

U.S. DEPARTMENT OF COMMERCE
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SPACE SHUTTLE VEHICLE ROCKET PLUME
INPINGEMENT STUDY FOR SEPARATION ANALYSIS

Lockheed Missiles and Space Company
Huntsville, AL

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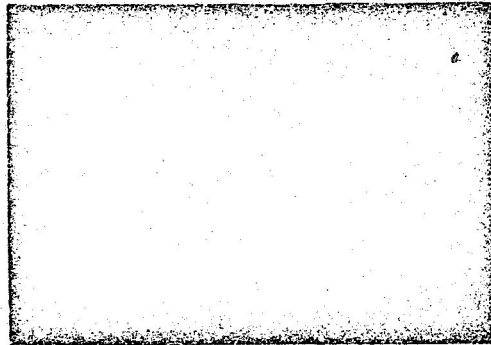
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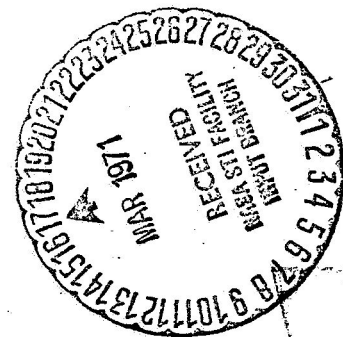
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SPACE SHUTTLE VEHICLE ROCKET
PLUME IMPINGEMENT STUDY
FOR SEPARATION ANALYSIS

FINAL REPORT

January 1971

Contract NAS9-11156

by

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FOREWORD

This final report, in conjunction with Lockheed-Huntsville documents LMSC-HREC D162574 dated October 1970 and LMSC-HREC D162657 dated November 1970, presents the results of studies conducted by Lockheed's Huntsville Research & Engineering Center, Huntsville, Alabama, under Contract NAS9-11156 for the Flight Technology Branch of NASA's Manned Spacecraft Center, Houston, Texas. The Contracting Officer's Representative was Mrs. I. H. Fossler of the Flight Technology Branch.

SUMMARY

A space shuttle plume impingement study was conducted in support of the Flight Technology Branch of NASA's Manned Spacecraft Center. The documentation of the study is presented in three parts. The first part is:

- Penny, M. M., and C. J. Wojciechowski, "Space Shuttle Vehicle Rocket Plume Impingement Study for Separation Analysis; Task I: A Program for Computing Heating Rate Indicators to Space Shuttle Vehicles," LMSC-HREC D162574, Lockheed Missiles & Space Company, Huntsville, Ala., October 1970.

This document presents the results obtained under Task I, the objective of which was to develop a simplified technique for calculating heating rates for integration with a separation trajectory computer program.

The technique of Task I permits heating rate indicators to be calculated which aid in determining the separation trajectories that are acceptable from a vehicle heating viewpoint. The technique was coded by Lockheed-Huntsville in computer subroutines for interfacing with the NASA-Manned Spacecraft Center EAO Space Shuttle Staging Simulation Computer Program. A minimum number of equations are used and computer execution time is minimal. The heating rate indicator permits the investigator to determine the relative heating rate magnitudes to be expected for specified areas on the subject vehicle.

The second part of the documentation is:

- Wojciechowski, C. J., M. M. Penny and R. J. Prozan, Space Shuttle Vehicle Rocket Plume Impingement Study for Separation Analysis; Tasks II and III: Definition and Preliminary Plume Impingement Analysis for the MSC Booster," LMSC-HREC D162657, Lockheed Missiles & Space Company, Huntsville, Ala., November 1970.

In Tasks II and III of the study, many relative orbiter/booster positions were analyzed in the region that contains the separation trajectories to define the environments during the staging maneuver. The data presented can be used to determine a separation trajectory which results in acceptable impingement heating rates, forces, and the resulting moments. The data, presented in graphical form, include the effect of roll, pitch and yaw maneuvers for the booster.

Quasi-steady state analysis methods were used with the orbiter engine operating at full thrust. To obtain partial thrust results, simple ratio equations are presented. Using a simplified thrust buildup curve, the heating rate time histories at selected points on the booster vertical tail are used in a one-dimensional heat conduction program to calculate the surface temperature-time histories. These surface temperature-time histories are calculated for two separation trajectories. The maximum calculated temperature at the leading edge of the vertical tail is 1800°F for both of the separation trajectories analyzed. The titanium skin on the sides of the vertical tail reached 480°F and 440°F for the two separation trajectories analyzed.

The third part of the documentation is:

- Penny, M.M., C.J. Wojciechowski and R.J. Prozan, "Space Shuttle Vehicle Rocket Plume Impingement Study for Separation Analyses," LMSC-HREC D162852, Lockheed Missiles & Space Company, Huntsville, Ala., January 1971;

which is this final report of the study. In this document, several remaining items of engineering interest are discussed. In addition, a description is given of inputs, computer tape setups, etc., for the several computer programs which are necessary to any subsequent analyses of the plume impingement problem. The engineering aspects are:

- The plume simulation used
- Engine-out analysis
- Shock interaction heating problems.

Two areas in which the theoretical analysis is deficient are recognized: (1) in the complex plume structure, and (2) the resultant shock interaction heating analysis. Future investigations should consider both analytical and experimental efforts to strengthen and/or corroborate the findings of this study.

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Section 1 INTRODUCTION

The separation of launch vehicle stages during boost usually results in the rocket exhaust plume from the upper stage impinging on the lower stage. For expendable boosters, the impingement has historically been of minor consequence. For the fully reusable space shuttle vehicle, however, the impingement problem is significant because control of the lower stage must be maintained, and the structure must not be damaged. The impingement environment imposed on the booster can be severe if ignition of the orbiter main propulsion system occurs while the stages are close together. If ignition of the orbiter is delayed until after the booster is far away, resulting in the impingement environment being either inconsequential or non-existent, payload performance may be penalized. The significance of the staging plume impingement problem should be assessed, and an "optimum" staging trajectory should be defined. The resulting optimum trajectory should provide an acceptable tradeoff between impact of the vehicle design to accept the plume impingement environment and the penalties that are incurred in system performance and/or operation.

The ensuing material treats several aspects of the impingement problem that were not previously covered in the Tasks I or Tasks II and III documentation.

Section 2

TECHNICAL DISCUSSION

2.1 BACKGROUND

When the Tasks II and III portion of the study was completed, it became apparent that much effort was required to generate the information maps of heating rates, forces and moments that were needed to conduct separation studies with a six-degree-of-freedom trajectory analysis. Furthermore any change in orbiter engine design, staging altitude or booster external configuration would require that this information be completely regenerated.

It was evident, then, that the incorporation of the entire plume impingement calculation as a subprogram to the separation trajectory analysis was warranted from both utilitarian and economic aspects. The necessary modifications to the plume impingement program were made. Input guides to the entire set of programs which are used in the analysis (with the exception of the separation trajectory program itself) are presented in the Appendix.

2.2 PLUME SIMULATION STUDY

A study was made of the use of an "effective" jet to simulate the actual two-engine orbiter exhaust plume. The effective jet is defined as the jet emanating from multiple engines which have the same characteristics as a single engine but the exit area and line of action of the cluster. This approximation to the actual situation is required since the use of three-dimensional plume solutions like those found in Refs. 1 and 2 appeared to be prohibitive from the computer economics standpoint, particularly when the state of flux of the engine design is considered. Another stumbling block to using one of these analyses is the fact that the impingement solution itself is limited to

an axisymmetric flow field. To consider a three-dimensional solution to the plume/plume interaction problem also means considering the development of an attendant plume impingement calculation. It was for these reasons that an axisymmetric jet approximation was chosen for the plume definition.

To gain some insight into the effects of an axisymmetric simulation of the three-dimensional flow, consider the schematic shown in Fig. 1. A two-dimensional analysis was performed utilizing the computer program of Refs. 3 and 4 in which the plume^e interaction was treated. A second 2-D calculation was made in which a single jet was treated having the same exit conditions and the same mass flow. Radial pitot pressure surveys were calculated for the two flow conditions at several axial stations. A typical result is shown in Fig. 2.

The single (effective) jet analysis shows that the pitot pressure falls smoothly from a high value at the centerline to a constant value near the periphery of the jet. The interaction (exact) solution, however, begins at a low value at the centerline (the center streamline passes through the impingement shock at its strongest point) and increases rapidly until it reaches a value approximating the effective jet solution. The sharp drop at a radius of seven indicates the presence of the impingement shock. From this point the pitot pressure decreases smoothly to the peripheral value. Integration of the pitot pressures across the jet reveals that the effective jet impingement force on a flat plate capturing the entire flow will range from 20 to 40 percent higher than the exact solution throughout the region of interest.

A similar analysis was made of the axisymmetric counterpart of the nozzle configurations in Fig. 1. This corresponds to a toroidal jet and an axisymmetric effective jet. In Fig. 3 radial pitot pressure surveys of these configurations are shown. The same trends found in the two-dimensional analysis are again evident. The rapid recompression at the periphery of the jet is caused by the free boundary shock wave. This shock wave had not yet formed in the two-dimensional case. Note that from a radius of

six outward, the results of the axisymmetric analyses are in close agreement. When the pitot pressure is integrated, an effective jet force is yielded that is no more than 6 percent higher than the toroidal solution in the region of interest.

Photographs of multiple rocket exhausts indicate that these jets tend to approach a circular cross section at great distances from the exit plane. Also, the true three-dimensional case will afford greater lateral relief than the toroidal jet and would more quickly weaken the impingement shock wave. The effect then should be that a three-dimensional analysis would yield a value between the toroidal solution and the effective jet solution. These conclusions are valid only for bodies which are large compared to the plume diameter. They could be considerably in error for small bodies. Fortunately the case under consideration is that of a large body.

It can be concluded then that the effective jet simulation is an adequate approximation to the plume insofar as the configuration analyzed in this study and the intent of this study are concerned; however, continued research into numerical methods should be conducted so that an economically feasible solution to these complex phenomena can ultimately be achieved.

2.3 ENGINE-OUT PLUME IMPINGEMENT ANALYSIS

Although the Manned Spacecraft Center (MSC) Space Shuttle concept employs two orbiter engines mounted one above the other, there are suggested configurations which employ side-by-side mountings. In the latter case, a single engine failure will result in an unsymmetrical loading on the booster. This produces a moment bias about the roll and yaw axis.

The plume documented in Ref. 5 was used to conduct the engine-out study. The area ratio for the engine is 200/1. The staging altitude was assumed to be 283,000 feet, with the vehicle Mach number = 12.08. All forces and moments are referenced to a coordinate system located at the

booster nose (Fig. 4). The impingement forces and the resulting moments are presented in Figs. 5 through 10, respectively. These data map the region which includes the expected nominal staging trajectory.

The variation of the force components with orbiter separation distance from the booster are presented in Figs. 5 through 7, respectively. As indicated in Fig. 6, an unsymmetrical loading is produced in the booster y coordinate direction (Fig. 4). This results from an unsymmetrical loading on the booster fuselage and wing surfaces (both horizontal and vertical). Hence as shown in Fig. 9, a moment is produced about the y axis (Fig. 4) which tends to induce a yaw maneuver. This effect is unstable in that once the moment bias is induced, the side loading on the fuselage and vertical tail surface will tend to rotate the booster in the direction of induced rotation. A roll (rotation about the booster x axis) is produced as indicated by the moment data shown in Fig. 8. This is also produced by the unsymmetrical loading. The roll coupled with the yaw rotation will tend to induce a tumbling effect on the booster. However, the magnitude of the effects on the booster may or may not be negligible and cannot be fully assessed until the engine-out case is analyzed by the staging simulation computer program.

2.4 SHOCK IMPINGEMENT HEATING

In Ref. 5 the effects of shock interactions on local heating rates were ignored. A description of heat transfer effects due to shock/surface interactions is presented here. Due to the multitude of plume shock or plume-generated shock situations encountered in this problem it is advisable first to select a separation trajectory neglecting this phenomenon. Having selected such a trajectory, it is then possible to investigate the shock-induced heating increase in detail.

Many experimental and analytic investigations have been conducted on the subject of shock impingement heating. The results of these investigations

indicate that the peak heat transfer in the shock impingement regions is localized. Hiers and Loubisky (Ref. 6) present photographic evidence of burn marks whose width is about $1/16$ of the leading edge diameter. The fact that the peak heating is localized is an important consideration. If the location of impinging shocks varies rapidly with separation, the total heat load to a particular area will remain small. If on the other hand the location does not vary, then the shock-induced heating can be severe and additional thermal protection must be considered in the design.

As the following discussion points out, internal plume shocks travel with the plume, which of course travels with the orbiter and as such the impingement location varies rapidly with time. The plume/fuselage interaction shock wave, however, will impinge on the vertical fin at a relatively constant location and therefore is a potentially serious problem.

2.4.1 Plume Boundary Shock

A schematic of the plume lip shock/booster fuselage interaction region is shown in Fig. 11. There are large uncertainties concerning the external flow environment between the booster and orbiter. Two possible extremes of orbiter base pressure can occur, one corresponds to no interference flow between the vehicles making the hypersonic plume boundary definition valid and the other occurs if the interference flow field between the vehicles produces a series of oblique shock waves which yield a high recovery pressure in the base region. The second effect will occur only at relatively small separation distances which correspond to low thrust (low chamber pressure) of the orbiter. In either case the plume boundary shock impingement location varies rapidly with separation distance and is therefore of relatively minor consequence.

2.4.2 Plume/Plume Interaction Shock Wave

A toroidal analysis of the plume/plume interaction problem yields a shock strength which is, as previously discussed, higher than the actual

case. Yet this same analysis shows that this shock wave is very weak, for all separation distances, in the vicinity of the booster. In the early stage of separation, this shock wave impinges on the vertical tail and in the later stages, it also impinges on the fuselage.

A schematic of the shock structure in the vicinity of the vertical tail is given in Fig. 12. The results of Refs. 7 and 8 indicate that the local heating increases that could be expected due to the shock impingement is about a factor of five. Since this shock impingement location varies with separation distance, however, it is also expected to be of minor consequence.

2.4.3 Fuselage-Generated Bow Shock Interaction with the Vertical Fin

For a class of separation trajectories in which the lateral separation occurs slowly, a plume/fuselage interaction shock is generated which impinges on the vertical tail. As long as the plume boundary intersects the fuselage top surface, this shock wave will remain. It is anticipated that this bow shock will move slowly outboard across the vertical tail and consequently create the worst shock/surface interaction from a total heat input standpoint. Figure 13 shows a schematic of this shock/fin interaction region.

It is predicted that a supersonic jet will form at the fuselage bow shock/vertical fin bow shock interaction point and that this jet will impinge directly on the vertical tail. The peak heating depends on the peak pressure generated by this jet at the impingement location as well as the length-to-width ratio of the jet, the impingement angle and whether the jet is laminar or turbulent.

The initial conditions for this jet are difficult to calculate exactly. The amount of turning that the jet undergoes is a function of the pressures that exist in the subsonic region bounding the supersonic region. A calculation of the maximum expected increase in local heat transfer was made assuming that: (1) the length-to-width ratio of the jet was small (eliminating large total pressure losses occurring due to shock structure within long, thin free

jets; (2) that the jet attaches at a 45-degree angle and; (3) that the jet is laminar. Based on these assumptions, the maximum expected heat transfer increase is a factor of 8.5. Fortunately, this shock surface interaction is expected to occur near the base of the vertical tail where the heat transfer rates are relatively low. The heating rates used in the transient temperature calculations presented in Ref. 5 were for a point near the top of the vertical tail where the heating rates are appreciably higher than they are near the root.

The tentative conclusion is reached that this shock/surface interaction does not seriously compromise the information given in Ref. 5. This particular phenomenon, however, is a potential problem area and further study is suggested.

Section 3

CONCLUSIONS

Based on the results of this study, it is concluded that the plume impingement phenomenon is an important consideration in the preliminary design of the Manned Spacecraft Center Space Shuttle concept and other related reusable booster designs. The thermal environment is severe and thermal protection for the vertical fin and aft fuselage areas should be carefully considered. It is also apparent that the forces and moments induced on the booster are of such a magnitude that to neglect their effects on the separation trajectory could lead to serious if not catastrophic booster motions.

The series of documented analyses culminating in an interrelated separation/impingement program produced under this study will enable the preliminary designer to determine a separation sequence in which plume impingement phenomena are adequately treated.

Two areas in which the theoretical analysis is deficient are recognized: (1) in the complex plume structure, and (2) the resultant shock interaction heating analysis. Future investigations should consider both analytical and experimental efforts to strengthen and/or corroborate the findings of this study.

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ILLUSTRATIONS

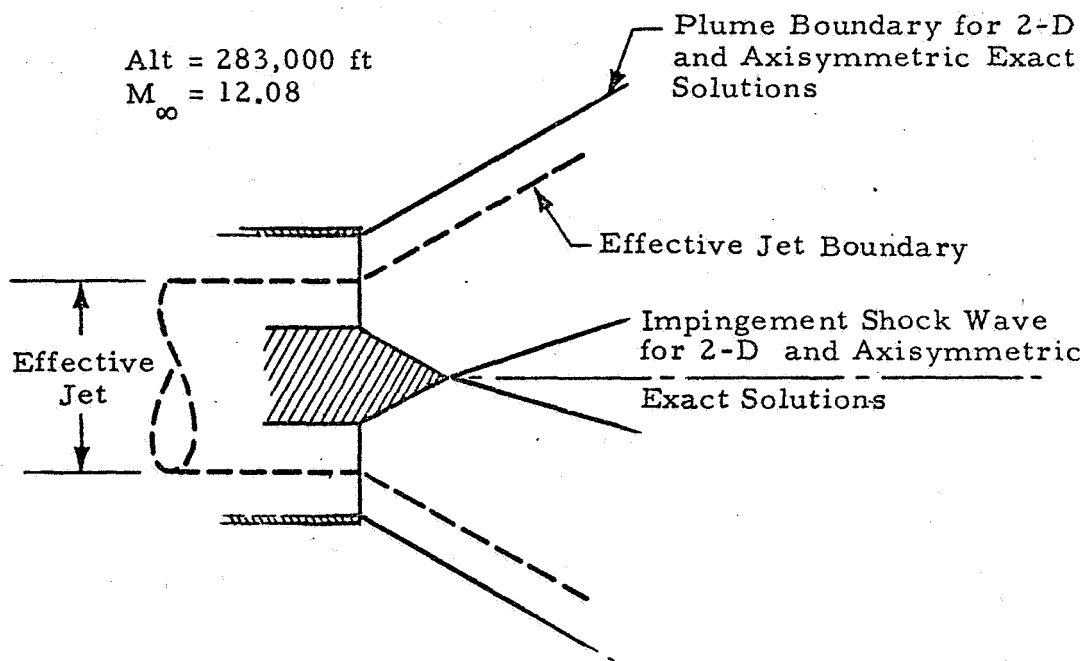


Fig. 1 - Schematic of Jet Simulation Study

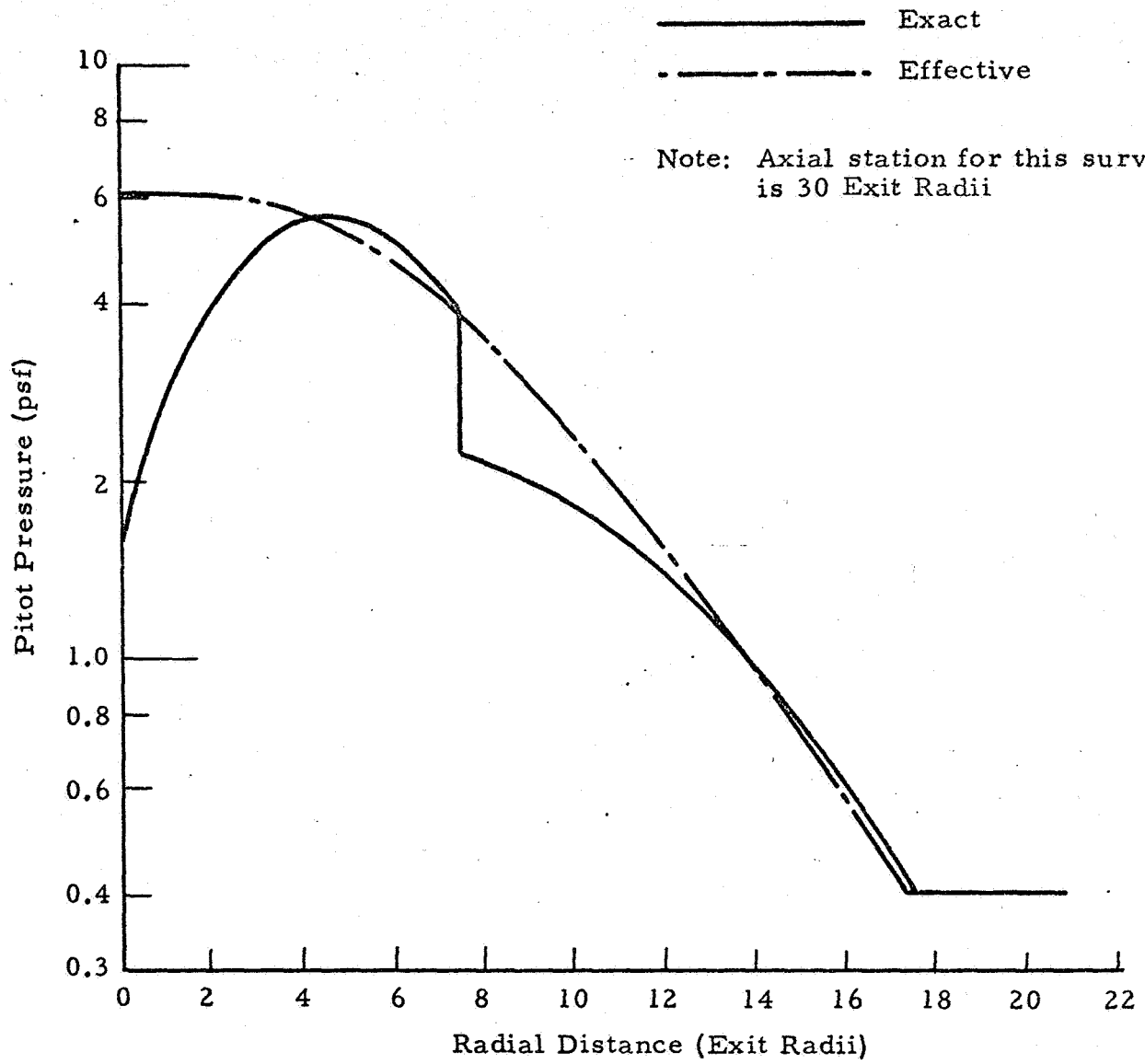


Fig.2 - Variation of Pitot Pressure vs Radial Distance
(Two Dimensional Calculation)

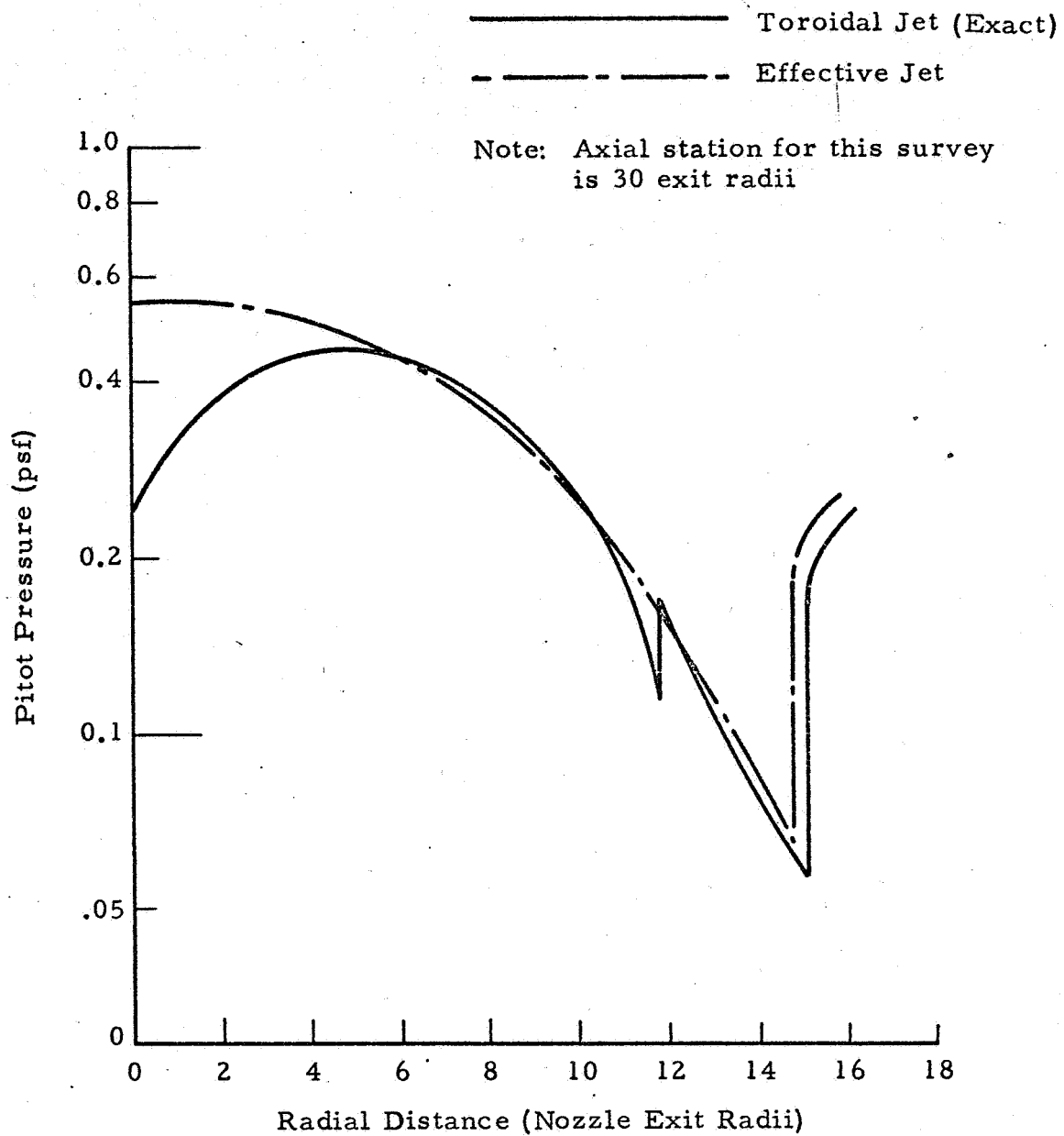


Fig. 3 - Variation of Pitot Pressure vs Radial Distance (Axisymmetric Calculation)

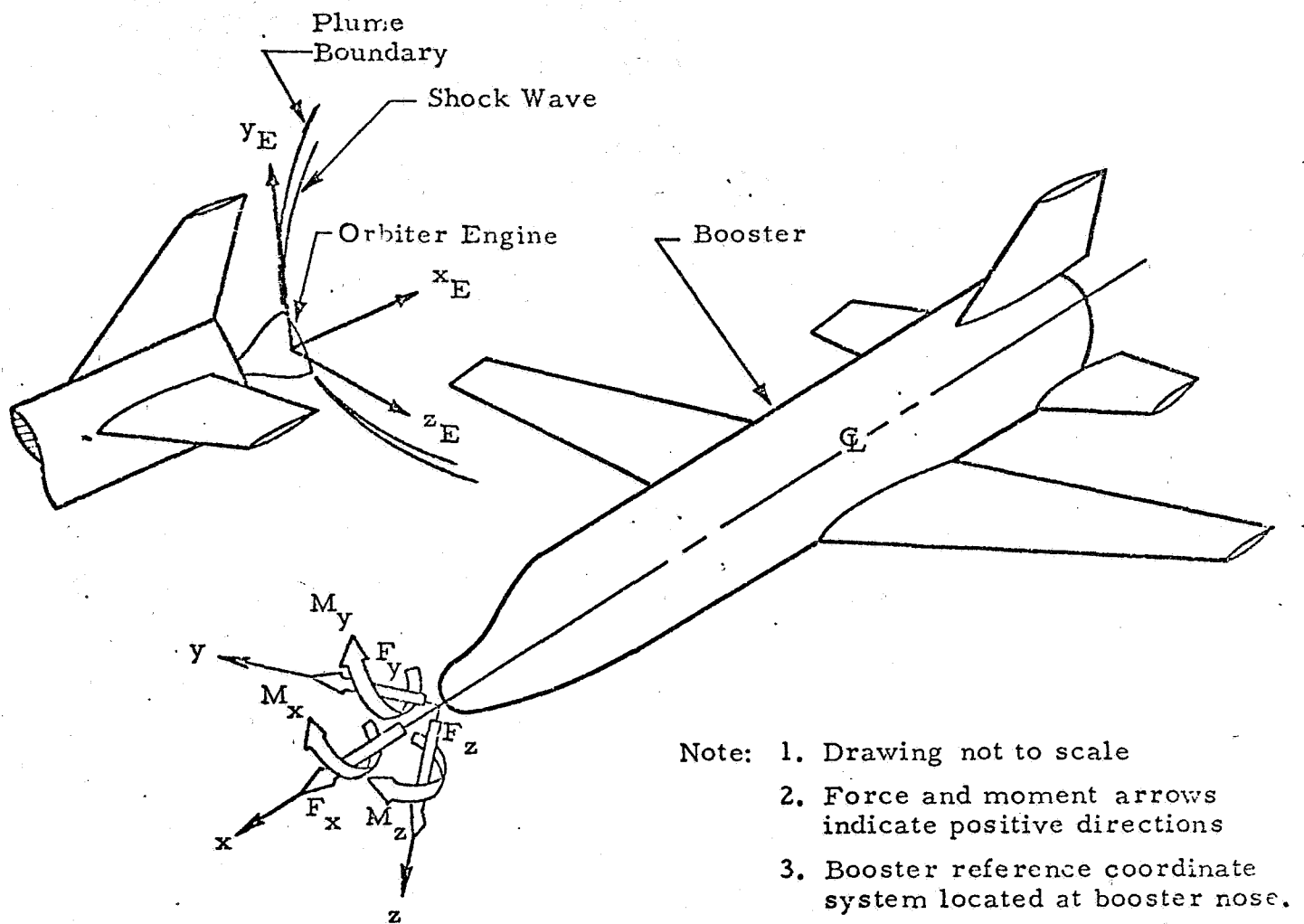


Fig. 4 - Three-Dimensional Perspective of the Booster Reference Coordinate System and the Orbiter Plume Coordinate System

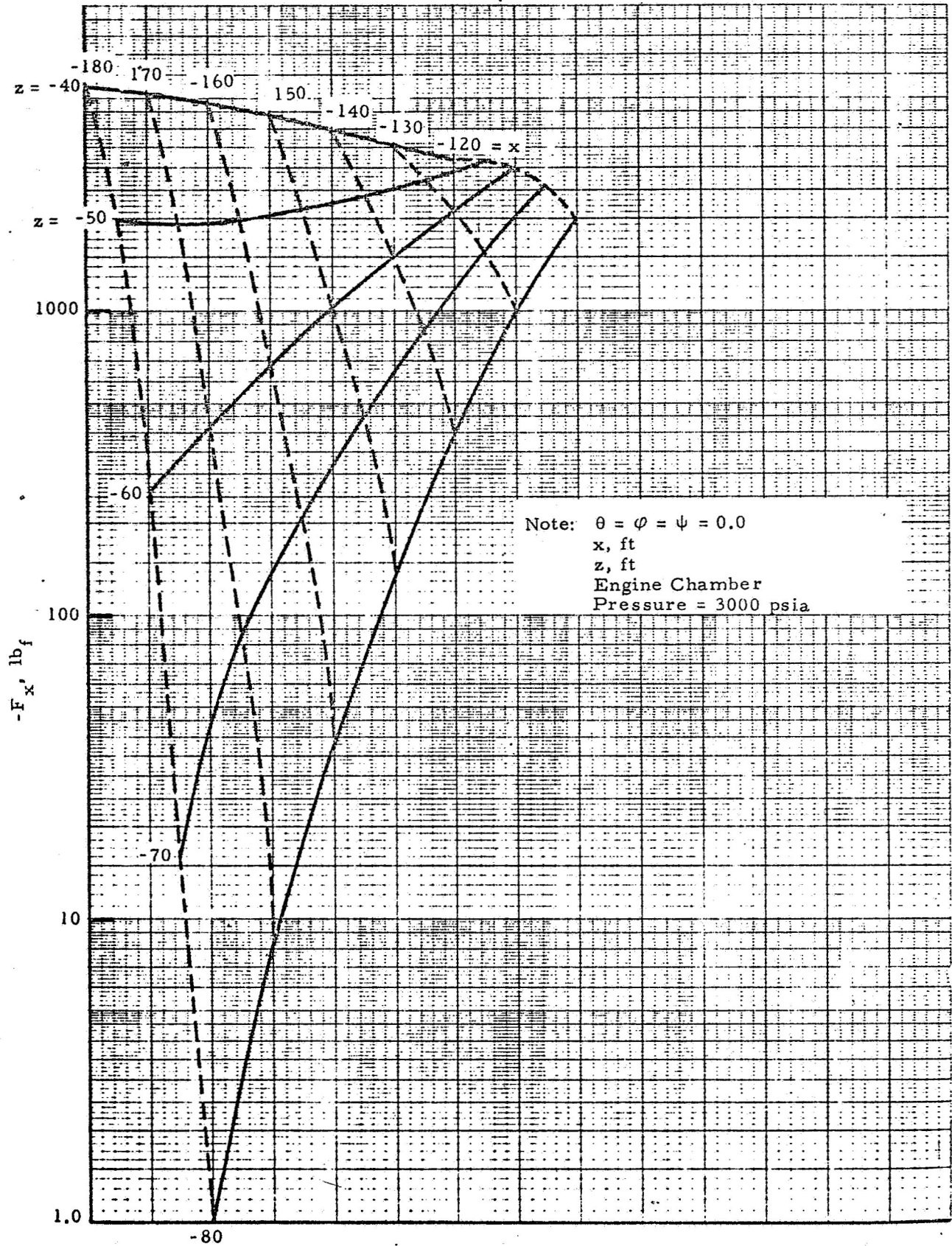


Fig. 5 - Variation of Booster Impingement Force for an Engine Out Case with Orbiter Separation Distance from the Booster (Side-by-side Engine Mounting)

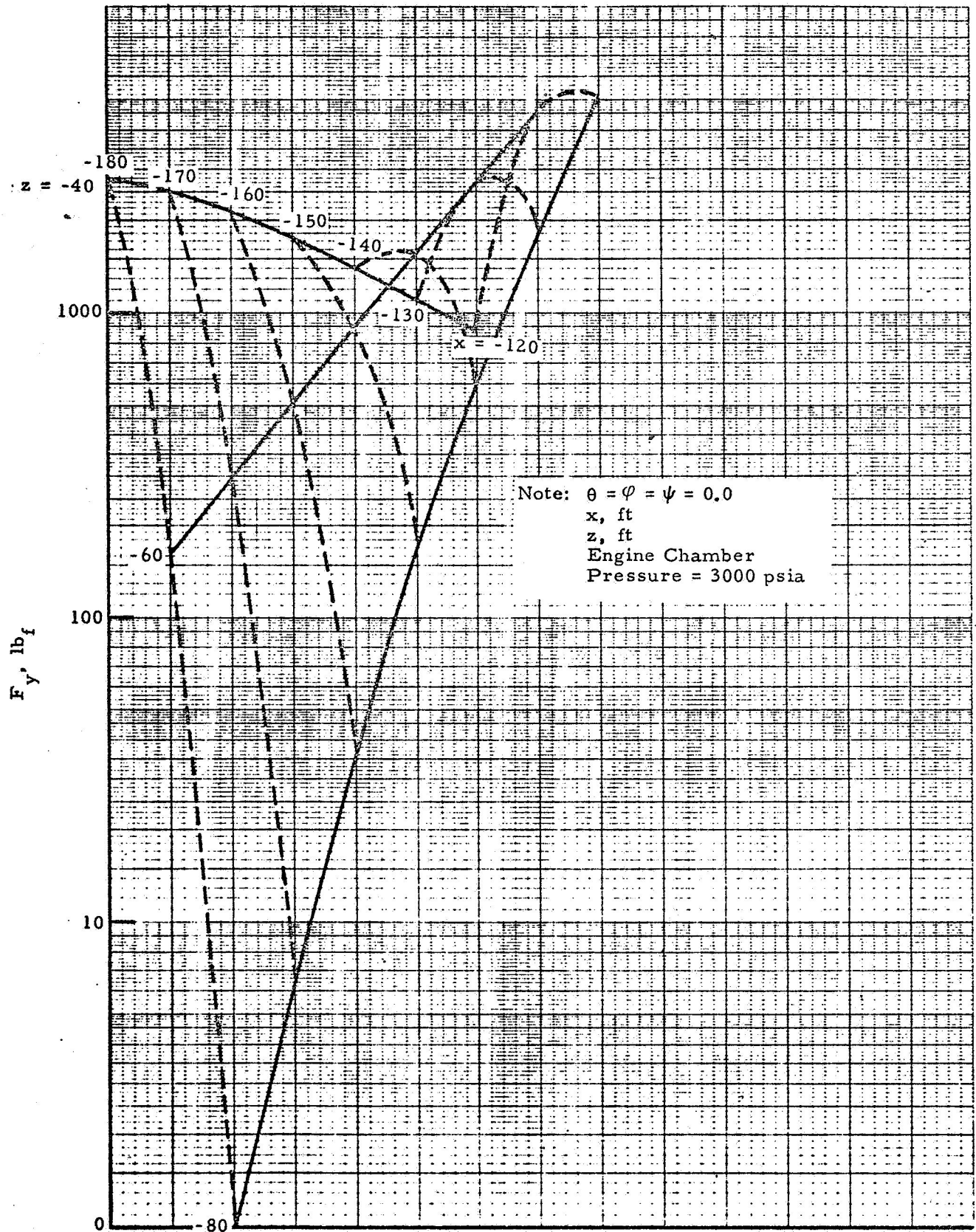


Fig. 6 - Variation of Booster Impingement Force for an Engine-Out Case with Orbiter Separation Distance from the Booster (Side-by-side Engine Mounting)

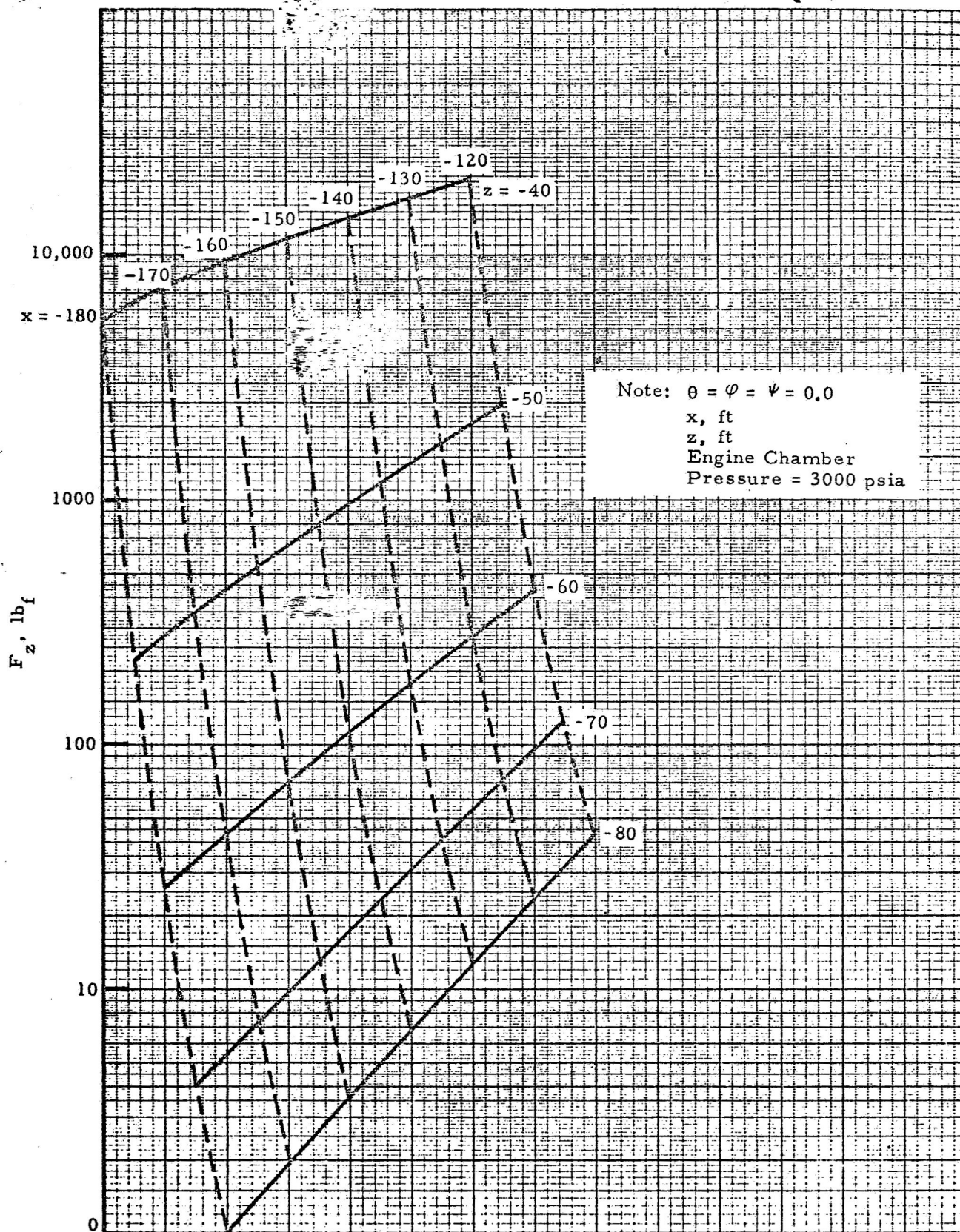


Fig. 7 - Variation of the Booster Impingement Force for an Engine-Out Case with Orbiter Separation Distance from the Booster (Side-by-side Engine Mounting)

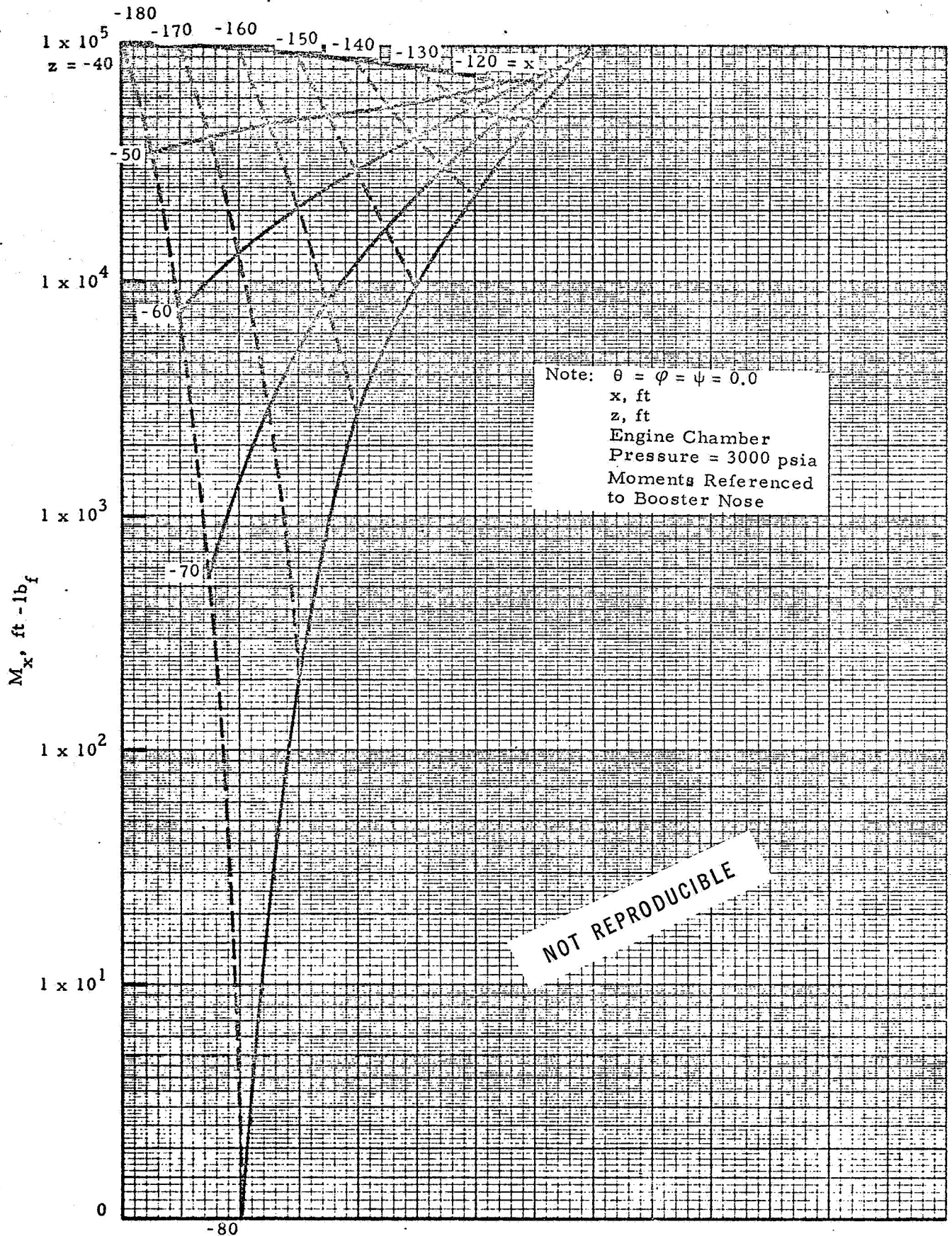


Fig. 8 - Variation of Booster Impingement Moment for an Engine-Out Case with Orbiter Separation Distance from the Booster (Side-by-side Engine Mounting)

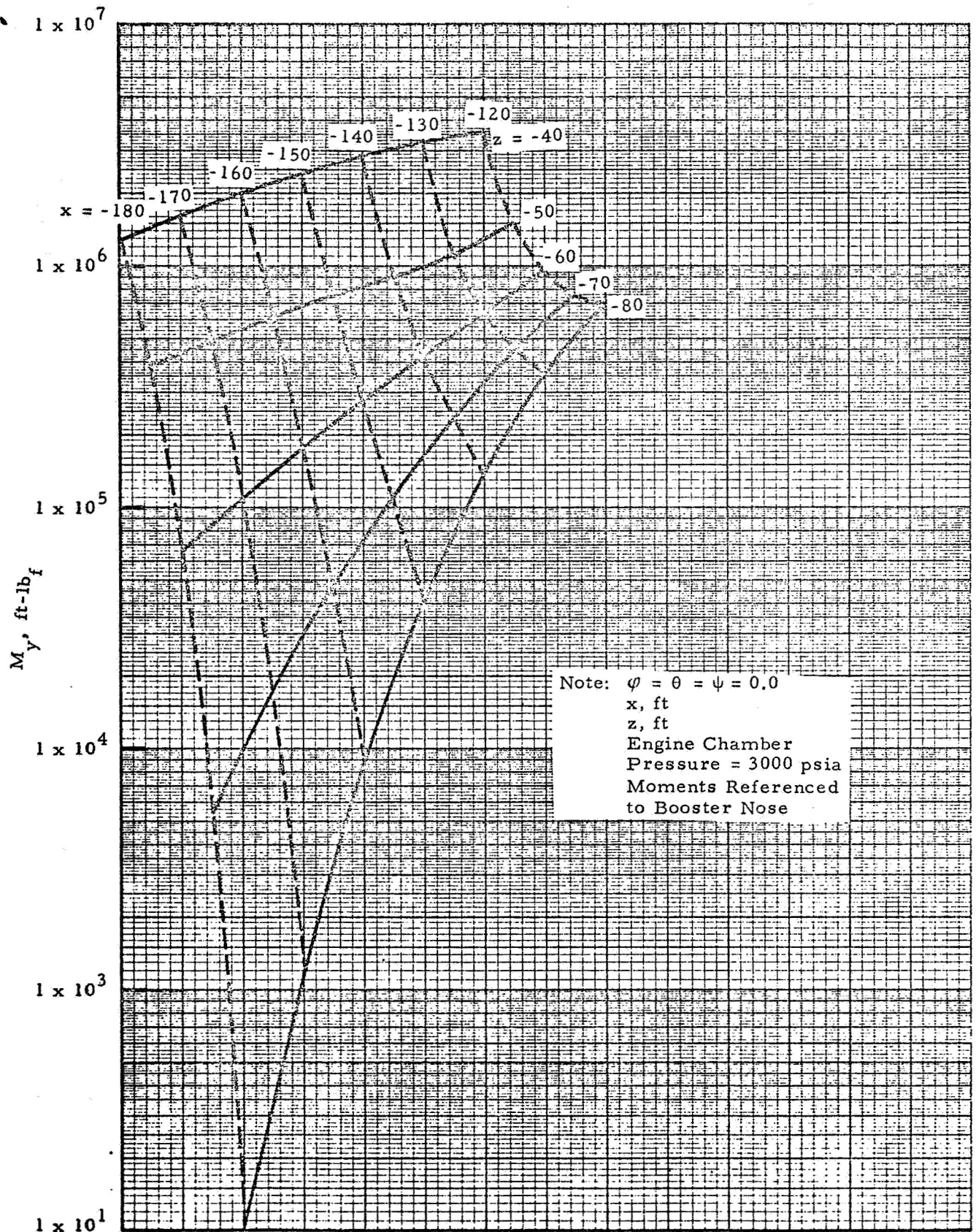


Fig. 9 - Variation of Booster Moment for an Engine-Out Case with Orbiter Separation Distance from the Booster (Side-by-side Engine Mounting)

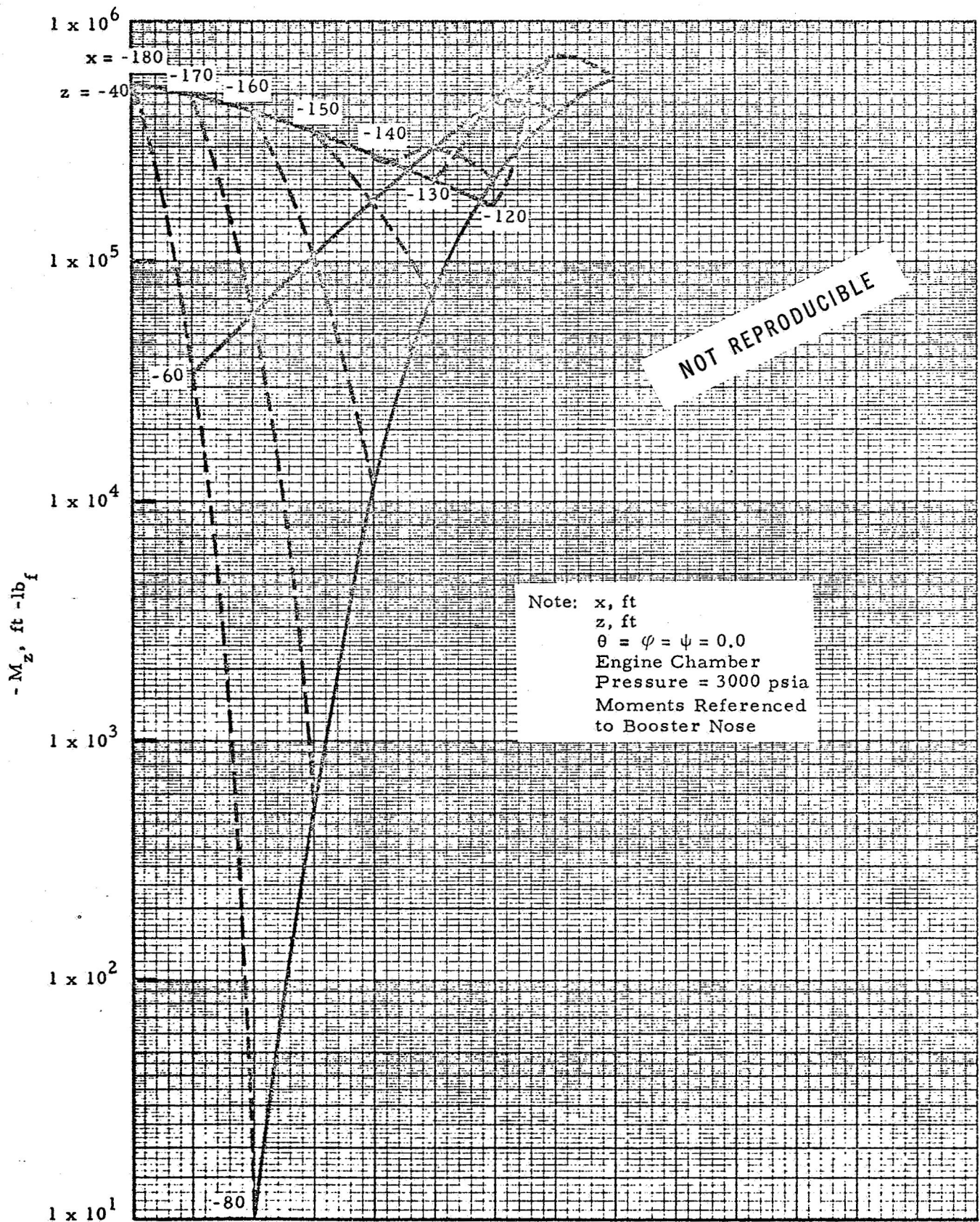


Fig. 10 - Variation of Booster Impingement Moment for an Engine-Out Case with Orbiter Separation Distance from the Booster (Side-by-side Engine Mounting)

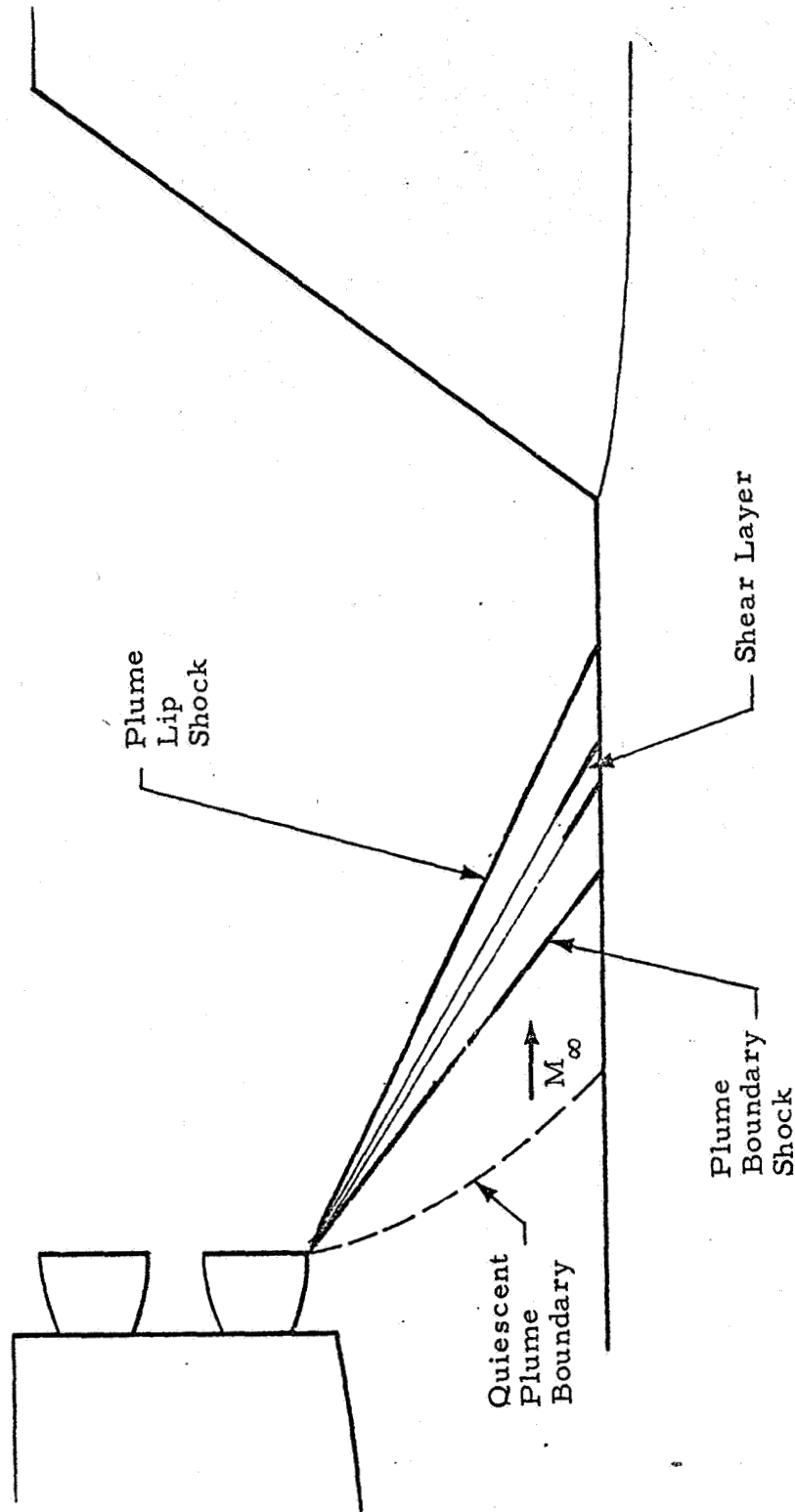


Fig. 11 - Simplified Sketch Showing Impingement of the Orbiter Engine Plume Boundary and Lip Shocks on the MSC Booster

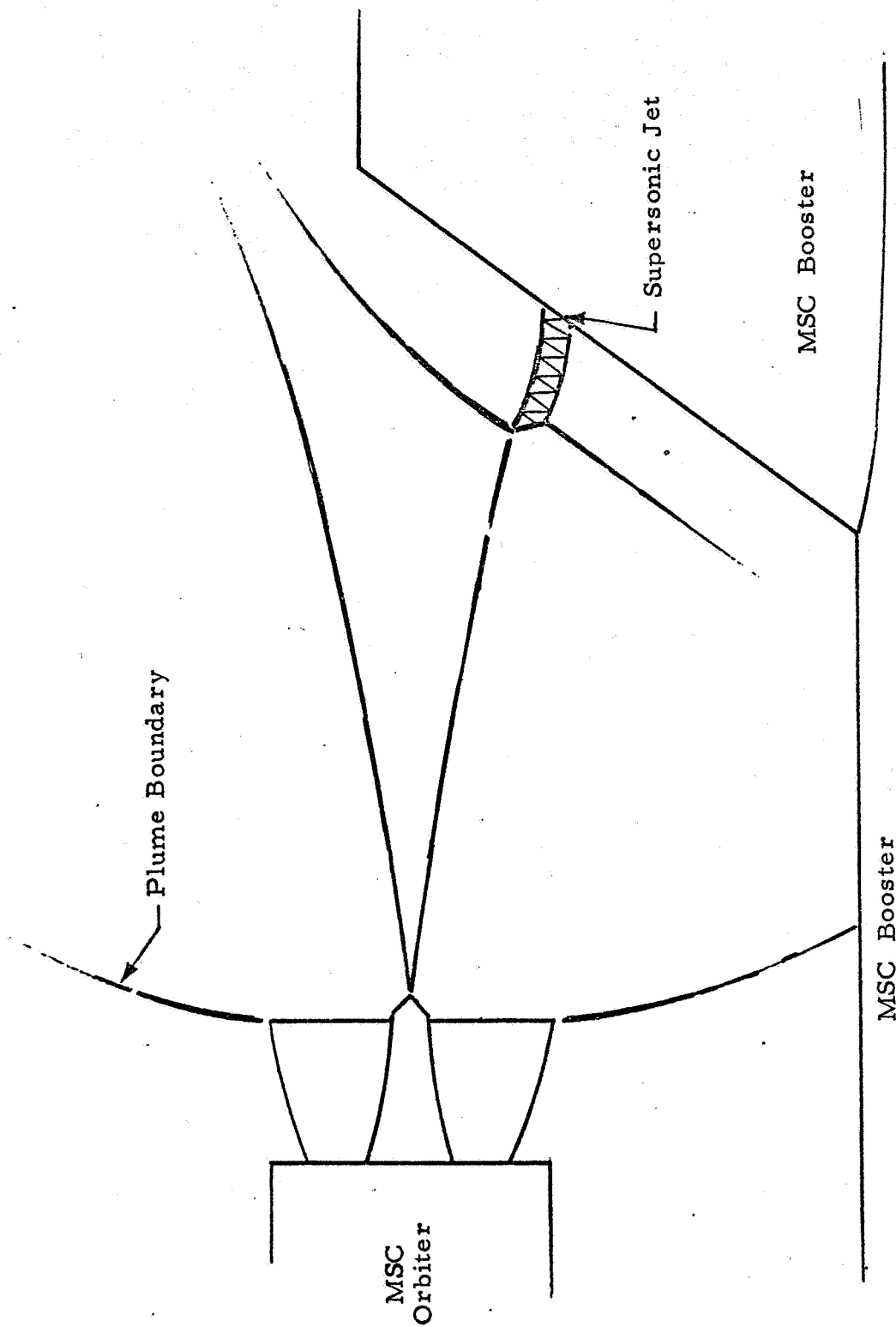


Fig. 12 - Simplified Sketch Showing Impingement of the Orbiter Plume Intersection Shock on the MSC Booster Vertical Tail

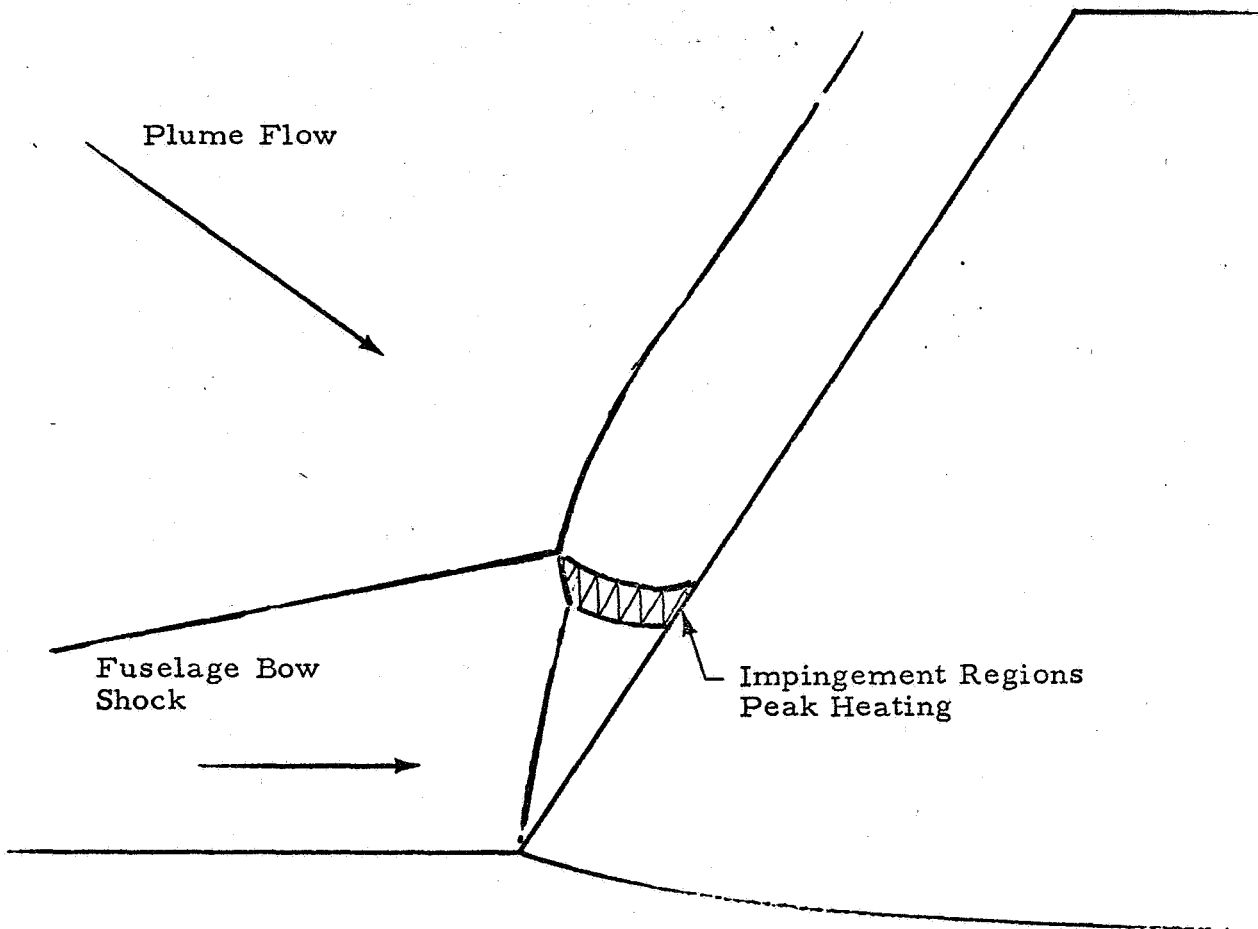


Fig. 13 - Simplified Sketch Showing Impingement of the Fuselage Bow Shock on the Vertical Tail

Appendix

DESCRIPTION OF THE INPUT GUIDES FOR THE
FLOWFIELD AND IMPINGEMENT
COMPUTER PROGRAMS

Appendix

The plume impingement characteristics (forces, moments and heating rates) for the staging sequence of the Manned Spacecraft Center (MSC) Space Shuttle configuration were defined during a previous study (Ref. A.1). These data include the effects of the booster rotated in the pitch, roll and yaw plane. Hence they are applicable for use in staging analyses which involve six degrees of freedom. However, a rather large amount of computer time and engineering effort is required to generate the data and arrange them in tabular form for use in a staging simulation program. Thus it became apparent that future studies involving a different configuration or staging attitude could best be conducted by combining the Lockheed-Huntsville plume impingement program (Ref. A.2) with the MSC staging simulation program. This task was initiated during the final phase of the subject contract and has now been completed.

In the combined mode of operation, the plume impingement program is utilized by the staging program to obtain the forces and the resulting moments acting on the booster for a given trajectory station. The staging program calls the impingement program with the vector which locates the orbiter engine exit plane with respect to the booster nose and the set of direction cosines which orientates the engine with respect to the booster. The forces resulting from the orbiter engine exhaust plume impingement on the booster surfaces and the resulting moments are obtained by numerically integrating the impact pressure distribution over the booster surfaces. Data required to perform the heating rate analysis are stored on magnetic tape for use in a heating rate analysis at a later time.

This procedure thus allows a six-degree-of-freedom staging analysis in one computer run with one additional run required to obtain the heating rates to the booster surface if these are desired.

Several programs are utilized in the generation of plume impingement data. These include a chemical equilibrium combustion (Ref. A.3) program which generates thermochemistry data for use in the Method-of-Characteristics Computer Program (Ref. A.4) which generates the plume flow field. These data are then used by the plume impingement program in the impingement analysis. The following sections provide an input guide for use of the computer programs utilized in the impingement analysis. Table A-1 indicates the FORTRAN tape unit number for which data tapes should be mounted for the various programs.

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- A.2 Wojciechowski, C. J., and A. W. Ratliff, "Study of High Altitude Impingement," LMSC-HREC D149118, Lockheed Missiles & Space Company, Huntsville, Ala., August 1969.
- A.3 McBride, Bonnie, and S. Gordon, "Preliminary Description of CEC: A Computer Program for Calculation of Chemical Equilibrium Compositions with Applications," NASA-Lewis Research Center, Cleveland, Ohio, May 1969.
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A.1 PROGRAM INPUT FOR THE CEC COMBUSTION PROGRAM

Program input data for a computer program for the Calculation of Chemical Equilibrium Compositions with Applications (CEC) are discussed under four categories. Three of the categories are required and one is optional. The three required categories and the code names by which they are referred are:

1. Library of thermodynamic data for reaction products (THERMO data)
2. Data pertaining to reactants (REACTANTS cards)
3. Namelist data which include the type of problem, required schedules, and options (NAMELISTS Input)

The optional category of data are chemical formulas of species which are singled out for special purposes (OMIT and INSERT cards).

The words THERMO, REACTANTS, NAMELISTS, OMIT and INSERT are control codes used by the program to identify the input read from data cards. The THERMO, REACTANTS, and NAMELISTS codes are punched on separate cards, each preceding their appropriate data cards. The OMIT and INSERT codes are on the same card as the data.

The required order of the data cards is:

1. THERMO code card
2. THERMO data (these cards and the preceding THERMO code card may be omitted if the data are to be read from tape).
3. REACTANTS code card
4. REACTANTS cards

5. OMIT and INSERT cards (if any)
6. NAMELISTS code card
7. NAMELISTS data

In a particular run, there may be any number of sets of REACTANTS cards (items 3 and 4 above), each followed by any number of sets of NAMELISTS input (items 6 and 7 above).

A.1.1 Thermo Data

The library of thermodynamic data for reaction products may be read either from cards or from tape. If the data are read in from cards, the program will write these data on tape 12. During a computer run, the appropriate reaction product data for each new set of REACTANTS cards will be selected from tape 12 and stored.

THERMO data may be read in from cards for each run. However, a permanent tape or disc containing the data may be made during any run by using the required type of control cards preceding the operating deck. Two advantages of using a permanent tape or disc is that the scratch tape will not be made for each run and handling the cards is eliminated.

A.1.2 Reactants Cards

This set of cards is required for all problems. The first card in the set contains the word REACTANTS punched in card columns 1-9. The last card in the set is blank. In between the first and last cards may be any number of cards up to a maximum of 15, one for each reactant species being considered.

Details on the preparation of the cards are given in Table A-2. Except for the first card, which contains the code REACTANTS, the cards are the same as the cards required for the program described in NASA TN D-1454 and TN D-1737.

A.1.3 Namelist Input

The program contains two namelists for input. Namelist INPT2 is required for all problems, while namelist RKTINP is required only for the RKT problem.

Namelist INPT2 must be preceded by a card with NAMELISTS punched in card columns 1-9. A list of variables and their definitions for INPT2 is given in Table A-3.

The first namelist, INPT2, must indicate:

1. the type of problem (TP, HP, RKT, or DETN),
2. at least one pressure (P) for any type of problem,
3. at least one temperature for assigned temperature problems (TP and RKT with an assigned chamber temperature),
4. the relative amounts of fuel(s) and oxidant(s).

Relative amounts of fuel(s) and oxidizer(s) – These quantities may be specified by assigning a value for either OF, FPCT, FA or EQRT. If no value is assigned for any of these, the program assumes the relative amounts of fuel(s) and oxidizer(s) to be those specified on the REACTANTS cards.

Pressure units – The program assumes the pressures in the P schedule to be in units of atmospheres unless either PSIA = T or MMHG = T.

TP Problem – Thermodynamic properties will be calculated for all combinations of assigned values for pressure P and temperature T in the schedules. Thus, if 26 T values and 26 P values are included in the INPT2 list, properties will be calculated for 676 P and T combinations.

HP Problem – Combustion temperature and corresponding properties will be calculated for each pressure in the P schedule.

NOT REPRODUCIBLE

To generate a thermochemical data tape MOCT must be set equal to 1. The data are then output on tape unit 9. If it is desirable to have the thermochemical data punched on cards simultaneously or in place of making the tape, MOCP must be set equal to 1. Both variables are preset equal to F before the data are read in.

If it is desirable to use the pressure freeze option, the variable PCEF must be set equal to the chamber pressure to local pressure ratio at which chemical freezing is desired.

A.1.4 Omit and Insert Cards

OMIT and INSERT cards are optional. They contain the names of particular species in the library of thermodynamic data for the specific purposes discussed below. Each card contains the word OMIT (in card columns 1-4) or INSERT (in card columns 1-6) and the names of from 1 to 4 species starting in columns 16, 31, 46, and 61. The names must be exactly the same as they appear in the THERMO data.

OMIT cards — These cards list species to be omitted from the THERMO data. If OMIT cards are not used, the program will consider as possible species all those species in the THERMO data which are consistent with the chemical system being considered. Occasionally it may be desired to specifically omit one or more species from considerations as possible species. This may be accomplished by means of OMIT cards.

INSERT cards — These cards contain the named condensed species only. They have been included as options for two reasons.

The first and less important reason is that if one knows that one or several particular condensed species will be present among the final equilibrium compositions for the first assigned point, a small amount of computer time can be saved by using an INSERT card. Those condensed species whose chemical formulas are included on an INSERT card will be considered by the

program during the initial iterations for the first assigned point. If the INSERT card were not used, only gaseous species will be considered during the initial iterations. However, after convergence, the program will automatically insert the appropriate condensed species and reconverge. Therefore, it usually is immaterial whether or not INSERT cards are used. For all other assigned points the inclusion of condensed species is handled automatically by the program.

The second and more important reason for including the INSERT card option is that, in rare instances, it is impossible to obtain convergence for assigned enthalpy problems (HP or RKT) without the use of an INSERT card. This occurs when, by considering gases only, the temperature becomes extremely low (say several degrees Kelvin). In these rare cases, the use of an INSERT card containing the name of the required condensed species will eliminate this kind of convergence difficulty. When this difficulty occurs, the following message is printed by the program: "LOW TEMPERATURE IMPLIES CONDENSED SPECIES SHOULD HAVE BEEN INCLUDED ON AN INSERT CARD."

A.2 PROGRAM INPUT FOR THE TAPE GENERATOR

This program arranges the thermochemical data in the format of the "CEC" program in the format used by the VOF program.

Initial data group is read in using namelist in this list.

Variable	Type	Value Before Read	Definition
IREAD	I	0	For IREAD = 1, read data from tape instead of from file. For IREAD = 0, read data from file instead of from tape.

The second data group contains one card having the following information:

Data Case Name
Blank Space
Number of O/F cuts
Number of Entropy cuts

NOT REPRODUCIBLE

A.3 PROGRAM INPUT FOR THE VARIABLE O/F METHOD-OF-CHARACTERISTIC PROGRAM

This program generates the nozzle and plume flow fields. The Detailed Guide for Input Data to MOC-O/F Program (VOFMOC)

<u>CARD NO. 1</u>		<u>Problem Title or Identification</u>
Format:	12A6	
Cols. 1-72	HOL	Comment card, header information such as problem title may go on this card. It is printed at the top of each page of output.
<u>CARD NO. 2</u>		<u>Run Control Card</u>
Format:	I6I5	
Col 5	ICON(1)	1 Read cards for gas properties
		2 Read tape 10 (A6) for gas properties
Col 9	ICON(2)	0 Normal start line
		1 Right-running characteristic start line
		2 Left-running characteristics start line
Col 10	ICON(2)	0 Straight start line M given
		1 Source start line A/A* given
		2 Starting line input
		3 Starting line calculated by conservation of mass
Cols 14, 15	ICON(3)	Number of starting line points (50 max)
Cols 16-20	ICON(4)	Number of upper boundary equations (100 max)
Option for ICON (4) when upper boundary is to be curve fit		
Cols 16-20	ICON(4)	1000 + number of discrete points specifying upper boundary + 2, where the 2 represents the nozzle throat equation and the free boundary equation
Cols 21-25	ICON(5)	Number of lower boundary equations (100 max)
Option for ICON(5) when lower boundary is to be curve fit		
Cols 21-25	ICON(5)	1000 + number of discrete points specifying lower boundary + 2, where the 2 represents the nozzle throat equation and the free boundary equation

Col 27	ICON(6)	0 The start line will not be output on punched cards 1 The start line will be output as punched cards
Cols 28-29	ICON(6)	The boundary equation at which it is desired to begin the characteristic solution after the automatic restart of the reflected shock is initiated.
Col 30	ICON(6)	If a zero is used the MOC data on Tape up to the shock reflection will not be saved on output tape. If a 1 is used the data up to the shock reflection data will be saved on the output tape.
Col 35	ICON(7)	0 Two-dimensional solution 1 Axisymmetric solution
Cols 37-38	ICON(8)	This option controls the type of output obtained after the problem has reached a free boundary equation. The same scheme is used in cols 37-38 as in 39 and 40.
Col 39	ICON(8)	0 Full output 1 Limited output (no interior points)
Col 40	ICON(8)	1 One line output (R, X, M, THETA, S, Shock Angle) 2 Two lines, above plus (Mach Angle, P, Density, T, V) 3 Three lines, above plus (MWT, GAMMA, TO*, PO*, S*)
Cols 41-43	ICON(9)	No. of left-running points up to and including upstream shock point. Used when $ICON(2) \geq 20$ and shock crosses starting line.
Cols 44, 45	ICON(9)	Number of regular start line points if $ICON(2) \geq 20$
Col 50	ICON(10)*	0 Radiance tape not desired* 1 Radiance tape desired (1 tape) 2 Radiance tape desired (2 tapes)
Cols 51-55	ICON(11)	Case number (prints at top of each page)
Col 60	ICON(12)	0 Calculate shock wave 1 No rotation option
Cols 61-65	ICON(13)	1 Use viscous boundary layer
Cols 66-70	ICON(14)	N Number of Prandtl-Meyer rays to be used in expansions 0 Program will determine number of rays to be used.
Col 74	ISTOP	0 Single case is being run 1 Multiple cases are being run
Cols 75	ICON(15)	0 Mesh control is not desired 1 Mesh control is desired
Cols 75-80	ICON(16)	1 Program debug 0 No debug

* This option is not operational use a 0.

CARD NO. 3

Describes physical boundaries of the flow field. For use when ICON(4) and/or ICON(5) ≤ 100 .

Format: II, 3X, II,
5X, 6E10.6

Col 1	IWALL	1, Conic equation $R=A^*(\text{SQRT}(B+C^*X+D^*X^{**2})+E)$
	IWALL	2, Polynomial equation $R=A^*X^{**4}+B^*X^{**3}+C^*X^{**2}+D^*X+E$
	IWALL	3, Free boundary equation $P=PINF^*(1+EX)^*(1+GAMMAINF^*(MINF^*\text{SIN}^*(THETAB - THETAINF))^{**2})$
	IWALL	6, Free boundary equation of same form as IWALL=3, except oblique shock solution is used to generate plume boundary. Use number 6 for free stream approach flow in range of Mach 1.5 to 5.5.
Col 5	ITRANS	0 No discontinuity follows this equation 1 Expansion corner follows this equation 2 Compression corner follows this equation
Cols 11-20	WALLCO	A(If IWALL = 1 or 2), PINF (If IWALL=3)
21-30	WALLCO	B(If IWALL = 1 or 2), GAMMAINF (If IWALL=3)
31-40	WALLCO	C(If IWALL = 1 or 2), MINF (If IWALL=3)
41-50	WALLCO	D(If IWALL = 1 or 2), THETAINF (If IWALL=3)
51-60	WALLCO	E(If IWALL = 1 or 2), E(If IWALL=3)
61-70	XMAX	Maximum X value for which this equation applies.

NOTE: The coefficients of each equation are contained on a single card. As many cards, i.e., equations, as necessary to describe the boundaries are input. The units of physical dimensions affect only the thrust calculations in which units of feet are assumed. Upper boundary information is given first. Program assumes that starting line is bounded by solid walls and that the equations are ordered with XMAX monotonically increasing.

CARD NO. 3A

Optional, physical flowfield boundary condition for use when ICON(4) and/or ICON(5) ≥ 1000 .

Format: 6E10.6

Cols 1-10	RC	Radius of curvature of nozzle throat
11-20	RT	Radius of nozzle throat
21-30	THETA	Nozzle throat divergence angle
31-40	XO	Axial coordinate shift
Cols 1-10	XIN(I)	Each pair of XIN(I) and YIN(I) represents a discrete point for spline-fitting of the nozzle solid boundary. As many of these points as necessary can be input to a maximum of 100. Points must be input with XIN(I) monotonically increasing.
11-20	YIN(I)	
21-30	XIN(I+1)	
31-40	YIN(I+1)	
41-50	XIN(I+2)	
51-60	YIN(I+2)	

Cols 1-10	XIN(I+3) YIN(I+3) etc	
Format:	I1, 3X, I1, 5X, 6E10.6	
Col 1	IWALL	3 Free boundary equation
Col 5	ITRANS	0 No discontinuity follows this equation.
Col 11-20	WALLCO	PINF
21-30	"	GAMMAINF
31-40	"	MINF
41-50	"	THETAINF
51-60	"	E
61-70	"	XMAX

NOTE: Optional boundary description, Card Type 3A, is set up specifically for a rocket nozzle. The first card describes the nozzle throat, which is followed by cards containing sets of discrete points, three per card, describing the nozzle contour. The points will be automatically spline-fit to form equations for the contour. It is assumed that a free boundary equation follows the last nozzle point. Card types 3 and 3A may be mixed, i.e., the upper boundary may be described by type 3A while the lower boundary is described by type 3, or vice versa. Card type 3 and 3A may not be used simultaneously for a given boundary.

<u>CARD NO. 4</u>		Gas Identification and Gas Property Input Control
Format:	4A6, 5X, A3, 6X, I2, 3X, I2	
Cols 1-24	ALPHA	Gas name, identification for real gas properties on tape. May be any name when gas properties are input via cards.
Cols 30-32	UNITS	ENG English units are to be input (cards only) MKS Metric units (cards or tape)
Cols 39-40	IOF	Number of O/F cuts, 1 min., 10 max.
Cols 44-45	IS	Number of entropy cuts (ignored for tape, 1 for ideal gas, 2 max for real gas via cards).
<u>CARD NO. 5</u>		O/F value of each table (must be input even if constant O/F case is run).
Format:	E10.6	
Cols 1-10	OFRTAT	
<u>CARD NO. 6</u>		Entropy value and number of velocity cuts. (Not input if ICON(1) = 2, i.e., gas properties via tape)

Format: E10.6, 8X, I2

Col 1-10 STAB
Col 19, 20 IVTAB

Entropy value
Number of Mach numbers for this entropy value 13 max, (1 if ideal gas)

CARD NO. 7

This card(s) gives the Mach number and associated gas properties at that Mach number and entropy.

Format: 5E10.6

Cols 1-10 TAB
Cols 11-20 TAB

Mach number
Gas constant (R) if UNITS = ENG, Molecular weight (MWT) if UNITS = MKS.
GAMMA

Cols 21-30 TAB
Cols 31-40 TAB
Cols 41-50 TAB

Temperature at this Mach number
Pressure at this Mach number

Units	MKS	ENG
Temperature	$^{\circ}\text{K}$	$^{\circ}\text{R}$
Pressure	Atmospheres	psfa
Gas Constant (R)	(Molecular Weight)	1545.2 x 32.2/Mwt

NOTE: Card nos. 5, 6 and 7 are omitted if gas properties are input via tape.

CARD NO. 8

This card specifies the necessary information for the starting line. (If ICON(2) $\neq$ 2, 12 or 22)

Format: 8E10.6

Cols 1-10 CORLIP

Axial coordinate of upper limit of start line.

Cols 11-20 CORLIP

Axial coordinate of lower limit of start line.

Cols 21-30 CORLIP

Mach number of A/A^* for start line.

Cols 31-40 CORLIP

Entropy level of start line.

Cols 41-50 STEP(5)

Area of nozzle throat (units consistent with boundary equations) (Must be input for thrust coefficient calculation).

Cols 51-60 CORLIP

Constant O/F value (not used if ICON(2)=2)

Cols 61-70 STEP(6)

Minimum ΔP for discontinuing shock calc.

CARD NO. 9

These cards are used to read in a known starting line (ICON(2) = 2, 12 or 22).

Omit when Card no. 8 is used. As many of these cards are input as specified by ICON(3) on the run control card. Used only if ICON(2) = 2, 12 or 22.

Format:	8E10.6	
Cols 1-10	PSI	Radial coordinate of this point
Cols 11-20	PSI	Axial coordinate of this point
Cols 21-30	PSI	Mach number of this point
Cols 31-40	PSI	Flow angle of this point
Cols 41-50	PSI	Entropy level of this point
Cols 51-60	PSI	Shock angle of downstream shock point.
Cols 51-60	STEP(5)	For last card only STEP(5) where STEP(5) is the area of nozzle throat (units consistent with boundary equations, must be input for thrust calculation).
Cols 61-70	STEP(6)	For last card only STEP(6) where STEP(6) is the minimum ΔP for discontinuing shock calculation.
Cols 71-80	PSI(8)	Value of O/F at each starting line point.

NOTE: To use of O/F capability, supply a value of O/F for each input point. Select Option 2 for ICON(2), i.e., starting line input. For constant O/F operation supply one O/F table and set O/F constant on card 8.

CARD NO. 10

This card contains the necessary information to limit the calculations to those areas of interest. An unusual scheme is employed in order to make these limits efficient for the many problem orientations which are possible.

Format:	8E10.6	
Cols 1-10	CUTDAT	Radial coordinate defining upper cutoff.
Cols 11-20	CUTDAT	Axial coordinate defining upper cutoff.
Cols 21-30	CUTDAT	Angle cutoff line makes with horizontal.
Cols 31-40	CUTDAT	Radial coordinate defining downstream cutoff.
Cols 41-50	CUTDAT	Axial coordinate defining downstream cutoff.
Cols 51-60	CUTDAT	Angle cutoff line makes with horizontal.
Cols 61-70	STEP(3)	Point Insert Criteria. If the change in axial location between two characteristic lines along the axis exceeds Step(3) a new characteristic point will be inserted.
Cols 71-80	TINF	Free stream temperature ($^{\circ}R$). Use only if IWALL=6 on card 3.

CARD NO. 11

Mesh control parameters, controls mesh size by inserting or deleting points.

Format: 6E10.6

Cols 1-10
Cols 11-20
Cols 21-30
Cols 31-40
Cols 41-50
Cols 51-60

Length control abs. Δl insert
Length control abs. Δl delete
Mach No. control abs. ΔM insert
Mach No. control abs. ΔM delete
Flow angle control abs. $\Delta \theta$ insert
Flow angle control abs. $\Delta \theta$ delete

CARD NO. 12

This card contains the input information for the viscous boundary layer option.

Format: I1, 2X, I2,
5X, 2E10.6

Col 1 NPOWER

Exponent of the velocity profile in the boundary layer

Cols 4, 5 NBLPTS

Number of boundary layer points specified

Cols 11-20 XL

A characteristics length (usually nozzle length)

Cols 21-30 CU

Conversion factor for mixed units of length.

A.4 AUTOMATIC PLOT PROGRAM

The Automatic Plot Program will plot contour maps of the flowfield properties. The flowfield data are obtained from the magnetic tape generated by the VOFMOC computer program. The user sets the geometric limits of the flow field that are to be examined and numerical ranges for the Mach number, entropy and O/F ratio which are then used to establish the incremental values of the contour data. The user also has the option to input specific contours of the various properties which are to be plotted.

One input data tape is required, which is the flowfield data tape generated by the VOFMOC computer program. The program uses the SC-4020 plot package to generate plots of the flowfield data. A description of the input data for the plot program is given in the following section.

A.4.1 Card Input Instructions for the Plot Program

Card 1

This card contains input options necessary to control program execution.

<u>Format</u>	<u>Column/Option</u>	<u>Item Description</u>
16I5	4-5/NFIND	Number of properties to be plotted (14 max) (i.e., pressure, Mach no., temperature, etc., Ref. Card 4).
	9-10/NUMBER	Number of contours plotted per property (20 max). Note: The program uses this option only if the number of contours per property are not specified on Card 4.
	15/IREF	0 - Program plots dimensional values of pressure, density, temperature, or radial and axial station. 1 - Program will non-dimensionalize pressure, density, temperature or radial and axial stations using reference values as read in from Card 5.

Card 1 (Continued)

<u>Format</u>	<u>Column/Option</u>	<u>Item Description</u>
	20/IWRITE	
	0 -	No intermediate printout
	1 -	Program will print out information at intermediate points (useful in checkout).
16I5	24-25/ISTART	
		The number of the characteristic line at which the program will be in searching for contour points.
	30/IAXO2D	
		Flowfield type
	0 -	Flow field is two-dimensional
	1 -	Flow field is axisymmetric
	35/IDIGIT	
		The number of significant places retained for property contours values, (max of 5), if IDIGIT if input as 0 to the program will set IDIGIT to 3 automatically.
	39-40/ICARD	
		This option allows the property contours to be read in from cards. ICARD is the total number of properties whose contours are to be read in from cards. (Ref. Cards 4 and 6).
	45/IALL	
	0 -	Program will read in from cards max and min; Mach numbers, O/F ratio, and entropy for setting up contours.
	1 -	The contours for all properties will be read in from cards.
	50/IMASS	
		Not presently used.
	55/IRUN(6)	
	0 -	No print out of flow properties at mass flow rate contour points.
	1 -	Will print out all properties of calculated contour points of mass flow rate.

Card 1 (Continued)

<u>Format</u>	<u>Column/Option</u>	<u>Item Description</u>
16I5	60/ICON(2)	
	0	- Program searches every characteristic line for contour values.
	N	- Number of characteristics lines skipped between searches.

Card 2

This card reads in maximum and minimum flow properties for use in setting up contours. These values should be based on the flowfield region which is to be mapped. Use this card only if IALL was set to zero.

<u>Format</u>	<u>Column</u>	<u>Item</u>
8E10.6	1-10	EMMAX - Maximum Mach Number
	11-20	EMMIN - Minimum Mach Number
	21-30	SMAX - Maximum Entropy
	31-40	SMIN - Minimum Entropy
	41-50	THETMX - Maximum Flow Angle (Degrees)
	51-60	THETMN - Minimum Flow Angle (Degrees)
	61-70	O/FM - Maximum O/F Ratio
	71-80	O/FN - Minimum O/F Ratio

Card 3

This card contains the necessary information for setting up the maximum and minimum radial and axial coordinates within which the program will operate.

<u>Format</u>	<u>Column</u>	<u>Item</u>
8E10.6	1-10	RMIN - Minimum Radial Coordinate
	11-20	RMAX - Maximum Radial Coordinate
	21-30	XMIN - Minimum Axial Coordinate
	31-40	XMAX - Maximum Axial Coordinate

Note: The units should be consistent with those on the flowfield tape.

Card 4

This card is the plot control card which identifies the properties to be plotted, sets the number of contours for each property and sets the number of significant places to be used for each set of property contours.

The first column of each 5-column array will determine the number (5 max) of significant figures the particular set of property contours will have. If a zero is used, the number of significant figures will be set equal to IDIGIT. The second and third column will set the number (20 max) of contours to be plotted. The fourth and fifth column will identify the property to be plotted.

<u>Format</u>	<u>Column/Property</u>	<u>Item</u>
16I5/Right Adjusted		J
4-5/J		1 - Mach Number
9-10/J		2 - Pressure-Static
14-15/J		3 - Temperature-Static
19-20/J		4 - Pressure (Stag Norm Shock)
24-25/J		5 - Gamma
29-30/J		6 - Molecular Weight
34-35/J		7 - Density
39-40/J		8 - Entropy
44-45/J		9 - Mass Flow
49-50/J		10 - Heat Rate
54-55/J		11 - Velocity
59-60/J		12 - O/F Ratio
64-65/J		13 - Characteristic Lines
69-70/J		14 - Flow Angle

Note: The order of these properties is arbitrary except that those properties whose contours are to be read in from cards must follow all the properties whose contours are to be selected by the program (Ref. Card 6).

Example: Flow angle and Mach number are desired with 2 significant figures for both properties and 20 flow angle contours set by the program and 9 Mach number contours read in from a card.

Cols.	1	2	3	4	5	6	7	8	9	10
	2	2	0	1	4	2	0	9	0	1
	<u> </u>					<u> </u>				
	Flow Angle					Mach No.				

Card 5

This card is used if IREF is set to 1. This card contains information the program may use in referencing pressure, density, temperature and radial/axial stations, (i.e. plots P/P_{ref} instead of P).

<u>Format</u>	<u>Column</u>	<u>Item</u>
8E10.6	1-10	RHOREF - Reference Density by Which Density Contours are Divided After Contour Points are Found.
	11-20	PREF - Reference Pressure by Which Pressure Contours are Divided After Contour Points are Found.
	21-30	TREF - Reference Temperature by Which Temperature Contours are Divided After Contour Points are Found.
	31-40	REFD - Reference Distance by Which Axial and Radial Lengths are Divided After a Contour Point is Found.
	41-50	REFL - A Reference Distance by Which the Axial Location of the Origin is Shifted.

Card(s) 6

These cards are used to read in contours for desired properties. Each card may contain 8 contours and up to 20 contours may be read in for each property. The total number of sets of these cards must equal ICARD. Arrange the sets in the same order in which the properties are read from Card 5, the plot control card. Use these cards only if ICARD was set greater than zero.

Format

8E10.6

Example: Use example for Card 4. Flow angle and Mach number are to be plotted. ICARD is set to 1, therefore flow angle contours will be set up by the program and Mach number contours will be read in from cards. Since nine contours are desired for Mach number, two cards are necessary.

Card 6 (Continued)

Card 6a

<u>Column</u>	<u>Mach No. Contour</u>
1-10	2.0
11-20	4.0
21-30	6.0
31-40	8.0
41-50	10.0
51-60	12.0
61-70	14.0
71-80	16.0

Card 6b

<u>Column</u>	<u>Mach No. Contour</u>
1-10	18.0

Card 7

This card is used to read in the total mass flow for finding mass flow streamlines. Set WTFLOW to the total mass flow as output by MOC program. Use this card only if mass flow streamlines are to be plotted.

<u>Format</u>	<u>Column</u>	<u>Item</u>
8E10.6	1-10	WTFLOW - The Total Mass Flow Passing Through the Nozzle.

Card 8

This card is used to read in information necessary for computing stagnation heating rates in the plume. (Assuming frozen chemistry and constant O/F ratio throughout plume). Use cards 8 and 9 only if heating rates are to be plotted.

Card 8 (Continued)

<u>Format</u>	<u>Column</u>	<u>Item</u>
I5, 5X, 7E10.6	5	NNN - Number of N th Chemical Specie of Flow Field Gas. N is the Highest Non-Zero Mole Fraction of the Species as Follows: N 1 - CO ₂ 2 - H ₂ 3 - H ₂ O 4 - HI 5 - OH 6 - CO 7 - N ₂ 8 - O ₂
	11-20	AMWE - Molecular Weight of the Mixture
	21-30	TWALL - Wall Temperature (°R)
	31-40	TD - Temperature of Gas at the Stagnation PT at Onset of Dissociation (°R)

<u>Format</u>	<u>Column</u>	<u>Item</u>
	41-50	RB - The Reference Radius (r*) at the Stagnation PT for Use in Velocity Gradient Calculation.
	51-60	FUDGE 1 - r* Input in ft 12 - r* Input in in.
	61-70	SHAPE 1.414 - Hemisphere 1.414 - Circular Disc 1.000 - Cylinder 1.000 - Flat Plate

Card 9

This card reads the mole fractions of the flowfield gas composition. There are presently eight of the most common constituents being considered and they must be input in the correct order. The sum of the mole fraction must equal one (1).

<u>Format</u>	<u>Column</u> *	<u>Item</u>
8E10.6	1-10	CO ₂ Mole Fraction
	11-20	H ₂ Mole Fraction
	21-30	H ₂ O Mole Fraction
	31-40	H ₁ Mole Fraction
	41-50	OH Mole Fraction
	51-60	CO Mole Fraction
	61-70	N ₂ Mole Fraction
	71-80	O ₂ Mole Fraction

* If species other than these are required, the data statements in subroutine PROPTY must be changed.

A.5 IMPINGEMENT PROGRAM INPUT DATA

The impingement program when operating in a combined mode with the staging program is subdivided into three sections. The first section arranges the flowfield data generated by the "VOFMOC" program in the format used in the impingement calculations. The main program for this section is called "SORTCT" for which data cards are required. These are described below. The second section is used as a subprogram by the staging program and performs the impingement analysis. The booster coordinates and the set of direction cosines which describe the orbiter engine location and orientation with respect to the booster nose are supplied to the impingement program by the staging program. The forces and resulting moments due to the orbiter exhaust plume impinging on the booster surfaces are returned to the staging program. If the heating rates to the booster surfaces are desired, the data required to perform this analysis are written on magnetic tape. The heating rate analysis is then performed on a subsequent computer run by executing a main program called "REHEET."

A.5.1 Input Guide for the Ordering Program

Card 1

<u>Format</u>	<u>Column</u>	<u>Item</u>
16I5	5	ISTART, ordering the flowfield data will begin with this characteristic line number.
	10	ISIGN, -1 if the flow field were generated with a reflected shock from the nozzle axis.
	15	NUMBER, number of flowfield data points desired per data record (maximum of 300).
	20	IDEL > 0 if any points are to be deleted from the flow field.
	25	IPRINT > 0 if intermediate is to be obtained as the flow field is ordered by distance from the engine exit plane.

Card 1 (Continued)

<u>Format</u>	<u>Column</u>	<u>Item</u>
16I5	30	ITERM, characteristic line number where ordering of flowfield data is to be terminated.
16I5	35	ISEND, 1 if plume boundary is to be curve fitted for use in the interpolation scheme, 2 if only the cutoff limits read as input data are to be used to see if a point is within a prescribed boundary.
	40	ISKIP, if ISEND = 1

Card 2

<u>Format</u>	<u>Column</u>	<u>Item</u>
6E10.6	1-10	RREF*, radial coordinate in which each flowfield data point will be referenced.
	11-20	XREF*, axial coordinate to which each flowfield data point will be referenced.
	21-30	DELETE if IDEL > 0, one of two points with a distance between them less than DELETE will be deleted from the flowfield data.

A.5.2 PLIMP Program Input Instructions

Card 1

This card contains a title or heading which is used for run identification.

<u>Format</u>	<u>Column</u>	<u>Item</u>
12A6	1-72	Title or Heading

* The coordinates XREF, RREF are used to accomplish any desired coordinate system translation.

Card 2

This card contains input options necessary to control program execution.

<u>Format</u>	<u>Column/Option</u>	<u>Item</u>
16I5	5/IOPT(1)	Flowfield Type
		1 - Flow Field is Axisymmetric
		0 - Flow Field is Two-Dimensional
	10/IOPT(2)	Desired Heating Options
		0 - Calc. Continuum and Free Molecular Heating
		1 - Calc. Continuum Heating Only
		2 - Calc. Free Molecular Heating Only
		3 - None
	15/IOPT(3)	Uniform Flow Assumptions
		0 - Composite Vehicle in Uniform Flow
		1 - Subshapes in Uniform Flow
		2 - Elemental Rings in Uniform Flow at Maximum Impingement
		3 - Elemental Areas in Uniform Flow
	18-20/IOPT(4)	Number of Subshapes in Composite Body
		N - Number of Subshapes (10 max)
	25/IOPT(5)	Type Output Desired
		0 - No Print-Out
		1 - Force and Torque Summary
	30/IOPT(6)	Local Flowfield Chemistry
		0 - Consider Property Variation with Entropy
		1 - Neglect Entropy Effects (Use Only 1 Gas Table)
	35/IOPT(7)	Optional Input of Boundary Layer Species
		0 - Use Species on Flowfield Tape
		> 0 - Number of Species Input
	40/IOPT(8)	
		(-ISTAG) - Number of Subshape Where Stagnation Point Located
	45/IOPT(9)	Type Local Properties
		1 - Newtonian Assumption
		2 - Modified Newtonian
		3 - Isentropic Expansion
		4 - Oblique Shock

Card 2 (Continued)

<u>Format</u>	<u>Column/Option</u>	<u>Item</u>
16I5	46-50/IOPT(10)	Debug Flag if > 0
	> 0	- Input the Number of Subshape at Which Debug Printout is Desired (Look Out!!)
	51-55/IOPT(11)	Plot Control Flag
Col. 51	0	- Do Not Connect Points
	1	- Connect Plotted Points with Lines
Cols. 52-53		Number of Tape Drive on Which Plot Data will be Stored; Usually ~ 14 on Univac 1108
Cols. 54-55		Number of Parameters to be Plotted
	56-60/IOPT(12)	Case Number
	65/IOPT(13)	
	0	- Impingement Program Dimensioned in Inches
	1	- Impingement Program Dimensioned in Feet
	70/IOPT(14)	
	0	- Flow Field Dimensioned in Inches
	1	- Flow Field Dimensioned in Feet
	75/IOPT(15)	Local Property Printout
	1	- Print Local Properties in Heating Rate Routine
	80/IOPT(16)	Heating Ratio Option
	1	- The heating values at each trajectory time step will be referenced to the engine chamber pressure at that time step.
	0	- The heating values at each trajectory time step will be referenced to the engine chamber pressure at full thrust.

Card 3

This lists the impingement parameters to be plotted. Format 16I5.
The parameters to be plotted are: Cols. 1 - 70 (Only if ITPLOT .GT.0)

1. Laminar Convective Heating Rate
2. Turbulent Convective Heating Rate
3. Transitional Flow Convective Heating Rate
4. Free Molecular Flow Convective Heating Rate
5. Local Reynolds Number Based on Momentum Thickness

Card 3 (Continued)

6. Impact Pressure
7. Impact Pressure-to-Chamber Pressure Ratio
8. Impact Force Distribution
9. Oxidizer-to-Fuel Ratio Distribution
10. Incident Mass Flow Rate
11. Freestream Mach Number
12. Local Mach Number
13. Local Temperature
14. Local Plume Impingement Angle

NOTE: The order of variable input is optional.

Col. 75 - Point deletion criteria. Every N^{th} point will be plotted.

Col. 80 - Line deletion criteria. Every N^{th} line will be plotted.

Card 4: Format 3(A6, 4X, E10.6)

This card reads the mole fractions of the flowfield gas composition.
Ten most dominant species (used only if IOPT(7).GT.0).

Cols. 1-6, 21-26, 41-46, Chemical Specie Name

Cols. 11-20, 30-40, 51-60, Mole Fraction

Cards 5 and 8: Format (8E10.6/7E10.6, 1X, A4)

Body Heating and Loads Supplementary Data.

Card 7

<u>Col.</u>	<u>Name</u>
1-10	(XTE) - Transfer Distance from Nozzle Throat to Exit Plane (in. or ft consistant with IOPT(13))
11-20	XMIN - (Minimum distance behind engine exit plane, plume search will be conducted, units consistant with IOPT(14))
21-30	(DIA) - Molecular Diameter (in. or ft, units consistant with IOPT(13))
31-40	Engine Reference Diameter if the Flow Field is in Non-Dimensional Form.

Card 7 (Continued)

<u>Col.</u>	<u>Name</u>
41-50	RICH - Diameter of Nozzle at Exit Plane for Use in Nondimensionalizing Program Output.
51-60	PC - Engine Chamber Pressure, psi
61-70	PCRAT - Ratio of Desired Plume Chamber Pressure to Chamber Pressure at which Plume Flowfield Tape was Generated.
71-80	(DELPHI) - Constant Angular Increment off Stagnation Line.

Card 6

1-10	(PAMB) - Pressure Outside Plume (psf)
11-20	(TAMB) - Temperature Outside Plume ($^{\circ}$ R)
21-30	(XSTAG) - Axial Distance from Subshape Origin to Stagnation Point.
31-40	(TW) - Wall Temperature ($^{\circ}$ R)
41-50	TD - Temperature of the Gas in the Boundary Layer at the Stagnation Point at Onset of Dissociation.
51-60	RS - The Reference Radius (r^*) at the Stagnation Point for Use in the Velocity Gradient Calculation.
61-70	FUDGE - 1 - r^* Input in ft 12 - r^* Input in in.
72-75	SHAP - Nose Shape 3DHM Hemisphere 2DHM Cylinder 3DDS Circular Disc 2DFP Rectangular Flat Plate

Card 7

This card contains the body reference dimensions to be used in determining the local flow regime.

Format: 6E10.6

Card 7 (Continued)

<u>Col.</u>	<u>Description</u>	
1-10	(REFL) - Reference Length (in. or ft)	} Subshape Number 1
11-20	(REFD) - Reference Diameter (in. or ft)	
21-30	REFL {	Subshape Number 2
31-40	REFD }	
41-50	REFL {	Subshape Number 3
51-60	REFD }	

Card 8

These cards identify the type surface (conic, rectangular plate, circular plate) and the coefficients of surface equation. There will be as many of these cards as there are subshapes, up to a maximum of 100 for the 1108 or 10 on the 7094.

<u>Format</u>	<u>Column</u>	<u>Item</u>	<u>Polynomial Curve Fit</u>
	1	<u>Conic</u> <u>R Plate</u> <u>C Plate</u> <u>T Plate</u> <u>Wing</u>	6
		1 2 3 4 5	
II, I9, 7E10.6	2-4	NPHI - Surface Integration Control Number of Angular (PHI) Increments for Conic and Circular Plate Subshape, or Number of Z Increments for Rectangular Plate Subshape Number of Span Increments for Wing 60 Max on 1108	
	5-7	NX - Surface Integration Control Number of X Increments for Conic Subshape Number of R Increments for Circular Plate, or Number of Y Increments for Rectangular Plate Subshape Number of Chord Increments on Wing (30 Max)	

Card 8 (Continued)

<u>Col.</u>	<u>Item</u>				
8-10	IHT - Continuum Regime Heat Rate Method				
	= 1 - Conic Body at Angle of Attack Less than 50 deg				
	= 2 - Flat Plate at Angle of Attack Less than 50 deg				
	= 3 - Conic Body at Angle of Attack Greater than 50 deg				
	= 4 - Body at Angle of Attack Greater than 50 deg; (Hemisphere, Cylinder, Rectangular Plate, Circular Plate).				
	= 5 Yawed Infinite Cylinder				Polynomial
	<u>Conic</u>	<u>R Plate</u>	<u>C Plate</u>	<u>Wing</u>	<u>Curve Fit</u>
11-20	A	YMAX	ROUTER	θ_s	a_1
21-30	B	(in. or ft)	(in. or ft)	R_c	a_2
31-40	C	ZMAX	RINNER	Span	a_3
41-50	D	(in. or ft)	(in. or ft)	TR	a_4
51-60	E			Dihedral	a_5
61-70	XNOSE			RT	XNOSE
71-80	(in. or ft)			IFLAG	XBASE
	XBASE			= 0 Both	
	(in. or ft)			= -1 -Z	
				= +1 +Z	

The conic equation is of the form

$$R = (\sqrt{B + CX + DX^2} + E), \quad XNOSE \leq X \leq XBASE$$

and

$$DA = R \Delta R \Delta PHI.$$

For the circular plate

$$DA = R \Delta R \Delta PHI \quad RINNER \leq R \leq ROUTER$$

the rectangular plate is defined as

$$DA = \Delta Y \Delta Z, \quad 0 \leq Y \leq YMAX \\ 0 \leq Z \leq ZMAX$$

The polynomial curve fit is of the form

$$R = a_1 + a_2 X + a_3 X^2 + a_4 X^3 + a_5 X^4, \text{ and}$$

$$DA = R \Delta R \Delta PHI$$

Card 9

Body Shading Data

Format 10I8

Cards 10

These cards contain the position vectors (RCI) from the composite structure to the subshape origins. RCI is measured in the composite system reference frame. There will be as many of these cards as there are subshapes.

<u>Format</u>	<u>Column</u>	<u>Item</u>
3E10.6	1-10	RCI(X) - X Component of Position Vector (in. or ft)
	11-20	RCI(Y) - Y Component of Position Vector (in. or ft)
	21-30	RCI(Z) - Z Component of Position Vector (in. or ft)

NOTE: RCI is measured in the composite ("C") system and "points" to the subshape origins.

The I system origin must be properly placed for the continuum heating rate results to be meaningful, i.e., for:

- Conic Bodies - The X_I coordinate must be placed along the body centerline in the direction of flow and Y_I coordinate must be facing the stagnation line* or most windward streamline. Z_I will be placed by the program using the right-hand rule.
- Rectangular Plate Bodies - The X_I coordinate must be placed perpendicular to the surface at the area centroid, and Y_I coordinate must be pointing in the direction of flow. Z_I will be placed by the program using the right-hand rule.

Cards 11

These cards contain the subshape unit vectors (I_I and J_I). There will be one of these cards for each subshape. I_I and J_I are measured in the composite system reference frame.

<u>Format</u>	<u>Column</u>	<u>Item</u>
6E10.6	1-10	II(X), X Component of Unit Vector I
	11-20	II(Y), Y Component of Unit Vector I
	21-30	II(Z), Z Component of Unit Vector I
	31-40	JI(X), X Component of Unit Vector J
	41-50	JI(Y), Y Component of Unit Vector J
	51-60	JI(Z), Z Component of Unit Vector J

Cards 12

These cards enable the program to limit the calculations to the area of interest on a conic body by limiting the angular surface integration. For all other bodies, blank cards should be used. These are as many of these cards as there are subshapes.

<u>Format</u>	<u>Column</u>	<u>Item</u>
2E10.6	1-10	PHIMI - Angle in degrees measured in the Y-Z plane from the +Y axis up to which calculations are to be made.
	11-20	PHIMZ - Angle measured same as PHIMI from which calculations are to be continued to the +Y axis.

Card 13

This card contains the necessary information to limit the calculations to those areas of interest. An unusual scheme is employed in order to make these limits efficient for the many problem orientations which are possible.

<u>Format:</u>	<u>8E10.6</u>	<u>Item</u>
Cols. 1-10	CUTDAT	Radial coordinate defining upper cutoff.
Cols. 11-20	CUTDAT	Axial coordinate defining upper cutoff.
Cols. 21-30	CUTDAT	Angle cutoff line makes with horizontal.
Cols. 31-40	CUTDAT	Radial coordinate defining downstream cutoff.
Cols. 41-50	CUTDAT	Axial coordinate defining downstream cutoff.
Cols. 51-60	CUTDAT	Angle cutoff line makes with horizontal.

Card 14

End of Case Card

Columns 1-3 END

A.5.3 Input Instructions for the Heating Rate Program

Card 1

This card is used to define the FORTRAN unit number on which the data tape generated by the impingement program is mounted. It is also used to provide instructions for plotting and printing the data.

<u>Format</u>	<u>Column</u>	<u>Item</u>
3IS	5	I, FORTRAN unit number data tape is mounted on.
	10	Not presently used.
	15	K, = 1 if the results of the impingement and heating rate calculations are to be printed only. = 2 if the results are to be plotted only. = 3 if the results are to be plotted and printed.

This card is used to redefine any variable as input to or set by the impingement program. The namelist is a free field input and only those variables which are desired to be changed need be input.

Card 2

<u>Format</u>	<u>Column</u>	<u>Item</u>
Namelist, \$INPTZ	Free Field	IOPT, IPLYSM, PCRAT, RICH, PRATIO, ITPLOT, TUNIT, IRUN, JM5, XP

Description of Variables:

1. IOPT: Defined in the input guide for the impingement program.
2. IPLSYM: Array which contains the plot variables. These would be stored in the order as input to the impingement program.
3. PCRAT: Parameter used to scale the heating rate values. This parameter can be set by the program or supplied by the staging program.
4. RICH: Parameter used to non-dimensionalize the subshape coordinates.
5. PRATIO Parameter used to non-dimensionalize the values of pressure.
6. ITPLOT: Number of variables to be plotted.
7. TUNIT: Parameter used to determine if subshape dimensions are in feet or inches. It is a 12 for inches and 1 for feet.
8. IRUN:
IRUN(2) Flag which indicates i^{th} point to be plotted.
IRUN(3) Flag which indicates j^{th} line to be plotted.
9. JM5: Number of species present if heating rate calculations are made and this data is to be input from cards.
10. XP: Specie data, see impingement input guide for description.

Table A-1
DESCRIPTION OF DATA TAPES REQUIRED IN THE

Program	Tape Units Univac 1108	Tape Unit Function
CEC Chemical equilibrium combustion program	12 9	Thermochemical products tape - not optional Scratch tape for VOFMOC thermochem data
TAPGEN Program which arranges CEC data output in a format compatible with MOC program	8 9 10	Old master gas data tape - optional Scratch tape from CEC - not optional New master gas data tape - must be used if old master gas tape (8) not used.
VOFMOC Variable O/F method-of- characteristics computer program	10 13	Thermochem data tape from TAPGEN program Flowfield tape generated by VOFMOC - optional, output
PLOT Program which will auto- matically plot VOFMAC output flowfield data	13	Flowfield data tape generated by VOFMOC program SC-4020 plot tape output

Table A-1 (Continued)

Program	TapeUnits Univac 1108	Tape Unit Function
PLIMP*		
Section 1 <u>SORTCT</u> This program is required each time the VOFMOC is used to generate new flowfield data	13 8 2	Flowfield tape generated by VOFMOC program Flowfield data ordered for use by impingement program-output tape Flowfield limits data used by impingement program-output tape
Section 2 <u>IMPINGEMENT Program</u> This program is called from the staging program and performs the impingement calculations	8 2 IUNIT	Ordered flowfield data generated by ordering program-input tape Flowfield limits data - input tape Variable tape unit number in which data required to perform heating calculation and plotting will be written

* The impingement program as combined with the MSC staging program operates as 3 separate programs. The main program "SORTCT" will arrange the MOC data for use in the impingement program. The second program operates as a subprogram to the staging program and performs the impingement analysis. The main program "REHEET" controls the heating rate analysis using the data generated by the impingement program.

Table A-1 (Continued)

Program	Tape Units Univac 1108	Tape Unit Function
Section 3 <u>REHEET</u> This program will perform the heating analysis and plot the impingement data	13 11 IUNIT	Ordered flowfield data generated by ordering program-input tape Coefficients data used is the thermochemistry calculation-input tape Data to be plotted by the SC-4020 plot package Impingement data generated by impingement program-input

Table A-2
REACTANT CARDS

Order	Contents	Format	Card Column
First	REACTANTS*	3A4	1-9
Any	One card for each reactant species (maximum 15). Each card contains:		
	(a) Atomic symbols and formula numbers (maximum 5 sets)	5(A2, F7.5)	1-45
	(b) Relative weights** or number of moles	F7.5	46-52
	(c) Blank if (b) is relative weights, or M if (b) is number of moles	A1	53
	(d) Enthalpy in calories/mole (not required for assigned temperature problems, i.e., TP)	F9.5	54-62
	(e) State: S, L, or G for solid, liquid, or gas respectively	A1	63
	(f) Temperature associated with enthalpy in (d)	F8.5	64-71
	(g) F if fuel or O if oxidant	A1	72
	(h) Density in g/cc (optional)	F8.5	73-80
Last	Blank		

* All reactants must be given in relative weights or all in number of moles.

** Relative weight of fuel in total fuels or oxidant in total oxidants.

Table A-3
VARIABLES IN INPT2 NAMELIST

Variable Name	Dimen.	Type	Common Label	Value before Read	Definition and Comments
KASE	--	I	INDEX	0	Optional assigned number associated with case
P	26	R	POINTS	0	Assigned pressures. Chamber pressure (one value) for rocket problems. Values in atm unless PSIA or MMHG = T (see below)
T	26	R	POINTS	0	Assigned temperature in °K
EQRAT	--	R	MISC	0	Equivalence ratio
OF	--	R	MISC	0	Oxidant to fuel weight ratio
FPCT	--	R	MISC	0	Percent fuel by weight
FA	--	R	-----	0	Fuel to air weight ratio
TP	--	L	INDX	False	*Assigned temperature and pressure problem
HP	--	L	INDX	False	*Assigned enthalpy and pressure problem
RKT	--	L	-----	False	*Rocket problem
DETN	--	L	-----	False	*Detonation problem
PSIA	--	L	-----	False	*Pressure in psia units. Values are converted to atm internally
MMHG	--	L	-----	False	*Pressure in mm mercury. Values are converted to atm internally
IONS	--	L	INDX	False	*Consider ionic species
IDEBUG	--	L	INDX	False	*Print intermediate output

*If variable is set to be true.

Table A-4
VARIABLES IN RKTINP* NAMELIST

Variable Name	Dimen.	Type	Common Label	Value before Read	Definition and Comments
EQL	--	L	PERF	True	Calculate rocket performance assuming equilibrium composition during expansion**
FROZ	--	L	PERF	True	Calculate rocket performance assuming frozen composition during expansion**
PCP	26	R	PERF	0	Ratio of chamber pressure to exit pressure. List should not include values for the chamber and throat. Storage allows for 22 values. Values should be in increasing order
SUBAR	13	R	PERF	0	Subsonic area ratios (optional)
SUPAR	13	R	PERF	0	Supersonic area ratios (optional)
MOCT	--	I		0	Generate thermochemical data tape for streamtube and VOFMOC application***
MOCP	--	I		0	Punch thermochemical data for VOFMOC application***
PCPEF	1	R		0.0	Set chamber pressure to local pressure ratio at which chemical freezing is desired.

* Required for rocket problems only.

** Set variable false if these calculations are not desired.

*** Set variable equal to one if these processes desired.

```

1
REACTANTS
H 2.0          1.0          0.0    G 298.15 F
O 2.0          1.0          0.0    G 298.15 O

NAMELISTS
$INPT2
RKT=T,KASE=1, OF=8.9 ,P=154.0,PSIA=T,MOCT=1,MOCP=1
$END
$RKTI NP
PCP=1.0,5.0,10.0,100.0,500.0,1000.0,5000.0,10000.0,50000.0,100000.0
$END
NAMELISTS
$INPT2
RKT=T,KASE=1, OF=8.9 ,P=100.0,PSIA=T,MOCT=1,MOCP=1
$END
$RKTI NP
PCP=1.0,5.0,10.0,100.0,500.0,1000.0,5000.0,10000.0,50000.0,100000.0
$END
NAMELISTS
$INPT2
RKT=T,KASE=1, OF=4.79,P=154.0,PSIA=T,MOCT=1,MOCP=1
$END
$RKTI NP
PCP=1.0,5.0,10.0,100.0,500.0,1000.0,5000.0,10000.0,50000.0,100000.0
$END
NAMELISTS
$INPT2
RKT=T,KASE=1, OF=4.79,P=100.0,PSIA=T,MOCT=1,MOCP=1
$END
$RKTI NP
PCP=1.0,5.0,10.0,100.0,500.0,1000.0,5000.0,10000.0,50000.0,100000.0
$END
NAMELISTS
$INPT2
RKT=T,KASE=1, OF=2.06,P=154.0,PSIA=T,MOCT=1,MOCP=1
$END
$RKTI NP
PCP=1.0,5.0,10.0,100.0,500.0,1000.0,5000.0,10000.0,50000.0,100000.0
$END
NAMELISTS
$INPT2
RKT=T,KASE=1, OF=2.06,P=100.0,PSIA=T,MOCT=1,MOCP=1
$END
$RKTI NP
PCP=1.0,5.0,10.0,100.0,500.0,1000.0,5000.0,10000.0,50000.0,100000.0
$END
STOP

```

Fig. A-1 - Thermochemistry Input Data for "CEC" Equilibrium Combustion Program