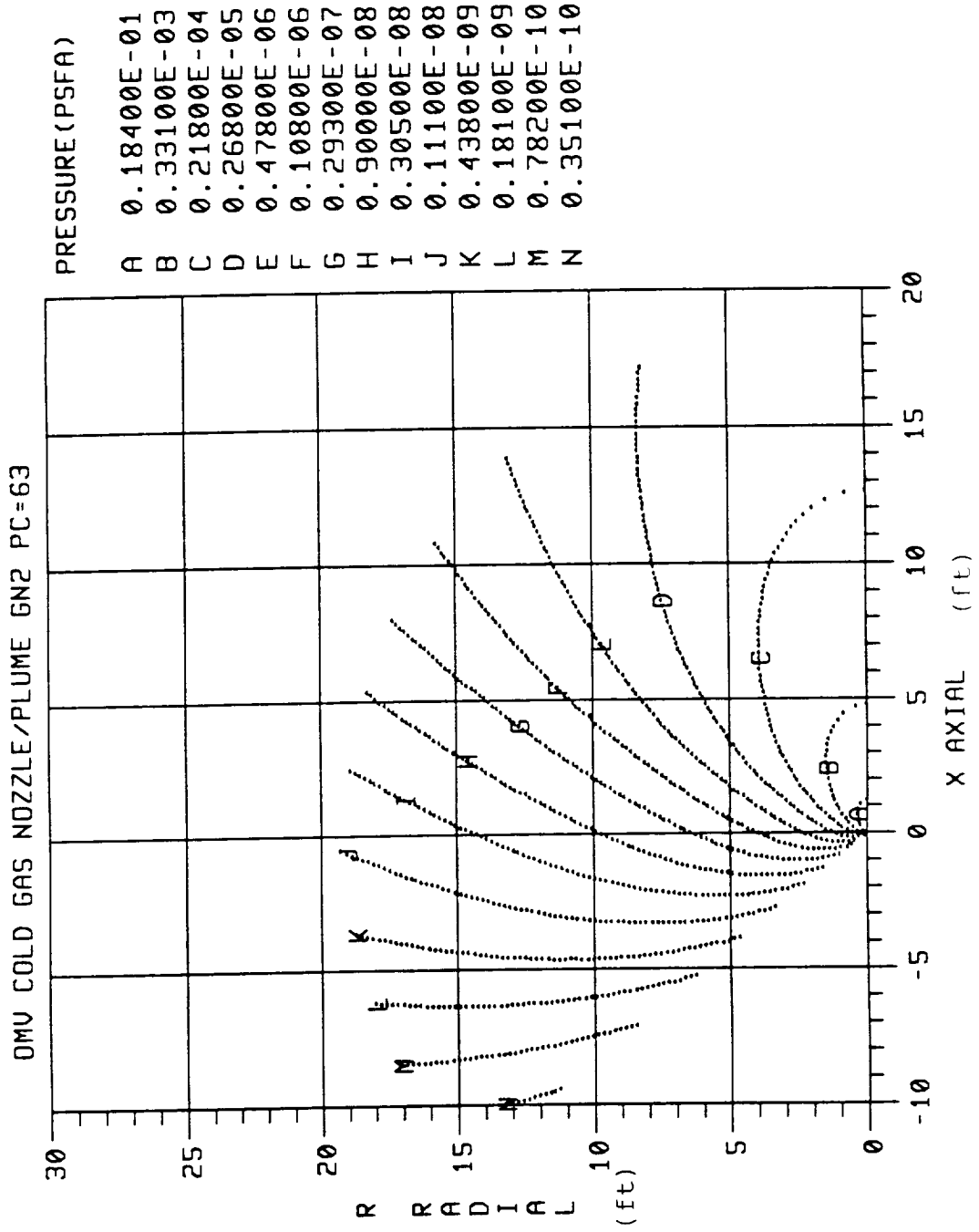Calculated Using SFPGEN

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Figure 11. Pressure Contours for GN2 Thruster Exhaust Plume
Calculated Using SFPGEN

Figure 12. Temperature Contours for GN2 Thruster Exhaust Plume Calculated Using SFPGEN

OMU COLD GAS NOZZLE/PLUME GN2 PC=63

STAG-P (PSFA)

A	0.45700E+01
B	0.24200E+00
C	0.32000E-01
D	0.66100E-02
E	0.17700E-02
F	0.56600E-03
G	0.20400E-03
H	0.80800E-04
I	0.34300E-04
J	0.15400E-04
K	0.72500E-05
L	0.35500E-05
M	0.17900E-05
N	0.92700E-06

Figure 13. Pitot Total Pressure Contours for GN2 Thruster Exhaust Plume Calculated Using SFPGEN

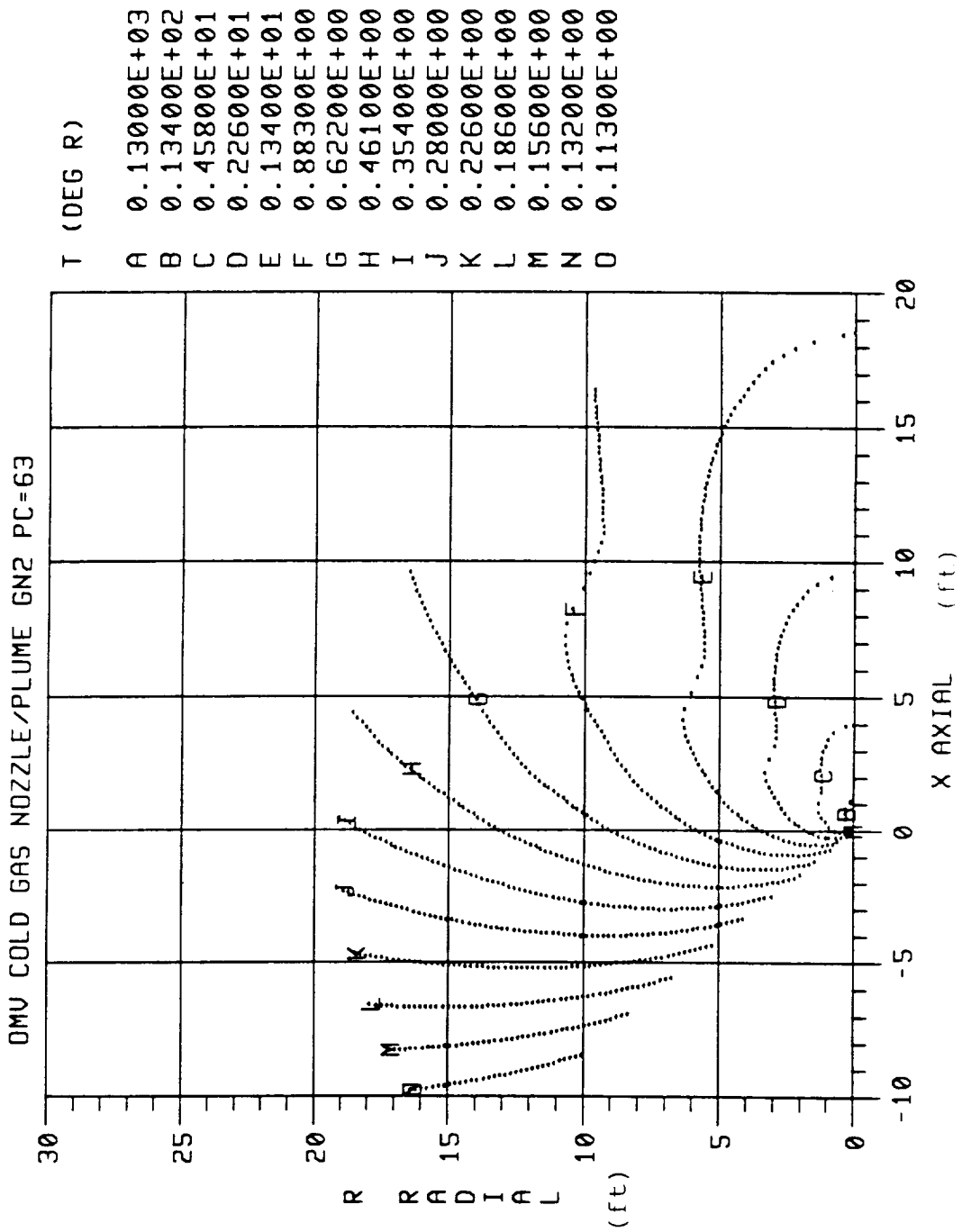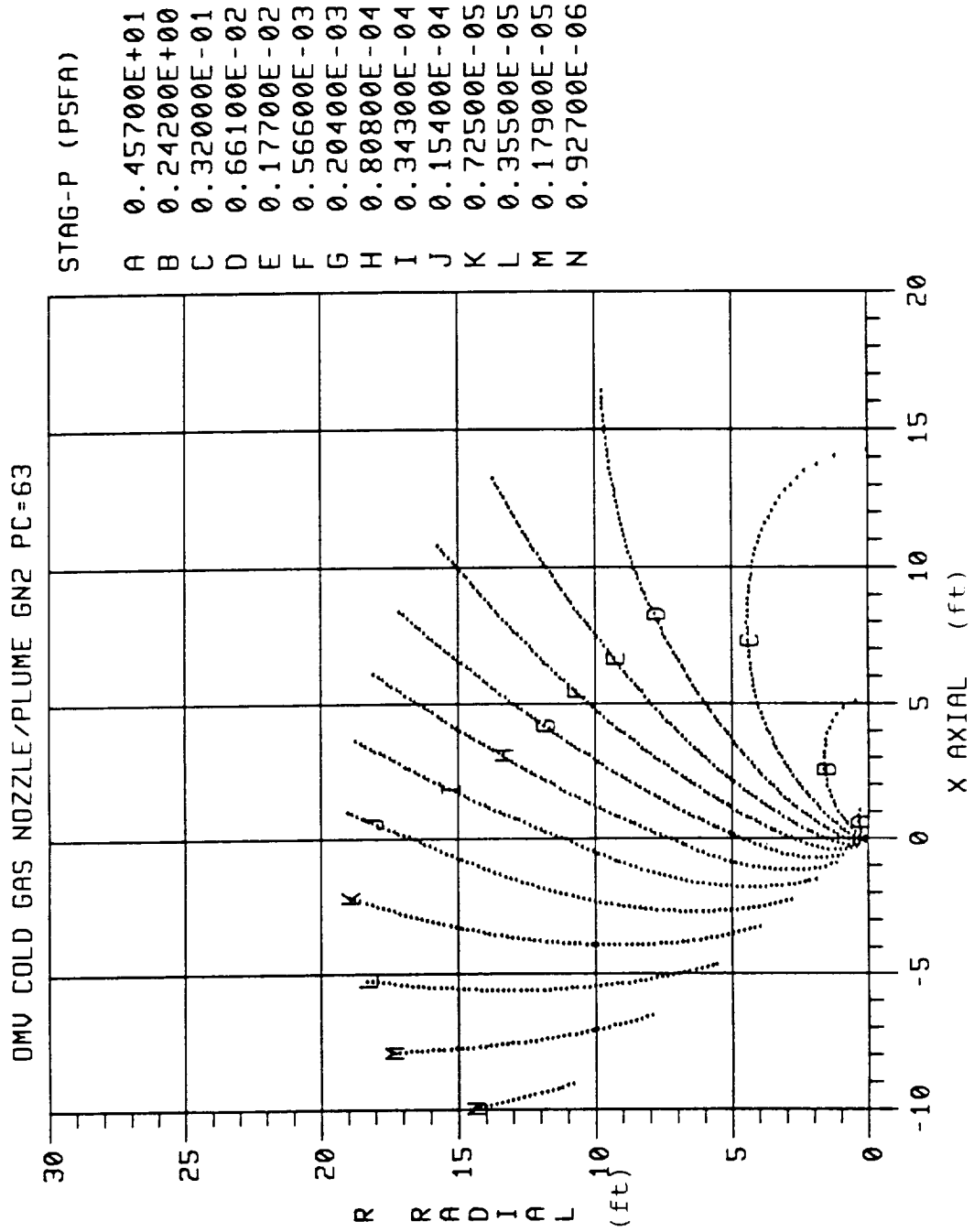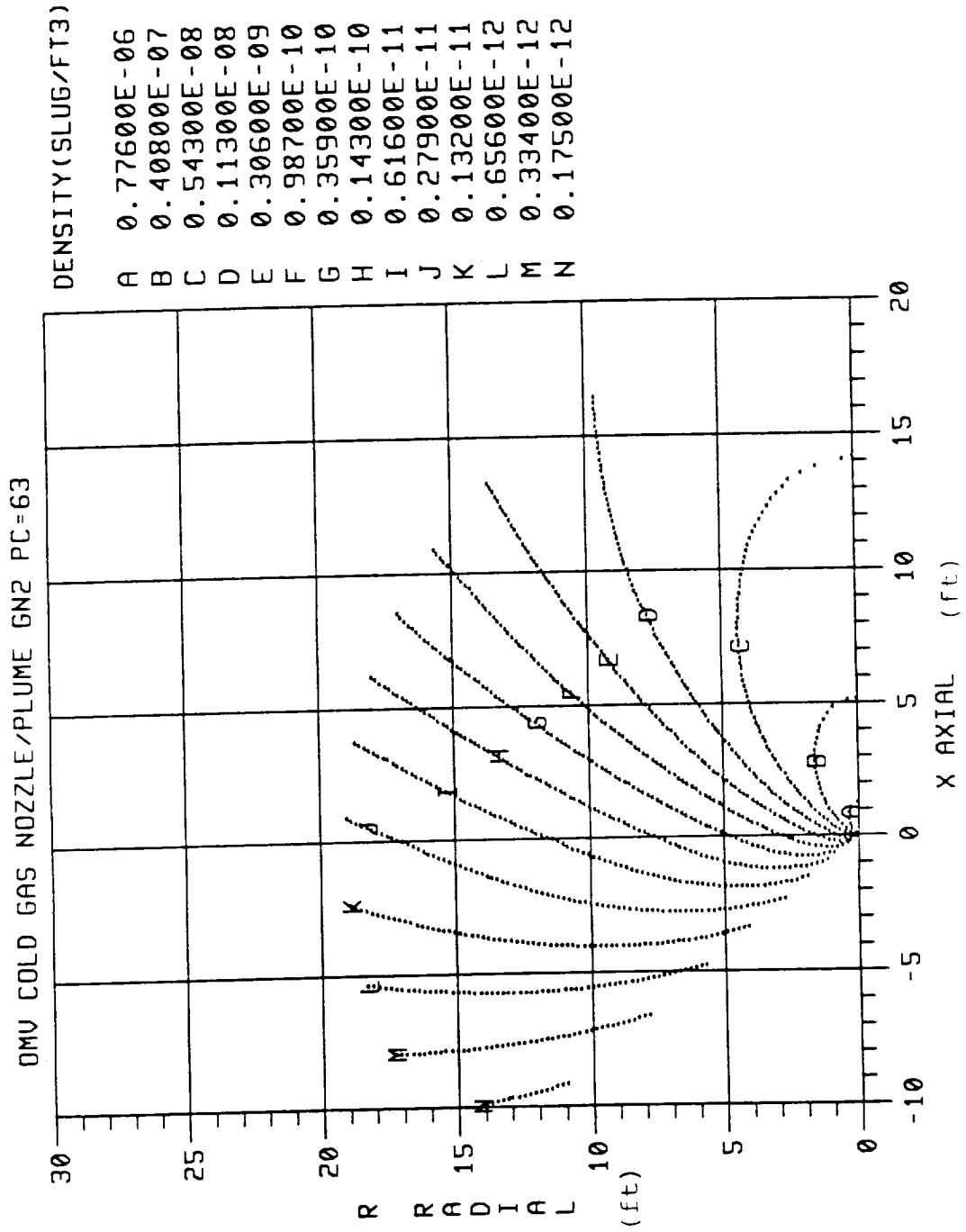Figure 14. Density Contours for GN2 Thruster Exhaust Plume
Calculated Using SPGEN

OMV COLD GAS NOZZLE/PLUME GN2 PC=63

DENSITY(SLUG/FT3)

A 0.77600E-06
B 0.40800E-07
C 0.54300E-08
D 0.11300E-08
E 0.30600E-09
F 0.98700E-10
G 0.35900E-10
H 0.14300E-10
I 0.61600E-11
J 0.27900E-11
K 0.13200E-11
L 0.65600E-12
M 0.33400E-12
N 0.17500E-12

24

OMV COLD GAS NOZZLE/PLUME GN2 PC=63

U (FT/SEC.)

A 0.25707E+04
B 0.25685E+04
C 0.25620E+04
D 0.25513E+04
E 0.25364E+04
F 0.25177E+04
G 0.24952E+04
H 0.24694E+04
I 0.24404E+04
J 0.24088E+04
K 0.23748E+04
L 0.23390E+04
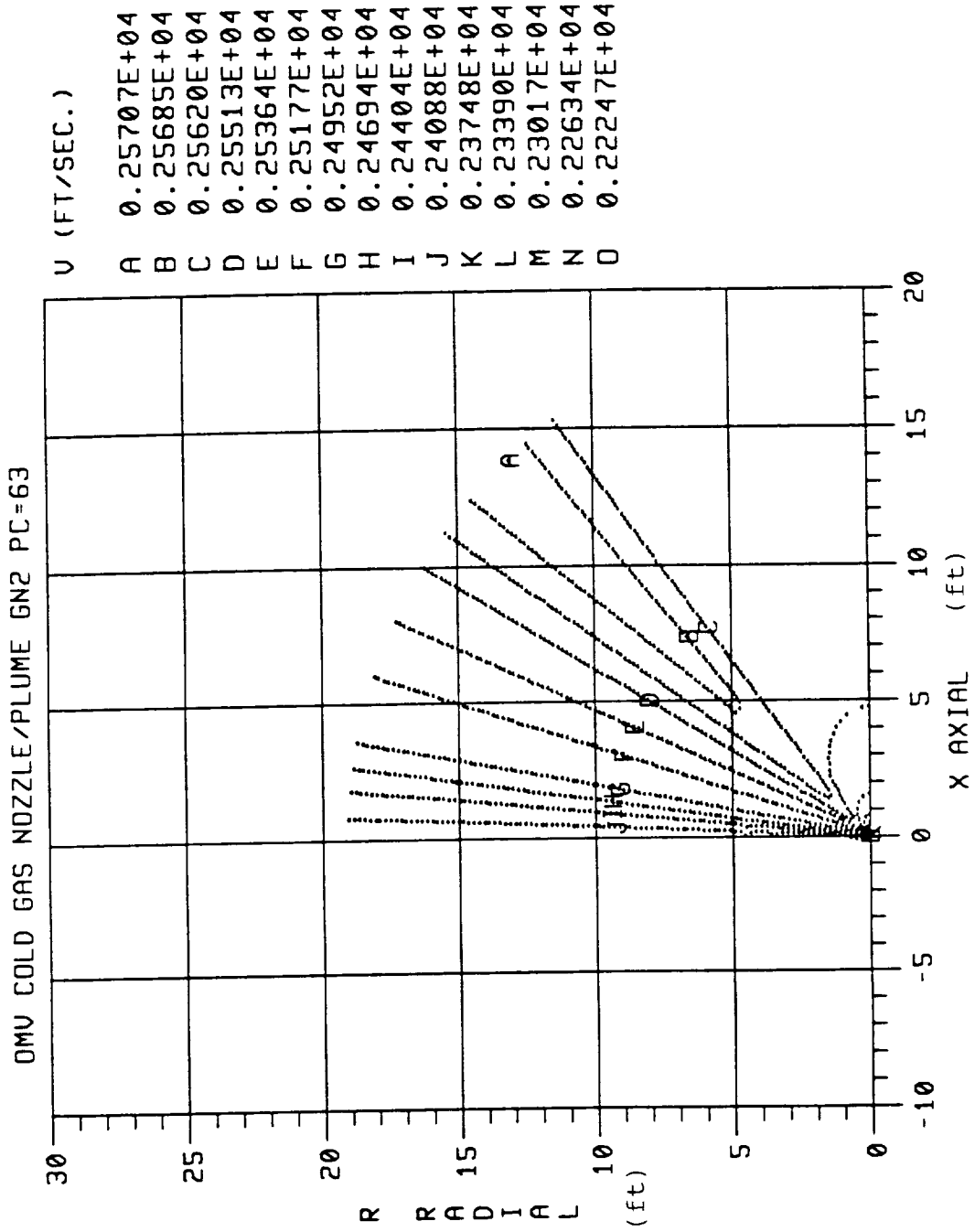M 0.23017E+04
N 0.22634E+04
O 0.22247E+04

Figure 15. Velocity Contours for GN2 Thruster Exhaust Plume
Calculated Using SPGEN