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HIGH-ALTITUDE PLUME COMPUTER CODE DEVELOPMENT
FINAL REPORT

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FOREWORD

This document presents the results of work performed by the Computational Mechanics Section of the Lockheed Missiles & Space Company, Inc., Huntsville Engineering Center, for NASA-Marshall Space Flight Center, Huntsville, Alabama.

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1. INTRODUCTION

The Space Shuttle has become an accomplished spacecraft and space carrier of varied payloads. As this new era of space usage evolved, it became necessary to develop a set of plume/plume impingement computer codes for high altitude or vacuum applications. The flowfield codes developed for low altitude plume calculations were used as a basis to accomplish the high altitude computations.

The basic plume/plume impingement codes are: (1) Method-of-Characteristics (MOC); (2) Reacting and Multiphase (RAMP2F); (3) Source Flow Plume; (4) Plume Impingement (PLIMP); (5) Radial Lookup; and (6) Contour Plot. An outline of the application and capabilities of these codes is shown in Table 1. The sequencing and communication of the several auxiliary programs with the main flowfield prediction code (RAMP2F) are shown in Fig. 1.

A systematic approach to plume/plume impingement calculations was developed. The procedure starts with the assignment of a rocket motor, propellant, and its envelope of operation. Propellant properties are required to input the thermochemical program, TRAN72 (Ref. 1). Sources for these properties are found in the TRAN72 documentation and in the JANNAF Propellant Handbook (Ref. 2).

The choice of flow calculation program required to calculate a rocket motor plume is dictated by the type of motor and the desired results. Motors with solid particles need the capabilities of the RAMP2F code. The MOC program can treat discrete shocks exactly. Far-field plumes may require the use of the Source Flow Plume Program for economy or accuracy reasons.

Table 1 LOCKHEED-HUNTSVILLE PLUME/PLUME IMPINGEMENT METHODOLOGY

Code	Application
Method-Of-Characteristics Program (MOC)	2D Planar/Axisymmetric, Real/Perfect Gas, Inviscid, Supersonic Plume Flowfield Calculation • Includes NASA-Lewis Chemical Equilibrium Composition and Transport Property Calculation (CEC/TRAN72)
Reacting and Multi-Phase Program (RAMP2F)	2D Planar/Axisymmetric, Two-Phase, Reacting Gas, Inviscid, Transonic/Supersonic Plume Flowfield Calculation • Includes NASA-Lewis Chemical Equilibrium Composition and Transport Property (CEC/TRAN72) Calculation • Includes Acurex Boundary Layer Integral Matrix Procedure (BLIMPJ) Nozzle Boundary Layer Calculation • Includes Kliegel Two-Phase Transonic Nozzle Calculation • Includes Finite Rate Gas Phase Chemistry Option
Source Flow Plume Program	Source Flow Approximation Plume Flowfield Calculation
Plume Impingement Program (PLIMP)	Calculates Plume Impingement Forces, Moments, and Heating Rates on Specified Body Surfaces Using MOC, RAMP2F or Source-Flow Plumes as Input
Radial Lookup Program (Gas/Solid Particle)	Organizes Plume Flowfield Data Along Lines of Constant Axial Station and Provides Data Interface for Other Plume Post Processors
Contour Plot Program (Gas/Solid Particle)	Produces Contour Plots of Plume Flowfield Properties

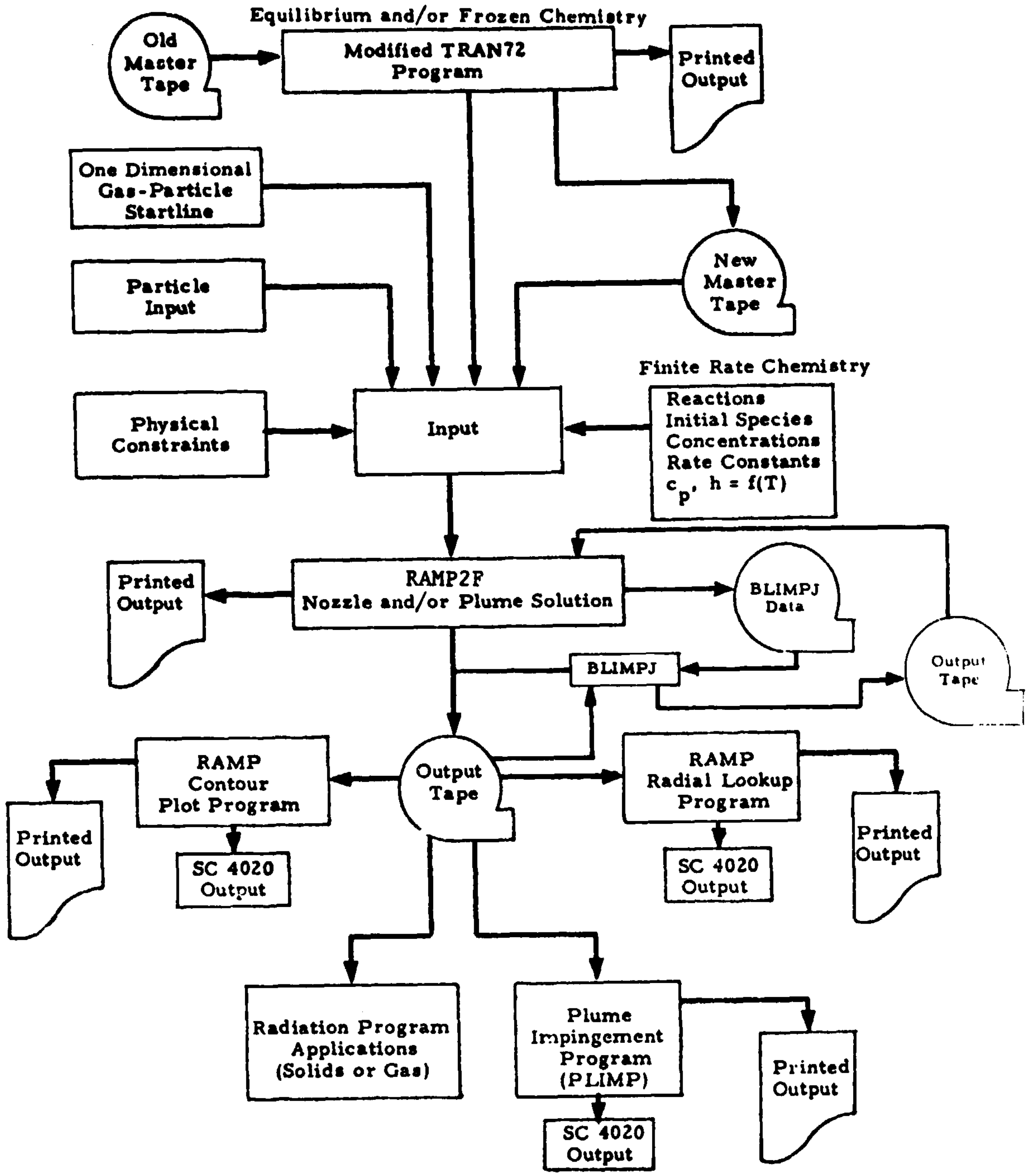

Fig. 1 Sequencing and Communication of Auxiliary Programs with the RAMP2F Program

With the RAMP2F and MOC programs the flow inside the nozzle can be calculated. The procedure for transforming either tabulated nozzle coordinates or nozzle drawings to radius of curvatures or smoothly joining line segments is detailed in the RAMP2F input guide (Ref. 3). The steps outlined in Ref. 3 will ensure that each portion of the nozzle geometry is input as a continuous surface without breaks unless a particular break (sharp change in slope) is desired.

For trend studies during the design phases, the description of the flow through the nozzle is not required. In these situations either the RAMP2F and MOC program can be used to start the calculation at the exit plane area ratio. The flow up to that point is treated as a one-dimensional expansion. Evaluations of different propellants and chamber operating conditions can be made quickly even before nozzle geometries have been defined.

The Radial Lookup and Contour Plot programs are used to organize and present the plume properties. The contour plot program is useful in describing plume structure such as the plume boundary, expansion, and shock flow regions. Constant value lines of specified physical parameters such as temperature or pressure further describe the plume structure. The Radial Lookup program gives detailed profiles for various physical parameters across the plume at prescribed axial stations.

The Plume Impingement (PLIMP) program uses the calculated plume as input and determines the impingement forces, moments and heating on a surface immersed in the plume. PLIMP can use a flow field calculated by RAMP2F, MOC or the Source Flow Program as an input plume. The flexibility of the PLIMP program provides the capability for the calculation of high altitude applications such as space stations.

2. HIGH ATTITUDE PLUME CALCULATIONS

To checkout the calculation procedure and to determine that all the necessary programs were operational in the high altitude regime, a sample case was executed. A case of interest was the Space Shuttle Reaction Control System (RCS) motor operating at near vacuum conditions. This motor is representative of those used in high altitude applications on space vehicles, satellites, or space stations. The RCS motor is a bipropellant motor and has the following characteristics:

Throat Radius	0.08508333 ft
Area Ratio (Unscarfed)	22.1
Chamber Pressure	153.0 psia
Chamber Temperature	5467 R
Chamber Molecular Weight	20.199
Chamber Specific Heat Ratio	1.1613
Fuel	Monomethylhydrazine (MMH)
Oxidizer	Nitrogen Tetroxide (N_2O_4)
Oxidizer-to-Fuel Ratio	1.63

Additionally experimental values for the pitot total pressure radial distributions are available from Ref. 4 for this motor at a position of 3.75 ft from the exit plane. A schematic of the RCS motor is shown in Fig. 2. The RCS nozzle coordinates are presented in Fig. 3. The tabulated nozzle coordinates were prepared for input to the RAMP2F program using the smoothing procedure described by Smith in Ref. 3. The resultant RCS boundary values are shown in Table 2.

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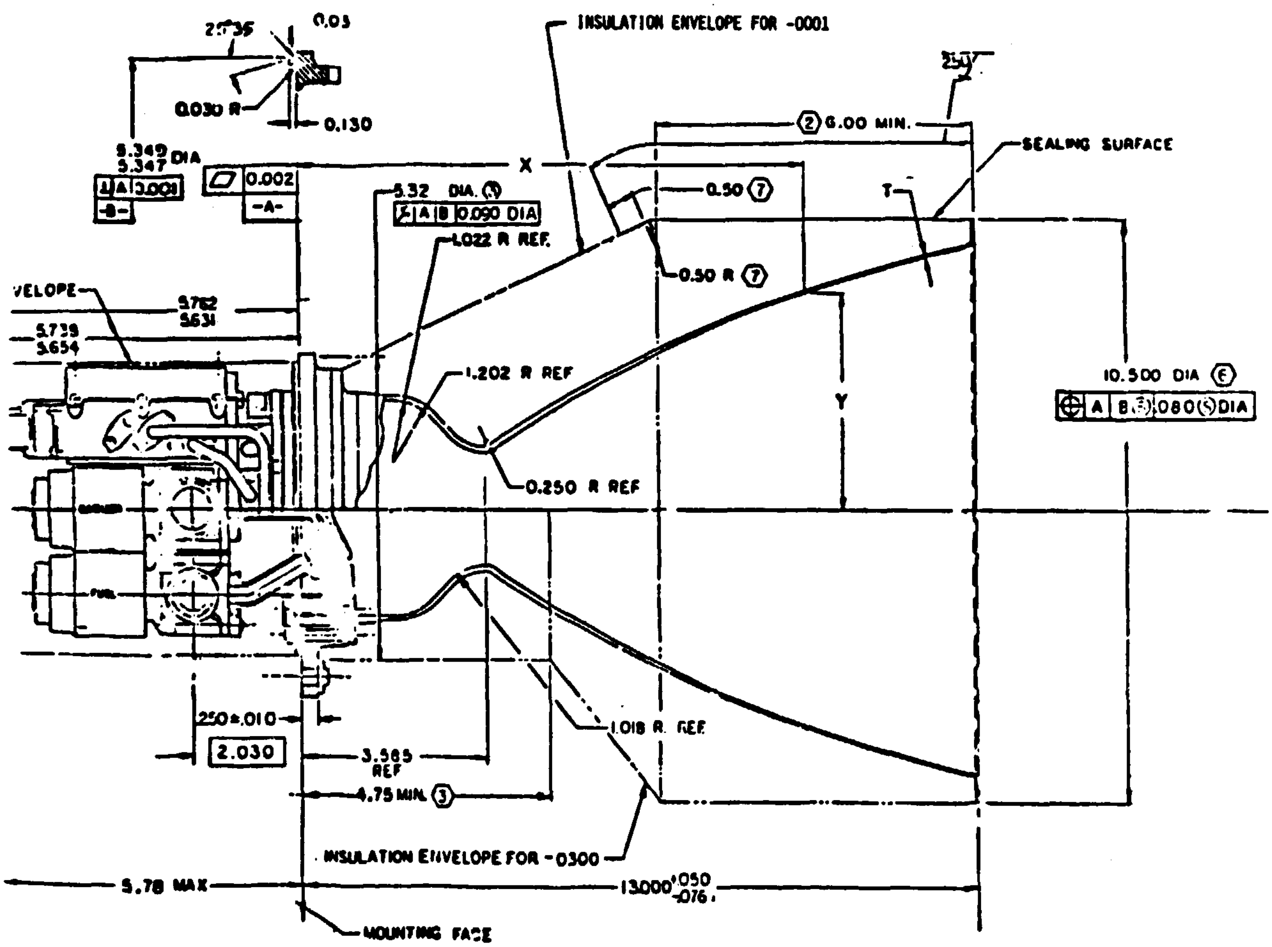

Fig. 2 Shuttle Reaction Control System Rocket Motor

Axial Distance from Throat, (in.) x	Radius (in.) y
0.0	1.021
0.135	1.059
0.241	1.126
0.374	1.210
0.506	1.294
0.615	1.365
0.755	1.455
0.874	1.530
1.000	1.609
1.135	1.693
1.243	1.760
1.359	1.830
1.500	1.913
2.000	2.201
3.000	2.720
4.000	3.166
5.000	3.560
6.000	3.909
7.000	4.211
8.000	4.489
9.000	4.729
9.300	4.799

Fig. 3 Space Shuttle Reaction Control Nozzle Contour

Table 2 SPACE SHUTTLE REACTION CONTROL SYSTEM MOTOR SMOOTHED WALL CONTOUR

Axial Distance From Throat (ft)	Radial Position (ft)	Wall Inclination (deg)
-.137719	0.155417	0.0
-.134747	0.155365	-2.0
-.131778	0.1552092	-4.0
-.128817	0.154950	-6.0
-.125866	0.154588	-8.0
-.120012	0.153556	-12.0
-.114244	0.152117	-16.0
-.111401	0.151248	-18.0
-.105815	0.149215	-22.0
-.100385	0.146797	-26.0
-.095219	0.144006	-30.0
-.082975	0.135491	-40.0
-.072478	0.124994	-50.0
-.068725	0.120181	-54.106921
-.064986	0.115387	-50.0
-.059986	0.109930	-45.0
-.054530	0.104931	-40.0
-.042417	0.096449	-30.0
-.037189	0.093669	-26.0
-.031779	0.091261	-22.0
-.026215	0.089235	-18.0
-.020523	0.087603	-14.0
-.017638	0.086937	-12.0
-.014731	0.086372	-10.0
-.011807	0.085909	- 8.0
-.008868	0.085548	- 6.0
-.005918	0.085290	- 4.0
-.002961	0.085135	- 2.0
.000000	.085083	.00000
.000833	.085100	2.292400
.001667	.085150	4.588590
.003333	.085350	9.206860
.005000	.085692	13.886780
.006667	.086175	18.663000
0.008333	0.086825	23.578300
0.0091667	0.087208	26.10388

Table 2 (Concluded)

Axial Distance From Throat (ft)	Radial Position (ft)	Wall Inclination (deg)
0.010000	0.087642	28.685000
0.0104180	0.087875	30.00230
0.011250	0.088383	30.327800
0.0200830	0.093833	31.90230
0.031200	0.100833	32.28
0.042200	0.107833	32.70
0.051300	0.113750	33.01
0.062900	0.121250	32.58
0.072800	0.127500	32.13
0.083300	0.134083	31.98
0.094600	0.141083	31.86
0.103600	0.146670	31.45
0.113300	0.152500	30.77
0.125000	0.159417	30.20
0.166700	0.183417	28.52
0.250000	0.226667	25.88
0.333300	0.263833	22.87
0.416700	0.296667	20.23
0.500000	0.325750	17.97
0.583300	0.350917	16.22
0.666700	0.374083	14.22
0.750000	0.394083	13.15
0.775000	0.399917	13.12

The RCS nozzle and plume flow fields were calculated using the MOC and the RAMP2F codes. Several cases were executed to ensure operation of the various options of the program.

Both MOC and RAMP2F were run using equilibrium chemistry through the nozzle and rerun using an equilibrium/sudden freeze criteria for the nozzle flow. A comparison of the difference in Mach number radial distribution at the exit plane caused by the chemistry assumptions for each code is shown in Fig. 4. The difference in the radial temperature profile at the nozzle exit caused by starting the solution at the throat for RAMP2F and MOC or using the RAMP2F transonic portion of the code to generate a start line is shown in Fig. 5. The inclusion of boundary layer effects has a dramatic impact on the plume boundary location for near vacuum plumes. This is demonstrated by the comparison of RAMP2F plume boundaries with and without the boundary layer calculated (Fig. 6).

Calculations were also made of the radial Mach number distributions throughout the RCS plume at several axial locations. The Mach number profiles shown in Fig. 7 demonstrate the smoothing of the gradients across the plume as the flow travels farther from the nozzle. Comparison of several of the plume calculation results with experimental pitot total pressure data (Ref. 4) is made in Fig. 8. The ideal gas computations gave close agreement with the data but the results were considered from past experience to be fortuitous. The two constant O/F cases gave pitot total pressures that were higher than the experimental data. The best match of data was for the equilibrium/ frozen, variable O/F representation of the plume.

The O/F distribution developed by Smith (Ref. 3) was used to perform the variable O/F analysis. The rationale used for obtaining the distribution is repeated here from Ref 3.

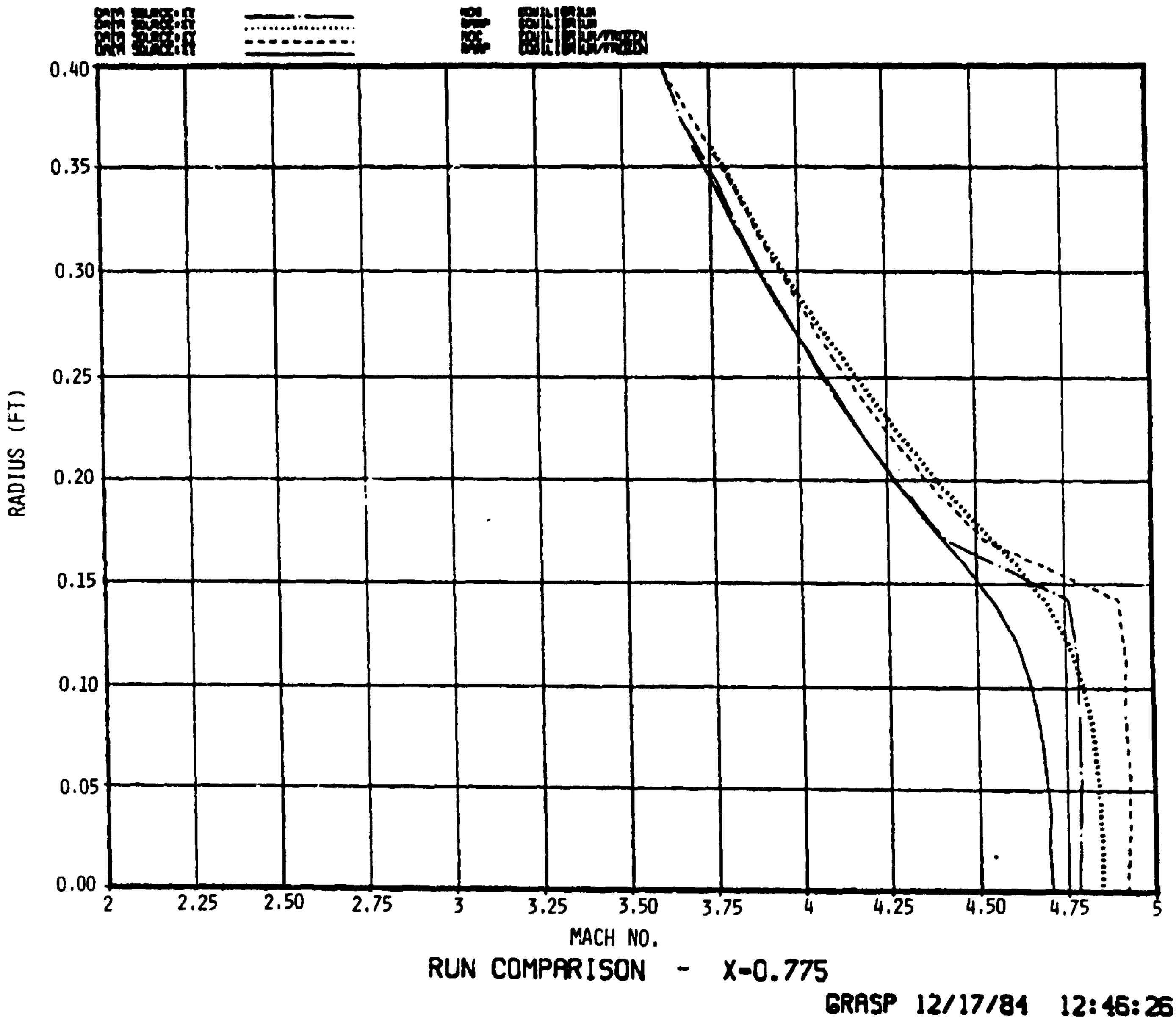

Fig. 4 Reaction Control System Motor Exit Plane Mach Number Distribution

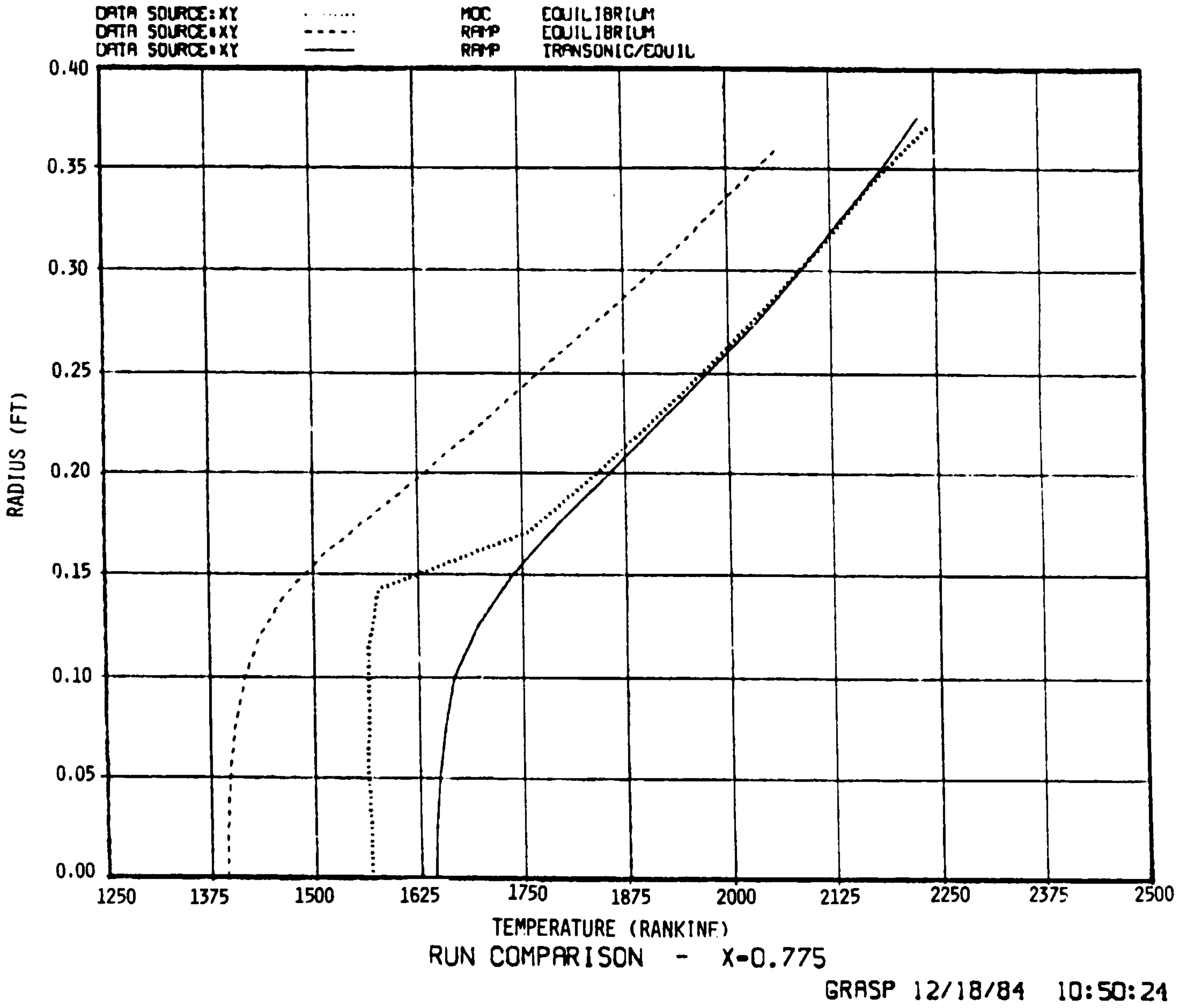

Fig. 5 Reaction Control System Motor Exit Plane Temperature Distribution

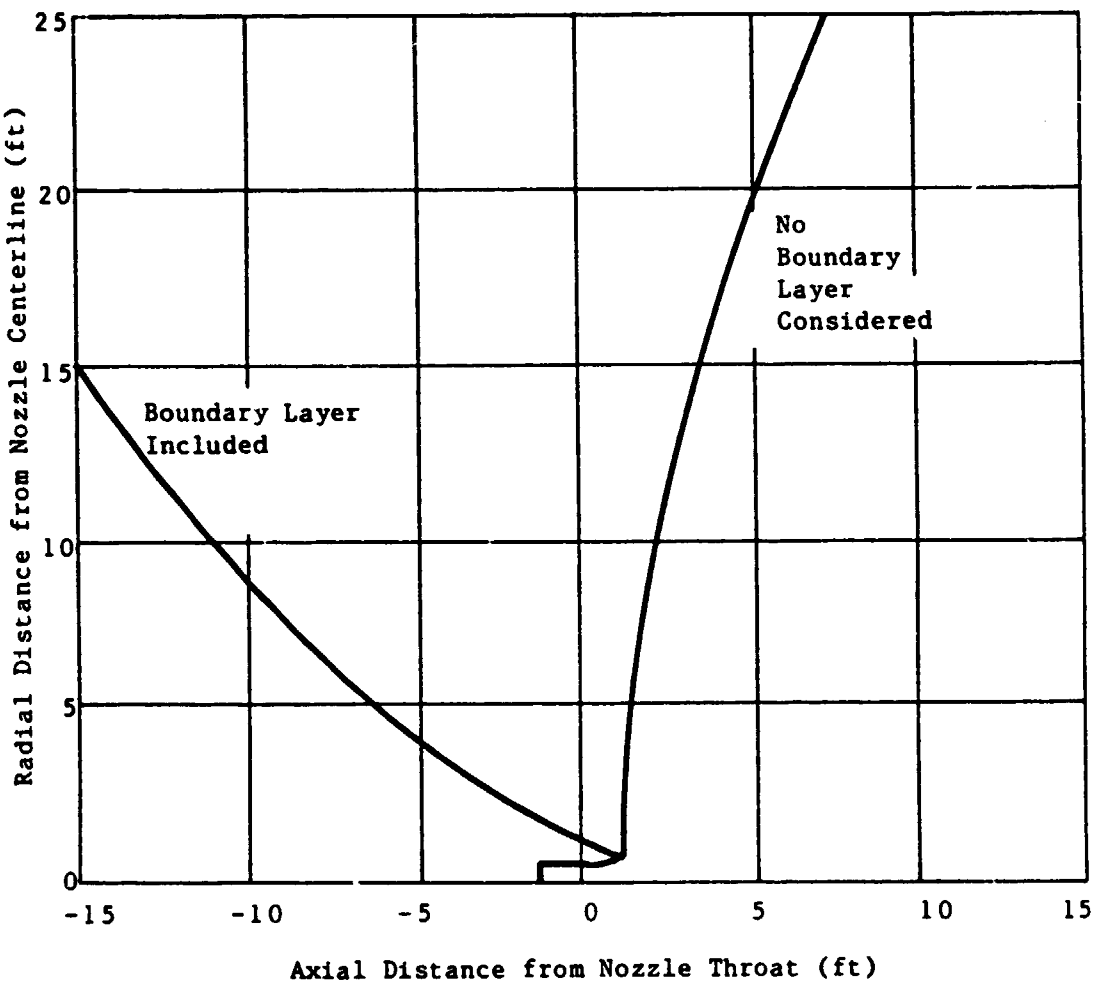

Fig. 6 Space Shuttle Reaction Control System Motor Exhaust Plume Boundary

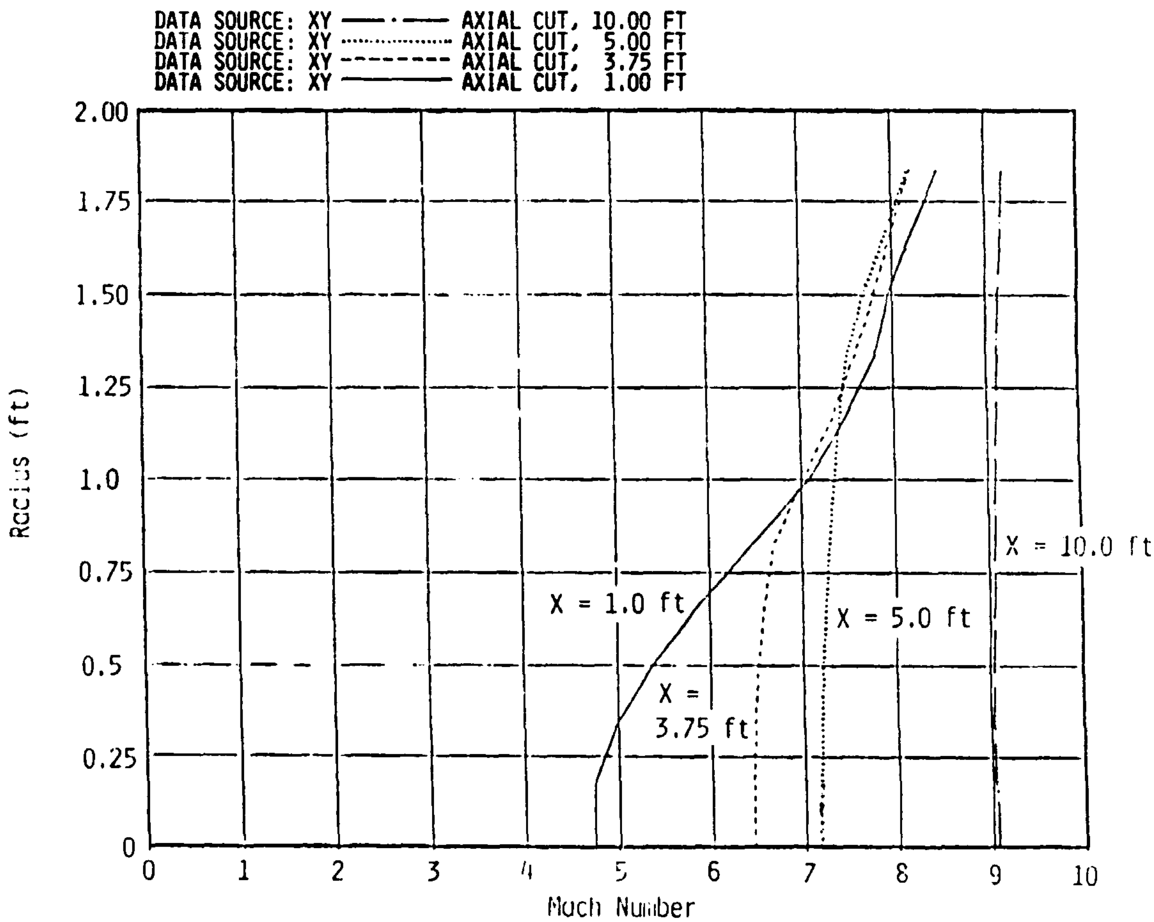

Fig. 7 Reaction Control System Plume Mach Number Distribution

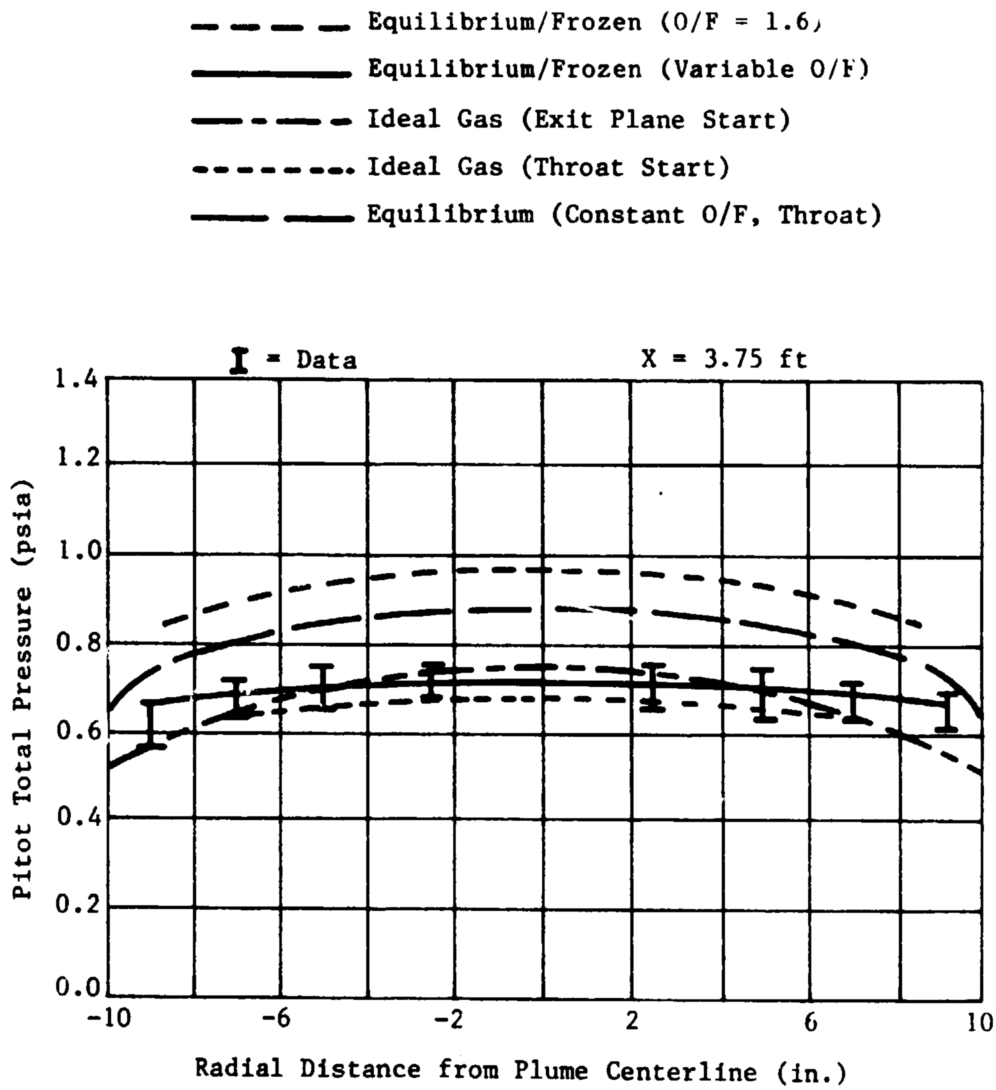

Fig. 8 Comparison of Reaction Control System Motor Plume Calculation with Pitot Pressure Survey

The variable O/F calculation was made with O/F ratios ranging from 0.8 on the wall to 2.2 on the nozzle axis. The O/F distribution used at the entrance to the contraction upstream of the throat is shown in Fig. 9. The results of Ref. 5 were used to infer this O/F distribution for the RCS motor. The RCS motor is film-cooled so that the O/F ratio near the wall at the injector is on the order of 0.1 to 0.2. The O/F ratio on the centerline is approximately 2.2. Reference 5 shows that the wall film does not hold the same O/F ratio through the transonic region. An estimate of 0.8 was selected. Using 0.8 at the wall and 2.2 on the axis a parabolic distribution of O/F was assumed and then slightly modified so that the integrated (over the inlet area) O/F ratio matched the overall O/F ratio (1.63) for the motor. This O/F distribution was then imposed on the transonic solution.

From this comparison and past experience, it has been found that more accurate plume distribution calculations are obtained with the treatment of the variable O/F gradients within rocket motors.

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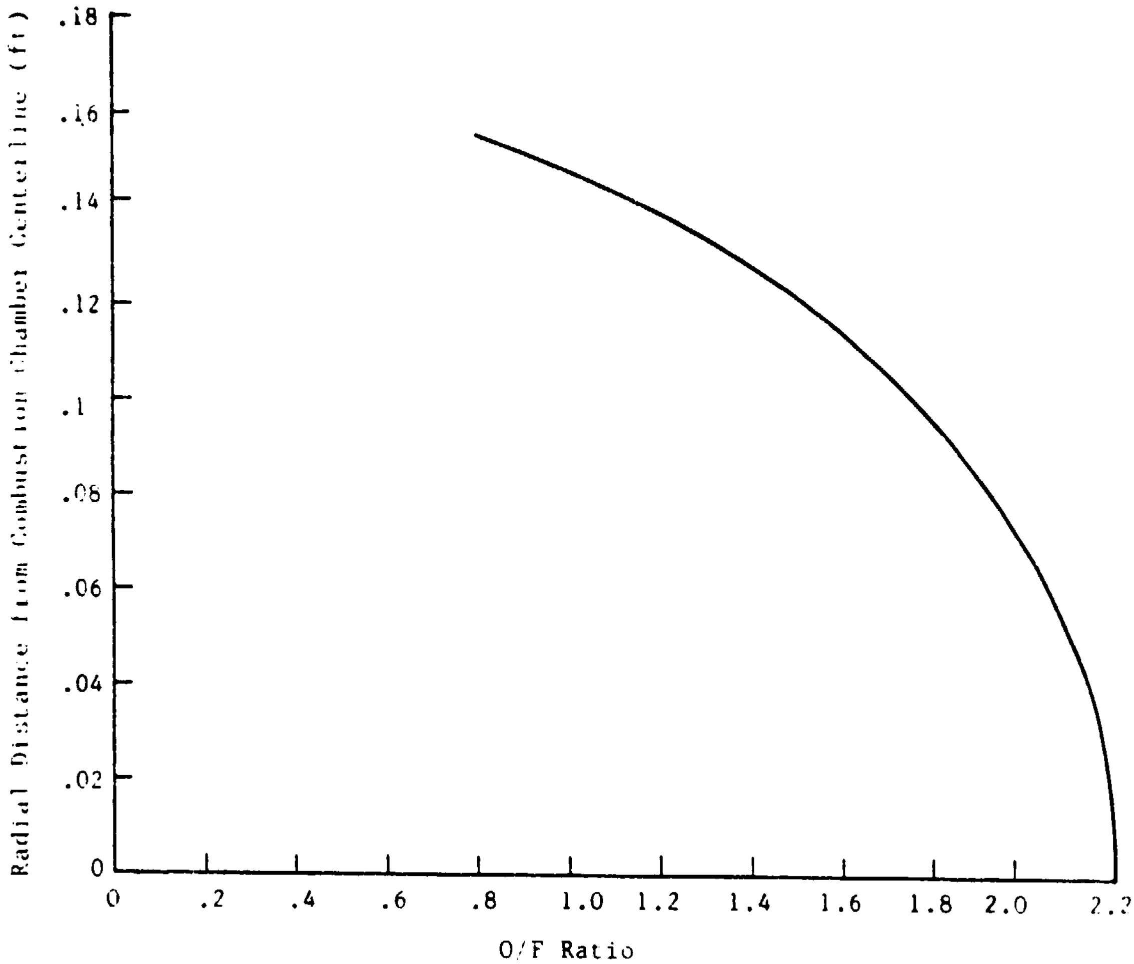

Fig. 9 Space Shuttle RCS Motor O/F Ratio Distribution at End of Combustion Chamber