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AN ANALYTICAL PROCEDURE AND AUTOMATED COMPUTER CODE USED TO DESIGN MODEL NOZZLES WHICH MEET MSFC BASE PRESSURE SIMILARITY PARAMETER CRITERIA

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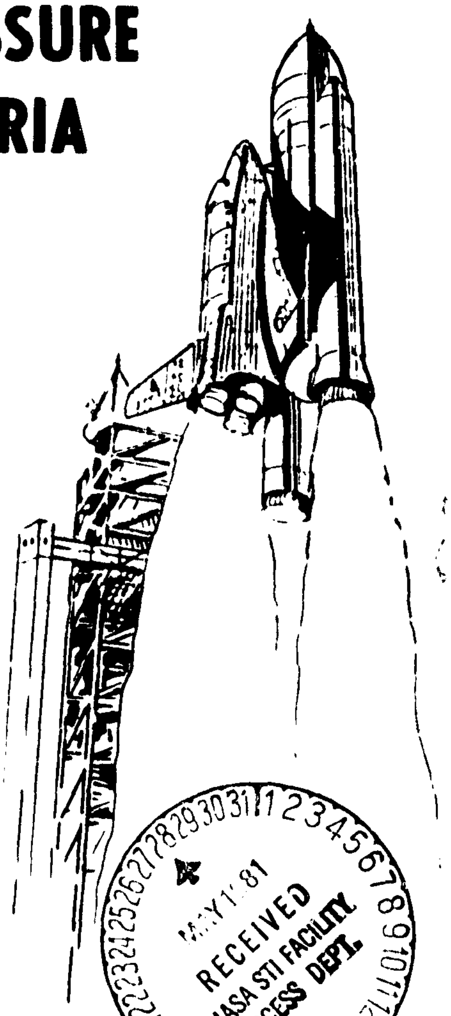

by

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FOREWORD

This report presents the results of a study performed by personnel in the Fluid Technology Application Section of the Lockheed-Huntsville Research & Engineering Center in fulfillment of the requirements of Contract NAS8-33801 with NASA-Marshall Space Flight Center. The NASA-MSFC contracting officer's technical representative for this study was Joseph L. Sims, ED33.

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SYMBOLS AND NOTATION

Symbol	Description
A	area, in^2
A_e/A^*	nozzle area ratio, dimensionless
D	diameter, in.
M	Mach number, dimensionless
M_e	nozzle exit plane Mach number, dimensionless
$\dot{m}$	mass flow rate, lbm/sec
P	static pressure, lbf/in^2
P_b	vehicle base region pressure, lbf/in^2
P_c	nozzle chamber pressure, lbf/in^2
P_e	nozzle exit plane static pressure, lbf/in^2
P_j	jet boundary static pressure, lbf/in^2
T_o	nozzle chamber temperature, R

Greek

γ	ratio of specific heats, dimensionless
δ	initial plume expansion angle measured from the nozzle centerline, deg
ν	Prandtl-Meyer turning angle, deg
θ	nozzle wall angle, deg

Subscripts

b	vehicle base region conditions
c	nozzle chamber conditions
e	nozzle exit plane conditions
j	jet boundary conditions
∞	wind tunnel freestream conditions

Superscript

*	nozzle throat conditions

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1. INTRODUCTION AND SUMMARY

This study was conducted in support of an experimental program to define power-on aerodynamic characteristics of the Space Shuttle over a range of ascent trajectory conditions.

MSFC has developed procedures to simulate Space Shuttle launch vehicle main propulsion jet plumes for use in aerodynamic wind tunnel tests using air to simulate the rocket plume. These procedures will be used by Rockwell International/Space Systems Group (RI/SSG) in conducting power-on aerodynamic wind tunnel tests of the thrust augmented Space Shuttle launch vehicle. These procedures include similarity parameter definition, data analysis procedures and model nozzle design criteria to match values of the prototype similarity parameters with the auxiliary air supply available at the wind tunnel.

The present form of the similarity parameter for base pressure matching is

$$\left(\frac{M_j \delta_j}{M_e^{\,a} \gamma_j^{\,b}}\right)_{\text{Model}} = \left(\frac{M_j \delta_j}{M_e^{\,a} \gamma_j^{\,b}}\right)_{\text{Prototype}}$$

where the values of a and b are functions of the freestream Mach number. M_j is the Mach number on the plume boundary, δ_j is the initial expansion angle of the plume, γ_j is the ratio of specific heats of the rocket exhaust gas at the plume boundary and M_e is the Mach number of the flow in the nozzle exit plane at the nozzle lip. This form of the similarity parameter was developed by the correlation of experimental base pressure data from a number of model nozzles flowing Freon 14 (CF_4) as a prototype gas and air as the simulant gas. No implicit similarity conditions were used in this correlation. This means that no single physical characteristic of the prototype engine needs to be matched by the model nozzle. Thus, for example, it is permissible to change the nozzle exit wall angle in order to change δ_j to achieve the correct numerical value of the similarity parameter with the model nozzle.

Sections 2 and 3 of this report present the computational steps of an analytical procedure used to design an "envelope" of model nozzles (the envelope is defined by nozzle exit plane Mach number, M_e, and nozzle exit wall angle, θ_e) which may be used to simulate Space Shuttle launch vehicle main propulsion jet plumes over a specified range of ascent trajectory conditions. Each nozzle in this "envelope" will be capable of achieving the desired similarity parameter values within the restriction of a fixed maximum auxiliary air pressure supply and mass flow rate imposed by the facility where the wind tunnel tests will be conducted. The analytical procedure, though developed in support of a Space Shuttle experimental program, is not limited to Space Shuttle vehicle configuration applications. In fact, the analytical procedure may be used to design model nozzles to simulate the prototype engine conditions of any single body-single nozzle; single body-triple nozzle or triple body engine system (see Fig. 3.3 for a definition of these engine systems).

A description of a computer code which automates the analytical procedures used to design the above "envelope" of model nozzles is presented in Section 4 of this report. An example of the computer code input requirements and resultant outputs are presented for the wind tunnel test IA-604 planned for the NASA-Ames Research Center's 11 x 11 wind tunnel (Ref. 1-1). Final model nozzle designs and power sweep operating characteristics for each of the desired flight conditions to be simulated in the wind tunnel tests is presented for representative model nozzles that exist in the "envelope" of designed model nozzles.

2. OUTLINE OF THE ANALYTICAL PROCEDURE

This section presents an outline of the computational steps of a computer code used to design model nozzles which may be used to simulate the prototype engine conditions of any single body-single nozzle, single body-triple triple nozzle or triple body engine system. Each model nozzle will be capable of achieving the desired similarity parameter values within the restrictions of maximum air pressure supply and mass flow rate imposed by the facility where wind tunnel testing will be performed. Section 3 of this report presents a more detailed discussion of each computational step performed by the computer code as well as a discussion of the computer code input requirements. It is strongly suggested that the computer code user make every possible use of Sections 2 and 3 of this report when setting up his data deck. Doing so will give the user a greater understanding of the model design problem and the actual use of the computer code.

The basic equations employed by the computer code are given in Table 2-1. Examination of these equations indicates that the design problem can be resolved by considering three primary variables to define the candidate model nozzle designs. These are: (1) model nozzle chamber pressure (P_c); (2) model nozzle exit plane Mach number (M_e) or area ratio (Ae/A^*); and (3) model nozzle exit plane wall angle (θ_e).

Utilizing the nozzle flow analysis described in Ref. 2-1 for a gaseous only flow, or Ref. 2-2 for a gas-particle flow and an initial plume Prandtl-Meyer expansion calculation, a parametric variation of the above three parameters is performed to define candidate model nozzle solutions which satisfy the base pressure similarity parameter relationship

$$\left(\frac{M_j \delta_j}{M_e^a \gamma_j^b}\right)_{\text{model}} = \left(\frac{M_j \delta_j}{M_e^a \gamma_j^b}\right)_{\text{prototype}}$$

Table 2-1
BASIC EQUATIONS USED IN THE MODEL NOZZLE DESIGN ANALYSIS

The nozzle design analysis is performed assuming that the model nozzle will be flowing a constant γ simulant gas during the wind tunnel tests, therefore:

$$\gamma_{model} = \gamma_c = \gamma_e = \gamma_j = \text{constant} \tag{2.1}$$

$$\left(\frac{M_j \delta_j}{M_e^a \gamma_j^b}\right)_{model} = \left(\frac{M_j \delta_j}{M_e^a \gamma_j^b}\right)_{prototype} \tag{2.2}$$

$$\frac{P_c}{P_e} = \left(1 + \frac{\gamma_e - 1}{2} M_e^2\right)^{\frac{\gamma_e}{\gamma_e - 1}} \tag{2.3}$$

$$\frac{P_c}{P_b} = \left(1 + \frac{\gamma_j - 1}{2} M_j^2\right)^{\frac{\gamma_j}{\gamma_j - 1}} \tag{2.4}$$

note: $P_b = P_j$

$$M = \left\{\frac{2}{\gamma - 1}\left[\left(\frac{P_c}{P}\right)^{\frac{\gamma - 1}{\gamma}} - 1\right]\right\}^{1/2} \tag{2.5}$$

$$\frac{A_e}{A^*} = \frac{1}{M_e}\left[\left(\frac{2}{\gamma_e + 1}\right)\left(1 + \frac{\gamma_e - 1}{2} M_e^2\right)\right]^{\frac{\gamma_e + 1}{2(\gamma_e - 1)}} \tag{2.6}$$

$$\nu = \left(\frac{\gamma + 1}{\gamma - 1}\right)^{1/2} \tan^{-1}\left[\left(\frac{\gamma - 1}{\gamma + 1}\right)(M^2 - 1)\right]^{1/2} - \tan^{-1}(M^2 - 1)^{1/2} \tag{2.7}$$

$$\delta_j = \theta_e + \nu_j - \nu_e \tag{2.8}$$

$$\theta_e = \delta_j + \nu_e - \nu_j \tag{2.9}$$

The final result is an envelope of candidate model nozzles (the envelope is defined by M_e and θ_e) which may be used to simulate the flight conditions that exist for all flight Mach numbers to be tested. The wall contour of the actual model nozzle used in the wind tunnel test is arbitrary and left up to the nozzle designer. Within the scope of the current technology it is felt that a conical nozzle with a designed value of M_e and θ_e will suffice for all cases.

● COMPUTATIONAL STEPS

The specific steps of the analytical procedure used to design model nozzles are outlined below. With the exception of actually calculating the value of similarity parameter in step 4, the first 6 steps of the analysis are performed by the computer code user and input to the computer code in the form of a data deck (see Section 4.2 for a description of the computer code input requirements.) The remaining computational steps have been automated by the computer code.

1. A schedule of flight Mach numbers that is to be simulated is determined as a function of the test purpose.
2. For each flight Mach number to be simulated, the corresponding values of freestream static pressure, P_∞, and prototype nozzle chamber pressure, P_c, are determined.
3. A predicted value of base pressure ratio (P_b/P_∞) is set for each flight Mach number to be simulated. The value of P_b/P_∞ used is based upon experience gained from previous wind tunnel tests.
4. Prototype plume similarity data are determined. These data, together with the above P_b/P_∞ and P_c, are used to determine the value of prototype base pressure similarity parameter to be simulated to ensure that base pressure matching occurs.
5. The physical restrictions of prototype nozzle exit diameter, scale of the model nozzle, maximum pressure supply and mass flow rate imposed by the facility are set.
6. A gasdynamic constraint on the ratio P_e/P_b is set to ensure that model nozzle flow separation does not occur. The minimum allowable value of P_e/P_b determined experimentally is 0.60.

7. Select a flight Mach number from the schedule of flight Mach numbers to be simulated.
8. Select a value of model nozzle exit plane Mach number. The value of M_e will be varied parametrically in subsequent iterations. Selecting a specific value of Mach number gives the model nozzle area ratio, A_e/A^*.
9. The next design parameter of concern is model nozzle chamber pressure, P_c. Selecting a specific value of P_c then permits the calculation of jet or plume boundary Mach number, M_j. The value of P_c chosen is usually set equal to 50% of the maximum available air pressure supply.
10. The value of δ_j can be found which ensures similarity using the following relationship:

$$\left.\delta_j\right)_{model} = \left(\frac{M_e^a\,\gamma_j^b}{M_j}\right)_{model} * \left(\frac{M_j\,\delta_j}{M_e^a\,\gamma_j^b}\right)_{prototype}$$

11. Finally, the model nozzle exit plane wall angle, θ_e, required to achieve $\left.\delta_j\right)_{model}$ is then

$$\theta_e = \left.\delta_j\right)_{model} + \left.\nu_e\right)_{model} - \left.\nu_j\right)_{model}$$

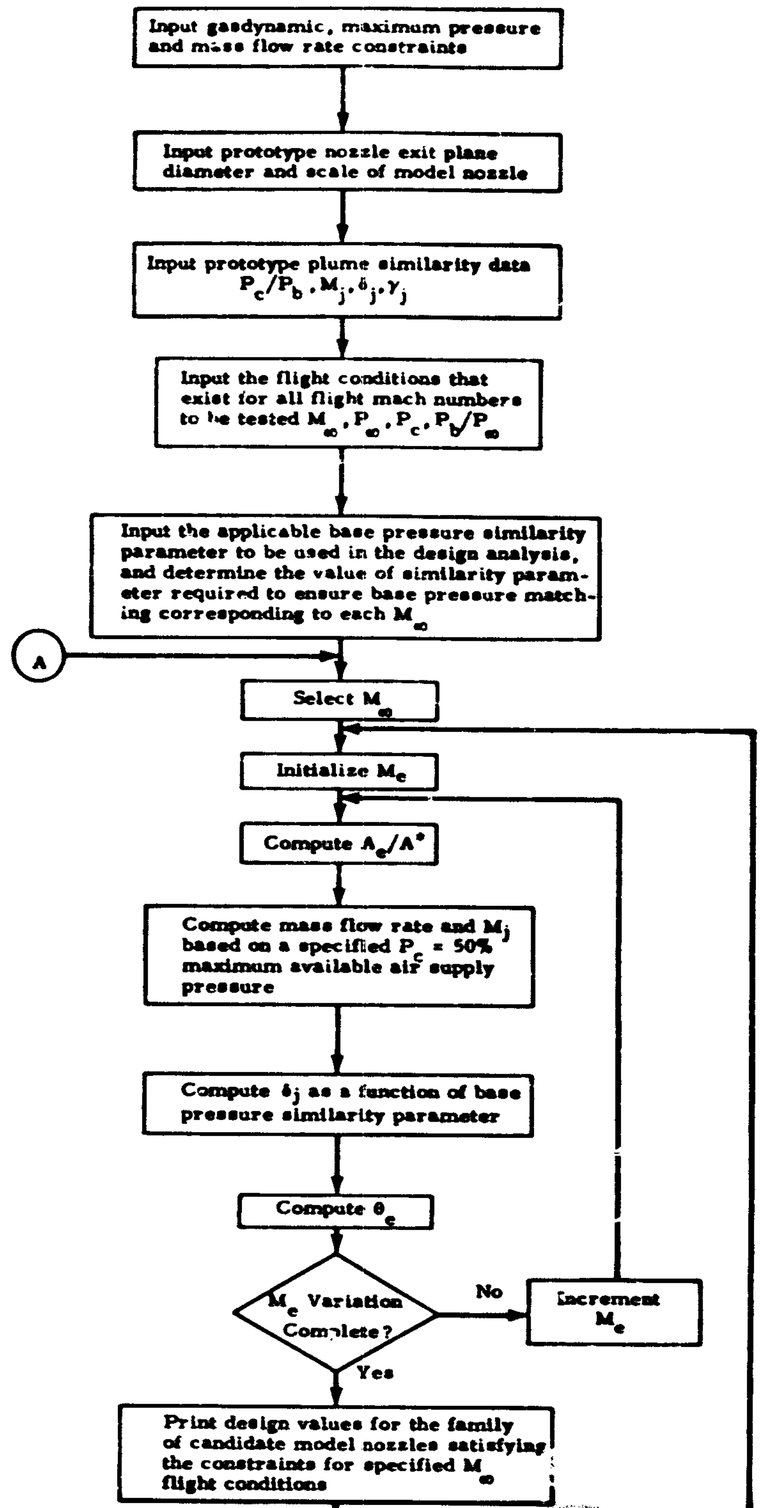
Incrementing the value of M_e and repeating steps 10 and 11 will define a family of candidate nozzles which will: (1) ensure base pressure matching for "one" specified set of flight conditions and satisfy the mass flow rate and maximum air pressure supply constraints set by the test facility.

12. Steps 7 through 11 are repeated for each of the flight Mach numbers to be simulated.
13. Once step 12 is completed, each family of candidate model nozzles derived for a particular flight Mach number is checked to see which nozzles are capable of simulating the flight conditions that exist for <u>all</u> other flight Mach numbers.

14. The final result is an envelope of model nozzles (the envelope is defined by M_e and θ_e) which may be used to simulate the flight conditions that exist for all flight Mach numbers to be tested.

15. Calculate the power sweep operating characteristics for each of the desired flight conditions to be simulated for representation model nozzles that exist in the envelope.

A flow chart of a computer code used to design model nozzles which meet MSFC base pressure similarity parameter criteria is presented in Chart 2-1.



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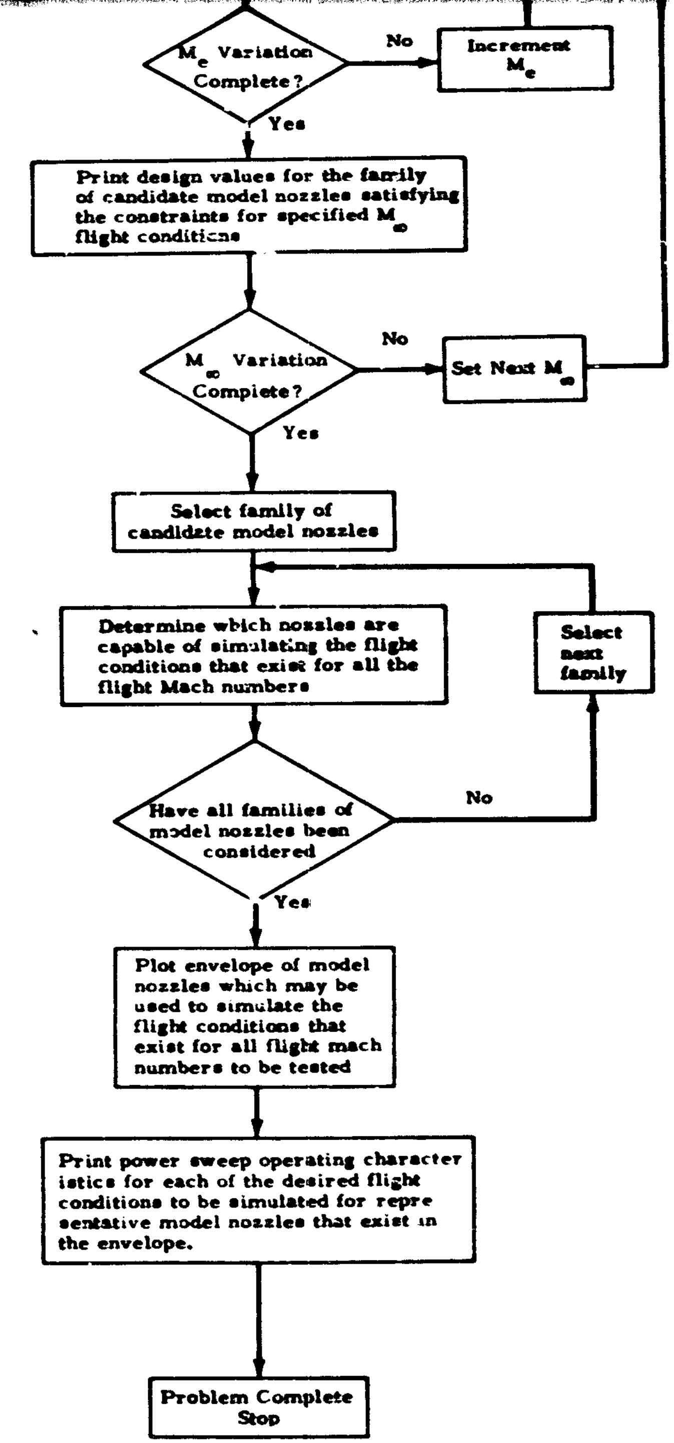


FOLDOUT FRAME 2

Chart 2-1 - Flow Chart of a Computer Code Used to Design Model Nozzles Which Meet MSFC Similarity Parameter Criteria

3. A DETAILED DESCRIPTION OF THE COMPUTATIONAL STEPS OF A COMPUTER CODE USED TO DESIGN MODEL NOZZLES WHICH MEET MSFC BASE PRESSURE SIMILARITY PARAMETER CRITERIA

This section presents a detailed discussion of each computational step as well as input requirements of a computer code used to design model nozzles used to simulate the prototype engine conditions that exist over a specified range of ascent trajectory conditions for any single body-single nozzle, single body-triple nozzle or triple body engine system. The general engine systems are defined in Fig. 3-3. Each model nozzle will be capable of achieving the desired similarity parameter values within the restriction of maximum air pressure supply and mass flow rate imposed by the facility where wind tunnel testing will be performed.

It is strongly suggested that the computer code user make every possible use of Sections 2 and 3 of this report when setting up his data deck. The user will thus gain a greater understanding of the model nozzle design problem and the actual use of the computer code.

3.1 FUNDAMENTAL EQUATIONS

The basic equations employed by the computer code are presented on the following page.

The nozzle design analysis is performed assuming that the model nozzle will be flowing a constant γ simulant gas during the wind tunnel tests, therefore

$$\gamma_{model} = \gamma_c = \gamma_e = \gamma_j = \text{constant} \qquad (3.1)$$

$$\frac{P_c}{P_e} = \left(1 + \frac{\gamma_e - 1}{2} M_e^2\right)^{\frac{\gamma_e}{\gamma_e - 1}} \tag{3.2}$$

$$\frac{P_c}{P_b} = \left(1 + \frac{\gamma_j - 1}{2} M_j^2\right)^{\frac{\gamma_j}{\gamma_j - 1}} \tag{3.3}$$

Note: $P_b = P_j$

$$\frac{A_e}{A^*} = \frac{1}{M_e} \left[\left(\frac{2}{\gamma_e + 1}\right)\left(1 + \frac{\gamma_e - 1}{2} M_e^2\right)\right]^{\frac{\gamma_e + 1}{2(\gamma_e - 1)}} \tag{3.4}$$

$$\nu = \left(\frac{\gamma + 1}{\gamma - 1}\right)^{1/2} \tan^{-1}\left[\left(\frac{\gamma - 1}{\gamma + 1}\right)(M^2 - 1)\right]^{1/2} - \tan^{-1}(M^2 - 1)^{1/2} \tag{3.5}$$

Solving for M in Eqs. (3.2) and (3.3) yields

$$M = \left\{ \frac{2}{\gamma - 1} \left[\left(\frac{P_c}{P} \right)^{\frac{\gamma - 1}{\gamma}} - 1 \right] \right\}^{1/2} \tag{3.6}$$

The equation for plume boundary initial angle is

$$\delta_j = \theta_e + \nu_j - \nu_e \tag{3.7}$$

and solving Eq. (3.7) for θ_e yields

$$\theta_e = \delta_j + \nu_e - \nu_j \tag{3.8}$$

Base pressure matching is achieved when

$$\text{Similarity Parameter}\Big)_{\text{model}} = \text{Similarity Parameter}\Big)_{\text{prototype}}$$

or,

$$\left(\frac{M_j \delta_j}{M_e^a \gamma_j^b} \right)_{\text{model}} = \left(\frac{M_j \delta_j}{M_e^a \gamma_j^b} \right)_{\text{prototype}} \tag{3.9}$$

(See Symbols and Notation for description of variables.)

Examination of Eqs. (3.1) through (3.9) indicates that the design problem can be resolved by considering three primary variables to define the candidate model nozzle designs. These are: (1) model nozzle chamber pressure (P_c); (2) model nozzle exit plane Mach number (M_e) or area ratio (A_e/A^*); and (3) model nozzle exit plane wall angle (θ_e).

Utilizing a nozzle flow analysis described in Ref. 2-1 for a gaseous only flow, or Ref. 2-2 for a gas-particle flow and an initial plume Prandtl-Meyer expansion calculation, a parametric variation of the above three parameters is performed to define candidate model nozzle solutions which satisfy the base pressure similarity parameter relationship

$$\left(\frac{M_j \delta_j}{M_e^a \gamma_j^b}\right)_{model} = \left(\frac{M_j \delta_j}{M_e^a \gamma_j^b}\right)_{prototype}$$

The final result is an envelope of model nozzles (the envelope is defined by M_e and θ_e) which may be used to simulate the flight conditions that exist for all flight Mach numbers to be tested. The wall contour of the actual model nozzle used in the wind tunnel test is arbitrary and left up to the nozzle designer. Within the scope of the current technology it is felt that a conical nozzle with a designed value of M_e and θ_e will suffice for all cases.

3.2 SIMILARITY PARAMETER DEFINITION AND APPLICATION

Before proceeding further in the description of the analytical design techniques a better understanding of the similarity parameter and how it is used in the data analysis stage of the test program is necessary.

The similarity parameters used in this analysis have been supplied by MSFC. The present similarity parameter (SP) used for base pressure matching is of the general form

$$SP)_{general} = \frac{M_j \delta_j}{M_e^a \gamma_j^b} \tag{3.10}$$

where the values of a and b are functions of freestream Mach number and vehicle test configuration. This form of the similarity parameter was developed by the correlation of experimental base pressure data from a number of model nozzles flowing Freon 14 (CF_4) as a prototype gas and air as the simulant gas. No implicit similarity conditions were used in this correlation. This means that no single physical characteristic of the prototype engine needs to be matched by the model nozzle. Thus, for example, it is permissable to change the nozzle exit wall angle in order to change δ_j to achieve the correct numerical value of the similarity parameter with the model nozzle.

The similarity parameter used in this analysis does not allow an explicit determination of the vehicle base region pressure (P_b) and therefore an implicit procedure was developed. Figure 3-1 presents a typical base pressure matching procedure utilizing the base pressure similarity parameter. The illustrated curve of possible prototype base pressure ratio as a function of similarity parameter can be computed knowing the prototype plume similarity data and specifying the flight conditions and corresponding engine chamber pressure values. For example, Table 3-1 presents prototype plume similarity data for a solid rocket booster high performance motor calculated by the use of a nozzle flow analysis described in Refs. 2-1 or 2-2. Table 3-2 presents a range of flight conditions to be simulated during wind tunnel tests. Choosing the flight conditions of P_c = 651.4 psia and P_∞ = 8.441 psia for M_∞ = .796; multiplying P_c/P_∞ by each value of $1.0/(P_c/P_b)$ of Table 3-1 will yield a prototype possibility curve similar to that of Fig. 3-1. The wind tunnel test is conducted at the same M_∞ = .796 while measurements are obtained at varying model nozzle chamber pressure. Chamber pressure varies directly with similarity parameter. The model nozzle is designed so that the experimental chamber pressures chosen cause the similarity parameter)$_{model}$ values to fall within the prototype range of interest. The minimum value of similarity parameter)$_{model}$ corresponds to that value of P_c that will cause flow separation in the model nozzle. This has been experimentally determined to occur for $P_e/P_b \leq 0.60$. The maximum value of similarity parameter)$_{model}$ corresponds to either the maximum auxiliary air pressure

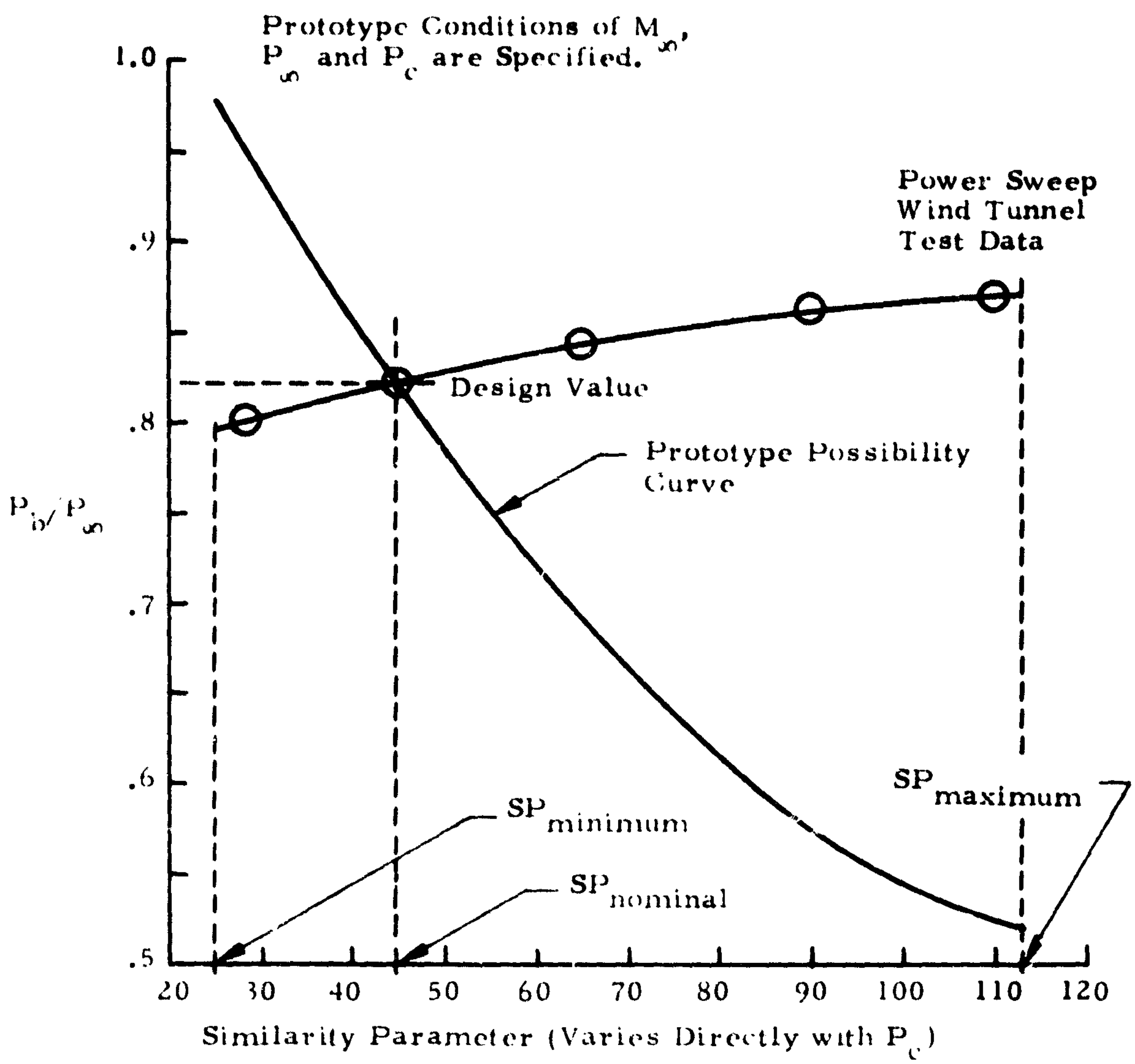


Fig. 3-1 - Base Pressure Matching Procedure

Note: This is a sample plot and does not represent data presented in Tables 3-1 and 3-2

Table 3-1

PROTOTYPE PLUME SIMILARITY DATA FOR A SOLID ROCKET BOOSTER HIGH PERFORMANCE MOTOR

P_c/P_b	M_j	δ_j	γ_j	SP*
.37640+02	.26599+01	.10490+02	.12541+01	.17422+02
.47970+02	.27864+01	.14258+02	.12685+01	.24524+02
.61940+02	.29223+01	.18025+02	.12805+01	.32211+02
.80990+02	.30761+01	.21793+02	.12843+01	.40873+02
.10732+03	.32393+01	.25561+02	.12887+01	.50311+02
.14428+03	.34131+01	.29329+02	.12934+01	.60603+02
.19694+03	.36005+01	.33096+02	.12997+01	.71792+02
.27355+03	.38026+01	.36864+02	.13062+01	.84034+02
.38720+03	.40212+01	.40632+02	.13124+01	.97486+02
.55923+03	.42585+01	.44395+02	.13184+01	.11229+03
.82699+03	.45204+01	.48167+02	.13248+01	.12869+03
.12551+04	.48153+01	.51935+02	.13326+01	.14695+03
.19609+04	.51499+01	.55703+02	.13406+01	.16756+03
.31679+04	.55320+01	.59471+02	.13485+01	.19104+03
.53173+04	.59676+01	.63237+02	.13559+01	.21793+03
.93368+04	.64766+01	.67006+02	.13627+01	.24937+03
.17281+05	.70874+01	.70774+02	.13687+01	.28697+03

*$SP = M_j \delta_j/(M_e^{.25} \gamma_j)$ where $M_e = 2.6599$.

Table 3-2

FLIGHT CONDITIONS TO BE SIMULATED DURING WIND TUNNEL TESTS

M_∞	P_b/P_∞	P_c	P_∞	$SP_{nominal}$
.59700+00	.89000+00	.72000+03	.10542+02	.39132+02
.79600+00	.82500+00	.65140+03	.84410+01	.45703+02
.90000+00	.77000+00	.62450+03	.74250+01	.50925+02
.95000+00	.67500+00	.61020+03	.68770+01	.57365+02
.10480+01	.61000+00	.58000+03	.57250+01	.65664+02
.11000+01	.64000+00	.57130+03	.54770+01	.64987+02
.11480+01	.65000+00	.57000+03	.48270+01	.68890+02
.12490+01	.69000+00	.57620+03	.41050+01	.73000+02
.14030+01	.77000+00	.58600+03	.32760+01	.77946+02

supply or maximum mass flow rate capability of the test facility. In the data analysis stage of the test program, the model P_b/P_∞ versus similarity parameter)$_{model}$ is plotted on the same graph with the prototype possibility curve. The intersection of these two curves is the condition which simultaneously satisfies both the prototype possibilities and the model actualities and thus

$$\text{Similarity Parameter})_{model} = \text{Similarity Parameter})_{prototype}$$

for the given flight conditions. It is this value of P_b/P_∞ that can be expected during the actual flight of the prototype vehicle.

Equation (3.10) presents the general form of the base pressure similarity parameter. More specifically, the similarity parameter takes three different forms. They are:

$$SP_1 = \frac{M_j \delta_j}{M_e^{.25} \gamma_j} \qquad \text{where } a = .25 \text{ and } b = 1.0$$

$$SP_2 = \frac{M_j \delta_j}{M_e^{.25} \gamma_j^{.5}} \qquad \text{where } a = .25 \text{ and } b = 0.5$$

and

$$SP_3 = \frac{M_j \delta_j}{\gamma_j} \qquad \text{where } a = 0.0 \text{ and } b = 1.0$$

The actual form of the similarity parameter used in the model nozzle design analysis is a function of freestream Mach number and vehicle test configuration to be considered during the wind tunnel tests.

Table 3-3 presents a schedule for the recommended use of each form of the similarity parameter as a function of freestream Mach number and

Table 3-3

SCHEDULE FOR THE RECOMMENDED USE OF EACH FORM OF THE SIMILARITY PARAMETER AS A FUNCTION OF FREESTREAM MACH NUMBER AND VEHICLE TEST CONFIGURATION

M_∞	Configuration		
	Single Body Single Nozzle	Single Body Triple Nozzle	Triple Body
0.9	$SP_1 = \frac{M_j \delta_j}{M_e^{0.25} \gamma_j}$	$SP_1 = \frac{M_j \delta_j}{M_e^{0.25} \gamma_j}$	$SP_1 = \frac{M_j \delta_j}{M_e^{0.25} \gamma_j}$
1.2	$SP_2 = \frac{M_j \delta_j}{M_e^{0.25} \gamma_j^{0.5}}$	$SP_1 = \frac{M_j \delta_j}{M_e^{0.25} \gamma_j}$	$SP_1 = \frac{M_j \delta_j}{M_e^{0.25} \gamma_j}$
1.46	$SP_2 = \frac{M_j \delta_j}{M_e^{0.25} \gamma_j^{0.5}}$	$SP_1 = \frac{M_j \delta_j}{M_e^{0.25} \gamma_j}$	
3.48	$SP_3 = \frac{M_j \delta_j}{\gamma_j}$	$SP_3 = \frac{M_j \delta_j}{\gamma_j}$	

vehicle test configuration. This table indicates that SP_1 is applicable for most test cases; SP_2 has limited applications; and SP_3 is best suited for hypersonic Mach numbers. Figure 3-2 defines the variables used in the similarity parameters. Figure 3-3 defines the model test configurations that may be tested using the recommended similarity parameters.

When using the computer code to perform the model nozzle design analysis, the model nozzles should be designed using the specific similarity parameters recommended in Table 3-3. However, it will ususally be found that one model nozzle will satisfy all three similarity parameters and therefore the choice of similarity parameter is arbitrary.

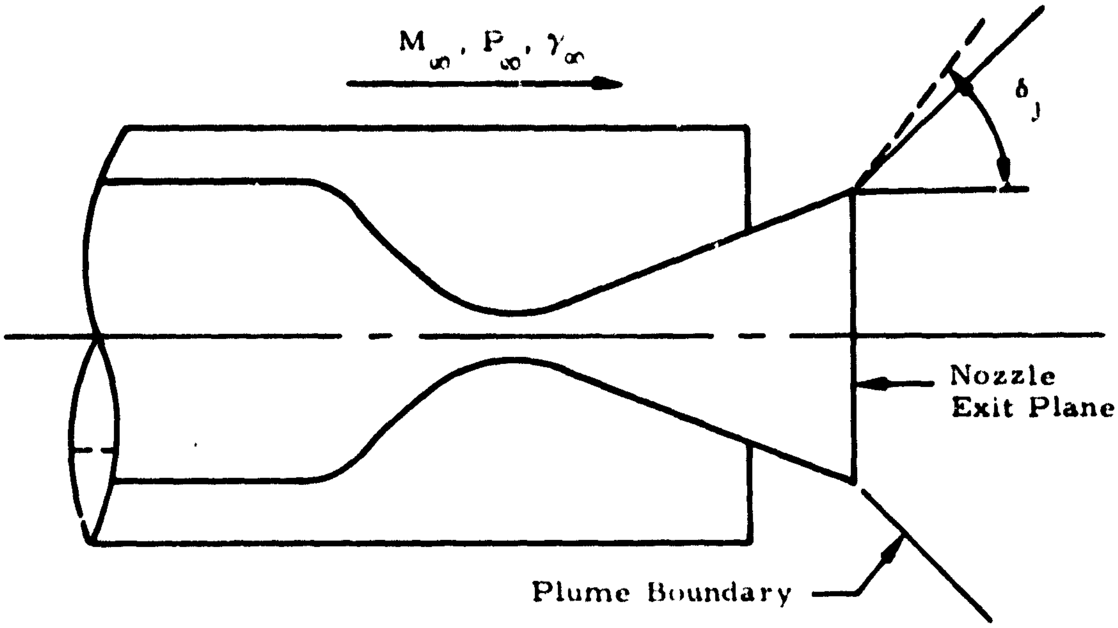
3.3 COMPUTATIONAL STEPS

Figure 3-1 presents a typical base pressure matching procedure utilizing the base pressure similarity parameter. The following paragraphs present a detailed discussion of each computational step used to design an envelope of candidate model nozzles that may be used in this base pressure matching procedure. With the exception of constraints 1 and 2 of Step 1, and the calculation of similarity parameters in Step 4, the first four steps of the analysis are performed by the computer code user and input to the computer code in the form of a data deck. (See Section 4-2 for a description of the computer code input requirements.) The remaining computational steps have been automated by the computer code.

<u>Step One:</u>

There are a number of gasdynamic and physical constraints that must be considered during the design of the candidate model nozzles. The gasdynamic constraints are:

1. The exit plane Mach number at the nozzle lip (M_e) must be supersonic. If $M_e < 1.0$, the flow external to the nozzle would affect the flow inside the nozzle and therefore, the nozzle would not perform as it is designed to. And $M_e > 1.0$ allows a simple calculation of δ_j.



δ_j - plume boundary initial angle

M_j - plume boundary Mach number

M_e - exit plane Mach number at nozzle lip

γ_j - ratio of specific heats on plume boundary

M_∞ - wind tunnel freestream Mach number

P_∞ - wind tunnel freestream static pressure

γ_∞ - ratio of specific heats of wind tunnel freestream flow

Fig. 3-2 - Definition of Variables Used in the Similarity Parameters

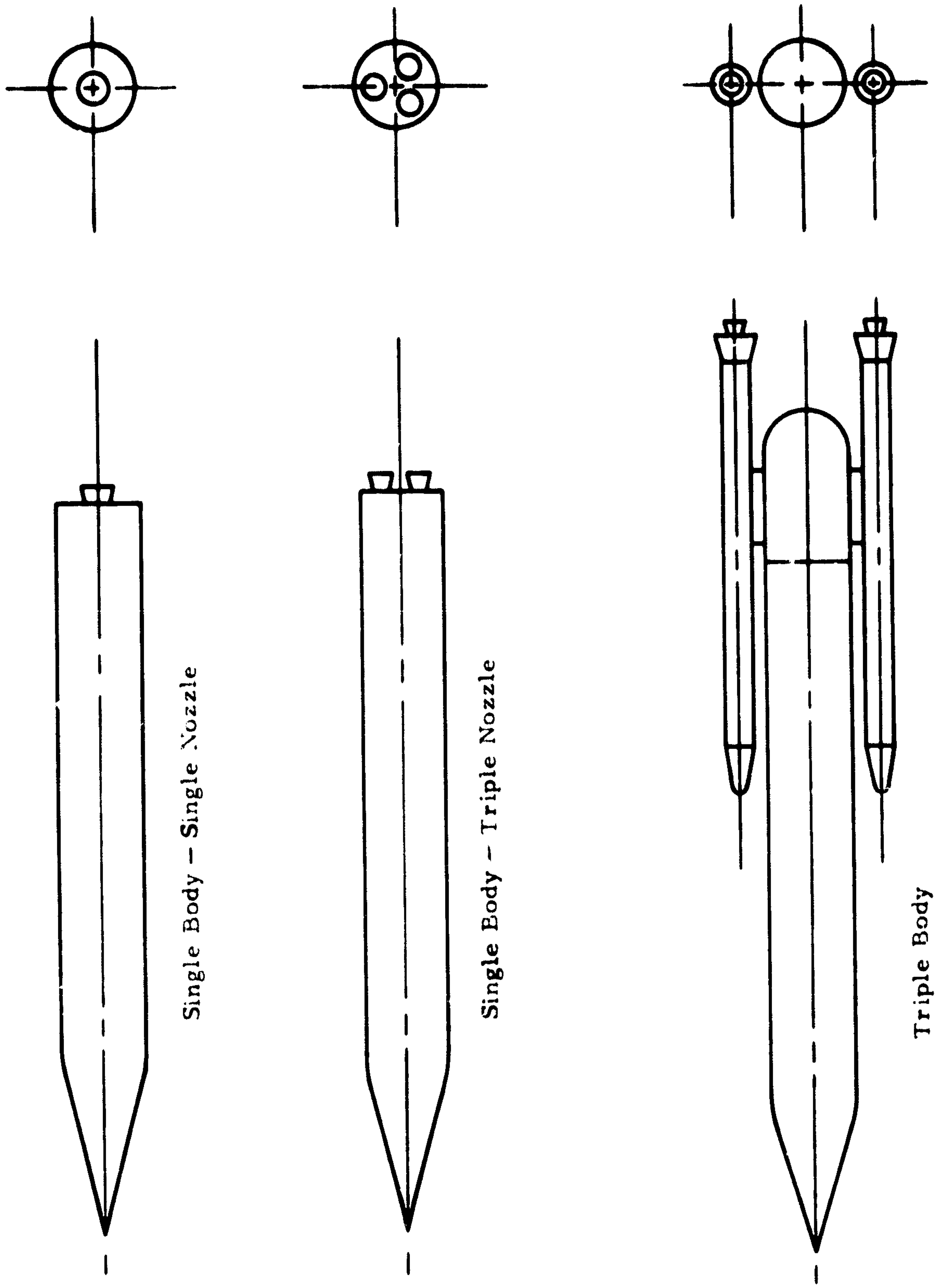


Fig. 3-3 - Definition of the Model Test Configurations That May be Tested Using the Recommended Similarity Parameters

2. The nozzle exit wall angle (θ_e) must be greater than 0 deg. Wall angles less than 0 deg can cause strong internal shocks resulting in subsonic exit plane Mach numbers just discussed.
3. A gasdynamic constraint on the ratio P_e/P_b is set to ensure that model nozzle flow separation does not occur. The minimum allowable value of P_e/P_b determined experimentally is 0.60.

It is desirable to have <u>one</u> nozzle simulate the flight conditions of a range of Mach numbers. This constraint sets a limit on the maximum value of exit plane Mach number ($M_{e_{max}}$) that may be used for the nozzle design. For a specified value of P_c and range of flight Mach numbers to be simulated, the value of $M_{e_{max}}$ is determined at the lowest value of flight Mach number to be simulated. In most cases, this also corresponds to that flight condition where base pressure (P_b) is maximum.

The physical constraints to be set are those imposed by the facility where testing is to be performed.

4. The restrictions of maximum air pressure supply and mass flow rate are set. These constraints directly affect the maximum obtainable value of similarity parameter. This is to say

$$\text{Similarity Parameter}\Big)_{max} \propto P_c\Big)_{max} \propto \dot{m}\Big)_{max}$$

The value of $P_c\Big)_{max}$ used to determine $SP\Big)_{max}$ is either set directly by the test facility or as is most often the case, determined as a function of $\dot{m}\Big)_{max}$ as described in Constraint 5 to follow.

Constraints 3 and 4 are very important considerations in the design of the model nozzles. In addition to setting a limit on the maximum value of M_e as already discussed; Constraint 3 also sets a limit on the minimum value of

P_c that may be used for a given nozzle and set of flight conditions to be simulated. Therefore, Constraint 3 sets $SP)_{min}$ in the same manner as Constraint 4 sets $SP)_{max}$ or

$$\text{Similarity Parameter})_{min} \propto P_c)_{min}$$

Therefore, a given candidate model nozzle may be eliminated from further consideration during the analysis simply by comparing the desired similarity parameter$)_{prototype}$ to the $SP)_{min}$ and $SP)_{max}$ just established by Constraints 3 and 4.

5. The prototype nozzle exit plane diameter and scale of the model nozzle are set. This constraint sets the model nozzle exit plane diameter and allows a direct calculation of A^* for a given model nozzle M_e. The value of A^* and the restriction on maximum mass flow rate of Constraint 4 yields the value of $P_c)_{max}$ used to calculate $SP)_{max}$ described above. $P_c)_{max}$ is calculated using the isentropic relationship for a nozzle flowing air:

$$P_c)_{max} = \frac{1}{.532} \frac{\dot{m})_{max} \sqrt{T_o}}{A^*} \qquad (3.11)$$

<u>Step Two:</u>

Determine a range of flight Mach numbers that is to be simulated during testing. Keep in mind that both analytically and physically there is no "one" nozzle that may be used to test an infinite range of Mach numbers. Therefore, as the range of flight Mach numbers to be simulated increases, the number of possible model nozzle solutions decrease and eventually become non-existant. This problem, and its solution will be discussed in detail later on in the analysis.

Once a range of flight Mach numbers is determined it is necessary to choose a schedule of flight Mach numbers to be simulated during testing. The schedule chosen will be a function of the test purpose. The actual schedule chosen will not affect the final model nozzle design; this has already been established when the range of flight Mach numbers to be tested has been chosen. Therefore, there is no analytical design limitations introduced by having a large number of flight Mach numbers simulated as long as they are all within the specified range of flight Mach numbers.

Step Three:

Determine the values of freestream static pressure (P_∞); prototype nozzle chamber pressure (P_c); and predicted base pressure ratio (P_b/P_∞) for each flight Mach number to be tested. The result will be a set of flight conditions to be simulated during wind tunnel tests similar to that presented in Table 3-2. The values of P_∞ and P_c are easily obtained as a function of M_∞ and/or flight time. Data of this type are presented in motor performance prediction and ascent trajectory prediction documentation such as Ref. 3-1 which is used to construct Table 3-2. The values of predicted base pressure ratio used in the analysis are based upon experience gained from previous wind tunnel tests. Care should be taken to use the best possible value of P_b/P_∞ for each M_∞. Referring to Step 1, Constraint 3, it is seen that a conservative approach may be taken if ratios of P_b/P_∞ slightly higher than is actually expected at low M_∞ are used in the analysis. This approach will decrease the maximum allowable value of model nozzle exit plane Mach number ($M_{e_{max}}$) and therefore decrease the size of the family of candidate model nozzles.

Step Four:

Determine the prototype plume similarity data for the rocket engine that the model nozzle is to simulate. Table 3-1 presents a sample of the required data. Figure 3-2 presents a pictorial definition of the variables. The tabulated values of M_j, δ_j and γ_j are the plume boundary properties corresponding to each value of P_c/P_b. These properties are determined utilizing the nozzle flow analysis described in Ref. 2-1 for a gaseous only flow, or Ref. 2-2 for a gas-particle flow and an initial plume Prandtl-Meyer expansion calculation. The form of the similarity parameter to be used is set according to the schedule presented in Table 3-3. The tabulated value of the similarity parameter is calculated by the computer code.

Step Five:

Determine the value of similarity parameter required to ensure base pressure matching at each scheduled M_∞ to be simulated. This corresponds to $SP_{nominal}$ in Table 3-2. First, a curve of possible prototype base pressure ratio as a function of similarity parameter is computed as was discussed in Section 3.2 and then plotted as in Fig. 3-4. Finally, plotting the predicted value of base pressure ratio on the prototype possibility curve yields the nominal value of Similarity Parameter ($SP_{nominal}$) required to ensure base pressure matching. At this point, it is important to realize that a "predicted" value of P_b/P_∞ is being used to determine $SP_{nominal}$ which is in turn used to design the model nozzle. Therefore, the design of the model nozzle is only as good as the "predicted" value of P_b/P_∞. This problem and its solution will be discussed in more detail later in the analysis.

Step Five must be repeated for each value of schedule M_∞ to be simulated. Table 3-2 is now complete.

> All data required to begin the model nozzle design computations, are now established. The computer code calculation is now at what corresponds to Step 7 of Section 2 or Point A of the computer code flow chart presented in Chart 2-1. These data were read by the computer code in Subroutine INPUT.

Step Six:

Select: (1) a flight Mach number from the schedule of Mach numbers to be simulated as determined in Step 2 and (2) the corresponding flight conditions determined in Step 3.

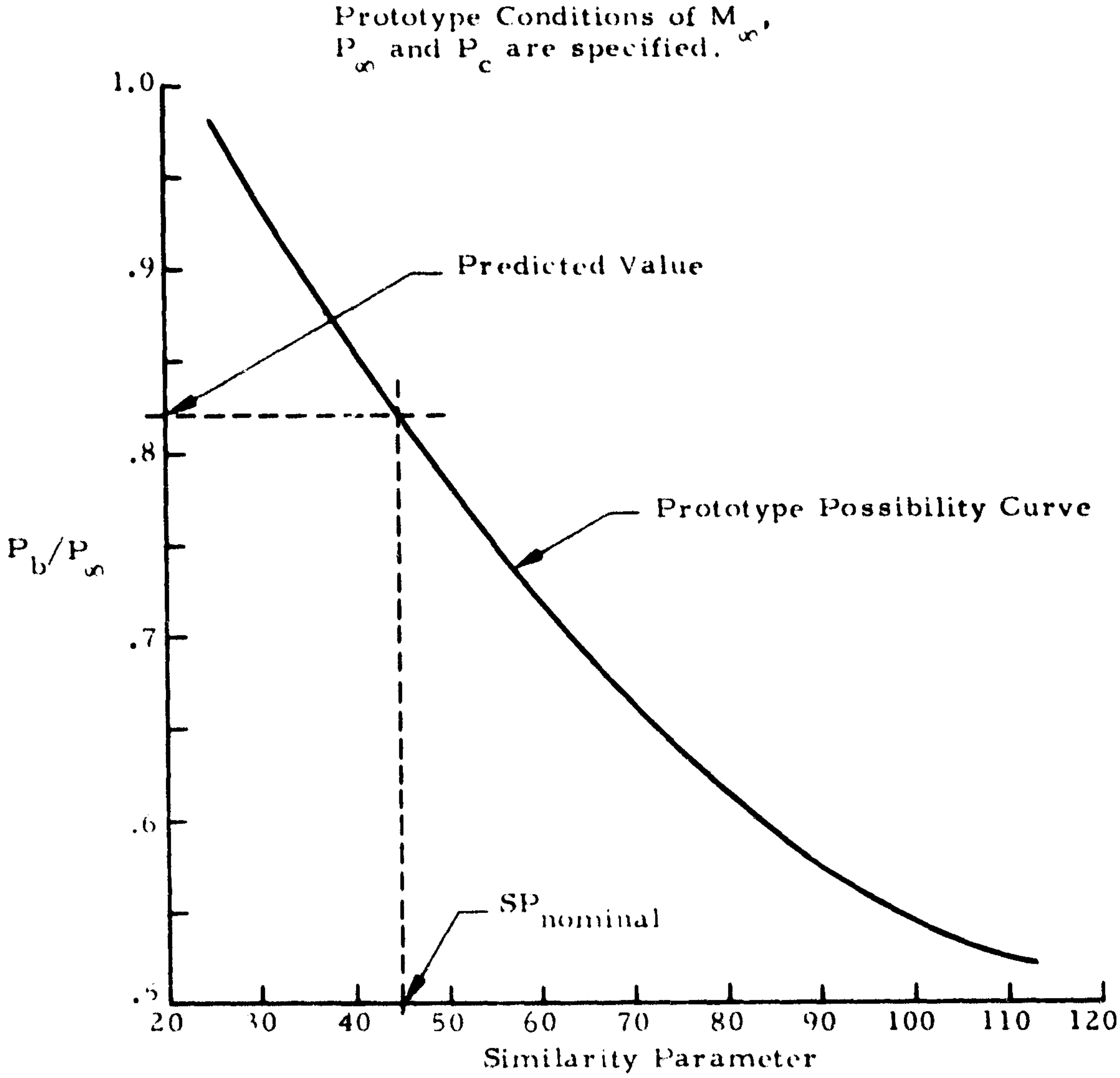


Fig. 3-4 - Determination of the Value of Similarity Parameter Required to Ensure Base Pressure Matching at Specified Flight Conditions

Note: This is a sample plot and does not represent data presented in Tables 3-1 and 3-2.

The computer code will begin the analysis with the lowest value of M_∞. This will allow an early calculation of $M_{e_{max}}$ and therefore eliminate the needless design calculations for nozzles with an M_e greater than $M_{e_{max}}$.

Step Seven:

Select a value of model nozzle exit plane Mach number slightly greater than 1.0. The value of M_e will be varied parameterically in subsequent iterations. Selecting a specific value of Mach number gives the model nozzle area ratio, A_e/A^*.

Step Eight:

The next design parameter of concern is the model nozzle chamber pressure, P_c. Selecting a specific value of P_c then permits the calculation of plume boundary Mach number according to Eq. (3.6)

$$M_j = \left\{ \frac{2}{\gamma_j - 1} \left[\left(\frac{P_c}{P_b} \right)^{\frac{\gamma_j - 1}{\gamma_j}} - 1 \right] \right\}^{1-2} \tag{3.12}$$

Note that the pressure on the jet boundary is assumed to be equal to the base pressure. P_b is determined as a function of the predicted value of P_b/P_∞ in Step 3 and $P_\infty)_{model}$ in the wind tunnel. Please note that the $P_\infty)_{prototype}$ is not used in this calculation. The value of P_c chosen in this step is held constant throughout the analysis and is usually set equal to 50% of the maximum available air pressure supply. This value of P_c is chosen to ensure that each model nozzle in the family of candidate nozzles being designed will be capable of producing a power sweep curve with a range of similarity parameter values bracketing $SP_{nominal}$ (See Fig. 3-1). The value of P_c is read in Subroutine INPUT.

Step Nine:

The value of δ_j can be found which ensures similarity using Eq. (3.9)

$$\delta_j\Big)_{model} = SP_{nominal}\Big)_{prototype} \left(\frac{M_e^a \gamma_j^b}{M_j}\right)_{model} \tag{3.13}$$

where: $\gamma_j = 1.4$ for a model nozzle flowing air; a and b are functions of flight Mach number and vehicle test configuration and are determined in accordance with the schedule presented in Table 3-3. This value of δ_j will ensure base pressure matching at the specified set of flight conditions, the chosen value of M_e and the constrained value of P_c only.

Step Ten:

Finally, the model nozzle exit plane wall angle, θ_e, required to achieve $\delta_j)_{model}$ for the specified conditions is calculated according to Eq. (3.8)

$$\theta_e = \delta_j)_{model} + \nu_e - \nu_j$$

where ν_e and ν_j are calculated according to Eq. (3.5)

$$\nu_e = \left(\frac{\gamma_e + 1}{\gamma_e - 1}\right)^{1/2} \tan^{-1}\left[\left(\frac{\gamma_e - 1}{\gamma_e + 1}\right)(M_e^2 - 1)\right]^{1/2} - \tan^{-1}(M_e^2 - 1)^{1/2}$$

and

$$\nu_j = \left(\frac{\gamma_j + 1}{\gamma_j - 1}\right)^{1/2} \tan^{-1}\left[\left(\frac{\gamma_j - 1}{\gamma_j + 1}\right)(M_j^2 - 1)\right]^{1/2} - \tan^{-1}(M_j^2 - 1)^{1/2}$$

At this point, "a" candidate nozzle with "a" defined value of θ_e and M_e and "a" constrained value of P_c has been designed which will ensure base pressure matching for "one" specified set of flight conditions. Should one flight condition change, the result would be a change in $SP_{nominal}$ and therefore base pressure matching would not occur. To regain the condition of base pressure matching requires only a change in P_c proportional to the change in $SP_{nominal}$. This assumes that the "new" $SP_{nominal}$ does satisfy the condition.

$$SP_{minimum} \leq \text{"new" } SP_{nominal} \leq SP_{maximum}$$

for the given candidate nozzle.

Step Eleven:

Incrementing the value of M_e and repeating Steps 9 and 10 will define a family of candidate nozzles which will: (1) ensure base pressure matching for "one" specified set of flight conditions; and (2) meet all of the constraints specified in Step 1. Figure 3-5 presents a sample plot of a family of candidate model nozzles that may be used to ensure base pressure matching for the flight conditions to be simulated for $M_\infty = .597$ present in Table 3-2. Note that nozzle flow separation occurs for M_e greater than 3.83.

Step Twelve:

Repeat Steps 6 through 11 for each flight Mach number in the schedule of Mach numbers to be simulated. The result will be one family of candidate model nozzles that may be used to ensure base pressure matching for each of the specified set of flight conditions to be simulated and can be plotted similar to that in Fig. 3-5.

Step Thirteen:

Each family of candidate model nozzles derived for a particular flight Mach number is now checked to see which nozzles in that family are capable

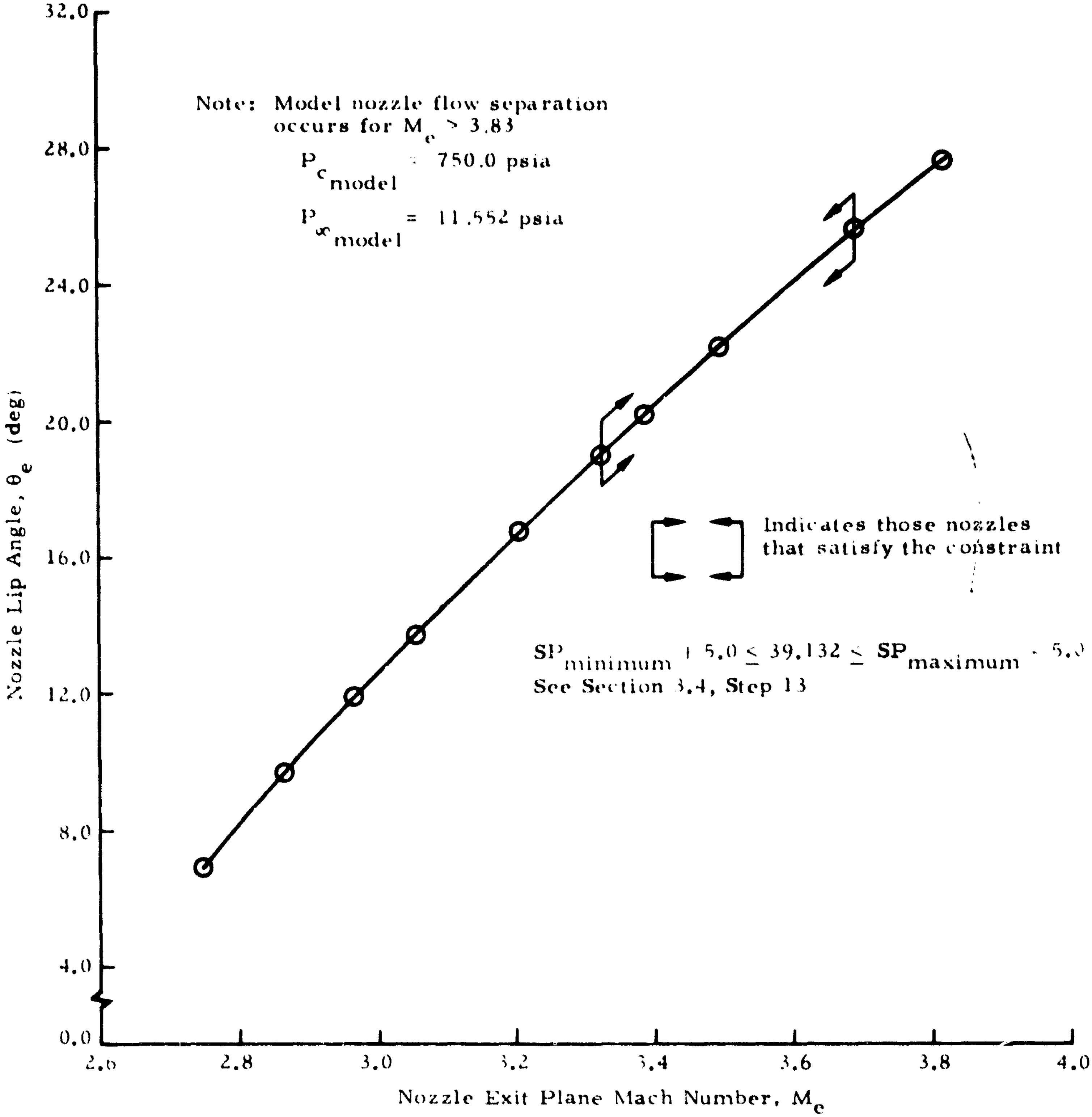


Fig. 3-5 - A Family of Candidate Model Nozzles That May be Used to Ensure Base Pressure Matching for Flight Conditions: $M_\infty = .597$, $P_b/P_\infty = .89$, $P_{c_{prototype}} = 720.0$ psia, $P_{\infty_{prototype}} = 10.542$ psia and $SP_{nominal} = 39.132$

of simulating the flight conditions that exist for each of the other flight Mach numbers. This is achieved as follows:

Select a family of candidate nozzles derived in Step 12. For each candidate nozzle in that family, calculate the values of $SP_{minimum}$ and $SP_{maximum}$ that are obtained when tested at each of the other fligh Mach numbers. Then, compare these values to the required $SP_{nominal}$ that corresponds to each flight Mach number to ensure that the constraint

$$SP_{minimum} + 5.0 \leq SP_{nominal} \leq SP_{maximum} - 5.0 \qquad (3.14)$$

is met (see Fig. 3-1 for a clear understanding of the importance of this constraint).

The result is a group of nozzle families that form an "envelope of model nozzles" that may be used to ensure base pressure matching for each set of flight conditions to be simulated. There is one envelope of nozzles for each set of flight conditions to be simulated.

The tolerance of + 5.0 on $SP_{minimum}$ and - 5.0 on $SP_{maximum}$ in Eq. (3.14) is applied to introduce a little more conservatism in the final nozzle design. These tolerances will: (1) allow for changes in $SP_{nominal}$ that may result if wind tunnel test conditions vary slightly, and (2) decrease the accuracy required on the initial predicted values of P_b/P_∞ used in Step 3.

Refer to Fig. 3-5 and note that each candidate nozzle represented along the curve will ensure base pressure matching for $SP_{nominal}$ = 39.132. However, when the above tolerances are applied, the final accepted nozzles in this family for this set of flight conditions become those that are bracketed by .

The values of $SP_{minimum}$ and $SP_{maximum}$ are calculated using the general form of the Similarity Parameter

$$SP)_{general} = \frac{M_j \delta_j}{M_e^a \gamma_j^b}$$

For a given value of M_e and a nozzle flowing air $\gamma_j = 1.4$; the minimum and maximum values of $SP)_{general}$ are determined simply by determining the minimum and maximum values of $M_j \delta_j$ respectively.

- Determination of $SP)_{minimum}$

  a. M_e, θ_e, P_c/P_e and ν_e are defined for each candidate nozzle.

  b. $M_j)_{min}$ and $\delta_j)_{min}$ occur for $\left.\frac{P_c}{P_b}\right)_{min}$

  c. For a given P_c/P_e; $(P_c/P_b)_{min}$ can be determined using constraint 3 of Step 1

$$\left.\frac{P_c}{P_b}\right)_{min} = \frac{P_c}{P_e} * \left.\frac{P_e}{P_b}\right)_{min} = \frac{P_c}{P_e} * 0.60$$

  For a given set of flight conditions, P_b is given and $P_c)_{min}$ can be calculated from the above equation

$$P_c)_{min} = \frac{P_c}{P_e} * 0.60 * P_b$$

d. $M_j)_{min}$ and $\delta_j)_{min}$ are then determined using Eqs. (3.6) and (3.7), respectively

$$M_j)_{min} = \left\{ \frac{2}{\gamma_j - 1} \left[\left(\frac{P_c}{P_b}\right)_{min}^{\frac{\gamma_j - 1}{\gamma_j}} - 1 \right] \right\}^{1/2}$$

$$\delta_j)_{min} = \theta_e + \nu_j)_{min} - \nu_e$$

where $\nu_j)_{min}$ is determined using Eq. (3.5)

$$\nu_j)_{min} = \left(\frac{\gamma_j + 1}{\gamma_j - 1}\right)^{1/2} \tan^{-1} \left\{ \left(\frac{\gamma_j - 1}{\gamma_j + 1}\right) \left[M_j^2)_{min} - 1\right] \right\}^{1/2} - \tan^{-1} \left[M_j^2)_{min} - 1\right]^{1/2}$$

finally,

e. $$SP_{minimum} = \frac{M_j)_{min} * \delta_j)_{min}}{M_e^a \gamma_j^b}$$

- Determination of $SP)_{maximum}$

a. M_e, θ_e, $\frac{P_c}{P_e}$ and ν_e is defined for each candidate nozzle.

b. $M_j)_{max}$ and $\delta_j)_{max}$ occur for $\left.\frac{P_c}{P_b}\right)_{max}$

c. For a given flight condition P_b is defined. Therefore P_c/P_b is maximum when P_c is maximum. The value of $P_c)_{max}$ is the lesser of the test facility $P_c)_{max}$ or as is most often the case, the value of $P_c)_{max}$ determined as a function of $\dot{m})_{max}$ for the facility

$$P_c)_{max} = \frac{1}{.532} \frac{\dot{m})_{max} \sqrt{T_o}}{A^*}$$

Therefore,

$$\left.\frac{P_c}{P_b}\right)_{max} = \frac{P_c)_{max}}{P_b}$$

d. $M_j)_{max}$, $\nu_j)_{max}$ and $\delta_j)_{max}$ are determined using Eqs. (3.6), (3.5), and (3.7), respectively.

$$M_j)_{max} = \left\{ \frac{2}{\gamma_j - 1} \left[\left(\frac{P_c}{P_b}\right)_{max}^{\frac{\gamma_j - 1}{\gamma_j}} - 1 \right] \right\}^{1/2}$$

$$\delta_j)_{max} = \theta_c + \nu_j)_{max} - \nu_e$$

where

$$\nu_j)_{max} = \left(\frac{\gamma_j + 1}{\gamma_j - 1}\right)^{1/2} \tan^{-1} \left\{\left(\frac{\gamma_j - 1}{\gamma_j + 1}\right)\left[M_j^2)_{max} - 1\right]\right\}^{1/2} - \tan^{-1} \left[M_j^2)_{max} - 1\right]^{1/2}$$

Finally,

e. $$SP_{maximum} = \frac{M_j)_{max} * \delta_j)_{max}}{M_e^a \gamma_j^b}$$

Step Fourteen

The results of Step 13 are plotted. Figure 3-6 presents the results of Step 13. For example, Fig. 3-6a presents an envelope of candidate model nozzles that may be used to simulate the flight conditions that exist for $M_\infty = 0.597$. Each candidate nozzle in this envelope will: (1) ensure base pressure matching for the $M_\infty = 0.597$ flight conditions, and (2) meet all of the constraints of Step 1.

Steps 15 through 18 compare each of the envelopes of nozzles plotted in Fig. 3-6 to determine a "final" envelope of model nozzles that may be used for all flight Mach numbers to be simulated.

Step Fifteen

The upper limit on M_e is a result of the separation constraint of Step 1 and usually occurs for the lowest value of flight Mach number to be simulated. Compare each envelope of model nozzles and choose the smallest value of $M_{e_{max}}$ as the upper limit on M_e of the "final" model nozzle envelope. This would correspond to $M_e = 3.53$ in Fig. 3-6a for $M_\infty = .597$.

Step Sixteen

The lower limit on M_e is a result of the mass flow constraint of Step 1. This constraint has its greatest influence at the highest value of flight Mach number to be simulated. This can be understood by examination of Table 3-2.

As flight Mach number to be simulated increases, the value of $SP_{nominal}$ required to ensure base pressure matching also increases. P_c is directly proportional to $SP_{nominal}$ and therefore also must increase with increasing flight Mach number to be simulated. For a given P_c and constrained nozzle exit diameter the mass flow rate increases as M_e decreases.

Therefore, examine the nozzle envelope for the highest flight Mach number to be simulated. Compare each of the nozzle families and choose the <u>largest</u> value of $M_{e_{min}}$ as the lower limit on M_e of the "final" model nozzle envelope. This would correspond to M_e = 3.49 in Fig. 3.6i for M_∞ = 1.403. Once the upper and lower limits of model nozzle exit Mach number are determined the value of the limits are compared. If the lower limit on M_e is greater than the upper limit on M_e no solution exists for the range of flight Mach numbers to be simulated (see step two). To solve this problem merely reduce the upper value on the range of flight Mach numbers to be simulated during testing established in Step 2. This will reduce the value of $M_{e_{min}}$ just determined to some value less than $M_{e_{max}}$ of Step 15.

In some instances, as is the case of the example being presented, the lower and upper limits of M_e are close to the same value (3.49 and 3.53). Further reduction in the upper value on the range of flight Mach number to be simulated during testing will increase the difference of $M_{e_{min}}$ and $M_{e_{max}}$ of the "final" model nozzle envelope.

<u>Step Seventeen</u>

Determine the maximum and minimum values of θ_e for all candidate nozzles whose M_e correspond to the upper limit of M_e determined in Step 15.

<u>Step Eighteen</u>

Determine the maximum and minimum values of θ_e for all candidate nozzles whose M_e correspond to the lower limit of M_e determined in Step 16.

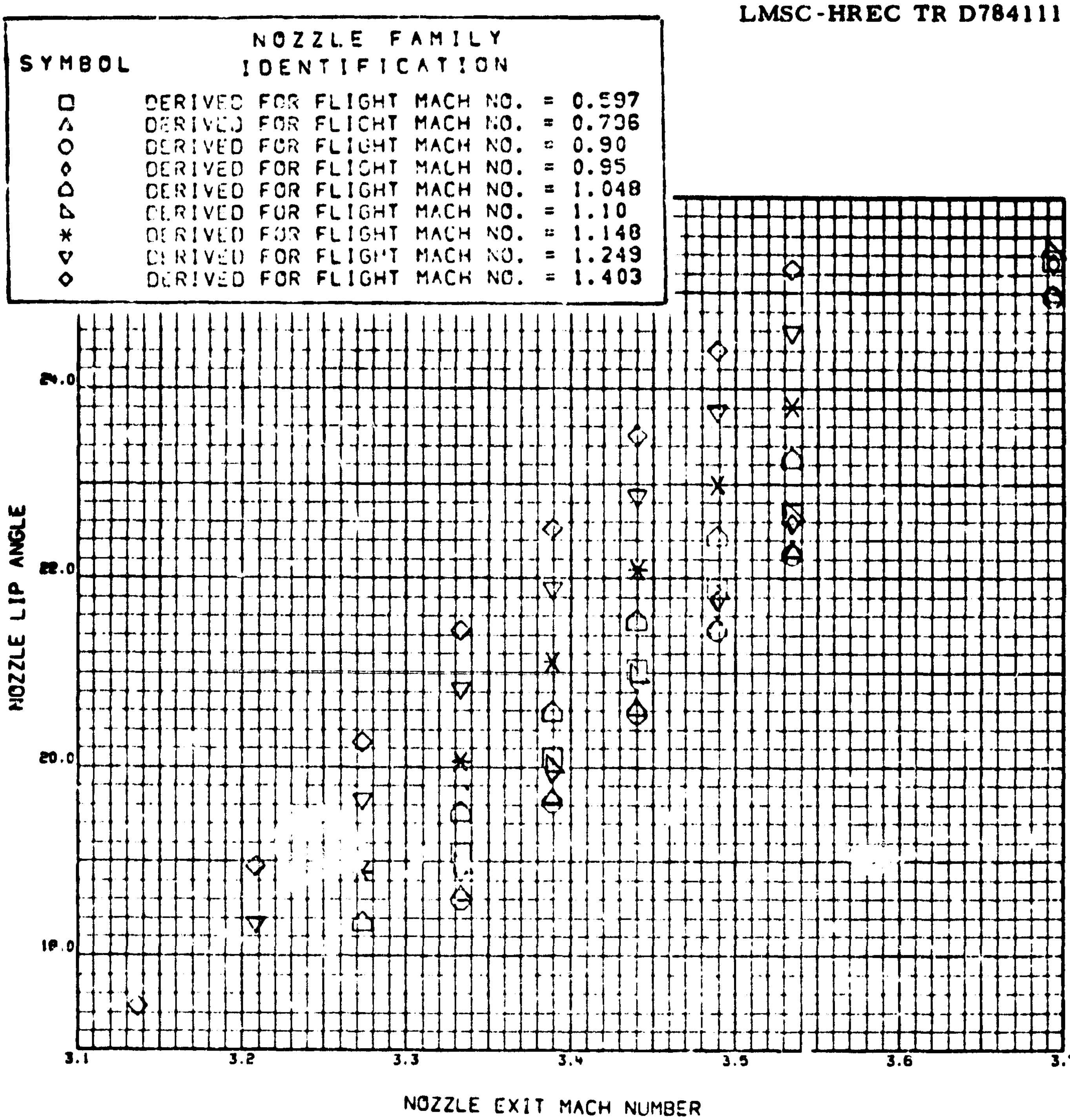


Fig. 3-6a - The Symbols Plotted Above Represent Model Nozzles that May be Used to Simulate Only the Flight Conditions that Exist for a Freestream Mach Number = .597

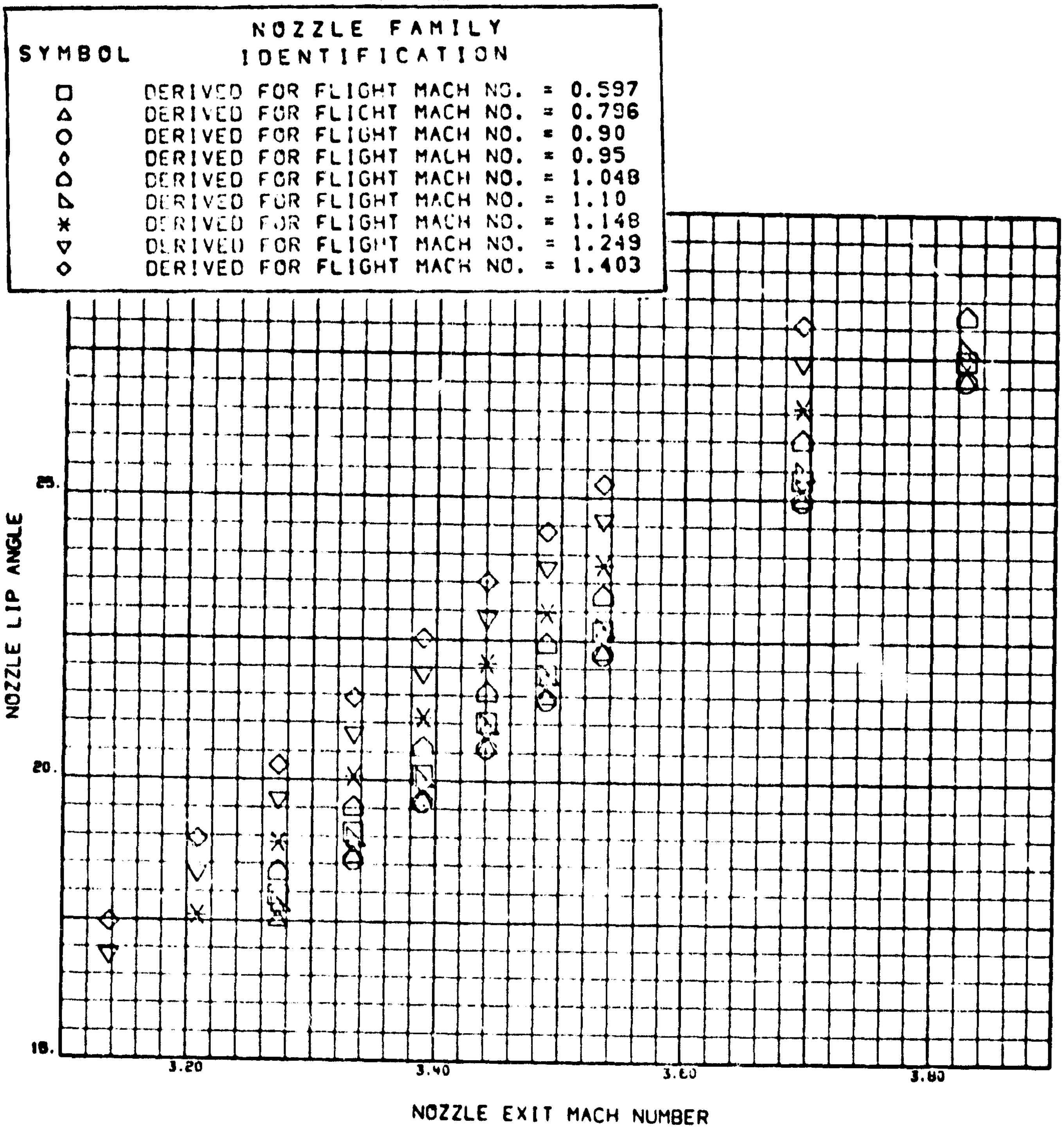


Fig. 3-6b - The Symbols Plotted Above Represent Model Nozzles that May be Used to Simulate Only the Flight Conditions that Exist for a Freestream Mach Number = .796

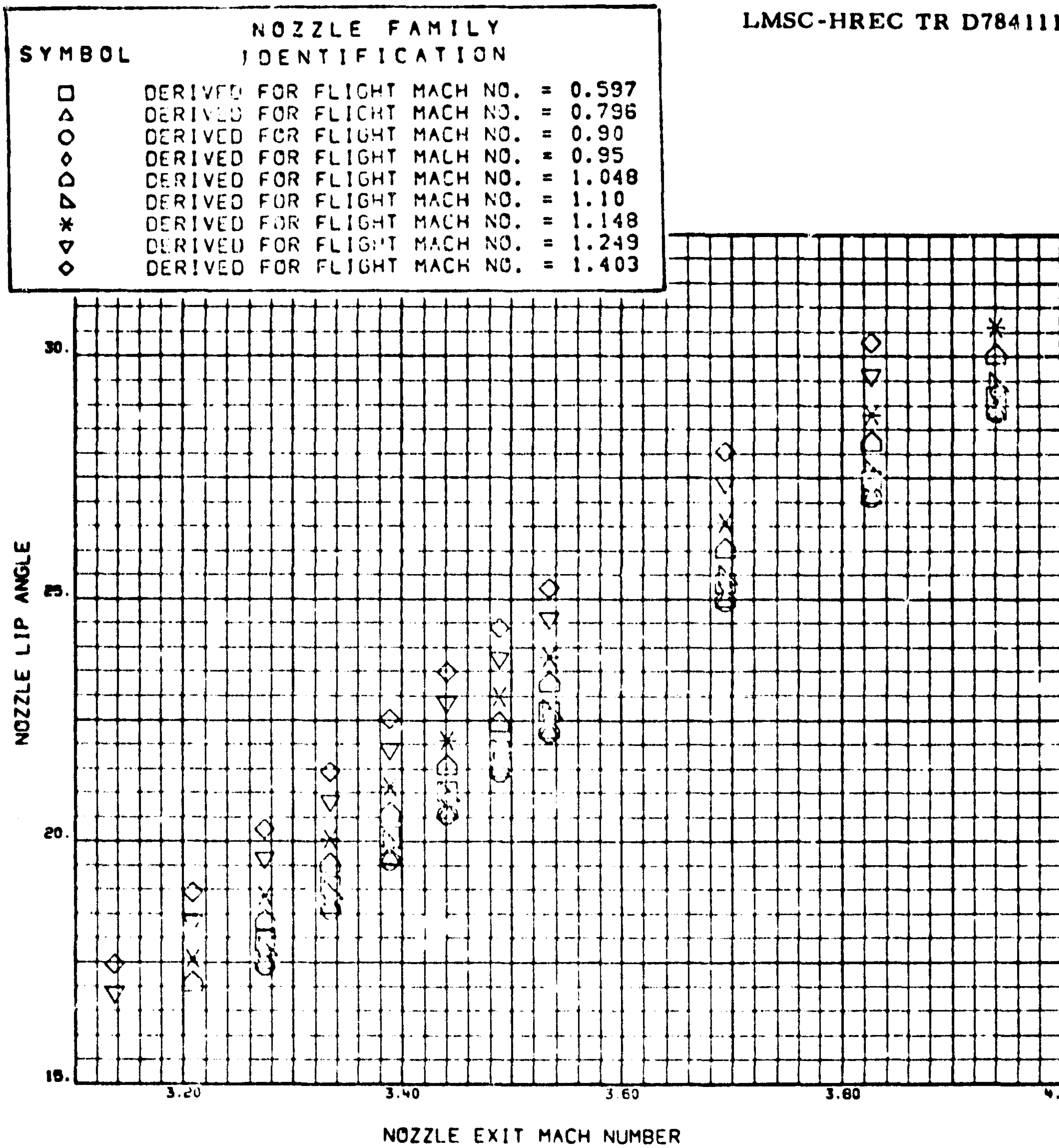


Fig. 3-6c - The Symbols Plotted Above Represent Model Nozzles that May be Used to Simulate Only the Flight Conditions that Exist for a Freestream Mach Number = .900

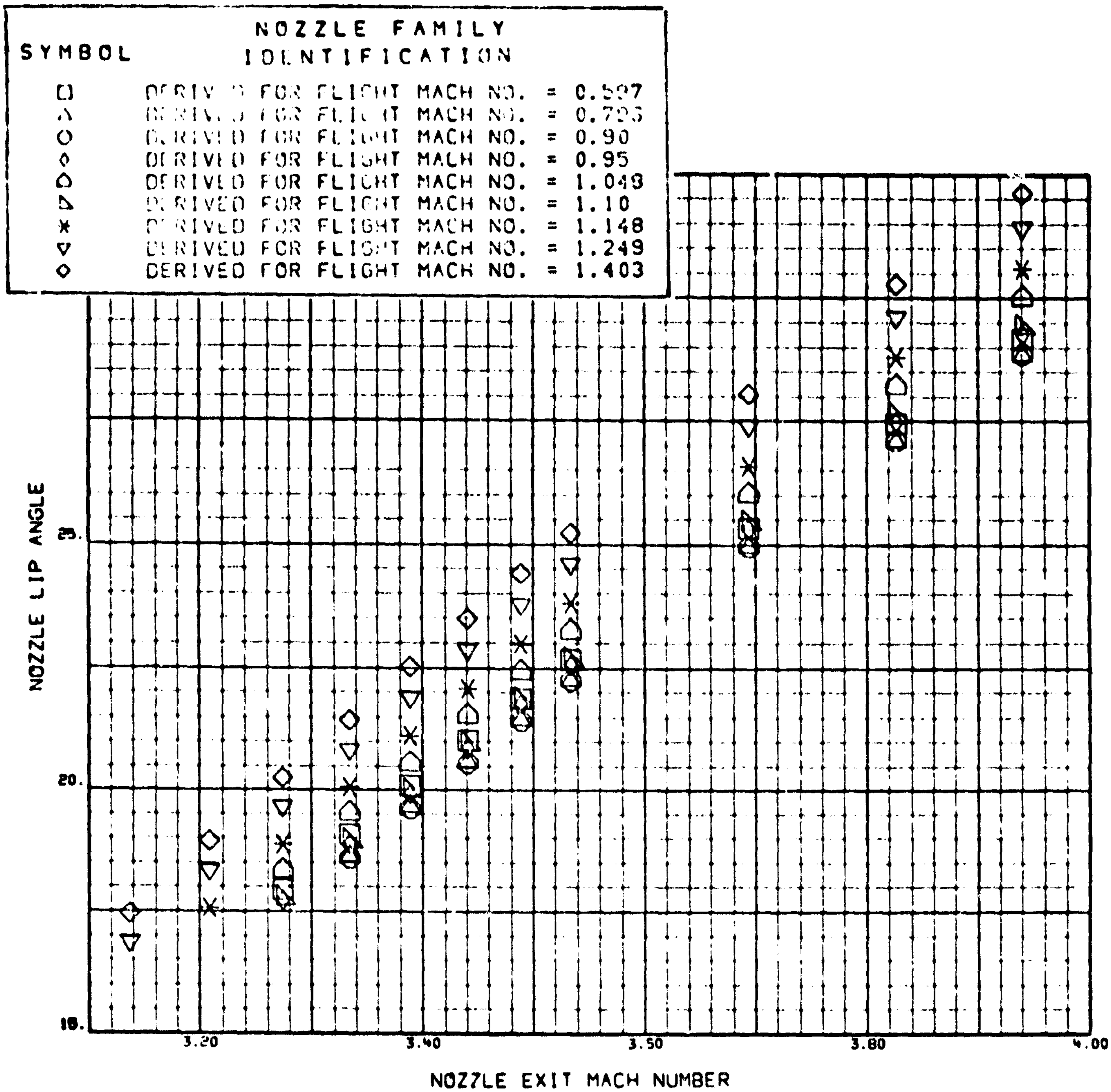


Fig. 3-6c - The Symbols Plotted Above Represent Model Nozzles that May be Used to Simulate Only the Flight Conditions that Exist for a Freestream Mach Number = .950

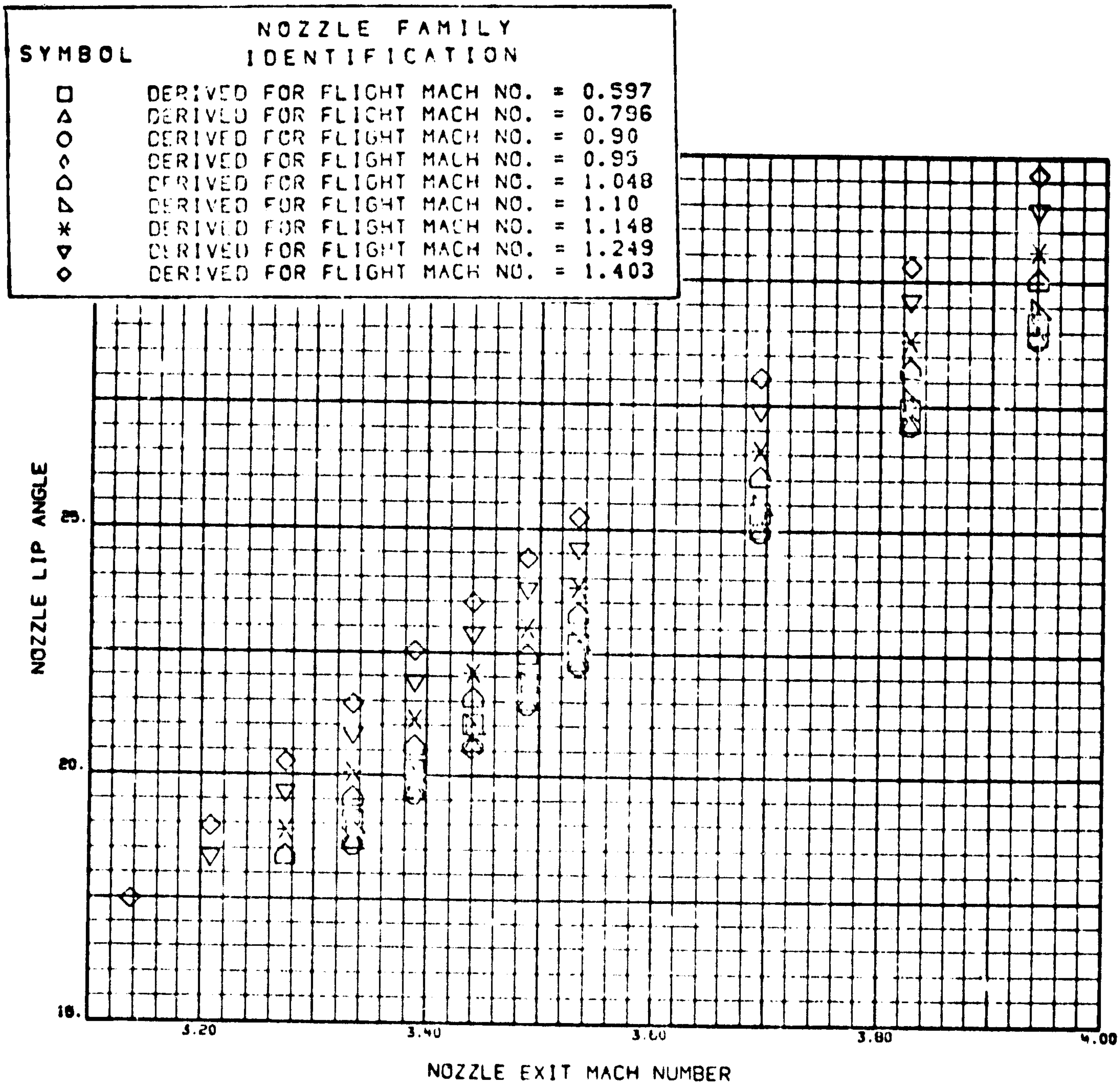


Fig. 3-6e - The Symbols Plotted Above Represent Model Nozzles that May be Used to Simulate Only the Flight Conditions that Exist for a Freestream Mach Number = 1.048

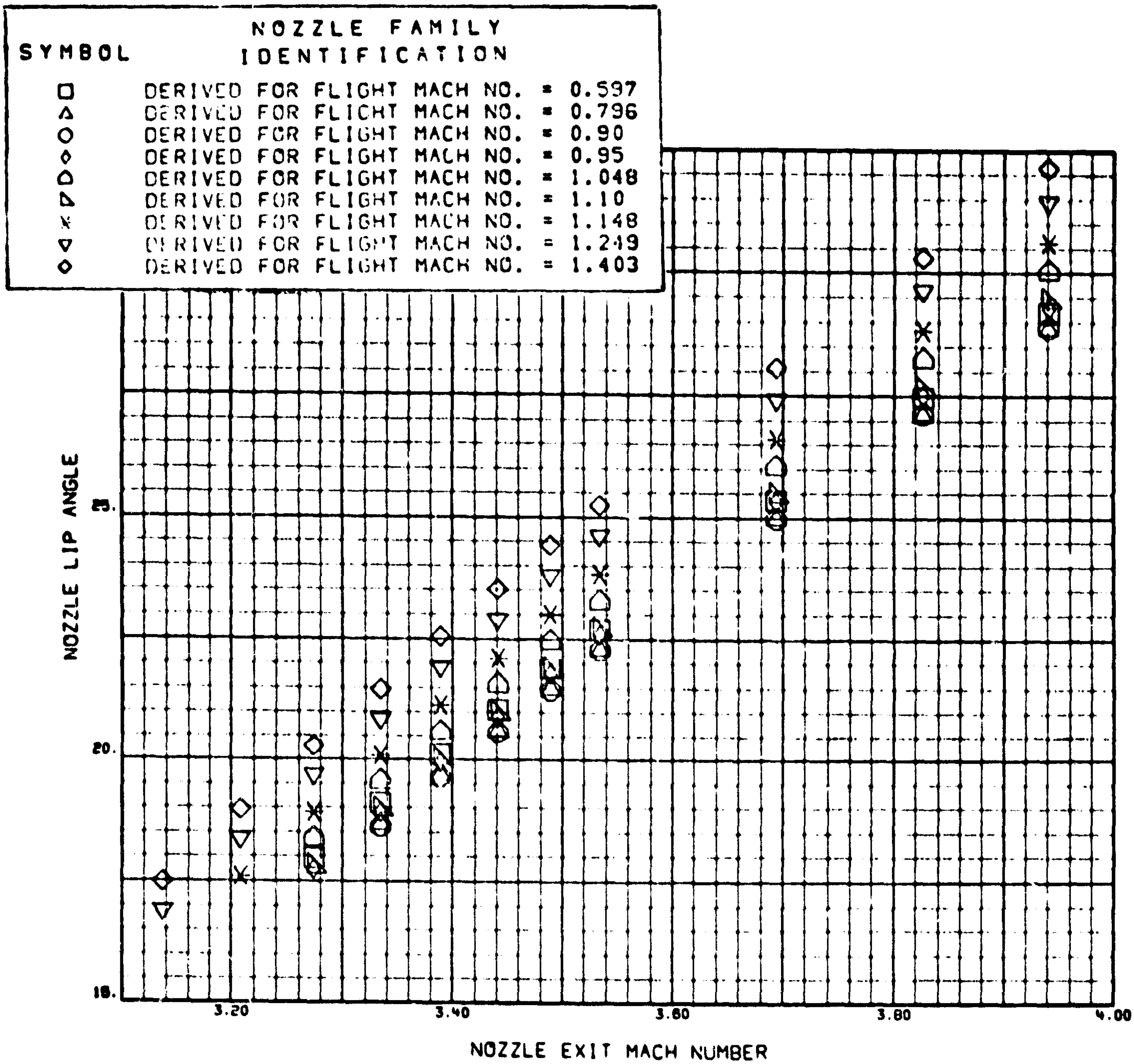


Fig. 3-65 - The Symbols Plotted Above Represent Model Nozzles that May be Used to Simulate Only the Flight Conditions that Exist for a Freestream Mach Number = 1.100

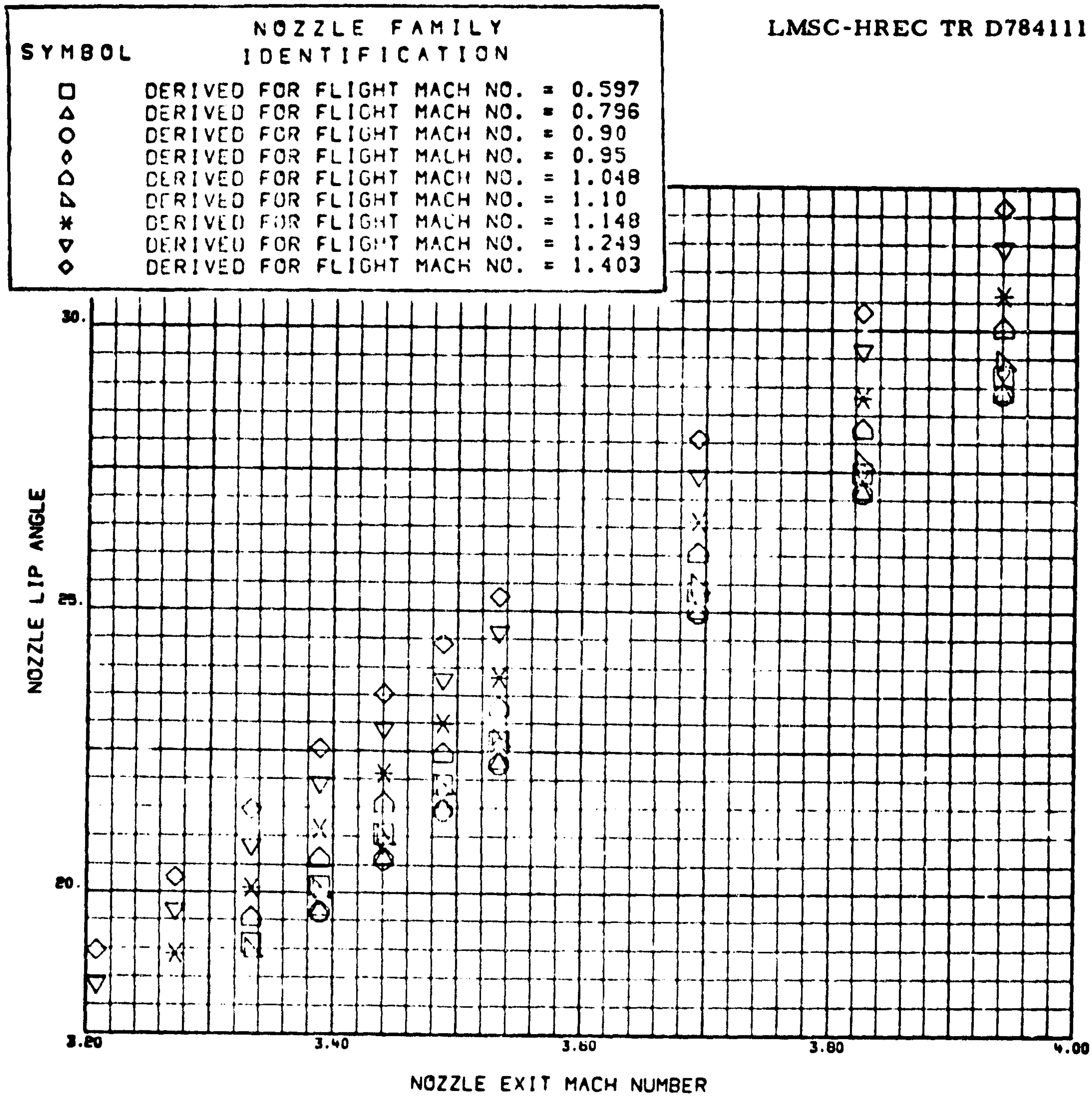


Fig. 3-6g - The Symbols Plotted Above Represent Model Nozzles that May be Used to Simulate Only the Flight Conditions that Exist for a Freestream Mach Number = 1.148

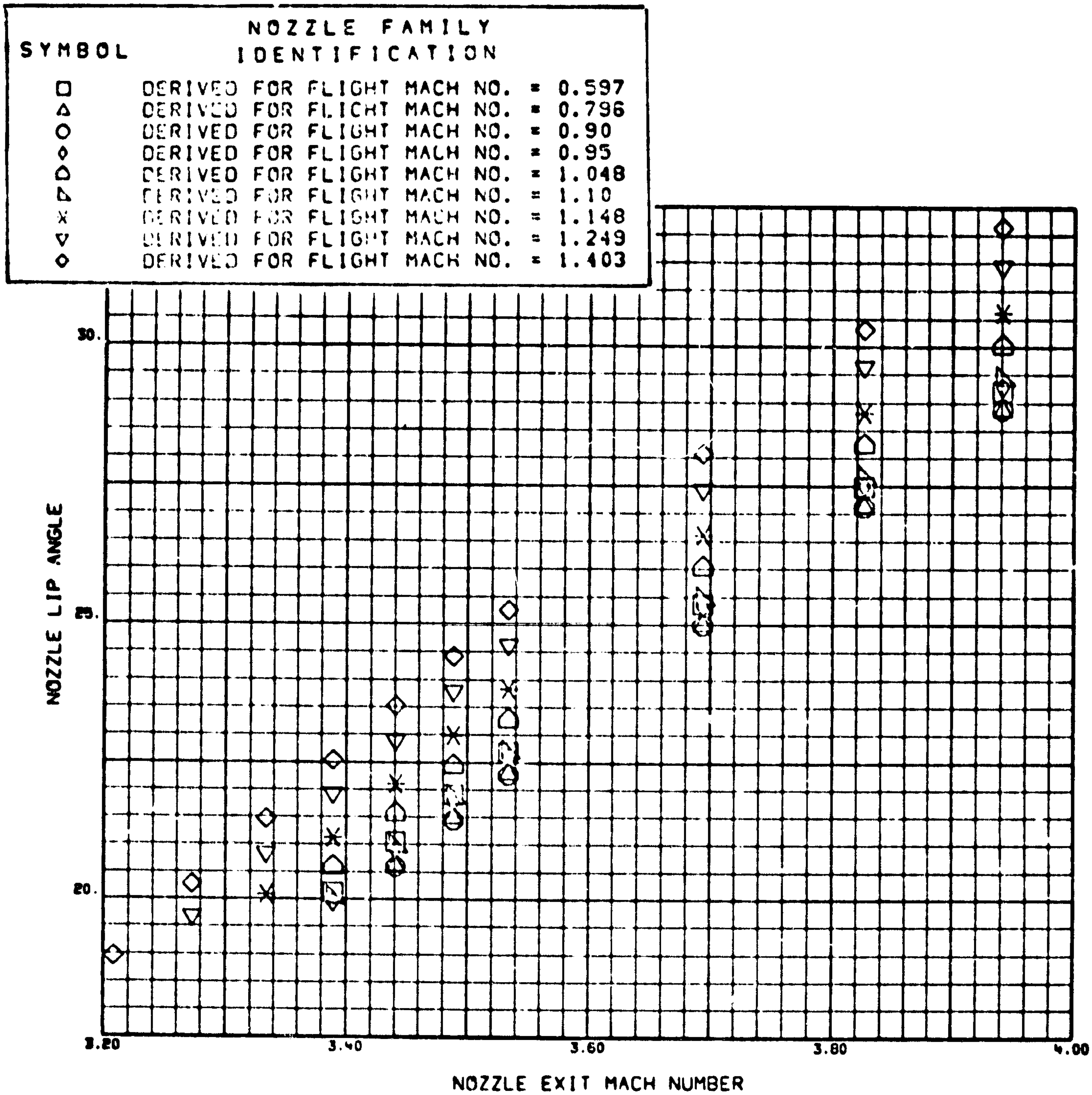


Fig. 3-6h - The Symbols Plotted Above Represent Model Nozzles that May be Used to Simulate Only the Flight Conditions that Exist for a Freestream Mach Number = 1.249

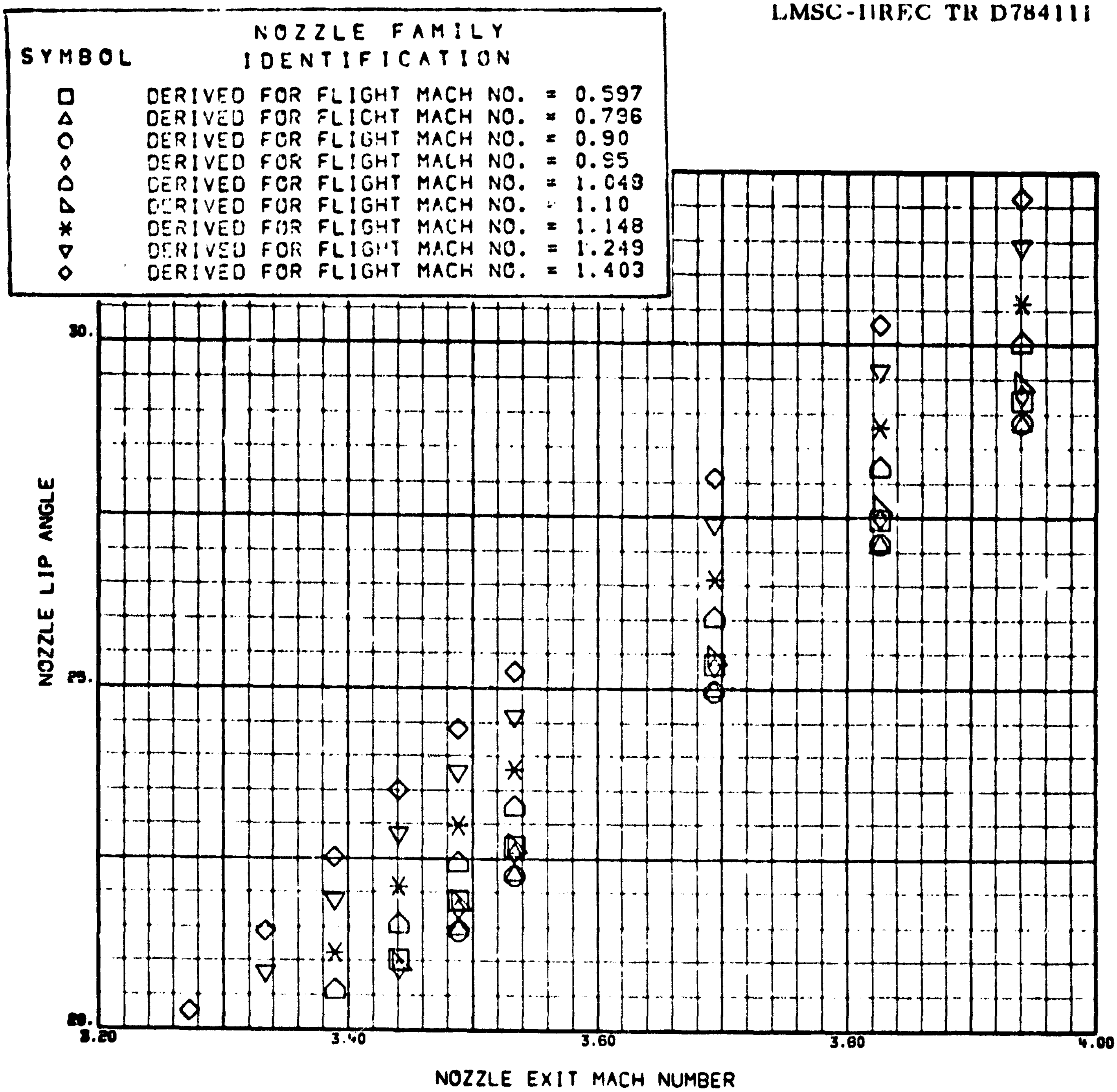


Fig. 3-6i - The Symbols Plotted Above Represent Model Nozzles that May be Used to Simulate Only the Flight Conditions that Exist for a Freestream Mach Number = 1.403

Step Nineteen

The results of Steps 15 through 18 can be plotted to yield the final envelope of model nozzles that may be used in the test program. Each model nozzle in this envelope will: (1) ensure base pressure matching for "all" specified sets of flight conditions to be simulated, and (2) meet all of the constraints specified in Step 1. Figure 3-7 presents a plot of the final envelope of nozzles that result, when Steps 15 through 18 are applied to Figs. 3-6a through 3-6i.

Step Twenty*

To ensure that base pressure matching does occur in the data analysis stage of the test program, it is necessary to know the power sweep operating characteristics of the model nozzle prior to actual testing. For a given model nozzle design, the power sweep operating characteristics of importance are: (1) the minimum obtainable value of similarity parameter ($SP_{minimum}$); (2) the maximum obtainable value of similarity parameter ($SP_{maximum}$) for each of the flight conditions to be simulated; (3) the nominal value of similarity parameter ($SP_{nominal}$) required to ensure base pressure matching and (4) the values of chamber pressure corresponding to each value of similarity parameter just noted.

The calculations of $SP_{maximum}$, $\left.P_c\right)_{max}$, $SP_{minimum}$ and $\left.P_c\right)_{min}$ have already been discussed in Step 13. The value of $SP_{nominal}$ required to ensure base pressure matching has already been defined in Step 5 for each scheduled M_∞ to be simulated. This leaves the value of chamber pressure, $\left.P_c\right)_{nom}$, corresponding to $SP_{nominal}$ as the only value undefined at this time.

*Refer to Fig. 3-1 when performing this step of the analysis.

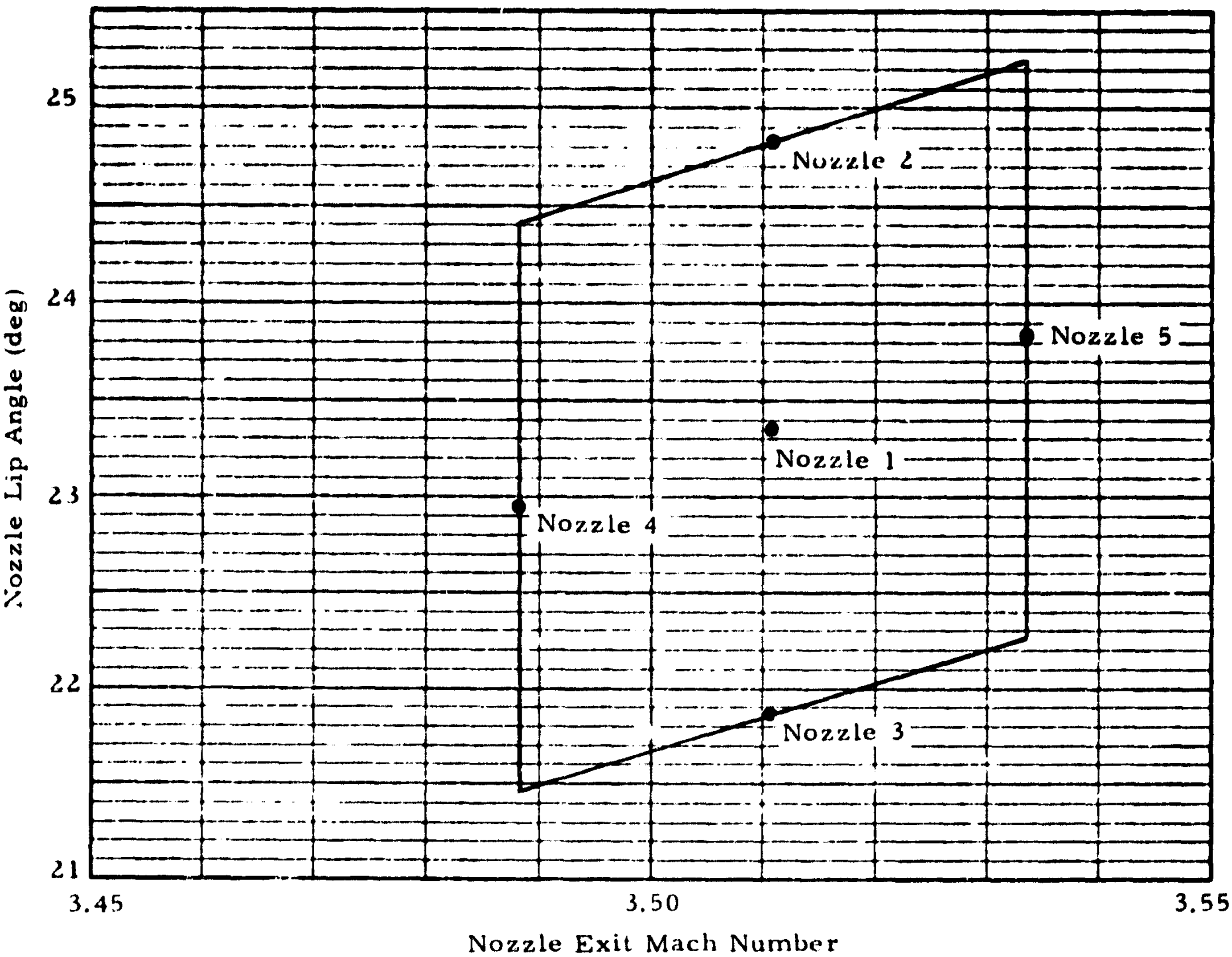


Fig. 3-7 - Final Envelope of Model Nozzles That May be Used in the Test Program

Notes: a. Each model nozzle in this envelope will: (1) ensure base pressure matching for "all" specified sets of flight conditions to be simulated, and (2) meet all the constraints specified in Step 1.

b. The similarity parameter used in this nozzle design study is

$$SP = \frac{M_j \delta_j}{M_e^{.25} \gamma_j}$$

The value of $P_c)_{nom}$ is calculated following the interation process described below. $P_c)_{nom}$ is a function of flight conditions to be simulated as well as model nozzle geometry.

a. M_e, θ_e, $\frac{P_c}{P_e}$, D_e, D^* and ν_e are defined for each candidate nozzle.

b. Set a value for the initial guess on M_j

c. Calculate δ_j using Eq.(3.10)

$$\delta_j = \frac{M_e^a \gamma_j^b}{M_j} * SP_{nominal}$$

d. Calculate θ_e using Eq. (3.8)

$$\theta_e = \delta_j + \nu_e - \nu_j$$

where ν_j is determined using Eq. (3.5)

$$\nu_j = \left(\frac{\gamma_j + 1}{\gamma_j - 1}\right)^{1/2} \tan^{-1}\left[\left(\frac{\gamma_j - 1}{\gamma_j + 1}\right)(M_j^2 - 1)\right]^{1/2} - \tan^{-1}(M_j^2 - 1)^{1/2}$$

e. Compare the value of θ_e just calculated with the actual value of θ_e for the model nozzle being considered. If the values of θ_e compare within an acceptable tolerance proceed to f; if not, adjust the value of M_j and repeat steps c, d and e until an acceptable tolerance is achieved.

f. At this point M_j is defined and the value of $\frac{P_c}{P_b}$ is determined using Eq. (3.3)

$$\frac{P_c}{P_b} = \left(1 + \frac{\gamma_j - 1}{2} M_j^2\right)^{\frac{\gamma_j}{\gamma_j - 1}} \qquad \text{note: } P_b = P_j$$

g. Finally, $P_c)_{nom}$ is calculated using the following relationship

$$P_c)_{nom} = \frac{P_c}{P_b} * \frac{P_b}{P_\infty} * P_\infty)_{model}$$

Table 3-4 presents power sweep operating characteristics of five representative model nozzles that exist in the final envelope of Fig. 3-7. The flight conditions to be simulated during wind tunnel tests are those of Table 3-2.

Examination of Table 3-4 indicates that each of the representative model nozzles considered are capable of base pressure matching well within the constraints of Step 1. This is indicated by the fact that the constraint

$$SP_{minimum} + 5.0 \leq SP_{nominal} \leq SP_{maximum} - 5.0$$

is satisfied for all model nozzles at all scheduled M_∞ to be simulated.

The analytical procedure used to design model nozzles which meet MSFC base pressure similarity parameter criteria is now complete. The following section presents an input guide for an automated computer code used to perform the described analytical procedure. It is strongly suggested that the computer code user make every possible use of the analytical portion of this document when setting up his input deck. Doing so will give the user a greater understanding of model nozzle design problem and the actual use of the computer code.

Table 3-4

POWER SWEEP OPERATING CHARACTERISTICS OF FIVE REPRESENTATIVE NOZZLES FOR EACH OF THE DESIRED FLIGHT CONDITIONS TO BE SIMULATED IN TABLE 3-2

Nozzle	M_e	θ_e	M_x	$P_c')_{min}$	SP_{min}	$P_c')_{nom}$	SP_{nom}	$P_c')_{max}$	SP_{max}	$P_r')_{model}$	D^*	D_e
1	.35109+01	.23344+02	.59700+00	.47785+03	.28603+02	.70229+03	.39132+02	.11067+04	.52609+02	.11552+02	.11427+01	.29928+01
1	.35109+01	.23344+02	.79600+00	.37124+03	.28603+02	.68425+03	.45703+02	.11067+04	.60545+02	.96818+01	.11427+01	.29928+01
1	.35109+01	.23344+02	.90000+00	.31105+03	.28603+02	.68234+03	.50925+02	.11067+04	.66356+02	.86915+01	.11427+01	.29928+01
1	.35109+01	.23344+02	.95000+00	.25801+03	.28603+02	.69611+03	.57365+02	.11067+04	.72576+02	.82241+01	.11427+01	.29928+01
1	.35109+01	.23344+02	.10480+01	.20800+03	.28603+02	.72598+03	.65664+02	.11067+04	.80037+02	.73364+01	.11427+01	.29928+01
1	.35109+01	.23344+02	.11000+01	.20479+03	.26603+02	.70041+03	.64987+02	.11067+04	.83584+02	.68848+01	.11427+01	.29928+01
1	.35109+01	.23344+02	.11480+01	.19582+03	.26503+02	.75351+03	.68890+02	.11067+04	.82170+02	.64820+01	.11427+01	.29928+01
1	.35109+01	.23344+02	.12490+01	.18224+03	.28603+02	.79198+03	.73000+02	.11067+04	.84740+02	.56826+01	.11427+01	.29928+01
1	.35109+01	.23344+02	.14030+01	.16462+03	.26603+02	.82562+03	.77946+02	.11067+04	.88423+02	.45999+01	.11427+01	.29928+01
2	.35109+01	.24832+02	.59700+00	.47785+03	.31055+02	.63978+03	.39132+02	.11067+04	.55518+02	.11552+02	.11427+01	.29928+01
2	.35109+01	.24832+02	.79600+00	.37124+03	.31055+02	.62363+03	.45703+02	.11067+04	.63597+02	.96818+01	.11427+01	.29928+01
2	.35109+01	.24832+02	.90000+00	.31105+03	.31055+02	.62135+03	.50925+02	.11067+04	.69462+02	.86915+01	.11427+01	.29928+01
2	.35109+01	.24832+02	.95000+00	.25801+03	.31055+02	.63401+03	.57365+02	.11067+04	.75843+02	.82241+01	.11427+01	.29928+01
2	[illegible]109+01	.24832+02	.10480+01	.20800+03	.31055+02	.66056+03	.65664+02	.11067+04	.83434+02	.73364+01	.11427+01	.29928+01
2	.35109+01	.24832+02	.11000+01	.20479+03	.31055+02	.63590+03	.64987+02	.11067+04	.63990+02	.68848+01	.11427+01	.29928+01
2	.35109+01	.24832+02	.11480+01	.19582+03	.31055+02	.68514+03	.68890+02	.11067+04	.85604+02	.64820+01	.11427+01	.29928+01
2	.35109+01	.24832+02	.12490+01	.18224+03	.31055+02	.71999+03	.73000+02	.11067+04	.88218+02	.56826+01	.11427+01	.29928+01
2	.35109+01	.24832+02	.14030+01	.16462+03	.31055+02	.75023+03	.77946+02	.11067+04	.91965+02	.45999+01	.11427+01	.29928+01
3	.35109+01	.21856+02	.59700+00	.47785+03	.26150+02	.77182+03	.39132+02	.11067+04	.49700+02	.11552+02	.11427+01	.29928+01
3	.35109+01	.21856+02	.79600+00	.37124+03	.26150+02	.75233+03	.45703+02	.11067+04	.57492+02	.96818+01	.11427+01	.29928+01
3	.35109+01	.21856+02	.90000+00	.31105+03	.26150+02	.75034+03	.50925+02	.11067+04	.63150+02	.86915+01	.11427+01	.29928+01
3	.35109+01	.21856+02	.95000+00	.25801+03	.26150+02	.76653+03	.57365+02	.11067+04	.69309+02	.82241+01	.11427+01	.29928+01
3	.35109+01	.21856+02	.10480+01	.20800+03	.26150+02	.79976+03	.65664+02	.11067+04	.76640+02	.73364+01	.11427+01	.29928+01
3	.35109+01	.21856+02	.11000+01	.20479+03	.26150+02	.77137+03	.64987+02	.11067+04	.77177+02	.68848+01	.11427+01	.29928+01
3	.35109+01	.21856+02	.11480+01	.19582+03	.26150+02	.82997+03	.68890+02	.11067+04	.78736+02	.64820+01	.11427+01	.29928+01
3	.35109+01	.21856+02	.12490+01	.18224+03	.26150+02	.87252+03	.73000+02	.11067+04	.81261+02	.56826+01	.11427+01	.29928+01
3	.35109+01	.21856+02	.14030+01	.16462+03	.26150+02	.91003+03	.77946+02	.11067+04	.84881+02	.45999+01	.11427+01	.29928+01
4	.34882+01	.22934+02	.59700+00	.46265+03	.27719+02	.70257+03	.39132+02	.10835+04	.51949+02	.11552+02	.11549+01	.29928+01
4	.34882+01	.22934+02	.79600+00	.35944+03	.27719+02	.68479+03	.45703+02	.10835+04	.59865+02	.96818+01	.11549+01	.29928+01
4	.34882+01	.22934+02	.90000+00	.30116+03	.27719+02	.68249+03	.50925+02	.10835+04	.65612+02	.86915+01	.11549+01	.29928+01
4	.34882+01	.22934+02	.95000+00	.24981+03	.27719+02	.69643+03	.57365+02	.10835+04	.71868+02	.82241+01	.11549+01	.29928+01
4	.34882+01	.22934+02	.10480+01	.20138+03	.27719+02	.72586+03	.65664+02	.10835+04	.79312+02	.73364+01	.11549+01	.29928+01
4	.34882+01	.22934+02	.11000+01	.19828+03	.27719+02	.69997+03	.64987+02	.10835+04	.79858+02	.68848+01	.11549+01	.29928+01
4	.34882+01	.22934+02	.11480+01	.18960+03	.27719+02	.75308+03	.68890+02	.10835+04	.81440+02	.64820+01	.11549+01	.29928+01
4	.34882+01	.22934+02	.12490+01	.17645+03	.27719+02	.79149+03	.73000+02	.10835+04	.84004+02	.56826+01	.11549+01	.29928+01
4	.34882+01	.22934+02	.14030+01	.15939+03	.27719+02	.82489+03	.77946+02	.10835+04	.87679+02	.45999+01	.11549+01	.29928+01
5	.35337+01	.23754+02	.59700+00	.49350+03	.29493+02	.70157+03	.39132+02	.11303+04	.53275+02	.11552+02	.11307+01	.29928+01
5	.35337+01	.23754+02	.79600+00	.38346+03	.29493+02	.68354+03	.45703+02	.11303+04	.61231+02	.96818+01	.11307+01	.29928+01
5	.35337+01	.23754+02	.90000+00	.32124+03	.29493+02	.68179+03	.50925+02	.11303+04	.67006+02	.86915+01	.11307+01	.29928+01
5	.35337+01	.23754+02	.95000+00	.26646+03	.29493+02	.69623+03	.57365+02	.11303+04	.73292+02	.82241+01	.11307+01	.29928+01
5	.35337+01	.23754+02	.10480+01	.21481+03	.29493+02	.72620+03	.65664+02	.11303+04	.80769+02	.73364+01	.11307+01	.29928+01
5	.35337+01	.23754+02	.11000+01	.21150+03	.29493+02	.70045+03	.64987+02	.11303+04	.81318+02	.68848+01	.11307+01	.29928+01
5	.35337+01	.23754+02	.11480+01	.20224+03	.29493+02	.75354+03	.68890+02	.11303+04	.82908+02	.64820+01	.11307+01	.29928+01
5	.35337+01	.23754+02	.12490+01	.18821+03	.29493+02	.79203+03	.73000+02	.11303+04	.85483+02	.56826+01	.11307+01	.29928+01
5	.35337+01	.23754+02	.14030+01	.17004+03	.29493+02	.82592+03	.77946+02	.11303+04	.89174+02	.45999+01	.11307+01	.29928+01

4. A COMPUTER CODE USED TO DESIGN MODEL NOZZLES WHICH MEET MSFC BASE PRESSURE SIMILARITY PARAMETER CRITERIA

This section describes a computer code used to design model nozzles which may be used to simulate prototype engine conditions that exist over a specified range of ascent trajectory conditions. Each of the model nozzle designs will be capable of achieving the desired similarity parameter values required to ensure base pressure matching within the restrictions of maximum air pressure supply and mass flow rate imposed by the facility where wind tunnel testing will be performed.

An example of the computer code input requirements and resultant outputs are presented for the wind tunnel test IA-604 planned for the NASA-Ames Research Center 11 x 11 wind tunnel (Ref. 1-1). A "final envelope" of model nozzle designs, and corresponding power sweep operating characteristics for each of the desired flight conditions to be simulated in the wind tunnel tests is presented for representative model nozzles in the "final envelope."

Subroutines that make up the computer code are listed in Table 4-1. The subroutines which call and are called by the particular routine as well as a brief statement regarding the function of the routine are also included in the table. Chart 4-1 presents a flow chart of the computer code. A listing of the computer code is presented in the Appendix.

Sections 2 and 3 of this report present a detailed development of analytical procedures used in the model nozzle design analysis and automated in this computer code. It is strongly suggested that the computer code user make every possible use of the analytical portion of this report when performing a model nozzle design analysis. By doing so, the user will gain a greater understanding of: (1) the model nozzle design problem being considered, and (2) the actual

Table 4-1

MODEL NOZZLE DESIGN COMPUTER CODE SUBROUTINE LIST

Subroutines No.	Name	Calls Following Routine(s)	Called by Following Routine(s)	Description
1	ARATIO	–	3	Determines nozzle exit plane area ratio as a function of M_e and γ
2	CHECK	–	12	Determines the upper and lower limits of each envelope of model nozzles derived in subroutine SPRNGE (not called if NPLOT = 0).
3	COMBO3	1, 11, 14, 15	4	Derives a family of candidate model nozzles for each of the scheduled flight Mach numbers to be simulated. Each family of candidate model nozzles will ensure base pressure matching at the scheduled flight Mach number for which it is designed, and satisfy the nozzle flow separation criteria.
4	DESIGN	3, 5, 9, 16	12	Driving routine for the main program flow.
5	FINAL	17, 18	4	Determines the "final envelope" of model nozzles that may be used in the test program. Each model nozzle in the envelope will: (1) ensure base pressure matching at all scheduled flight Mach numbers to be simulated; and (2) meet all of the model nozzle design constraints. Determines the range of application of the "final envelope" of model nozzles. Plots the "final envelope" of model nozzles.
6	FIRST	–	12	Plots the lead frame which identifies: (1) the model design problem being considered; and (2) candidate model nozzle family plot symbols (not called if NPLOT = 0)
7	GRAPH	13, 18	12	Sets up grids and controls plotting of all optional plots (not called if NPLOT = 0).
8	HPM	–	–	Data file routine for wind tunnel test IA604 planned for the NASA/Ames Research Center 11 x 11 Wind Tunnel (Ref. 1-1).
9	INPUT	–	4	Reads all data necessary to perform a model nozzle design study and prints these data on the first page of computer printout.
10	ITSUB	–	17	General purpose iteration control routine. Solves a function of one variable.
11	MACH	–	3, 16, 17	Determines Mach number as a function of γ and pressure ratio.
12	MORE	4	–	Driver program.
13	POINTX	–	7	Plots the symbols representing each family of candidate model nozzles (not called if NPLOT = 0).
14	PRATIO	–	3, 17	Determines pressure ratio as a function of γ and Mach number.
15	PRND	–	3, 16, 17	Determines the Prandtl-Meyer turning angle (ν) as a function of γ and Mach Number.
16	SPRNGE	11, 15	4	Examines each family of candidate model nozzles to determine an envelope of model nozzles that may be used for each of the scheduled flight Mach numbers to be simulated. Each envelope of model nozzles will: (1) ensure base pressure matching at the corresponding flight Mach number, and (2) meet all of the model nozzle design constraints.
17	TEST	1, 10, 11, 14, 15	5	Determines the power sweep operating characteristics of representative model nozzles that exist in the "final envelope" of model nozzles for each of the scheduled flight Mach numbers to be simulated in the wind tunnel tests.
18	XYLIM	–	5, 7	Determines the plot limits and grid size to be used when plotting the "final envelope" of model nozzles, and (if NPLOT = 1) optional nozzle envelope data.
19	NXV	–	5, 13	Function to convert x data coordinates into x raster coordinates for use by Univac 1108 system plot routines.
20	NYV	–	5, 13	Function to convert y data coordinates into y raster coordinates for use by Univac 1108 system plot routines.

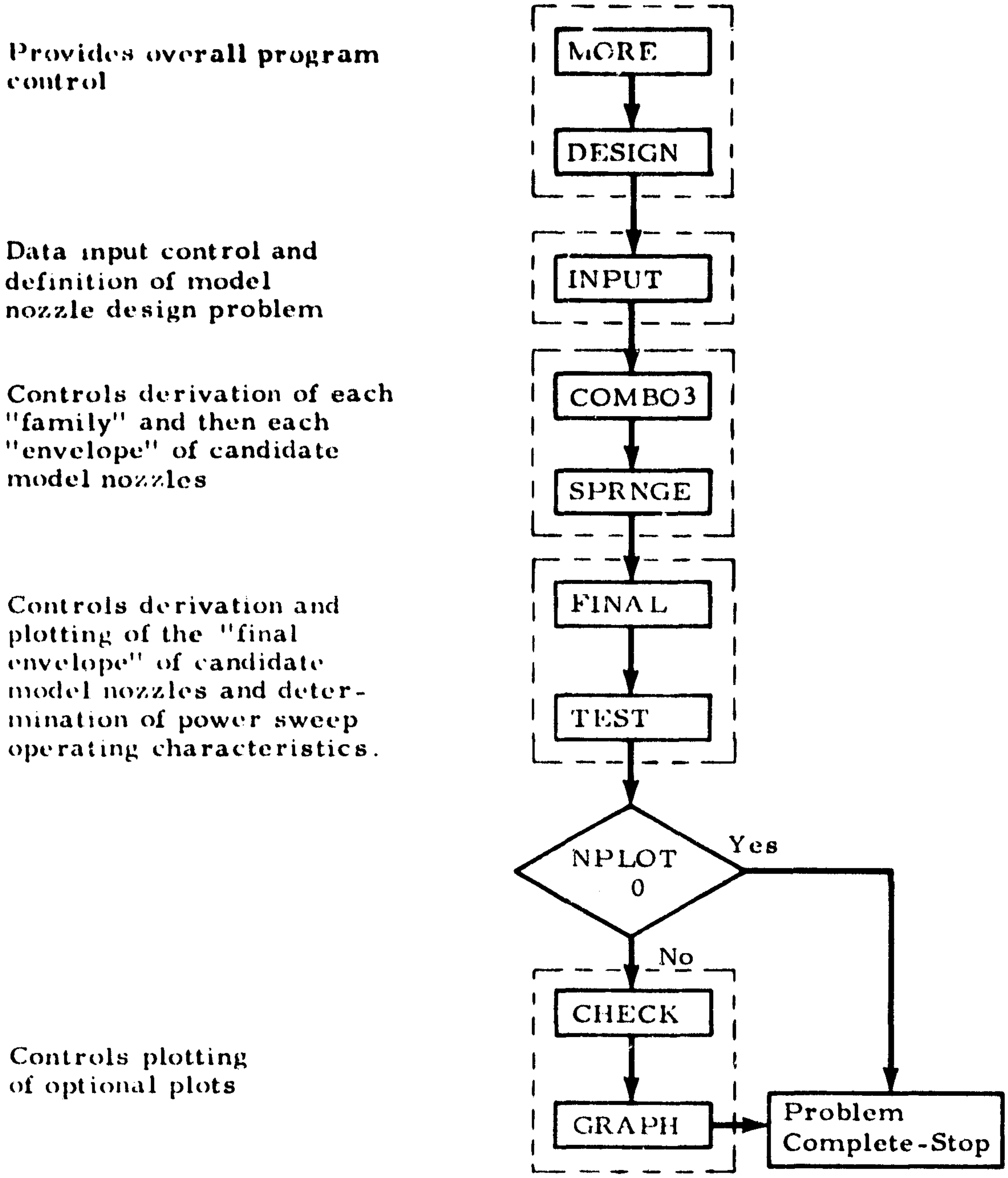


Chart 4-1 - Flow Chart of a Computer Code Used to Design Model Nozzles Which Meet MSFC Base Pressure Similarity Parameter Criteria use of the computer code. This section of the report will make continuous reference to the applicable paragraphs of Sections 2 and 3; this will allow the user to go directly to the paragraphs which will help answer possible questions.

4.1 COMPUTER CODE CAPABILITIES

The computer code described in this section automates the analytical procedures described in Sections 2 and 3 and is used to design an "envelope" of model nozzles (the envelope is defined by model nozzle exit plane Mach number, M_e, and model nozzle exit wall angle, θ_e) that may be used in a specified wind tunnel test program. Each model nozzle in this envelope will: (1) be capable of achieving the desired similarity parameter values required to ensure base pressure matching for all specified sets of flight conditions to be simulated, and (2) meet all the gasdynamic and physical constraints that must be considered during the design of a model nozzle. (See Section 3.3, Step One, for a discussion of these constraints.)

The analytical procedure discussed in Sections 2 and 3 is not limited to Space Shuttle vehicle configuration applications. Consequently, this computer code may be used to design model nozzles to simulate prototype engine conditions of <u>any</u> single body-single nozzle, single body-triple nozzle or triple-body engine system. (See Fig. 3-3 for a definition of these engine systems.)

To ensure that base pressure matching occurs in the data analysis stage of the test program, it is necessary to know the power sweep operating characteristics of the model nozzle prior to testing. The computer code will calculate the power sweep operating characteristics of representative model nozzles that exist in the "final envelope" of model nozzle designs for each of the desired flight conditions to be simulated during the test program. Section 3.3, Step Twenty, lists the power sweep operating characteristics of importance, presents their method of calculation, and shows how they may be used to choose a final model nozzle design that will ensure base pressure matching at all flight conditions to be simulated.

The final model nozzle design chosen is defined by a model nozzle exit plane Mach number, M_e, and a model nozzle exit wall angle, θ_e. The wall contour of the actual model nozzle used in the wind tunnel test is arbitrary and left up to the nozzle designer. Within the scope of the current technology it is felt that a conical nozzle would suffice for all cases.

4.2 USER'S INPUT GUIDE FOR THE MODEL NOZZLE DESIGN COMPUTER CODE

This section outlines in detail the procedures for using the model nozzle design computer code. Each card and its use are explained in Section 4.2.1. The control card set-up for the Univac 1108 Exec 8 is presented in Section 4.2.2.

4.2.1 Computer Code Input Information

The input data are organized into sections determined by their use. An example of the computer code input requirements used to design an "envelope" of model nozzles for possible use in wind tunnel test IA-604 planned for NASA-Ames Research Center 11 x 11 wind tunnel (Ref. 1-1) is presented in Table 4-2. A description of these cards is given below.

Computer Code Input Instructions

Card 1 — Run Control Card — Format 5I5 (Right Adjusted)

Column	Parameter	Value	Description
5	NMACH		Refer to Section 3.3, Steps 2 and 16. Anticipated number of scheduled flight Mach numbers to be simulated during testing. If the range of flight Mach numbers to be simulated is such that no solution exists the upper value on the range of flight Mach numbers will be reduced automatically until a nozzle design solution does exist. The value of NMACH will be adjusted accordingly internal to the computer code (20 max.).
10	NSP		Refer to Section 3.2. Controls the form of the similarity parameter used in each nozzle design analysis. The similarity parameter to be used in the analysis is specified according to the schedule recommended in Table 3-3.
		1	$SP = \frac{M_j \delta_j}{M_e^{0.25} \gamma_j}$ is used in the analysis

Card 1 (Cont'd)

Column	Parameter	Value	Description
10	NSP	2	$SP = \dfrac{M_j \delta_j}{M_e^{0.25} \gamma_j^{0.5}}$ is used in the analysis
		3	$SP = \dfrac{M_j \delta_j}{\gamma_j}$ is used in the analysis
15	NPRINT	0	Refer to Section 3.3, Step 20. There will be no intermediate printout. Only the power sweep operating characteristics of representative model nozzles for each of the flight conditions to be simulated will be printed.
		1	Print intermediate data showing the results of the calculations in Section 3.3, Steps 12 and 14 (Fig. 3-7).
20	NPLOT	0	Refer to Section 3.3, Steps 15-19. There will be no intermediate plots. Only the "final envelope" of model nozzles that may be used in the test program will be plotted. Each model nozzle in this envelope will: (1) ensure base pressure matching for all specified sets of flight conditions to be simulated, and (2) meet all the constraints specified in Section 3.3, Step 1.
		1	Plot intermediate data showing the results of the calculations in Section 3.3, Step 14 (Fig. 3-7).
25	NNOZF	1, 2, 3, 4 or 5	Number of representative model nozzles in Fig. 3-8 that power sweep operating characteristics will be determined for (max. of 5). Example: If NNOZF = 4, power sweep operating characteristics will be determined for Nozzles 1, 2, 3 and 4.

Cards 2 Axes Identification Labels for the "Final Envelope" of Model Nozzles

The following set of cards contains the labels placed on the horizontal and vertical axes when the "final envelope" of model nozzles that may be used in the test program is plotted. Please note that model nozzle exit Mach number and model nozzle lip angle are always plotted on the horizontal and vertical axes, respectively. Cards 2 merely allow the program user to clearly identify the axes labels with the model nozzle design problem being considered. (Refer to Fig.4-1).

Card	Column	Parameter	Description	Format
2.1	1-48	XFINAL	Horizontal axis label	8A6
2.2	1-48	YFINAL	Vertical axis label	8A6

Cards 3 Vertical axis and nozzle design problem identification for optional plots (The following cards are not required if NPLOT = 0).

The following set of cards contain the labels placed on the vertical axis on each of the optional plots and problem identification information. These labels do not change from plot to plot. As in Cards 2, the nozzle lip angle is always plotted on the vertical axis and Card 3.2 merely shows the program user to more clearly identify the axes labels with the model nozzle design problem being considered (Refer to Fig.4-2 and 4-2a).

Card	Column	Parameter	Description	Format
3.1	1-48	TITLE	Nozzle design problem identification label	8A6
3.2	1-36	XLINE	Vertical axis label	6A6

Cards 4, 5 and 6 contain the prototype plume similarity data for the rocket engine that the model nozzle is to simulate. These data are calculated in Section 3.3, Step Four. Table 3-1 presents a sample of the required data (the column labeled SP is not required input). Figure 3-2 presents a pictorial definition of the parameters input on these cards. The values of M_j, δ_j and γ_j

are the plume boundary properties corresponding to each value of P_c/P_b. These properties are determined by means of a numerical integration through a Prandtl-Meyer expansion.

Card 4 - Format E10.5

Column	Parameter	Description
1-10	PXME	M_e prototype exit plane Mach number at nozzle lip.

Card 5 - Format I5 (Right Adjusted)

Column	Parameter	Description
1-5	NPMRAY	Number of plume boundaries for which plume similarity data are given (30 max.)

Cards 6 — Prototype Plume Similarity - Format 4E10.5 Data (each card contains the required similarity data along one plume boundary and is repeated NPMRAY times). Card 6 is input in order of increasing value of PPCOPB.

Column	Parameter	Description
1-10	PPCOPB	P_c/P_b - Prototype pressure ratio where P_c is nozzle chamber pressure and P_b is the pressure along the plume boundary. P_c/P_b may be considered the independent variable, with the remaining parameters on this card determined as a function of P_c/P_b.
11-20	PXMJ	M_j - Prototype plume boundary Mach number corresponding to P_c/P_b.
21-30	PDELJ	δ_j - Prototype plume boundary initial expansion angle corresponding to P_c/P_b.
31-40	PGAMAJ	γ_j - Prototype ratio of specific heats on the plume boundary corresponding to P_c/P_b.

Cards 7 and 8 contain both the program constants and the gasdynamic and physical constraints that must be considered during the design of the model nozzle. The constraints that are input are described as Constraints 3, 4 and 5 in Section 3.3, Step Two. Constraints 1 ($M_e > 1.0$) and 2 ($\theta_e > 0$) of Step 2 are set internal to the computer code and are not input requirements.

Card 7 - Format 7E10.5

Column	Parameter	Description
1-10	PCMAX	$\left.P_c\right)_{max}$ - Refer to Section 3.3, Step 1, Constraints 4 and 5. Maximum model nozzle chamber pressure (psia). This corresponds to the maximum air pressure supply capability imposed by the facility where testing is to be performed. This value serves as an upper limit only. The actual maximum value of P_c is calculated as a function of A^*, T_o and $\left.\dot{m}\right)_{max}$.
11-20	PC	P_c - Refer to Section 3.3, Step 8. This is a specified value of model nozzle chamber pressure (psia). This value is held constant throughout the nozzle design analysis and is usually set at 0.50 * PCMAX.
21-30	PEPBMN	$\left.P_e/P_b\right)_{min}$ - Refer to Section 3.3, Step 1, Constraint 3. Minimum allowable value of P_e/P_b set to ensure that nozzle flow separation does not occur. The value of $\left.P_e/P_b\right)_{min}$ determined experimentally is 0.60.
31-40	PATM	Wind tunnel total pressure (psia).

Note: The nozzle design analysis is performed assuming that the model nozzle will be flowing a constant γ simulant gas during wind tunnel tests. Therefore, the values of GAMAJ (Column 41-50) and GAMAE (Columns 51-60) must be equal and are held constant throughout the nozzle design analysis.

Column	Parameter	Description
41-50	GAMAJ	γ_j - Refer to Fig. 3-2. Model nozzle ratio of specific heats on the plume boundary. For a nozzle flowing air $\gamma_j = 1.40$.

Column	Parameter	Description
51-60	GAMAE	γ_e - Refer to Fig. 3-2. Model nozzle ratio of specific heats at the nozzle exit plane. For a nozzle flowing air $\gamma_e = 1.40$.
61-70	GAMAI	γ_∞ - Refer to Fig. 3-2. Ratio of specific heats of wind tunnel freestream flow. For air $\gamma_\infty = 1.40$.

Card 8 - Format 4E10.5

Column	Parameter	Description
1-10	SCALE	Refer to Section 3.3, Step One, Constraint 5. Ratio of model nozzle exit diameter to prototype nozzle exit diameter. This constraint sets the model nozzle exit diameter and allows a direct calculation of A^* for a given model nozzle M_e.
11-20	PEXITD	Prototype nozzle exit diameter used to define SCALE (in.)
21-30	WMAX	$\dot{m})_{max}$ - Refer to Section 3.3, Step One, Constraint 4. Maximum model nozzle mass flow rate. This corresponds to the maximum air mass flow rate capability imposed by the facility where testing is to be performed (lbm/sec).
31-40	TO	T_o - Refer to Section 3.3, Step 1, Constraint 5. Model nozzle chamber temperature used in the $P_c)_{max}$ calculation (R).

Card 9 Flight Simulation Data and Labels for Optional Plots (the following cards are repeated NMACH times). Cards 9 are input in order of increasing value of XMI.

The following set of cards contain the values of freestream static pressure (P_∞), prototype nozzle chamber pressure (P_c), and predicted base pressure ratio (P_b/P_∞) determined in Step 3 for each flight Mach number to be simulated during testing as established in Step 2. The result will be a set of flight conditions to be simulated during wind tunnel tests similar to that presented in Table 3-2. If NPLOT equals 1, additional labels for the optional plots are also input at this time.

Card 9.1 - Flight Simulation Data - Format 4E10.5

Column	Parameter	Description
1-10	XMI	M_∞ - Refer to Section 3-3, Step 2, and Fig. 3-2. Scheduled flight Mach number to be simulated during the wind tunnel test.
11-20	PBOPI	P_b/P_∞ - Refer to Section 3-3, Step 3. Predicted base pressure ratio to occur at the specified value of XMI in the ascent trajectory.
21-30	PPC	P_c - Refer to Section 3-3, Step 3. Prototype nozzle chamber pressure which occurs at the specified value of XMI in the ascent trajectory (psia).
31-40	PPI	P_∞ - Refer to Section 3-3, Step 3, and Fig. 3-2. Prototype freestream static pressure which occurs at the specified value of XMI is the ascent trajectory (psia).

Card 9.2 - Nozzle Family Identification Label - Format 10A6
(not required if NPLOT equals 0)

Column	Parameter	
1-60	NOZD	Refer to Fig. 4-2 and Section 3-3, Step 11. This label identifies the family of candidate nozzles which have been designed to ensure base pressure matching for the flight conditions that exist at the specified value of XMI on Card 9.1.

Card 9.3 - Horizontal Axis Label - Format 6A6
(not required if NPLOT equals 0)

Column	Parameter	
1-36	HEDRP	Refer to Fig. 4-2a. Horizontal axis label for the specified value of XMI on Card 9.1. Please note that model nozzle exit Mach number is a always plotted on the horizontal axis. Card 9.3 merely allows the program user to more clearly identify the axis label with the model design problem being considered.

Table 4-2

AN EXAMPLE CASE SHOWING THE REQUIRED INPUT FORMAT USED TO DESIGN AN "ENVELOPE" OF MODEL NOZZLES FOR POSSIBLE USE IN WIND TUNNEL TEST IA-604 PLANNED FOR NASA-AMES RESEARCH CENTER 11 x 11 WIND TUNNEL (REF.1-1)

```
Card 1          9    1    1    1    5
Card 2.1    .02 SCALE HPM NOZZLE EXIT MACH NUMBER
Card 2.2    .02 SCALE HPM NOZZLE LIP ANGLE
Card 3.1    .02 SCALE HPM NOZZLE DESIGN ANALYSIS TEST IA-604
Card 3.2    NOZZLE LIP ANGLE
Card 4      2.6599
Card 5         17
            37.64       2.6599     10.490     1.2541
            47.97       2.7864     14.258     1.2685
            61.94       2.9223     18.025     1.2805
            80.99       3.0761     21.793     1.2843
            107.32      3.2393     25.561     1.2887
            144.28      3.4131     29.329     1.2934
            196.94      3.6005     33.096     1.2997
            273.55      3.8026     36.864     1.3062
Card 6      387.20      4.0212     40.632     1.3124
Repeated    559.23      4.2585     44.395     1.3184
NPMRAY      826.99      4.5204     48.167     1.3248
Times       1255.1      4.8153     51.935     1.3326
            1960.9      5.1499     55.703     1.3406
            3167.9      5.5320     59.471     1.3485
            5317.3      5.9676     63.237     1.3559
            9336.8      6.4766     67.006     1.3627
            17281.0     7.0874     70.774     1.3687
Card 7      1500.0      750.0      0.60       14.70      1.40      1.40      1.40
Card 8      .02         149.64     27.0       500.0
Card 9.1    .597        .89        720.0      10.542
Card 9.2    NOZZLE FAMILY DERIVED FOR FLIGHT MACH NO. = 0.597
Card 9.3    NOZZLE EXIT MACH NUMBER    MINF=0.597
            .796        .825       651.4      8.441
            NOZZLE FAMILY DERIVED FOR FLIGHT MACH NO. = 0.796
            NOZZLE EXIT MACH NUMBER    MINF=0.796
            .90         .77        624.5      7.425
            NOZZLE FAMILY DERIVED FOR FLIGHT MACH NO. = 0.90
            NOZZLE EXIT MACH NUMBER    MINF=0.90
            .95         .675       610.2      6.877
            NOZZLE FAMILY DERIVED FOR FLIGHT MACH NO. = 0.95
Repeated    NOZZLE EXIT MACH NUMBER    MINF=0.95
NMACH       1.048       .61        580.0      5.725
Times       NOZZLE FAMILY DERIVED FOR FLIGHT MACH NO. = 1.048
            NOZZLE EXIT MACH NUMBER    MINF=1.048
            1.10        .64        571.3      5.477
            NOZZLE FAMILY DERIVED FOR FLIGHT MACH NO. = 1.10
            NOZZLE EXIT MACH NUMBER    MINF=1.10
            1.148       .65        570.0      4.827
            NOZZLE FAMILY DERIVED FOR FLIGHT MACH NO. = 1.148
            NOZZLE EXIT MACH NUMBER    MINF=1.148
            1.249       .69        576.2      4.105
            NOZZLE FAMILY DERIVED FOR FLIGHT MACH NO. = 1.249
            NOZZLE EXIT MACH NUMBER    MINF=1.249
            1.403       .77        586.0      3.276
            NOZZLE FAMILY DERIVED FOR FLIGHT MACH NO. = 1.403
            NOZZLE EXIT MACH NUMBER    MINF=1.403
```

4.2.2 Control Card Set-Up for Univac 1108 Exec 8

A typical run stream set-up for the Univac 1108 Exec 8 computer is presented in this section. It is presented to acquaint the program user with the magnetic tape assignments and required communications with the computer. The data deck has been described in Section 4.2.1 and an example case presented in Table 4-2.

The program tape referenced on the following page contains a data file designated as HPM. The data in this file are presented in Table 4-2 for the wind tunnel test IA-604 planned for NASA-Ames Research Center 11 x 11 ft wind tunnel (Ref. 1-1). Therefore, if the program user wishes to run a sample case, all that is necessary is to replace the DATA DECK cards with the one card:

∇ADD, P HPM

If the program user desires to add his own new data file to the program tape the following cards must be inserted as indicated by "optional insert" in the runstream.

"Optional Insert"

∇END

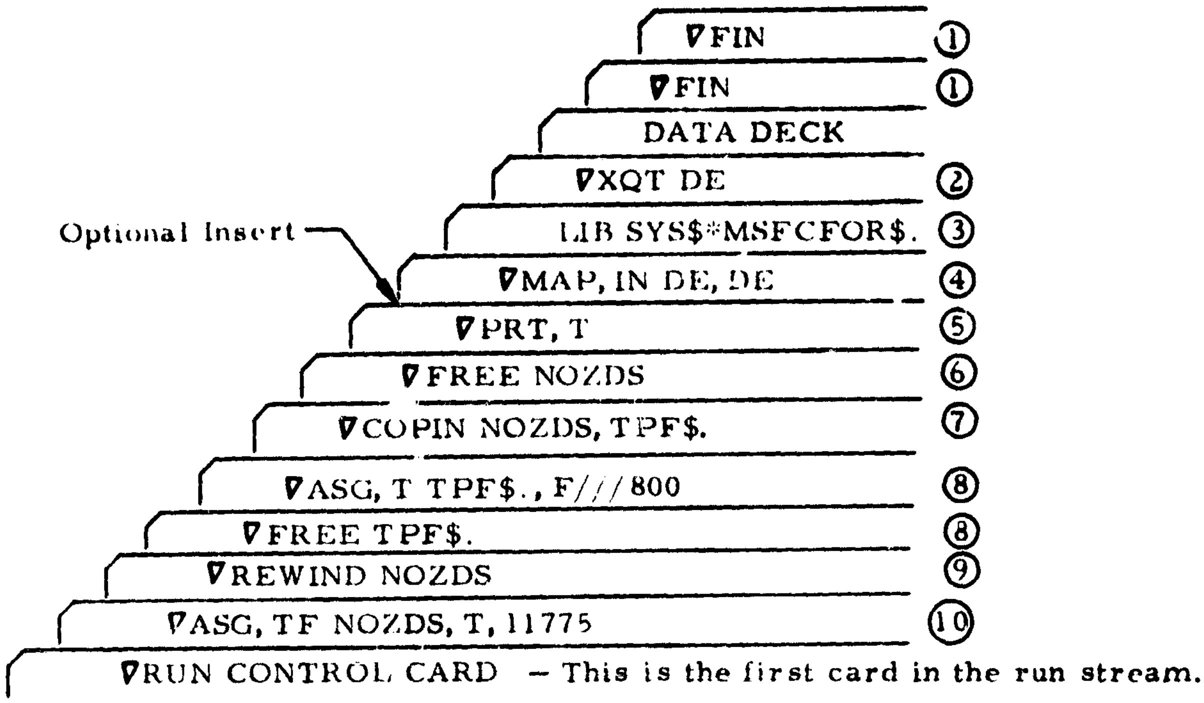
NEW DATA DECK (according to Section 4.2.1)

∇ELT, DIL NEW, NEW

note: NEW is the designation of the new data file.

and the original DATA DECK is replaced with the one card:

∇ADD, P NEW



① The analysis is finished

② Program is executed

③ System subroutines are made available for program use

④ The program is mapped

⑤ A listing of subroutine names in program is printed

⑥ The program tape is removed from tape reader

⑦ Copies the program tape into computer storage

⑧ Assigns sufficient computer storage for the program tape

⑨ Returns the tape to its beginning

⑩ Assigns the program tape

CONTROL CARD SET-UP

Once the new program tape is made containing the two data files, the program user has the option of using either of the two data files. This process can be continued until several data files are available for the program user. The data file chosen will be a function of the nozzle design problem being considered and can be called by replacing the DATA DECK with the one card

∇ADD, P OPTION

where OPTION is the name of the data file chosen.

4.3 OUTPUT FORMAT

This section describes the printed output as well as the plotted output for the computer code. The example output presented is for the model nozzle design analysis performed for the wind tunnel test IA-604 planned for the NASA-Ames Research Center 11 x 11 wind tunnel (Ref. 1-1) and is the result of the input data presented in Table 4-2.

The computer code output is organized so that the initial page contains a description of the model nozzle design problem being considered. The problem description is presented in such a manner that most of the input data are listed. If NPRINT has been set equal to 1, the second and subsequent pages will contain a listing of the intermediate data showing the results of the calculations performed in Section 3.3, Steps 12 and 14 (Fig. 3-7). A typical printout for each of the two steps are presented to demonstrate the output for each step. The final pages of the computer code output contain the final "envelope" of model nozzle designs, and corresponding power sweep operating characteristics of representative model nozzles for each of the desired flight conditions to be simulated in the wind tunnel test. Numbered flags on the example printout sheets correspond to the numbered comments in the following description of the printout. The calculations are performed in English units.

GROUP 1 - MODEL NOZZLE DESIGN PROBLEM DESCRIPTION

1. This corresponds to the value of NMACH input on Card 1, and is equal to the anticipated number of scheduled flight Mach numbers to be simulated during testing.

2. Identifies the form of the similarity parameter used in the nozzle design analysis.

Items 3 through 7 identify the prototype plume similarity data for the rocket engine that the model nozzle is to simulate. Figure 3-2 presents a pictorial definition of these parameters. The values of M_j, δ_j and γ_j are the plume boundary properties corresponding to each value of P_c/P_b. These properties are determined by means of a numerical integration through a Prandtl-Meyer expansion.

3. PC/PB: Prototype pressure ratio along the plume boundary (P_c/P_b) where P_c is the nozzle chamber pressure and P_b is the vehicle base pressure.

4. MJET: Prototype plume boundary Mach number (M_j).

5. DELJ: Prototype plume boundary initial expansion angle (δ_j).

6. GAMAJ: Prototype ratio of specific heats on the plume boundary (γ_j).

7. SP: This is the value of similarity parameter corresponding to each value of P_c/P_b that results when using the values of A and B specified in item 2 .

Items 8 through 12 identify the flight conditions that the model nozzle will be designed to simulate during the wind tunnel tests.

8. MINF: Scheduled flight Mach number to be simulated during the wind tunnel test (M_∞). The values of P_b/P_∞, P_c and P_∞ are those flight conditions corresponding to each value of M_∞ in the ascent trajectory.

9. PB/PI: Predicted value of base pressure ratio (P_b/P_∞).

10. PC: Prototype nozzle chamber pressure (P_c, psia).

11. PI: Prototype freestream static pressure (P_∞, psia).

12. SPNOM: Value of similarity parameter required to ensure base pressure matching corresponding to each value of M_∞.

GROUP 2 - OPTIONAL NOZZLE "FAMILY" DATA (not printed if NPRINT = 0)

Items 13 through 23 define a "family" of candidate model nozzles which have been designed to ensure base pressure matching for "one" specified set of flight conditions. Each candidate nozzle in this family is defined by θ_e and M_e and is designed based on a constant value of P_c (usually set equal to 50% of the maximum available air pressure supply). The nozzle flow separation constraint of Section 3.3, Step 1, is the only constraint considered at this point in the analysis.

One "family" of candidate model nozzles is presented for each scheduled flight Mach number to be simulated during testing.

13. WIND TUNNEL PI: Wind tunnel free stream static pressure (psia). This is not necessarily equal to the prototype freestream static pressure.

14. LIP ANGLE: Model nozzle exit plane wall angle (θ_e, deg)

15. MEXIT: Model nozzle exit plane Mach number (M_e, dimensionless)

16. PC/PI: Ratio of model nozzle chamber pressure to wind tunnel static pressure. (This ratio is constant for a specified set of flight conditions.)

17. PE/PB: Ratio of model nozzle exit plane static pressure to vehicle base region pressure. Nozzles with a P_e/P_b less than 0.60 will experience nozzle flow separation and are not considered further in the analysis.

18 PC/PB: Ratio of model nozzle chamber pressure to vehicle base region pressure. (This ratio is constant for a specified set of flight conditions.)

19 PC/PE: Ratio of model nozzle chamber pressure to exit plane static pressure.

20 MJET: Plume boundary Mach number determined as a function of PC/PB (M_j, dimensionless).

21 AE/A*: Model nozzle area ratio (A_e/A^*, dimensionless).

22 DELJ: Initial plume expansion angle measured from the model nozzle centerline (δ_j, deg).

23 Lowest value of exit plane Mach number in the iterative solution that results in a PE/PB less than 0.60. Model nozzles with $M_e \geq$ 23 are not considered further in the analysis.

GROUP 3 - OPTIONAL NOZZLE "ENVELOPE" DATA (not printed if NPRINT = 0; not plotted if NPLOT = 0).

The data presented in Group 3 define an "envelope" of candidate model nozzles that will: (1) ensure base pressure matching for "one" specified set of flight conditions to be simulated, and (2) meet all of the constraints that must be considered in the nozzle design study for that set of flight conditions. Each "family" of nozzles presented in the Group 3 data are those nozzles in each "family" of the Group 2 data that satisfy the model nozzle design constraint

$$SP_{minimum} - 5.0 \leq SP_{nominal} \leq SP_{maximum} - 5.0$$

where $SP_{nominal}$ = SPNOM corresponding to each flight Mach number, $SP_{minimum}$ corresponds to that value of P_c that will result in flow separation in the model nozzle, and $SP_{maximum}$ corresponds to either the maximum auxiliary air pressure supply or maximum mass flow rate capability of the test facility.

One "envelope" of candidate model nozzles is presented for each scheduled flight Mach number to be simulated during testing.

Figure 4-2 is a graphical representation of the Group 3 data. These plots are made automatically if NPLOT = 1.

24 SPMIN: Minimum obtainable value of similarity parameter for the given model nozzle and specified flight conditions. Corresponds to that value of P_c (PCMIN) that will result in flow separation in the model nozzle.

25 SPMAX: Maximum obtainable value of similarity parameter for the given model nozzle and specified flight conditions. Corresponds to PCMAX.

26 PCMAX: Maximum allowable value of model nozzle chamber pressure. PCMAX is set equal to the lesser of either the maximum auxiliary air pressure supply or the chamber pressure corresponding to the maximum mass flow rate capability of the test facility.

GROUP 4 - FINAL MODEL NOZZLE ENVELOPE DEFINITION AND RANGE OF APPLICATION

Items 27 and 28 are the coordinates which define the "final envelope" of model nozzles that may be used in the test program. Each model nozzle in this envelope will: (1) ensure base pressure matching for "all" specified sets of flight conditions to be simulated, and (2) meet all of the constraints that must be considered in the nozzle design study. Figure 4-1 presents a computer code plot of the final envelope of model nozzles that may be used in wind tunnel test IA-604. A plot of the final envelope of model nozzles is made automatically independent of the value of NPLOT.

29 Schedule of flight Mach numbers that may be simulated with the "final envelope" of model nozzles defined above. The power sweep operating characteristics will be presented in the Group 5 data for each of these scheduled flight Mach numbers.

GROUP 5 - POWER SWEEP OPERATING CHARACTERISTICS

Items 30 through 35 12 through 15, 8, 24 and 25 define the power sweep operating characteristics of five representative model nozzles that exist in the "final envelope" of Fig. 4-1 for each of the scheduled flight Mach numbers to be simulated.

30 NOZZLE: Nozzle identification. See Fig. 3-8 for the relative location of each nozzle in the "final envelope."

15 MEXIT: Model nozzle exit plane Mach number (M_e, dimensionless).

14 LIP ANGLE: Model nozzle exit plane wall angle (θ_e, deg).

8 MINF: Scheduled flight Mach number to be simulated during the wind tunnel test (M_∞).

24 SPMIN: Minimum obtainable value of similarity parameter for the given model nozzle and specified flight conditions.

31 PCMIN: Value of model nozzle chamber pressure corresponding to SPMIN (psia).

12 SPNOM: Value of similarity parameter required to ensure base pressure matching for the given model nozzle and specified flight conditions.

32 PCNOM: Value of model nozzle chamber pressure corresponding to SPNOM (psia).

25 SPMAX: Maximum obtainable value of similarity parameter for the given model nozzle and specified flight conditions.

33 PCMAX: Value of model nozzle chamber pressure corresponding to SPMAX (psia).

(13) **WIND TUNNEL PINF:** Wind tunnel freestream static pressure (psia).

(34) **DSTAR:** Model nozzle throat diameter (in.)

(35) **DEXIT:** Model nozzle exit diameter (in.).

Example Computer Code Printout and Plots for the Model Nozzle Design Analysis Performed for the Wind Tunnel Test IA-604 Planned for the NASA/Ames Research Center 11 x 11 Wind Tunnel (Ref. 1-1)

1

BEGIN A NEW NOZZLE DESIGN STUDY. IT IS ANTICIPATED THAT THE NOZZLE WILL BE DESIGNED FOR 9 FREE STREAM MACH NUMBERS.

THE SIMILARITY PARAMETER USED IN THIS NOZZLE DESIGN STUDY IS DEFINED BY THE RELATIONSHIP
SP = MJET*DELJ/(MEXIT**A*GAMAJ**B). WHERE A = .25000+00 AND B = .10000+01

2

Group 1

THE NOZZLE WILL BE DESIGNED BASED UPON THE
FOLLOWING PROTOTYPE PLUME SIMILARITY DATA

3	4	5	6	7
FC/PB	MJET	DELJ	GAMAJ	SP
.37640+02	.25599+01	.10490+02	.12541+01	.17422+02
.47970+02	.27864+01	.14258+02	.12685+01	.24524+02
.61940+02	.29223+01	.18025+02	.12805+01	.32211+02
.80990+02	.30761+01	.21793+02	.12843+01	.40873+02
.10732+03	.32393+01	.25561+02	.12887+01	.50311+02
.14428+03	.34131+01	.29329+02	.12934+01	.60603+02
.19694+03	.36005+01	.33096+02	.12997+01	.71792+02
.27355+03	.38026+01	.36864+02	.13062+01	.84034+02
.38720+03	.40212+01	.40632+02	.13124+01	.97486+02
.55923+03	.42585+01	.44395+02	.13184+01	.11229+03
.82699+03	.45204+01	.48167+02	.13246+01	.12869+03
.12551+04	.48153+01	.51935+02	.13326+01	.14695+03
.19609+04	.51499+01	.55703+02	.13406+01	.16756+03
.31679+04	.55320+01	.59471+02	.13485+01	.19104+03
.53173+04	.59676+01	.63237+02	.13555+01	.217[illegible]3+03
.93368+04	.64766+01	.67006+02	.13627+01	.24937+03
.17281+05	.70874+01	.70774+02	.13687+01	.28697+03

THE NOZZLE WILL BE DESIGNED TO SIMULATE
THE FOLLOWING FLIGHT CONDITIONS

8	9	10	11	12
MINF	PB/PI	PC	PI	SPNOM
.59700+00	.89000+00	.72000+03	.10542+02	.39132+02
.79600+00	.82500+00	.65140+03	.84410+01	.45703+02
.90000+00	.77000+00	.62450+03	.74250+01	.50925+02
.95000+00	.67500+00	.61020+03	.68770+01	.57365+02
.10480+01	.61000+00	.56000+03	.57250+01	.65664+02
.11000+01	.64000+00	.57130+03	.54770+01	.64987+02
.11460+01	.65000+00	.57000+03	.48270+01	.68890+02
.12490+01	.69000+00	.57620+03	.41050+01	.73000+02
.14030+01	.77000+00	.58600+03	.32760+01	.77946+02

8 13 9 12

THE FOLLOWING IS A NOZZLE FAMILY DERIVED TO SIMULATE THE FLIGHT CONDITIONS
MINF = .59700+00 WIND TUNNEL PI = .11552+02 PB/PI = .89000+00 SPNOM = .39132+02

Group 2

14	15	16	17	18	19	20	21	22
LIP ANGLE	MEXIT	PC/PI	PE/PB	PC/PE	PC/PE	MJET	AE/A*	DELJ
-.21911+02	.17085+01	.64924+02	.14590+02	.72949+02	.50000+01	.34687+01	.13457+01	.18057+02
-.82729+01	.21572+01	.64924+02	.72949+01	.72949+02	.10000+02	.34687+01	.19307+01	.19141+02
-.11935+01	.24164+01	.64924+02	.48632+01	.72949+02	.15000+02	.34687+01	.24398+01	.19692+02
.34780+01	.26015+01	.64924+02	.36474+01	.72949+02	.20000+02	.34687+01	.29000+01	.20058+02
.69197+01	.27463+01	.64924+02	.29179+01	.72949+02	.25000+02	.34687+01	.33261+01	.20332+02
.96221+01	.28659+01	.64924+02	.24316+01	.72949+02	.30000+02	.34687+01	.37265+01	.20550+02
.11835+02	.29678+01	.64924+02	.20842+01	.72949+02	.35000+02	.34687+01	.41068+01	.20730+02
.13700+02	.30570+01	.64924+02	.18237+01	.72949+02	.40000+02	.34687+01	.44705+01	.20884+02
.15307+02	.31362+01	.64924+02	.16211+01	.72949+02	.45000+02	.34687+01	.48204+01	.21018+02
.16716+02	.32077+01	.64924+02	.14590+01	.72949+02	.50000+02	.34687+01	.51585+01	.21137+02
.17968+02	.32728+01	.64924+02	.13263+01	.72949+02	.55000+02	.34687+01	.54862+01	.21243+02
.19092+02	.33327+01	.64924+02	.12158+01	.72949+02	.60000+02	.34687+01	.58048+01	.21340+02
.20111+02	.33881+01	.64924+02	.11223+01	.72949+02	.65000+02	.34687+01	.61153+01	.21428+02
.21041+02	.34398+01	.64924+02	.10421+01	.72949+02	.70000+02	.34687+01	.64185+01	.21509+02
.21897+02	.34862+01	.64924+02	.97265+00	.72949+02	.75000+02	.34687+01	.67151+01	.21584+02
.22688+02	.35337+01	.64924+02	.91186+00	.72949+02	.80000+02	.34687+01	.70057+01	.21654+02
.23357+02	.36930+01	.64924+02	.72949+00	.72949+02	.10000+03	.34687+01	.81165+01	.21894+02
.27465+02	.38255+01	.64924+02	.60790+00	.72949+02	.12000+03	.34687+01	.91605+01	.22088+02
.29198+02	.39394+01	.64924+02	.52106+00	.72949+02	.14000+03	.34687+01	.10152+02	.22251+02

FLOW SEPARATION OCCURS FOR MEXIT GREATER THAN .39394+01 WHEN MINF = .59700+00

23

8 13 9 12

OF THE PREVIOUSLY DERIVED NOZZLE FAMILIES, THE FOLLOWING NOZZLES MAY BE USED TO SIMULATE THE FLIGHT CONDITIONS
MINF : .59700+01 WIND TUNNEL PI : .11552+02 PB/PI : .89000+00 SPNOM : .99132+02

15 MEXIT	14 LIP ANGLE	24 SPMIN	25 SPMAX	26 PCMAX		
.33327+01	.19092+02	.20224+02	.45622+02	.93659+03	Family 1	Group 3
.33881+01	.20111+02	.22283+02	.47157+02	.98669+03		
.34398+01	.21041+02	.24210+02	.48588+02	.10356+04		
.34882+01	.21897+02	.26020+02	.49921+02	.10835+04		
.35337+01	.22688+02	.27728+02	.51187+02	.11303+04		
.36930+01	.25357+02	.33737+02	.55592+02	.13096+04		
.33327+01	.18865+02	.19550+02	.44804+02	.93659+03	Family 2	
.33881+01	.19694+02	.21616+02	.46357+02	.98669+03		
.34398+01	.20634+02	.23549+02	.47791+02	.10356+04		
.34882+01	.21497+02	.25365+02	.49148+02	.10835+04		
.35337+01	.22296+02	.27079+02	.50420+02	.11303+04		
.36930+01	.24992+02	.33110+02	.54865+02	.13096+04		
.33327+01	.18600+02	.19448+02	.44675+02	.93659+03	Family 3	
.33881+01	.19636+02	.21524+02	.46242+02	.98669+03		
.34398+01	.20583+02	.23467+02	.47698+02	.10356+04		
.34882+01	.21453+02	.25292+02	.49062+02	.10835+04		
.35337+01	.22258+02	.27015+02	.50344+02	.11303+04		
.36930+01	.24974+02	.33079+02	.54829+02	.13096+04		
.33327+01	.18895+02	.19914+02	.45245+02	.93659+03	Family 4	
.33881+01	.19941+02	.22012+02	.46830+02	.98669+03		
.34398+01	.20896+02	.23974+02	.48305+02	.10356+04		
.34882+01	.21774+02	.25818+02	.49688+02	.10835+04		
.35337+01	.22586+02	.27559+02	.50987+02	.11303+04		
.36930+01	.25327+02	.33688+02	.55533+02	.13096+04		
.32728+01	.18346+02	.18598+02	.44684+02	.88518+03	Family 5	
.33327+01	.19511+02	.20886+02	.46476+02	.93659+03		
.33881+01	.20568+02	.23015+02	.48039+02	.98669+03		
.34398+01	.21533+02	.25007+02	.49542+02	.10356+04		
.34882+01	.22421+02	.26879+02	.50950+02	.10835+04		
.35337+01	.23242+02	.28666+02	.52273+02	.11303+04		
.33327+01	.18959+02	.20014+02	.45367+02	.93659+03	Family 6	
.33881+01	.20014+02	.22129+02	.46971+02	.98669+03		
.34398+01	.20978+02	.24107+02	.48465+02	.10356+04		
.34882+01	.21864+02	.25967+02	.49864+02	.10835+04		
.35337+01	.22684+02	.27721+02	.51180+02	.11303+04		
.36930+01	.25452+02	.33900+02	.55781+02	.13096+04		
.32728+01	.18899+02	.19458+02	.45737+02	.88518+03	Family 7	
.33327+01	.20069+02	.21767+02	.47495+02	.93659+03		
.33881+01	.21131+02	.23916+02	.49124+02	.98669+03		
.34398+01	.22100+02	.25926+02	.50642+02	.10356+04		
.34882+01	.22992+02	.27816+02	.52063+02	.10835+04		
.35337+01	.23817+02	.29598+02	.53400+02	.11303+04		
.32077+01	.18339+02	.16099+02	.45230+02	.83231+03	Family 8	
.32728+01	.19649+02	.20625+02	.47166+02	.88518+03		
.33327+01	.20826+02	.22962+02	.48947+02	.93659+03		
.33881+01	.21894+02	.25137+02	.50596+02	.98669+03		
.34398+01	.22869+02	.27172+02	.52133+02	.10356+04		
.34882+01	.23766+02	.29084+02	.53572+02	.10835+04		
.35337+01	.24596+02	.30888+02	.54925+02	.11303+04		
.31362+01	.17071+02	.16256+02	.44246+02	.77776+03	Family 9	
.32077+01	.18456+02	.19039+02	.46393+02	.83231+03		
.32728+01	.20272+02	.21594+02	.48352+02	.88518+03		
.33327+01	.21456+02	.23957+02	.50154+02	.93659+03		
.33881+01	.22530+02	.26156+02	.51824+02	.98669+03		
.34398+01	.23512+02	.28213+02	.53375+02	.10356+04		
.34882+01	.24414+02	.30146+02	.54836+02	.10835+04		
.35337+01	.25249+02	.31970+02	.56206+02	.11303+04		

THE FINAL ENVELOPE OF MODEL NOZZLES THAT MAY BE USED IN THE TEST PROGRAM WHICH MEET THE SIMILARITY PARAMETER CRITERIA, MASS FLOW AND FLOW SEPARATION RESTRICTIONS ARE DEFINED BY THE COORDINATES

(27) NOZZLE EXIT MACH NUMBER	(28) NOZZLE LIP ANGLE (DEG)
.34882+01	.21453+02
.34882+01	.24414+02
.35337+01	.25249+02
.35337+01	.22258+02

(29) THE FLIGHT MACH NUMBERS THAT MAY BE SIMULATED WITH THIS ENVELOPE OF NOZZLES ARE
FREE STREAM MACH NUMBERS = .59700+00 .79600+00 .90000+00 .95000+00 .10480+01 .11000+01 .11480+01 .12490+01 .14030+01

POWER SWEEP OPERATING CHARACTERISTICS FOR EACH OF THE DESIRED FLIGHT CONDITIONS TO BE SIMULATED IN WIND TUNNEL TESTS IS PRESENTED BELOW FOR REPRESENTATIVE NOZZLES THAT EXIST IN THE FINAL ENVELOPE DEFINED ABOVE.

Group 4

(30) NOZZLE	(15) MEXIT	(14) LIP ANGLE	(8) MINF	(31) PCMIN	(24) SPMIN	(32) PCNOM	(12) SPNOM	(33) PCMAX	(25) SPMAX	(13) WIND TUNNEL MINF	(34) CSTAR	(35) DEXIT
1	.35109+01	.23344+02	.59700+00	.47785+03	.28603+02	.70229+03	.39132+02	.11067+04	.52609+02	.11552+02	.11427+01	.29928+01
1	.35109+01	.23344+02	.79600+00	.37124+03	.28603+02	.68425+03	.45703+02	.11067+04	.60545+02	.96818+01	.11427+01	.29928+01
1	.35109+01	.23344+02	.90000+00	.31105+03	.28603+02	.68234+03	.50925+02	.11067+04	.66306+02	.86915+01	.11427+01	.29928+01
1	.35109+01	.23344+02	.95000+00	.25801+03	.28603+02	.69611+03	.57365+02	.11067+04	.72576+02	.82241+01	.11427+01	.29928+01
1	.35109+01	.23344+02	.10480+01	.20800+03	.28603+02	.72598+03	.65664+02	.11067+04	.80037+02	.73364+01	.11427+01	.29928+01
1	.35109+01	.23344+02	.11000+01	.20479+03	.28603+02	.70041+03	.64987+02	.11067+04	.80584+02	.68848+01	.11427+01	.29928+01
1	.35109+01	.23344+02	.11480+01	.19582+03	.28603+02	.75351+03	.68890+02	.11067+04	.82170+02	.64820+01	.11427+01	.29928+01
1	.35109+01	.23344+02	.12490+01	.18224+03	.28603+02	.79198+03	.73000+02	.11067+04	.84740+02	.56826+01	.11427+01	.29928+01
1	.35109+01	.23344+02	.14030+01	.16462+03	.28603+02	.82562+03	.77946+02	.11067+04	.86423+02	.45999+01	.11427+01	.29928+01
2	.35109+01	.24832+02	.59700+00	.47785+03	.31055+02	.63978+03	.39132+02	.11067+04	.55518+02	.11552+02	.11427+01	.29928+01
2	.35109+01	.24832+02	.79600+00	.37124+03	.31055+02	.62363+03	.45703+02	.11067+04	.63597+02	.96818+01	.11427+01	.29928+01
2	.35109+01	.24832+02	.90000+00	.31105+0	.31055+02	.62135+03	.50925+02	.11067+04	.69462+02	.86915+01	.11427+01	.29928+01
2	.35109+01	.24832+02	.95000+00	.25801+03	.31055+02	.63401+03	.57365+02	.11067+04	.75843+02	.82241+01	.11427+01	.29928+01
2	.35109+01	.24832+02	.10480+01	.20800+03	.31055+02	.66256+03	.65664+02	.11067+04	.83434+02	.73364+01	.11427+01	.29928+01
2	.35109+01	.24832+02	.11000+01	.20479+03	.31055+02	.63590+03	.64987+02	.11067+04	.83990+02	.68848+01	.11427+01	.29928+01
2	.35109+01	.24832+02	.11480+01	.19562+03	.31055+02	.68514+03	.68890+02	.11067+04	.85604+02	.64820+01	.11427+01	.29928+01
2	.35109+01	.24832+02	.12490+01	.18224+03	.31055+02	.71999+03	.73000+02	.11067+04	.88218+02	.56826+01	.11427+01	.29928+01
2	.35109+01	.24832+02	.14030+01	.16462+03	.31055+02	.75023+03	.77946+02	.11867+04	.91965+02	.45999+01	.11427+01	.29928+01

Group 5 (Continued)

Group 5 (Continued)

Group 5

30	15	14	8	31	24	32	12	33	25	13	34	35
3	.35109+01	.21856+02	.59700+00	.47785+03	.26150+02	.77182+03	.39132+02	.11067+04	.49700+02	.11552+02	.11427+01	.29920+01
3	.35109+01	.21856+02	.79600+00	.37124+03	.26150+02	.75233+03	.45703+02	.11067+04	.57492+02	.96818+01	.11427+01	.29920+01
3	.35109+01	.21856+02	.90000+00	.31105+03	.26150+02	.75034+03	.50925+02	.11067+04	.63150+02	.86915+01	.11427+01	.29920+01
3	.35109+01	.21856+02	.95000+00	.25801+03	.26150+02	.76653+03	.57365+02	.11067+04	.69309+02	.82241-01	.11427+01	.29920+01
3	.35109+01	.21856+02	.10480+01	.20800+03	.26150+02	.79976+03	.65664+02	.11067+04	.76640+02	.73364+01	.11427+01	.29920+01
3	.35109+01	.21856+02	.11000+01	.20479+03	.26150+02	.77137+03	.64987+02	.11067+04	.77177+02	.68848+01	.11427+01	.29920+01
3	.35109+01	.21856+02	.11480+01	.19582+03	.26150+02	.82997+03	.68890+02	.11067+04	.78736+02	.64820+01	.11427+01	.29920+01
3	.35109+01	.21856+02	.12490+01	.18224+03	.26150+02	.87252+03	.73000+02	.11067+04	.81261+02	.56826+01	.11427+01	.29920+01
3	.35109+01	.21856+02	.14030+01	.16462+03	.26150+02	.91003+03	.77946+02	.11067+04	.84881+02	.45999+01	.11427+01	.29920+01
4	.34882+01	.22934+02	.59700+00	.46265+03	.27719+02	.70257+03	.39132+02	.10835+04	.51949+02	.11552+02	.11549+01	.29920+01
4	.34882+01	.22934+02	.79600+00	.35944+03	.27719+02	.68479+03	.45703+02	.10835+04	.59865+02	.96818+01	.11549+01	.29920+01
4	.34882+01	.22934+02	.90000+00	.30116+03	.27719+02	.68249+03	.50925+02	.10835+04	.65612+02	.86915+01	.11549+01	.29920+01
4	.34882+01	.22934+02	.95000+00	.24981+03	.27719+02	.69643+03	.57365+02	.10835+04	.71868+02	.82241+01	.11549+01	.29920+01
4	.34882+01	.22934+02	.10460+01	.20138+03	.27719+02	.72586+03	.65664+02	.10835+04	.79312+02	.73364+01	.11549+01	.29920+01
4	.34882+01	.22934+02	.11000+01	.19828+03	.27719+02	.69997+03	.64987+02	.10835+04	.79858+02	.69848+01	.11549+01	.29920+01
4	.34882+01	.22934+02	.11480+01	.18960+03	.27719+02	.75308+03	.68897+02	.10835+04	.81440+02	.64820+01	.11549+01	.29920+01
4	.34882+01	.22934+02	.12490+01	.17645+03	.27719+02	.79149+03	.73030+02	.10835+04	.84004+02	.56826+01	.11549+01	.29920+01
4	.34882+01	.22934+02	.14030+01	.15539+03	.27719+02	.82489+03	.77946+02	.10835+04	.87679+02	.45999+01	.11549+01	.29920+01
5	.35337+01	.23754+02	.59700+00	.49350+03	.29493+02	.70157+03	.39132+02	.11303+04	.53275+02	.11552+02	.11307+01	.29920+01
5	.35337+01	.23754+02	.79600+00	.38340+03	.29493+02	.68354+03	.45703+02	.11303+04	.61231+02	.96818+01	.11307+01	.29920+01
5	.35337+01	.23754+02	.90000+00	.32124+03	.29493+02	.68179+03	.50925+02	.11303+04	.67006+02	.86915+01	.11307+01	.29920+01
5	.35337+01	.23754+02	.95000+00	.26646+03	.29493+02	.69623+03	.57365+02	.11303+04	.73292+02	.82241+01	.11307+01	.29920+01
5	.35337+01	.23754+02	.10480+01	.21481+03	.29493+02	.72620+03	.65664+02	.11303+04	.80769+02	.73364+01	.11307+01	.29920+01
5	.35337+01	.23754+02	.11000+01	.21150+03	.29493+02	.70045+03	.64987+02	.11303+04	.81318+02	.68848+01	.11307+01	.29920+01
5	.35337+01	.23754+02	.11480+01	.20224+03	.29493+02	.75354+03	.68890+02	.11303+04	.82908+02	.64620+01	.11307+01	.29920+01
5	.35337+01	.23754+02	.12490+01	.18821+03	.29493+02	.79203+03	.73000+02	.11303+04	.85483+02	.56826+01	.11307+01	.29920+01
5	.35337+01	.23754+02	.14030+01	.17001+03	.29493+02	.82592+03	.77946+02	.11303+04	.89174+02	.45999+01	.11307+01	.29920+01

FINAL ENVELOPE OF MODEL NOZZLES THAT MAY BE USED IN THE TEST PROGRAM WHICH MEET THE SIMILARITY PARAMETER CRITERIA, MASS FLOW AND FLOW SEPARATION RESTRICTIONS IS PLOTTED BELOW. THE SIMILARITY PARAMETER USED IN THE NOZZLE DESIGN STUDY IS DEFINED BY THE RELATIONSHIP SP=MJET*DELJ/(MEXIT**A*GAMAJ**B). WHERE A= .250 AND B= 1.000 . THE MODEL NOZZLES REPRESENTED BELOW MAY BE USED TO SIMULATE THE FLIGHT CONDITIONS THAT EXIST FOR ALL FREE STREAM MACH NUMBERS TO BE TESTED.

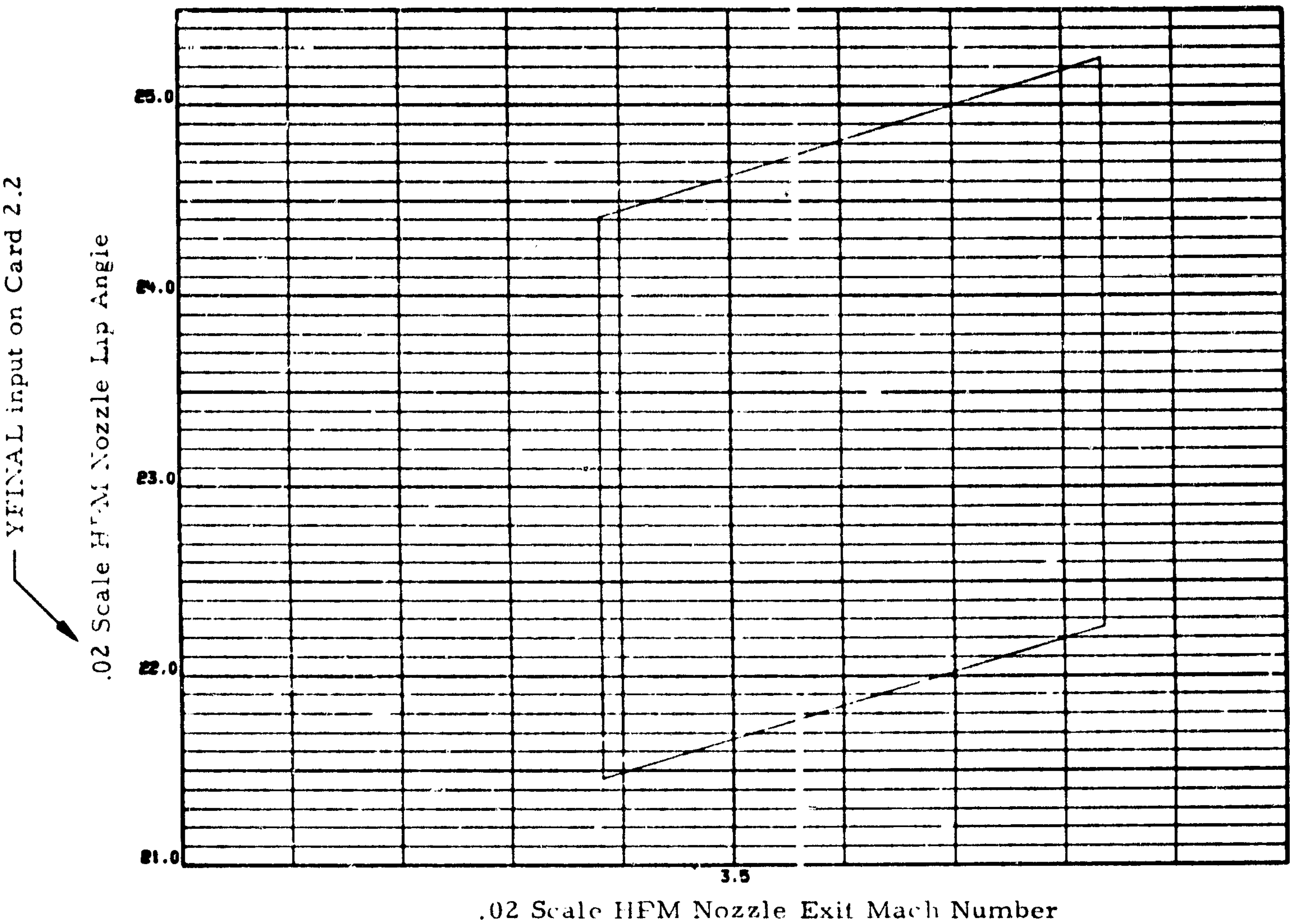


Fig. 4-1

TITLE input on Card 3.1

JOB NO 1HED32N10382 PAGE 1

.02 SCALE HPM NOZZLE DESIGN ANALYSIS TEST IA-604

SYMBOL	NOZZLE FAMILY IDENTIFICATION
□	NOZZLE FAMILY DERIVED FOR FLIGHT MACH NO. = 0.597
△	NOZZLE FAMILY DERIVED FOR FLIGHT MACH NO. = 0.796
○	NOZZLE FAMILY DERIVED FOR FLIGHT MACH NO. = 0.90
◇	NOZZLE FAMILY DERIVED FOR FLIGHT MACH NO. = 0.95
⌂	NOZZLE FAMILY DERIVED FOR FLIGHT MACH NO. = 1.048
◺	NOZZLE FAMILY DERIVED FOR FLIGHT MACH NO. = 1.10
✱	NOZZLE FAMILY DERIVED FOR FLIGHT MACH NO. = 1.148
▽	NOZZLE FAMILY DERIVED FOR FLIGHT MACH NO. = 1.249
◇	NOZZLE FAMILY DERIVED FOR FLIGHT MACH NO. = 1.403

NOZD Input on Card 9.2 for Each Card 9.1 if NPLOT Equals 1

Fig. 4-2

JOB NO 1HED32410382 PAGE 2

THE SYMBOLS PLOTTED BELOW REPRESENT MODEL NOZZLES THAT MAY BE USED TO SIMULATE THE FLIGHT CONDITIONS THAT EXIST FOR A FREE STREAM MACH NUMBER= .597

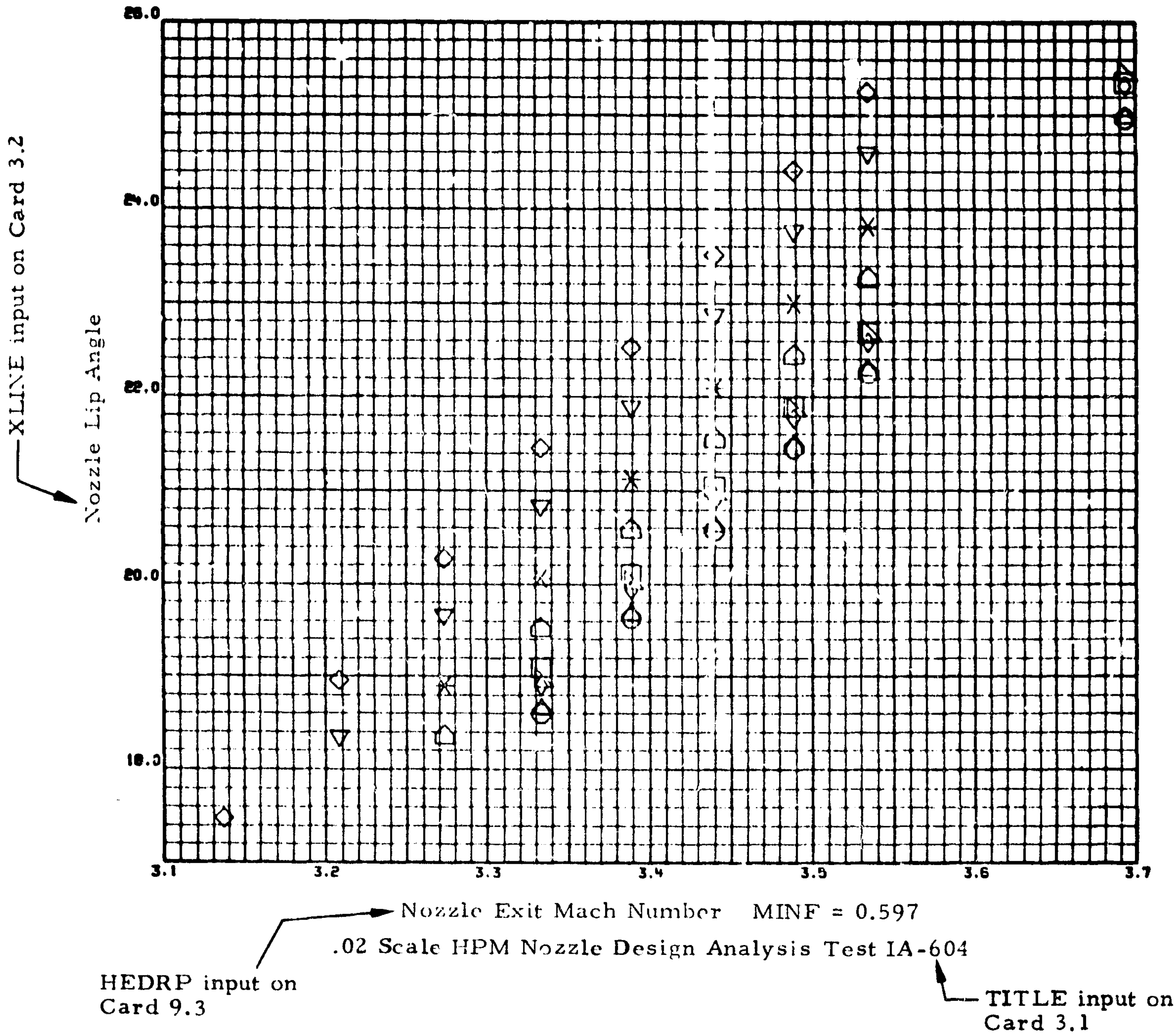
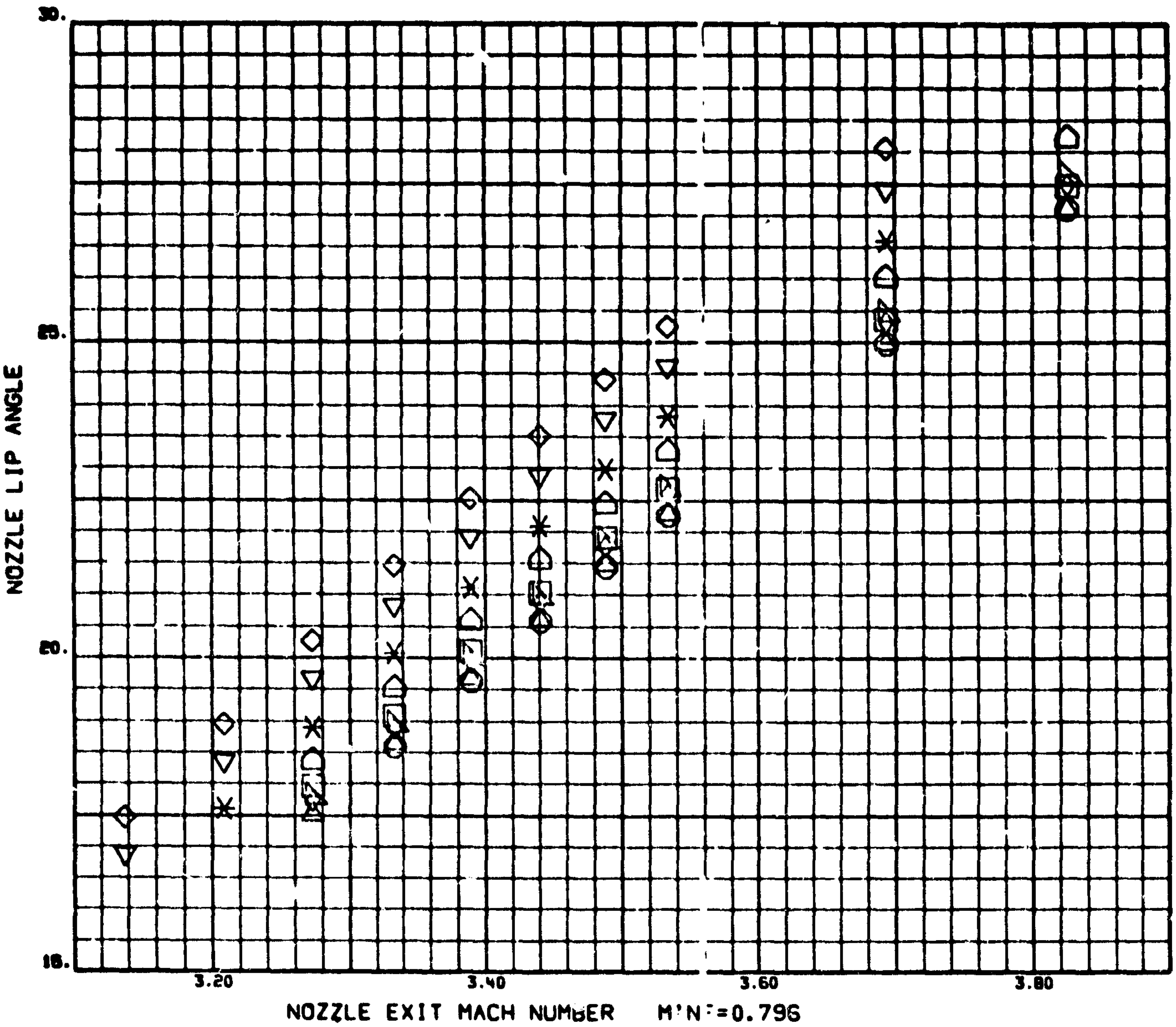


Fig. 4-2a

JOB NO 1HED32410382 PAGE 3

THE SYMBOLS PLOTTED BELOW REPRESENT MODEL NOZZLES THAT MAY BE USED TO SIMULATE THE FLIGHT CONDITIONS THAT EXIST FOR A FREE STREAM MACH NUMBER= .796

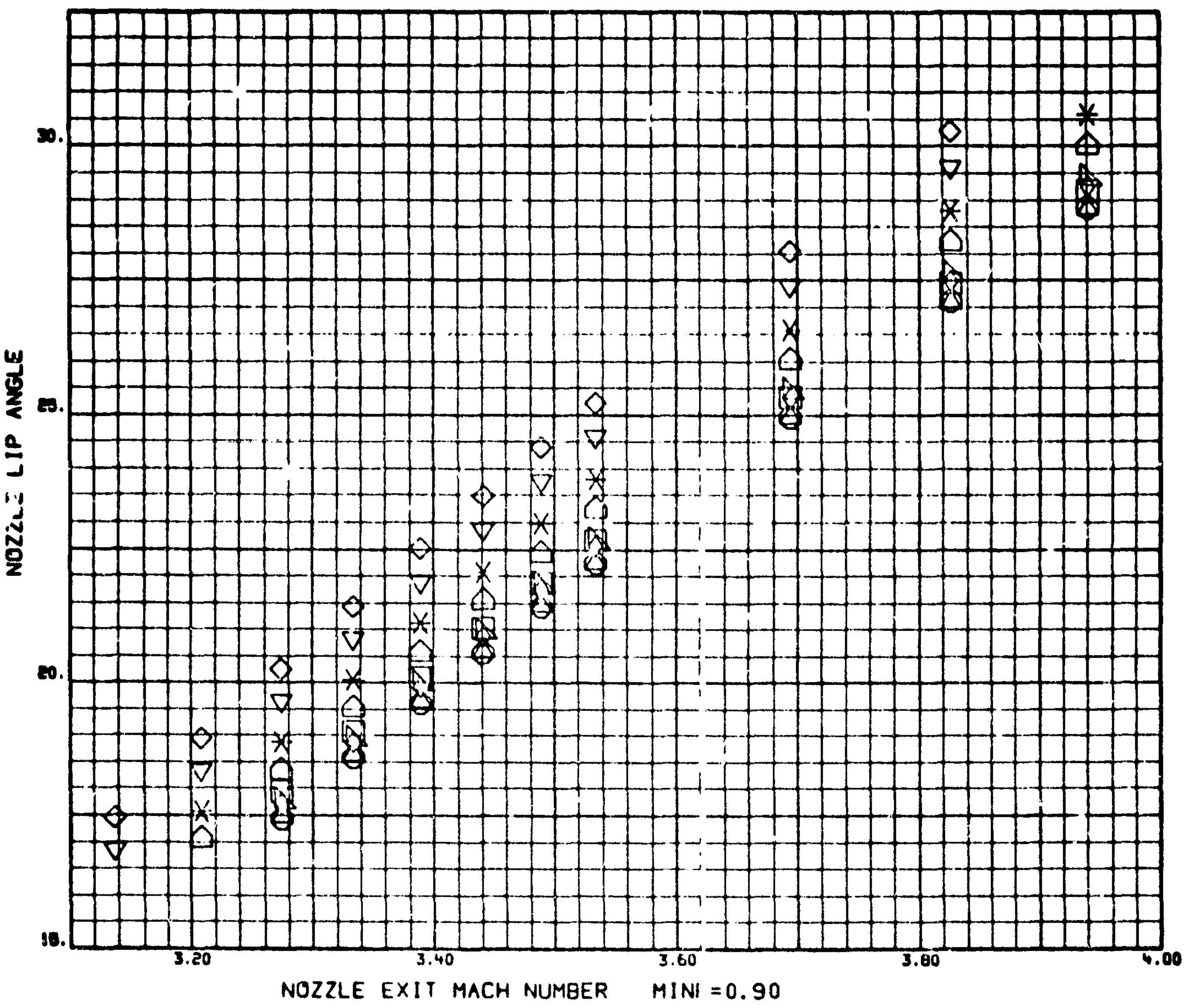


.02 SCALE HPM NOZZLE DESIGN ANALYSIS TEST IA-604

Fig. 4-2b

JOB NO 1HED32410362 PAGE 4

THE SYMBOLS PLOTTED BELOW REPRESENT MODEL NOZZLES THAT MAY BE USED TO SIMULATE THE FLIGHT CONDITIONS THAT EXIST FOR A FREE STREAM MACH NUMBER= .900

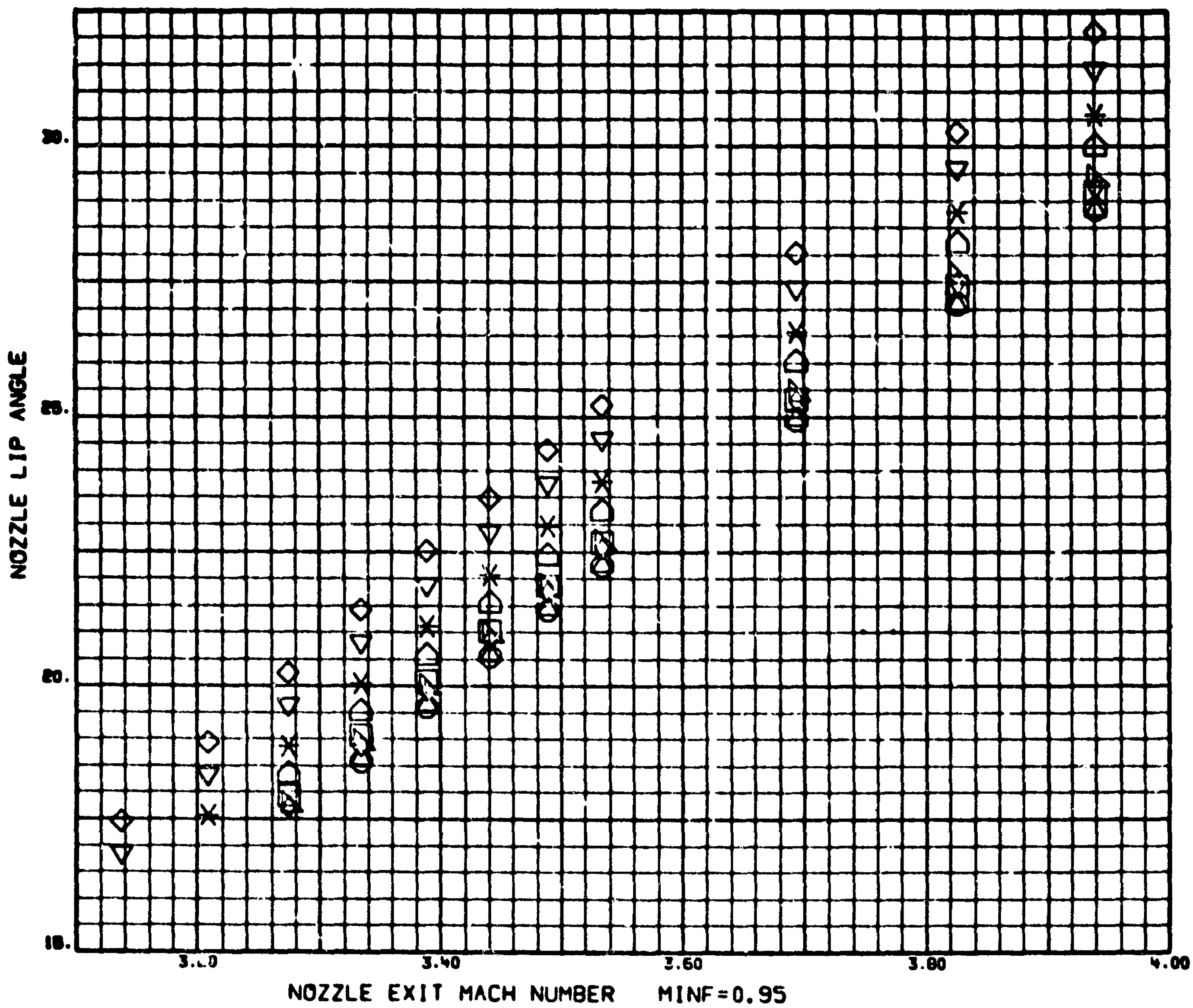


.02 SCALE HPM NOZZLE DESIGN ANALYSIS TEST IA-604

Fig. 4-2c

JOB NO 1HED3E410382 PAGE 8

THE SYMBOLS PLOTTED BELOW REPRESENT MODEL NOZZLES THAT MAY BE USED TO SIMULATE THE FLIGHT CONDITIONS THAT EXIST FOR A FREE STREAM MACH NUMBER= .950

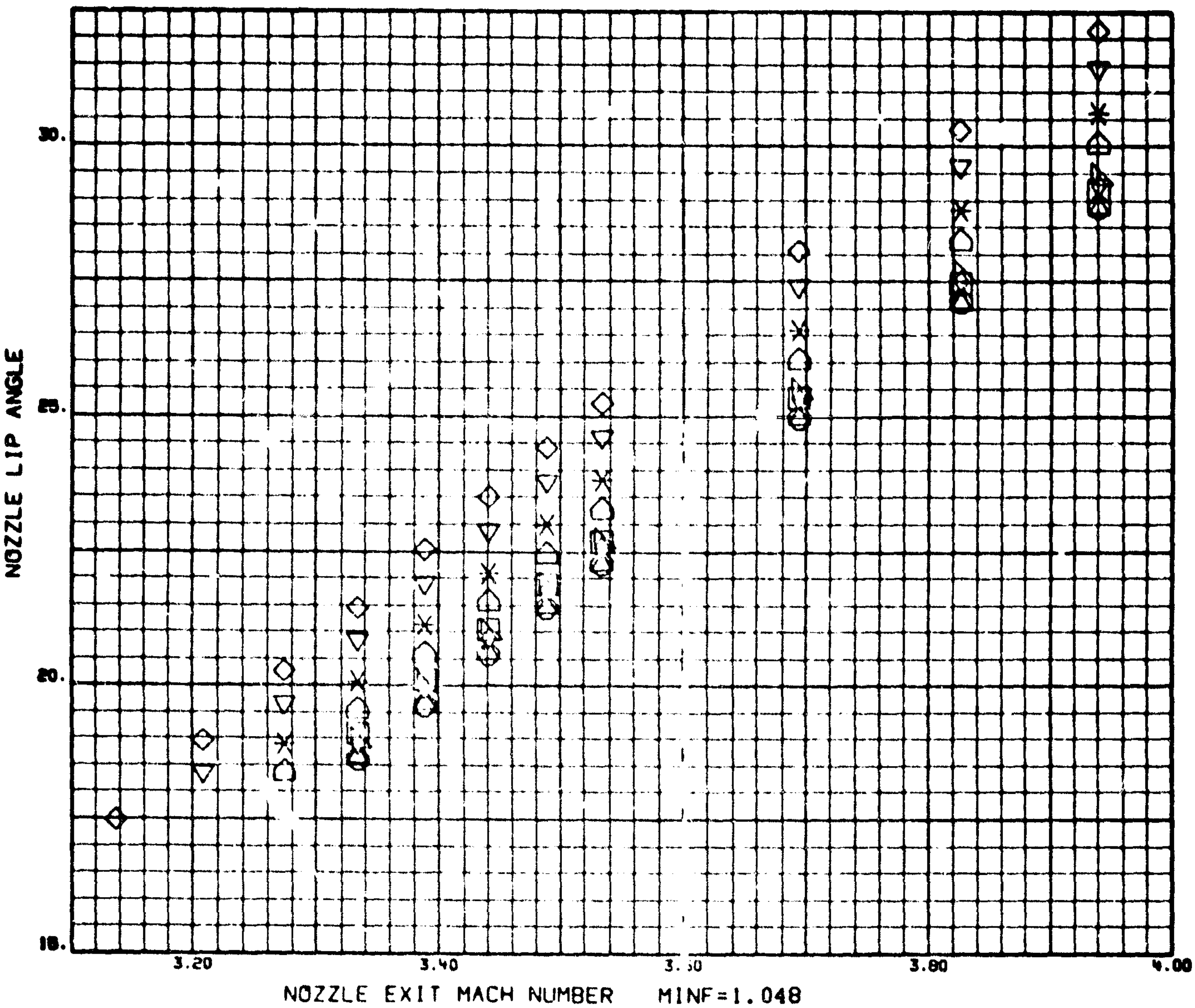


.02 SCALE HPM NOZZLE DESIGN ANALYSIS TEST IA-604

Fig. 4-2d

JOB NO 1HED38410368 PAGE 8

THE SYMBOLS PLOTTED BELOW REPRESENT MODEL NOZZLES THAT MAY BE USED TO SIMULATE THE FLIGHT CONDITIONS THAT EXIST FOR A FREE STREAM MACH NUMBER= 1.048

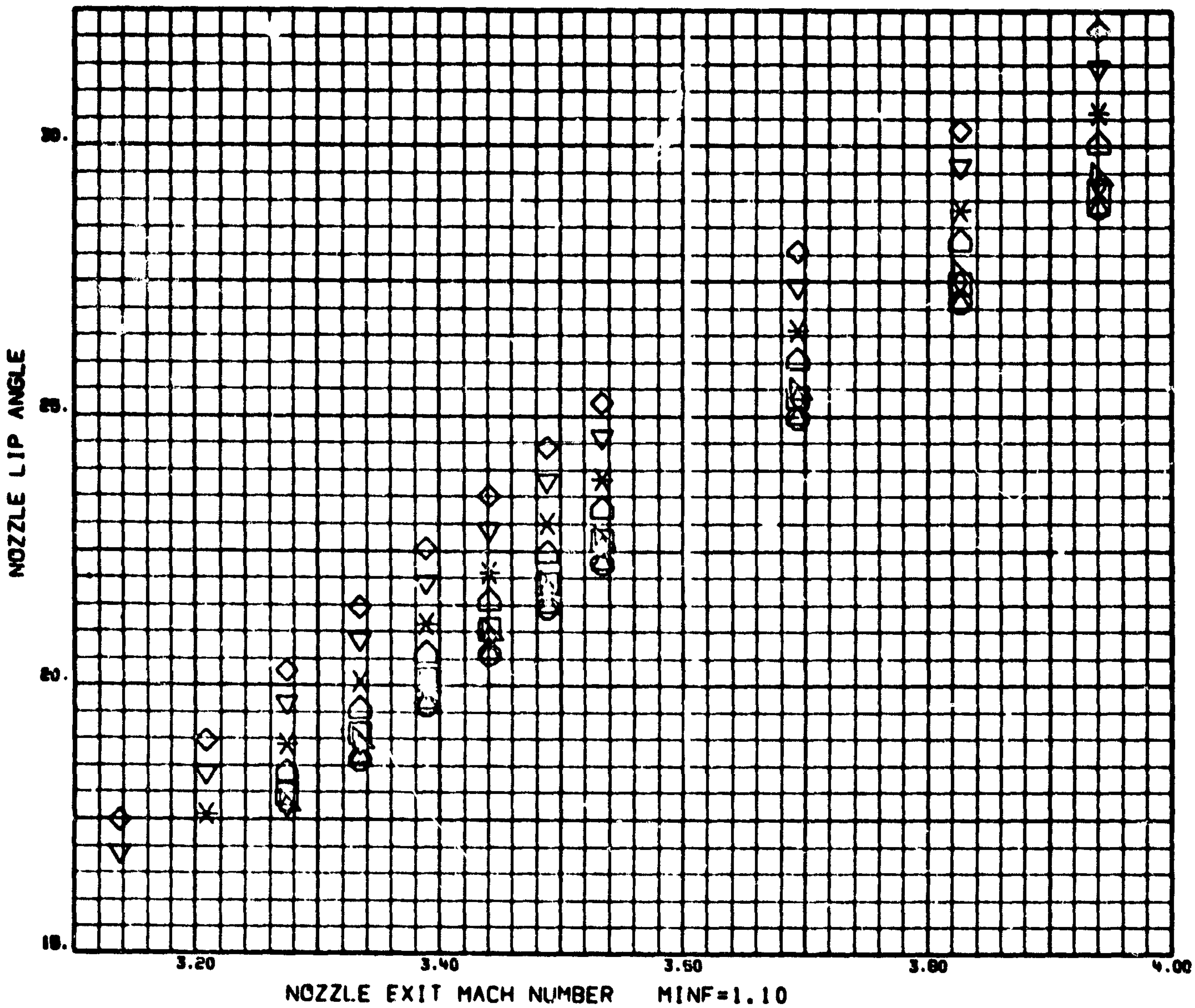


.02 SCALE HPM NOZZLE DESIGN ANALYSIS TEST IA-604

Fig. 4-2e

JOB NO 1HEDJE410382 PAGE 7

THE SYMBOLS PLOTTED BELOW REPRESENT MODEL NOZZLES THAT MAY BE USED TO SIMULATE THE FLIGHT CONDITIONS THAT EXIST FOR A FREE STREAM MACH NUMBER= 1.100

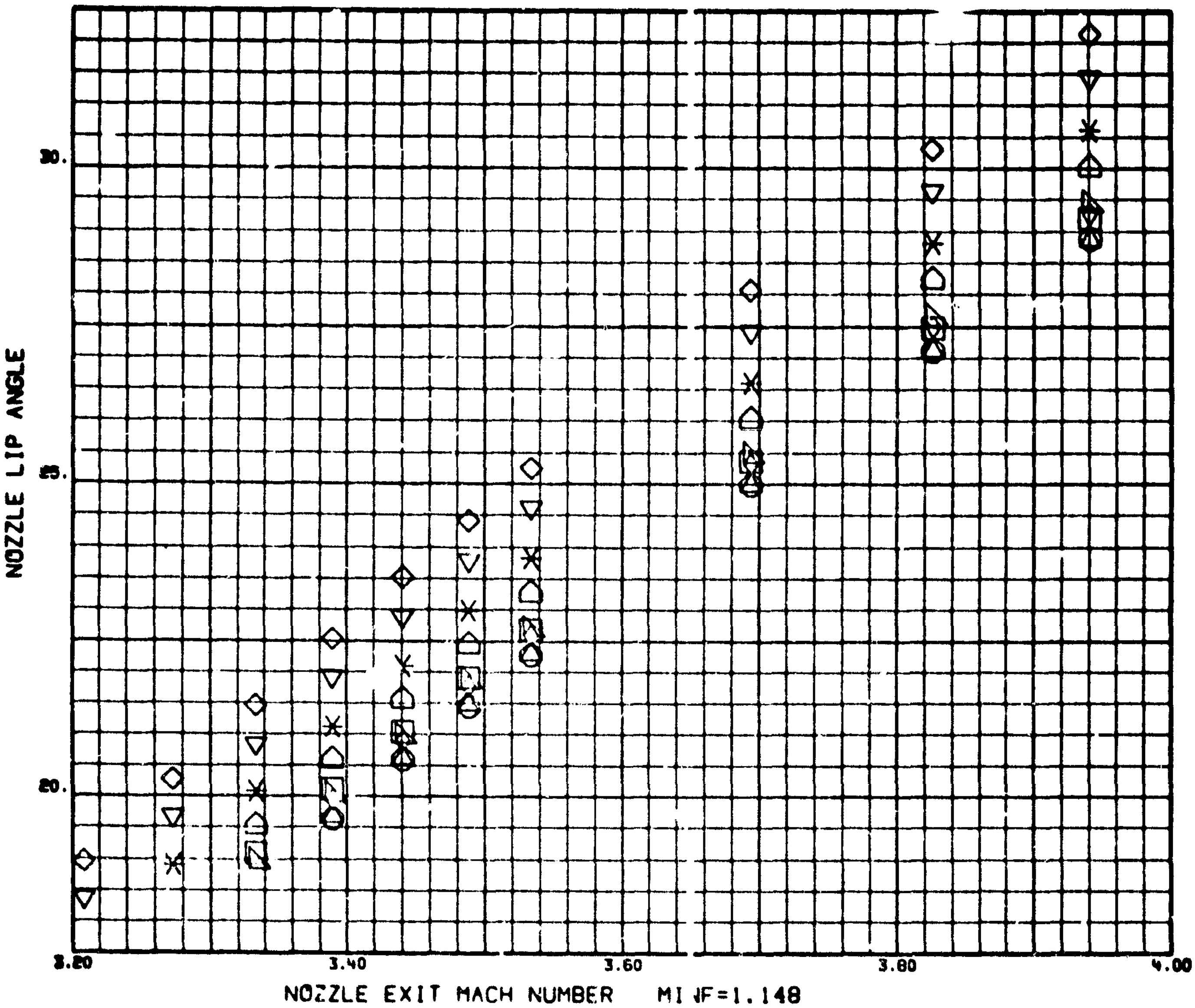


.02 SCALE HPM NOZZLE DESIGN ANALYSIS TEST IA-604

Fig. 4-2f

JOB NO 1HED3P410388 PAGE 8

THE SYMBOLS PLOTTED BELOW REPRESENT MODEL NOZZLES THAT MAY BE USED TO SIMULATE THE FLIGHT CONDITIONS THAT EXIST FOR A FREE STREAM MACH NUMBER= 1.148

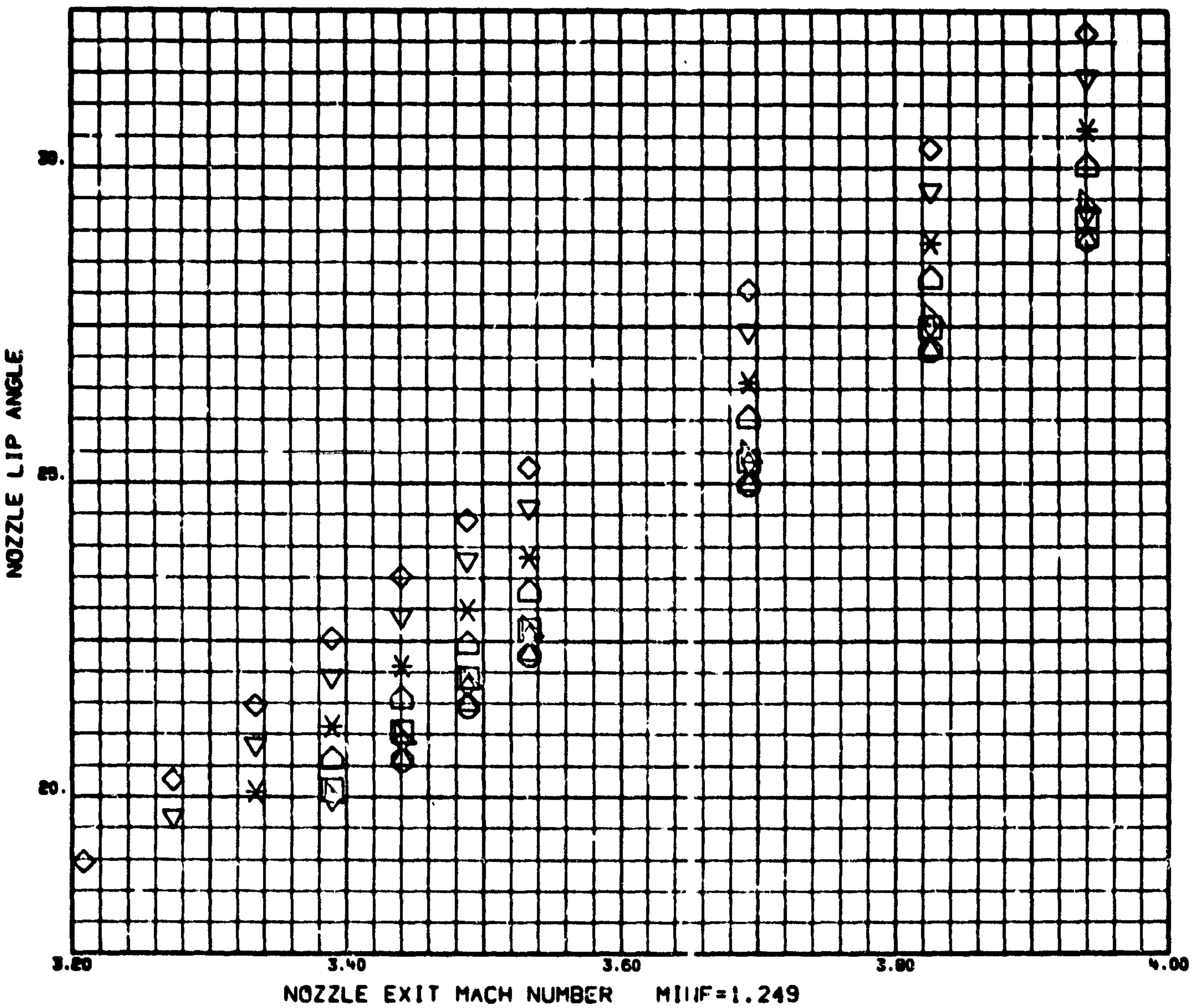


.02 SCALE HPM NOZZLE DESIGN ANALYSIS TEST IA-604

Fig. 4-2g

JOB NO 1HED3R410382 PAGE 9

THE SYMBOLS PLOTTED BELOW REPRESENT MODEL NOZZLES THAT MAY BE USED TO SIMULATE THE FLIGHT CONDITIONS THAT EXIST FOR A FREE STREAM MACH NUMBER= 1.249

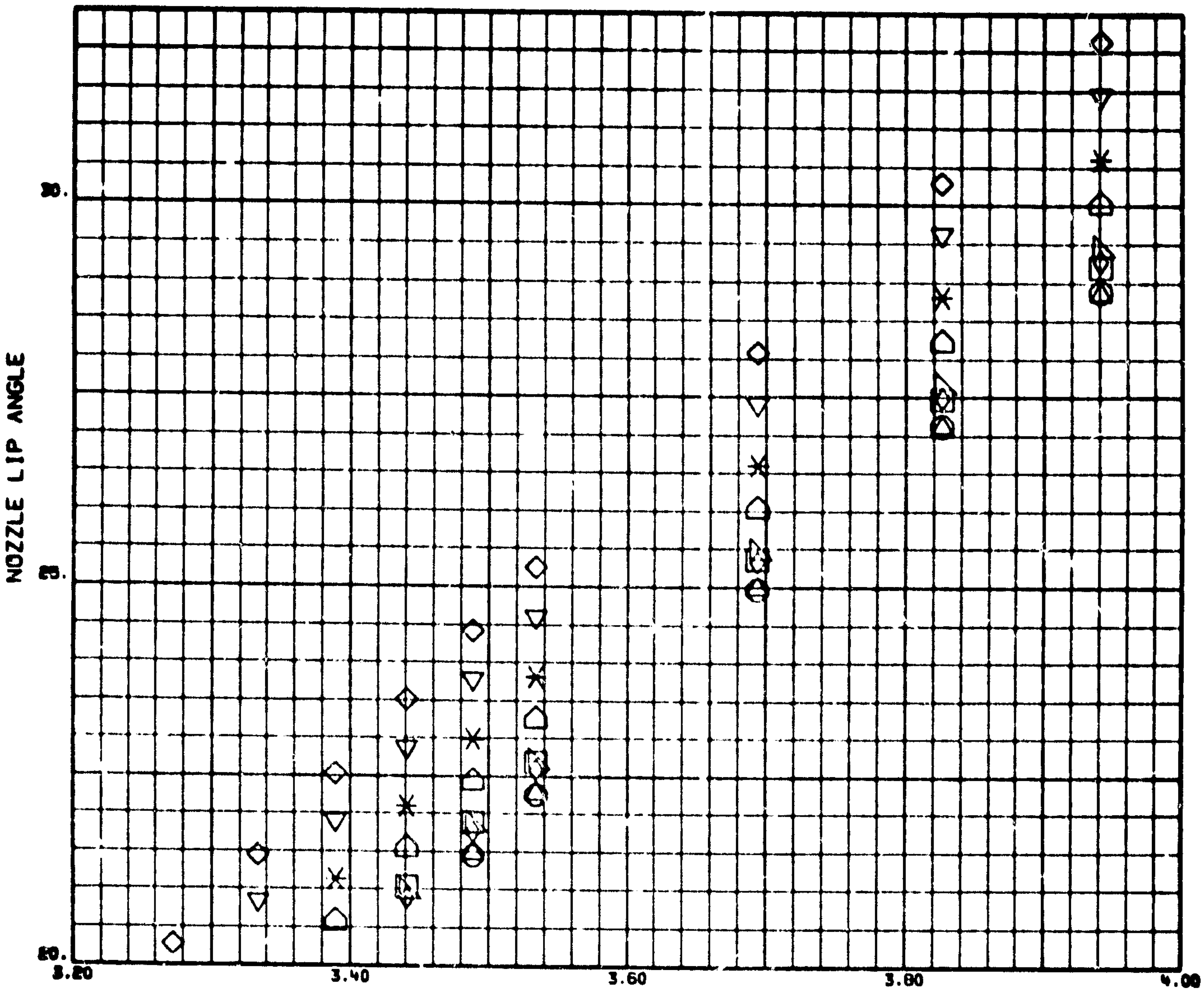


.02 SCALE HPM NOZZLE DESIGN ANALYSIS TEST IA-604

Fig. 4-2h

JOB NO 1HED3E410382 PAGE 10

THE SYMBOLS PLOTTED BELOW REPRESENT MODEL NOZZLES THAT MAY BE USED TO SIMULATE THE FLIGHT CONDITIONS THAT EXIST FOR A FREE STREAM MACH NUMBER= 1.403



.02 SCALE HPM NOZZLE DESIGN ANALYSIS TEST IA-604

Fig. 4-31

Section 5
REFERENCES

1-1. Lemoine, P. L., "Model Design Requirements for Thrust Augmented SSV Plume Effects Test IA-604 (Model 88-OTS)," Internal Letter No. SAS/AERO/80-381, Rockwell International, Downey, Calif., 1980.

2-1. Prozan, R.J., "Solution of Non-Isoenergetic Supersonic Flows by Method of Characteristics – Vol. III," LMSC-HREC D162220-III, Lockheed Missiles & Space Company, Huntsville, Ala., July 1971.

2-2. Penny, M. M., S. D. Smith, P. G. Anderson, P. R. Sulyma and M. L. Pearson, "Supersonic Flow of Chemically Reacting Gas Particle Mixtures – Vol. II – RAMP, A Computer Code for Analysis of Chemically Reacting Gas-Particle Flows," LMSC-HREC TR D496555-II, Lockheed Missiles & Space Company, Huntsville, Ala., January 1976.

3-1. Thomason, H. E., "SRM Nominal Performance Prediction and Proposed Thrust-Time Limits/Impulse Gates for the High Performance SRM Which Provides ~3,000 Pounds of Shuttle Payload Over the Current SRB Configuration," EL01 (112-80), George C. Marshall Space Flight Center, Huntsville, Ala., 29 May 1980.

Appendix

A LISTING OF A COMPUTER CODE USED TO DESIGN MODEL NOZZLES WHICH MEET MSFC BASE PRESSURE SIMILARITY PARAMETER CRITERIA

```
      SUBROUTINE ARATIO(GAMMA,XM,AR)
      GM1=GAMMA-1.0
      GP1=GAMMA+1.0
      EXP=GP1/(2.0*GM1)
      A=2.0/GP1
      B=1.0+(GM1/2.0)*XM*XM
      AR=((A*B)**EXP)/XM
      RETURN
      END



      SUBROUTINE CHECK(XD,NNOZ,NP,XL,XR,K)
      DIMENSION XD(20,25,20),NP(20,25)
      XR=0.
      XL=100000000000.0
      DO 102 I=1,NNOZ
      N=NP(I,K)
      IF(N.EQ.0)GO TO 102
      DO 103 J=1,N
      IF(XD(I,J,K)-XR)100,100,101
  101 XR=XD(I,J,K)
  100 IF(XL-XD(I,J,K))103,103,104
  104 XL=XD(I,J,K)
  103 CONTINUE
  102 CONTINUE
      RETURN
      END



      SUBROUTINE COMBO3(JMAX)
      COMMON/CO1/GAMAJ,GAMAE,GAMAI,PATM,A,B
      COMMON/CO2/PCMAX,PEPBMN,PC
      COMMON/CO3/NMACH,NSP,NNOZ,NPRINT,NPLOT
      COMMON/CO4/SP1(20),PBOPI(20),XMI(20),PI(20)
      COMMON/CO5/PTOPI(20),PCOPI(20),PCOPB(20),XMJ(20),PMJ(20)
      COMMON/CO6/PCOPE(20,25),XME(20,25),PME(20,25),AOAS(20,25),
     $DELTAJ(20,25),THETL(20,25),PEOPI(20,25),PEOPB(20,25)
    1 FORMAT(8E10.5)
    2 FORMAT(1H0,11H ITSUB WNC 8E10.5)
    3 FORMAT(1X,10E10.5)
    4 FORMAT(I5)
    5 FORMAT(2X,'MINF = ',E10.5,'   WIND TUNNEL PI = ',E10.5,'   PB/PI =
     $ ',E10.5,'   SPNOM = ',F10.5)
    6 FORMAT(1H0,1X,'MEXIT IS SUBSONIC AND TEMPORARILY SET = 1.10')
    7 FORMAT(1H0,1X,'LIP ANGLE    MEXIT      PC/PI      PE/PB      PC/PB
     $ PC/PE       MJET       AE/A*       DELJ    ')
    8 FORMAT(1H0,1X,'FLOW SEPARATION OCCURS FOR MEXIT GREATER THAN ',
     $E10.5,' WHEN  MINF = ',E10.5)
    9 FORMAT(1H1,1X,'THE FOLLOWING IS A NOZZLE FAMILY DERIVED TO SIMULAT
     $E THE FLIGHT CONDITIONS')
      JMAX=25
      DO 130 I=1,NMACH
C*    FREE STREAM PRESSURE RATIO
      CALL PRATIO(GAMAI,XMI(I),PTOPI(I))
C*    FREE STREAM STATIC PRESSURE
      PI(I)=PATM/PTOPI(I)
      IF(NPRINT.EQ.0)GO TO 15
      WRITE(6,9)
      WRITE(6,5)XMI(I),PI(I),PBOPI(I),SP1(I)
      WRITE(6,7)
   15 CONTINUE
```

Subroutine COMBO3 (Cont'd)

```
      PCOPI(I)=PC/PI(I)
      PCOPB(I)=PCOPI(I)/PBOPI(I)
C*    MACH NUMBER ON THE JET BOUNDARY
      CALL MACH(GAMAJ,PCOPB(I),XMJ(I))
C*    JET BOUNDARY ISENTROPIC EXPANSION ANGLE
      CALL PRND(GAMAJ,XMJ(I),PMJ(I))
C*
C*    THE FOLLOWING STATEMENTS CALCULATE NOZZLE LIP ANGLE FOR
C*    A DESIGNATED PC/PE
C*
      PCOPE(I,1)=5.0
      DO 110 J=1,JMAX
C*    MACH NUMBER ON THE NOZZLE EXIT PLANE
      CALL MACH(GAME,PCOPE(I,J),XME(I,J))
C*    NOZZLE LIP ISENTROPIC EXPANSION ANGLE
      CALL PRND(GAMAE,XME(I,J),PME(I,J))
C*    NOZZLE EXIT PLANE AREA RATIO   AE/A*
      CALL ARATIO(GAMAE,XME(I,J),AOAS(I,J))
C*    PLUME BOUNDARY INITIAL EXPANSION ANGLE
      DELTAJ(I,J)=(SPI(I)/XMJ(I))*(XME(I,J)**A*GAMAJ**B)
C*    NOZZLE LIP ANGLE
      THETL(I,J)=DELTAJ(I,J)+PME(I,J)-PMJ(I)
      PEOPI(I,J)=PBOPI(I)*PCOPB(I)/PCOPE(I,J)
      PEOPB(I,J)=PCOPB(I)/PCOPE(I,J)
      IF(NPRINT.EQ.0)GO TO 20
      WRITE(6,3)THETL(I,J),XME(I,J),PCOPI(I),PEOPB(I,J),
     $PCOPB(I),PCOPE(I,J),XMJ(I),AOAS(I,J),DELTAJ(I,J)
   20 CONTINUE
      IF(PEOPB(I,J).LE.PEPBMN)GO TO 120
      IF(XME(I,J).GT.3.5)GO TO 30
      PCOPE(I,J+1)=PCOPE(I,J)+5.0
      GO TO 100
   30 CONTINUE
      PCOPE(I,J+1)=PCOPE(I,J)+20.0
  100 CONTINUE
  110 CONTINUE
      GO TO 125
  120 CONTINUE
      JMAX=J
  125 CONTINUE
      IF(NPRINT.EQ.0)GO TO 130
      WRITE(6,8)XME(I,J),XMI(I)
  130 CONTINUE
      RETURN
      END


      SUBROUTINE DESIGN
      CALL INPUT
      CALL COMBO3(JMAX)
      CALL SPRNGE(JMAX)
      CALL FINAL
      RETURN
      END
```

```
      SUBROUTINE FINAL
C*    THIS SUBROUTINE DETERMINES THE FINAL ENVELOPE OF NOZZLES THAT MAY  . BE USED
C*    IN THE TEST PROGRAM SUBJECT TO MASS FLOW AND FLOW SEPARATION CONST . RAINTS
      COMMON/C01/GAMAJ,GAMAE,GAMAI,PATM,A,B
      COMMON/C03/NMACH,NSP,NNOZ,NPRINT,NPLOT
      COMMON/C04/SP1(20),PBOPI(20),XMI(20),PI(20)
      COMMON/C08/XMED(20,25,20),THETLD(20,25,20),NP(20,25)
      COMMON/C09/HEDRP(12,20),XLINE(12),XFINAL(12),YFINAL(12)
      COMMON/TEST1/XMEL,XMER,THLB,THLT,THUT,THUB,KMAX
      DIMENSION THETLL(20),THETLU(20)
      DIMENSION ENVEL(80),YTIT(12),XTIT(12)
      DATA (ENVEL(I),I=1,80)/'FINAL ENVELOPE OF MODEL NOZZLES THAT MAY B
     $E USED IN   THE TEST PROGRAM WHICH MEET THE SIMILARITY PARAMETER
     $CRITERIA, MASS FLOW AND FLOW SEPARATION RESTRICTIONS  IS PLOTTED B
     $ELOW. THE SIMILARITY PARAMETER USED IN    THE NOZZLE DESIGN STUDY
     $IS DEFINED BY THE RELATIONSHIPSP=MJET*DELJ/(MEXIT**A*GAMAJ**B). WH
     $ERE A:             AND B:        . THE MODEL NOZZLES REPRESENTED BEL
     $OW MAYBE USED TO SIMULATE THE FLIGHT CONDITIONS THAT EXIST  FOR AL
     $L FREE STREAM MACH NUMBERS TO BE TESTED.  '/
      DATA BLANK/6H      /
    1 FORMAT(1H1,5X,'THE FINAL ENVELOPE OF MODEL NOZZLES THAT MAY BE USE
     $D IN THE TEST PROGRAM WHICH MEET THE SIMILARITY'/2X,'PARAMETER CRI
     $TERIA, MASS FLOW AND FLOW SEPARATION RESTRICTIONS ARE DEFINED BY T
     $HE COORDINATES')
    2 FORMAT(1H0,13X,'NOZZLE EXIT MACH NUMBER',24X,'NOZZLE LIP ANGLE (DE
     $G)')
    3 FORMAT(1X,19X,E10.5,36X,E10.5)
    4 FORMAT(1H0,1X,'THE FLIGHT MACH NUMBERS THAT MAY BE SIMULATED WITH
     $THIS ENVELOPE OF NOZZLES ARE')
    5 FORMAT(2X,'FREE STREAM MACH NUMBERS =',10E10.5)
C*    THE FOLLOWING STATEMENTS DETERMINE THE UPPER LIMIT ON NOZZLE EXIT  . MACH NO.
      XMER=100000.0
      XMEL=0.0
      DO 102 I=1,NNOZ
      N=NP(I,1)
      IF(XMER-XMED(I,N,1))102,102,101
  101 XMER=XMED(I,N,1)
  102 CONTINUE
C*    THE FOLLOWING STATEMENTS DETERMINE THE LOWER LIMIT ON NOZZLE EXIT  . MACH NO.
      KMAX=NMACH
  103 CONTINUE
      DO 105 I=1,NNOZ
      IF(XMED(I,1,KMAX)-XMEL)105,105,104
  104 XMEL=XMED(I,1,KMAX)
  105 CONTINUE
      IF(XMEL.LE.XMER)GO TO 106
      KMAX=KMAX-1
      GO TO 103
C*    THE FOLLOWING STATEMENTS DETERMINE THE UPPER AND LOWER LIMITS OF N . OZZLE
C*    LIP ANGLE CORRESPONDING TO THE LOWER LIMIT AND UPPER LIMIT OF NOZZ . LE EXIT
C*    MACH NUMBER RESPECTIVELY
  106 CONTINUE
      JJ=0
      DO 110 I=1,NNOZ
      N=NP(I,KMAX)
      DO 109 J=1,N
      IF(ABS(XMED(I,J,KMAX)-XMEL).LE..01)GO TO 108
      GO TO 109
  108 CONTINUE
      JJ=JJ+1
      THETLL(JJ)=THETLD(I,J,KMAX)
      GO TO 110
  109 CONTINUE
  110 CONTINUE
      JJMAX=JJ
      KK=0
```

Subroutine FINAL (Cont'd)

```
      DO 115 I=1,NNOZ
      N=NP(I,1)
      DO 114 J=1,N
      IF(ABS(XMED(I,J,1)-XMER).LE..01)GO TO 113
      GO TO 114
  113 CONTINUE
      KK=KK+1
      THETLU(KK)=THETLD(I,J,1)
      GO TO 115
  114 CONTINUE
  115 CONTINUE
      KKMAX=KK
      THLB=100000.0
      THLT=0.0
      THUB=100000.0
      THUT=0.0
      DO 120 I=1,JJMAX
      IF(THETLL(I)-THLT)117,117,116
  116 THLT=THETLL(I)
  117 IF(THLB-THETLL(I))119,119,118
  118 THLB=THETLL(I)
  119 CONTINUE
  120 CONTINUE
      DO 125 I=1,KKMAX
      IF(THETLU(I)-THUT)122,122,121
  121 THUT=THETLU(I)
  122 IF(THUB-THETLU(I))124,124,123
  123 THUB=THETLU(I)
  124 CONTINUE
  125 CONTINUE
      WRITE(6,1)
      WRITE(6,2)
      WRITE(6,3)XMEL,THLB
      WRITE(6,3)XMEL,THLT
      WRITE(6,3)XMER,THUT
      WRITE(6,3)XMER,THUB
      WRITE(6,4)
      WRITE(6,5)(XMI(I),I=1,KMAX)
      ENCODE(698,ENVEL(53))A
      ENCODE(698,ENVEL(56))B
  698 FORMAT(F6.3)
      CALL CHSIZV(2,2)
      CALL SITE2V(50,1000,1023,90,2,480,1,ENVEL,IER)
C*    LOAD LABELS FOR AXES
      DO 699 II=1,12
      YTIT(II)=YFINAL(II)
  699 XTIT(II)=XFINAL(II)
      DO 700 KK=1,12
      JK=KK
      IF(XTIT(JK).EQ.BLANK)GO TO 701
  700 CONTINUE
  701 CONTINUE
      JK=JK-2
      IXSHF=512-JK*54
C*    SET UP GRID ORIGIN
      CALL SETMIV(30,30,34,250)
      IWY=0
      IWX=0
      YMIN=THLB
      YMAX=THUT
      XMIN=XMEL
      XMAX=XMER
```

Subroutine FINAL (Cont'd)

```
      CALL XYLIM(YMIN,YMAX,IWY,AMIN,AMAX,DY,NY,NYL,NYZ)
      YMIN=AMIN
      YMAX=AMAX
      CALL XYLIM(XMIN,XMAX,IWX,AMIN,AMAX,DX,NX,NXL,NXZ)
      XMIN=AMIN
      XMAX=AMAX
C*
C*    SET UP GRID
      CALL CHSIZV(2,2)
      CALL GRIDIV(2,XMIN,XMAX,YMIN,YMAX,DX,DY,NX,NY,NXL,NYL,NXZ,NYZ)
C*
C*    PRINT VERTICAL SCALE LABEL
      CALL RITE2V(12,200,1023,180,2,48,1,YTIT,IER)
C*    PRINT HORIZONTAL SCALE LABEL
      CALL RITE2V(IXSHF,16,1023,90,2,48,1,XTIT,IER)
C*
C*    PLOT FINAL NOZZLE ENVELOPE
      IXMEL=NXV(XMEL)
      IXMER=NXV(XMER)
      ITHLT=NYV(THLT)
      ITHLB=NYV(THLB)
      ITHUT=NYV(THUT)
      ITHUB=NYV(THUB)
      CALL LINEV(IXMEL,ITHLB,IXMEL,ITHLT)
      CALL LINEV(IXMEL,ITHLT,IXMER,ITHUT)
      CALL LINEV(IXMER,ITHUT,IXMER,ITHUB)
      CALL LINEV(IXMER,ITHUB,IXMEL,ITHLB)
      CALL TEST
      RETURN
      END



      SUBROUTINE FIRST(NNOZ)
      EXTERNAL TABL4V,TABL1V
      COMMON/XIM/TITLE(8)
      COMMON/CD/NOZD(10,20)
      DIMENSION HEAD(6)
      DATA HEAD/6HSYMBOL,6H  NOZZ,6HLE FAM,6HILY ID,6HENTIFI,6HCATION/
      CALL FRAMEV(0)
      CALL CHSIZV(3,3)
      CALL RITE2V(150,995,1023,90,2,48,1,TITLE,IER)
C**   PRINT TABLE HEADING
      CALL CHSIZV(2,2)
      CALL RITE2V(144,600,1023,90,2,36,1,HEAD,IER)
C
C**   SYMBOL TABLE
      IX=174
      IY=568
      NY=IY-10
      IJM=1
      CALL CHSIZV(2,2)
      DO 15 I=1,NNOZ
      CALL VCHARV(90,2,IX,NY,IJM,TABL4V)
      CALL RITSTV(13,12,TABL1V)
      NA=NY+6
      CALL RITE2V(290,NA,1023,90,2,60,1,NOZD(1,I),IER)
      IY=IY-20
      NY=IY-10
   15 IJM=IJM+1
      RETURN
      END
```

```
      SUBROUTINE GRAPH(YMAX,YMIN,XMAX,XMIN,XD,DCN,XTIT,YTIT,NP,NNOZ,K)
C
C**   SUBROUTINE GRAPH SETS UP THE GRIDS AND CONTROLS PLOTTING
C
      EXTERNAL TABLIV
      COMMON/XMS/IXS
      COMMON/XIM/TITLE(8)
      COMMON/C04/SPI(20),PBOPI(20),XMI(20),PI(20)
  698 FORMAT(F6.3)
      DIMENSION XTIT(12),YTIT(12),SYMBOL(25)
      DATA (SYMBOL(I),I=1,25)/'THE SYMBOLS PLOTTED BELOW REPRESENT MODEL
     $ NOZZLES THATMAY BE USED TO SIMULATE THE FLIGHT CONDITIONS THAT
     $ EXIST FOR A FREE STREAM MACH NUMBER=        '/
      DIMENSION NP(20,25),XD(20,25),DCN(20,25)
C
C** ADVANCE FRAME
      CALLFRAMEV(0)
C
C**   SETUP GRID ORIGIN
      CALL SETMIV(3 ,30,68,134)
      YSAVV=YMAX
      YSAVA=YMIN
      XSAVV=XMAX
      XSAVA=XMIN
C
      IWY=0
      IWX=0
      CALLXYLIM(YMIN,YMAX,IWY,AMIN,AMAX,DY,NY,NYL,NYZ)
      YMIN=AMIN
      YMAX=AMAX
      CALLXYLIM(XMIN,XMAX,IWX,AMIN,AMAX,DX,NX,NXL,NXZ)
      XMIN=AMIN
      XMAX=AMAX
C
C**   SET UP GRID
      CALL CHSIZV(2,2)
      CALL RITSTV(12,26,TABLIV)
      CALL GRIDIV(2,XMIN,XMAX,YMIN,YMAX,DX,DY,NX,NY,NXL,NYL,NXZ,NYZ)
      YMAX=YSAVV
      YMIN=YSAVA
      XMAX=XSAVV
      XMIN=XSAVA
C
C
C**   PRINT VERTICAL LABEL
      CALL RITE2V(12,404,1023,180,2,36,1,YTIT,IER)
C**   PRINT HORIZONTAL SCALE TITLE
      CALLRITE2V(IXS,50,1023,90,2,36,1,XTIT,IER)
C
C**   PRINT FIGURE TITLE
      CALL CHSIZV(3,3)
      CALL RITE2V(150,10,1023,90,2,48,1,TITLE,IER)
C**   PRINT DEFINITIVE NOTE
      CALL CHSIZV(2,2)
      CALL RITSTV(18,26,TABLIV)
      ENCODE(698,SYMBOL(25))XMI(K)
      CALL RITE2V(50,1000,1023,90,2,150,1,SYMBOL,IER)
   43 CONTINUE
      IJM=1
      DO 299 INK=1,NNOZ
      NPJ=NP(INK,K)
      DO 301 JJ=1,NPJ
      CALLPOINTX(XD(INK,JJ),DCN(INK,JJ),IJM)
  301 CONTINUE
      IJM=IJM+1
  299 CONTINUE
      RETURN
      END
```

Data File HPM

```
     9     1     1     1     5
.02 SCALE HPM NOZZLE EXIT MACH NUMBER
.02 SCALE HPM NOZZLE LIP ANGLE
.02 SCALE HPM NOZZLE DESIGN ANALYSIS TEST IA-604
NOZZLE LIP ANGLE
2.6599
    17
37.64       2.6599      10.490      1.2541
47.97       2.7864      14.258      1.2685
61.94       2.9223      18.025      1.2805
80.99       3.0761      21.793      1.2843
107.32      3.2393      25.561      1.2887
144.28      3.4131      29.329      1.2934
196.94      3.6005      33.096      1.2997
273.55      3.8026      36.864      1.3062
387.20      4.0212      40.632      1.3124
559.23      4.2585      44.395      1.3184
826.99      4.5204      48.167      1.3248
1255.1      4.8153      51.935      1.3326
1960.9      5.1499      55.703      1.3406
3167.9      5.5320      59.471      1.3485
5317.3      5.9676      63.237      1.3559
9336.8      6.4766      67.006      1.3627
17281.0     7.0874      70.774      1.3687
1500.0      750.0       0.60        14.70       1.40        1.40        1.40
.02         149.64      27.[illegible]      500.0
.597        .89         720.0       10.542
NOZZLE FAMILY DERIVED FOR FLIGHT MACH NO. = 0.597
NOZZLE EXIT MACH NUMBER    MINF=0.597
.796        .825        651.4       8.441
NOZZLE FAMILY DERIVED FOR FLIGHT MACH NO. = 0.796
NOZZLE EXIT MACH NUMBER    MINF=0.796
.90         .77         624.5       7.425
NOZZLE FAMILY DERIVED FOR FLIGHT MACH NO. = 0.90
NOZZLE EXIT MACH NUMBER    MINF=0.90
.95         .675        610.2       6.877
NOZZLE FAMILY DERIVED FOR FLIGHT MACH NO. = 0.95
NOZZLE EXIT MACH NUMBER    MINF=0.95
1.048       .61         580.0       5.725
NOZZLE FAMILY DERIVED FOR FLIGHT MACH NO. = 1.048
NOZZLE EXIT MACH NUMBER    MINF=1.048
1.10        .64         571.3       5.477
NOZZLE FAMILY DERIVED FOR FLIGHT MACH NO. = 1.10
NOZZLE EXIT MACH NUMBER    MINF=1.10
1.148       .65         570.0       4.827
NOZZLE FAMILY DERIVED FOR FLIGHT MACH NO. = 1.148
NOZZLE EXIT MACH NUMBER    MINF=1.148
1.249       .69         576.2       4.105
NOZZLE FAMILY DERIVED FOR FLIGHT MACH NO. = 1.249
NOZZLE EXIT MACH NUMBER    MINF=1.249
1.403       .77         586.0       3.276
NOZZLE FAMILY DERIVED FOR FLIGHT MACH NO. = 1.403
NOZZLE EXIT MACH NUMBER    MINF=1.403
```

```
      SUBROUTINE INPUT
      COMMON/C01/GAMAJ,GAMAE,GAMAI,PATM,A,B
      COMMON/C02/PCMAX,PEPBMN,PC
      COMMON/C03/NMACH,NSP,NNOZ,NPRINT,NPLOT
      COMMON/C04/SPI(20),PBOPI(20),XMI(20),PI(20)
      COMMON/C07/SCALE,PEXITO,WMAX,TO
      COMMON/C09/HEDRP(12,20),XLINE(12),XFINAL(12),YFINAL(12)
      COMMON/TEST2/NNOZF
      COMMON/XIM/TITLE(8)
      COMMON/CD/NOZO(10,20)
      DIMENSION PPCOPB(30),PXMJ(30),PDELJ(30),PGAMAJ(30),PSP(30),PPC(20)
     $,PPI(20)
    1 FORMAT(5I5)
    2 FORMAT(8E10.5)
    3 FORMAT(1H1,1X,'BEGIN A NEW NOZZLE DESIGN STUDY. IT IS ANTICIPATED
     $THAT THE NOZZLE WILL BE DESIGNED FOR ',I2,' FREE STREAM MACH NUMBE
     $RS.')
   13 FORMAT(1H0,1X,'THE SIMILARITY PARAMETER USED IN THIS NOZZLE DESIGN
     $ STUDY IS DEFINED BY THE RELATIONSHIP'/2X,'SP = MJET*DELJ/(MEXIT**
     $A*GAMAJ**B). WHERE A = ',F10.5,' AND B = ',E10.5)
    4 FORMAT(1H0,5X,'THE NOZZLE WILL BE DESIGNED BASED UPON THE'/6X,'FOL
     $LOWING PROTOTYPE PLUME SIMILARITY DATA')
    5 FORMAT(1X,10E10.5)
    6 FORMAT(1H0,1X,'    PC/PB      MJET       DELJ       GAMAJ        SP    ')
    7 FORMAT(1H0,6X,'THE NOZZLE WILL BE DESIGNED TO SIMULATE'/11X,'THE F
     $OLLOWING FLIGHT CONDITIONS')
    8 FORMAT(1H0,1X,'    MINF       PB/PI       PC          PI       SPNOM    ')
    9 FORMAT(10A6)
   12 FORMAT(12A6,A6,I2)
C*    PCMAX=MAXIMUM ALLOWABLE NOZZLE CHAMBER PRESSURE (PSIA)
C*    PC=MIDRANGE VALUE OF NOZZLE CHAMBER PRESSURE USUALLY = PCMAX/2.0
C*    PEPBMN=EXPERIMENTALLY OBSERVED VALUE OF PEXIT/PBASE AT WHICH FLOW
C*    SEPARATION OCCURS IN THE NOZZLE
C*    PATM=TOTAL PRESSURE OF WIND TUNNEL (PSIA)
C*    GAMAJ=RATIO OF SPECIFIC HEATS OF THE NOZZLE EXHAUST AT THE PLUME B . OUNDARY
C*    GAMAE=RATIO OF SPECIFIC HEATS OF THE NOZZLE EXHAUST IN THE NOZZLE  . EXIT
C*    PLANE AT THE NOZZLE LIP
C*    GAMAI=RATIO OF SPECIFIC HEATS OF AIR
C*    NMACH=ANTICIPATED NUMBER OF FREE STREAM MACH NUMBERS IN THE TEST P . ROGRAM
C*    THAT THE NOZZLE WILL BE DESIGNED FOR
C*    NPMRAY=NUMBER OF RAYS IN PROTOTYPE PRANDTL-MEYER EXPANSION DATA
      READ(5,1)NMACH,NSP,NPRINT,NPLOT,NNOZF
      READ(5,12)XFINAL
      READ(5,12)YFINAL
      IF(NPLOT.EQ.0)GO TO 40
      READ(5,9)(TITLE(I),I=1,8)
      READ(5,12)XLINE
   40 CONTINUE
      NNOZ=NMACH
      GO TO(10,20,30),NSP
   10 CONTINUE
      A=.25
      B=1.0
      GO TO 35
   20 CONTINUE
      A=.25
      B=.5
      GO TO 35
   30 CONTINUE
      A=0.0
      B=1.0
   35 CONTINUE
```

Subroutine INPUT (Cont'd)

```
      WRITE(6,3)NMACH
      WRITE(6,13)A,B
      READ(5,2)PXME
      READ(5,1)NPMRAY
      WRITE(6,4)
      WRITE(6,6)
      DO 100 I=1,NPMRAY
      READ(5,2)PPCOPB(I),PXMJ(I),PDELJ(I),PGAMAJ(I)
      PSP(I)=PXMJ(I)*PDELJ(I)/(PXME**A*PGAMAJ(I)**B)
      WRITE(6,5)PPCOPB(I),PXMJ(I),PDELJ(I),PGAMAJ(I),PSP(I)
      PPCOPB(I)=ALOG(PPCOPB(I))
  100 CONTINUE
      READ(5,2)PCMAX,PC,PEPBMN,PATM,GAMAJ,GAMAE,GAMAI
      READ(5,2)SCALE,PEXITD,WMAX,TO
      WRITE(6,7)
      WRITE(6,8)
      DO 200 I=1,NMACH
      READ(5,2)XMI(I),PBOPI(I),PPC(I ,PPI(I)
      IF(NPLOT.EQ.0)GO TO 110
      READ(5,9)(NOZD(II,I),II=1,10)
      READ(5,12)(MEDRP(K,I),K-1,6)
  110 CONTINUE
      PCPB=PPC(I)/(PBOPI(I)*PPI(I))
      PCPB=ALOG(PCPB)
      DO 250 J=1,NPMRAY
      JS=J
      IF(PPCOPB(J).GT.PCPB)GO TO 260
  250 CONTINUE
  260 CONTINUE
      JT=JS-1
      FACTOR=(PCPB-PPCOPB(JT))/(PPCOPB(JS)-PPCOPB(JT))
      SP1(I)=PSP(JT)+FACTOR*(PSP(JS)-PSP(JT))
      WRITE(6,5)XMI(I),PBOPI(I),PPC(I),PPI(I),SP1(I)
  200 CONTINUE
      RETURN
      END


      SUBROUTINE ITSUB (FOFY,Y,SAVE,CONV,NTIMES)
C     THIS SUBROUTINE PROVIDES ITERATION CONTROL FOR ANY FUNCTION
C        SAVE(4-7)=STORAGE LOCATIONS FOR X AND FOFX
C     (CONV)-CONVERGENCE CRITERIA
C     (NTIMES)-MAX NUMBER OF ITERATIONS
      DIMENSIONSAVE(8)
      N1=SAVE(3) +.1
      FOFXCK=SAVE(8)
C     FOFY AND Y ARE DUMMY INPUT ARGUMENTS
      FOFX=FOFY
      X=Y
C     CHECK FOR CONVERGENCE
      IF(ABS (FOFX)-CONV.LE.0.)GOTO110
      ITIME=SAVE(1)+.1
C     ITIME CONTROLS THE TYPE CALCULATION TO BE PERFORMED
C        ITIME=1,FIRST TIME THROUGH
C     ITIME=2,POS FIRST TIME THROUGH
C       ITIME=3,NEG FIRST TIME THROUGH
C       ITIME=4,SOLUTION IS BRACKETED
C       ITIME=5,SOLUTION HAS CONVERGED
C       ITIME=6,SOLUTION WILL NOT CONVERGE
```

Subroutine ITSUB (Cont'd)

```
      GOTO(10,30,50,70),ITIME
C     INITIALIZE
   10 N1=1
      ITIME=2
      FOFXCK=FOFX
      SAVE(8)=FOFXCK
      IF(FOFX.LT.0.)GOTO50
   30 IF(FOFX.LT.0.)GOTO70
      IF(FOFXCK.GE.FOFX)GOTO35
      SAVE(2)=-1.*SAVE(2)
      X=X-2.*SAVE(2)
      GOTO90
   35 SAVE(4)=X
      SAVE(5)=FOFX
      X=X-SAVE(2)
C     OF ONE VARIABLE
C     (FOFX)-FUNCTION WHICH IS DRIVEN TO ZERO
C     (X)-VARIABLE WHICH IS ITERATIVELY SOLVED FOR
C     (SAVE)-PROGRAM CONTROL
C       SAVE(1)=ITIME
C         SAVE(2)=X INCREMENT
C         SAVE(3)=COUNTER DENOTING NTH ITERATION
      GOTO90
   50 ITIME=3
      IF(FOFX.GT.0.)GOTO70
      IF(FOFXCK.LE.FOFX)GOTO55
      SAVE(2)=-1.*SAVE(2)
      X=X+2.*SAVE(2)
      GOTO90
   55 SAVE(6)=X
      SAVE(7)=FOFX
      X=X+SAVE(2)
      GOTO90
   70 ITIME=4
      N1=SAVE(3)
      IF(FOFX.LT.0.)GOTO75
      SAVE(4)=X
      SAVE(5)=FOFX
      GOTO80
   75 SAVE(6)=X
      SAVE(7)=FOFX
C       PICK NEW GUESS FOR X ACCORDING TO TYPE CALCULATION
   80 X=SAVE(4)-SAVE(5)*((SAVE(6)-SAVE(4))/(SAVE(7)-SAVE(5)))
   90 IF(N1.GE.NTIMES)GOTO100
      N1=N1+1
      SAVE(3)=N1
      GOTO120
  100 ITIME=6
      GOTO120
  110 ITIME=5
      SAVE(4)=X
      SAVE(5)=FOFX
      SAVE(6)=X
      SAVE(7)=FOFX
  120 SAVE(1)=FLOAT(ITIME)+.1
      Y=X
      RETURN
      END
```

```
      SUBROUTINE MACH(GAMMA,P,XM)
      GM106=(GAMMA-1.)/GAMMA
      GM1=GAMMA-1.
      XM=SQRT(2.*(P**GM106-1.)/GM1)
      RETURN
      END
```

MORE

```
      COMMON/XIM/TITLE(8)
      COMMON/CD/NOZO(10,20)
      COMMON/C03/NMACH,NSP,NNOZ,NPRINT,NPLOT
      COMMON/C08/XMED(20,25,20),THETLD(20,25,20),NP(20,25)
      COMMON/C09/HEDRP(12,20),XLINE(12),XFINAL(12),YFINAL(12)
      COMMON/XHS/IXSHF
      DIMENSION XTIT(12),YTIT(12)
      INTEGER ADARY(22)
      DIMENSION XAXIS(20,25)
      DATA BLANK/6H      /
      DATA (ADARY(I),I=1,5)/'105 MM  1 HARD COPY REQUIRED  '/
      CALL IDENT(105,ADARY)
      CALL FRMODE(1)
      DO 19 I=1,20
      DO 18 J=1,12
      HEDRP(J,I)=BLANK
   18 CONTINUE
   19 CONTINUE
      CALL DESIGN
      IF(NPLOT.EQ.0)GO TO 209
C*    LEAD FRAME IDENTIFIES NOZZLE DESIGN PROBLEM AND NOZZLE FAMILY NUMB
      CALL FIRST(NNOZ)
      DO 200 K=1,NMACH
C**   DETERMINE PLOT LIMITS OF HORIZONTAL AXIS
      CALL CHECK(XMED,NNOZ,NP,XL,XR,K)
C**   CALCULATE Y AXIS LIMITS
      CALL CHECK(THETLD,NNOZ,NP,YB,YT,K)
C**   SET THE DEPENDENT VARIABLES
      DO 109 I=1,NNOZ
      N=NP(I,K)
      DO 108 J=1,N
      XAXIS(I,J)=XMED(I,J,K)
  108 CONTINUE
  109 CONTINUE
C**   LOAD TITLE FOR AXES
      DO 699 II=1,12
      YTIT(II)=XLINE(II)
  699 XTIT(II)=HEDRP(II,K)
      DO 700 KK=1,12
      JK=KK
      IF(XTIT(JK).EQ.BLANK)GO TO 701
  700 CONTINUE
  701 CONTINUE
      JK=JK-2
      IXSHF=512-JK*54
C**   PLOT DATA
      CALL GRAPH(YT,YB,XR,XL,XAXIS,THETLD(1,1,K),XTIT,YTIT,NP,NNOZ,K)
  200 CONTINUE
  209 CONTINUE
      CALL ENDJOB
      STOP
      END
```

```
FUNCTIONNXV(X)
CALLXSCLVI(X,IX,IER)
NXV=IX
RETURN
END


FUNCTIONNYV(Y)
CALLYSCLVI(Y,IY,IER)
NYV=IY
RETURN
END


SUBROUTINE POINTX(X,Y,NS)
EXTERNAL TABL4V
MS=IABS(NS)
CALL CHSIZV(3,3)
IX=NXV(X)
IY=NYV(Y)
NX=IX-6
NY=IY-9
CALL VCHARV(90.,2,NX,NY,MS,TABL4V)
CALL CHSIZ[illegible],3)
RETURN
END


SUBROUTINE PRATIO(GAMMA,XM,PR)
GM1O2=(GAMMA-1.0)/2.0
GOGM1=GAMMA/(GAMMA-1.0)
PR=(1.0+GM1O2*XM*XM)**GOGM1
RETURN
END


SUBROUTINE PRND(GAMMA,XM,PM)
GP1GM1=(GAMMA+1.)/(GAMMA-1.)
GM1GP1=1./GP1GM1
XMS1=XM*XM-1.
FA=SQRT(GM1GP1*XMS1)
FB=SQRT(XMS1)
FC=SQRT(GP1GM1)
PM=FC*ATAN(FA)-ATAN(FB)
PM=PM*57.2957795
RETURN
END
```

```
      SUBROUTINE SPRNGE(JMAX)
      COMMON/C01/GAMAJ,GAMAE,GAMAI,PATM,A,B
      COMMON/C02/PCMAX,PEPBMN,PC
      COMMON/C03/NMACH,NSP,NNOZ,NPRINT,NPLOT
      COMMON/C04/SPI(20),PBOPI(20),XMI(20),PI(20)
      COMMON/C05/PTOPI(20),PCOPI(20),PCOPB(20),XMJ(20),PMJ(20)
      COMMON/C06/PCOPE(20,25),XME(20,25),PME(20,25),AOAS(20,25),
     $DELTAJ(20,25),THETL(20,25),PEOPI(20,25),PEOPB(20,25)
      COMMON/C07/SCALE,PEXITD,WMAX,TO
      COMMON/C08/XMED(20,25,20),THETLD(20,25,20),NP(20,25)
      DIMENSION DENOM(20,25),PCUOPI(20,25),PCUOPB(20,25),XMJMAX(20,25),
     $PMJMAX(20,25),DELJMX(20,25),SPMAX(20,25),PCLOPB(20,25),
     $XMJMIN(20,25),PMJMIN(20,25),DELJMN(20,25),SPMIN(20,25)
    1 FORMAT(8E10.5)
    3 FORMAT(1X,10E10.5)
    4 FORMAT(1H1,1X,'OF THE PREVIOUSLY DERIVED NOZZLE FAMILIES, THE FOLL
     $OWING NOZZLES MAY BE USED TO SIMULATE THE FLIGHT CONDITIONS')
    5 FORMAT(2X,'MINF = ',E10.5,'   WIND TUNNEL PI = ',E10.5,'   PB/PI =
     $ ',E10.5,'   SPNOM = ',E10.5)
    6 FORMAT(1H0)
    7 FORMAT(1H0,1X,'  MEXIT   LIP ANGLE   SPMIN    SPMAX    PCMAX  ')
      EXITD=SCALE*PEXITD
      AEXIT=(3.14159*EXITD**2.0)/4.0
      DO 1000 K=1,NMACH
      IF(NPRINT.EQ.0)GO TO 10
      WRITE(6,4)
      WRITE(6,5)XMI(K),PI(K),PBOPI(K),SPI(K)
      WRITE(6,7)
   10 CONTINUE
      DO 100 I=1,NNOZ
      WRITE(6,6)
      JJ=0
      NP(I,K)=0
      DO 50 J=1,JMAX
      IF(THETL(I,J).LE.0.0)GO TO 50
      ASTAR=AEXIT/AOAS(I,J)
      POMAX=1.88*WMAX*SQRT(TO)/ASTAR
      IF(POMAX.GT.PCMAX)POMAX=PCMAX
      DENOM(I,J)=XME(I,J)**A*GAMAJ**B
C*    THE FOLLOWING STATEMENTS CALCULATE SPMAX
      PCUOPI(I,J)=POMAX/PI(K)
      PCUOPB(I,J)=PCUOPI(I,J)/PBOPI(K)
C*    MACH NUMBER ON THE JET BOUNDARY - MAXIMUM
      CALL MACH(GAMAJ,PCUOPB(I,J),XMJMAX(I,J))
C*    JET BOUNDARY ISENTROPIC EXPANSION ANGLE - MAXIMUM
      CALL PRND(GAMAJ,XMJMAX(I,J),PMJMAX(I,J))
C*    PLUME BOUNDARY INITIAL EXPANSION ANGLE - MAXIMUM
      DELJMX(I,J)=THETL(I,J)+PMJMAX(I,J)-PME(I,J)
      SPMAX(I,J)=XMJMAX(I,J)*DELJMX(I,J)/DENOM(I,J)
C*    THE FOLLOWING STATEMENTS CALCULATE SPMIN
      PCLOPB(I,J)=PCOPE(I,J)*PEPBMN
C*    MACH NUMBER ON THE JET BOUNDARY - MINIMUM
      CALL MACH(GAMAJ,PCLOPB(I,J),XMJMIN(I,J))
C*    JET BOUNDARY ISENTROPIC EXPANSION ANGLE - MINIMUM
      CALL PRND(GAMAJ,XMJMIN(I,J),PMJMIN(I,J))
C*    PLUME BOUNDARY INITIAL EXPANSION ANGLE - MINIMUM
      DELJMN(I,J)=THETL(I,J)+PMJMIN(I,J)-PME(I,J)
      SPMIN(I,J)=XMJMIN(I,J)*DELJMN(I,J)/DENOM(I,J)
      IF(SPI(K).GT.SPMIN(I,J)+5.0.AND.SPI(K).LT.SPMAX(I,J)-5.0)GO TO 40
      GO TO 50
   40 CONTINUE
```

Subroutine SPRNGE (Cont'd)

```
      IF(NPRINT.EQ.0)GO TO 45
      WRITE(6,3)XME(I,J),THETL(I,J),SPMIN(I,J),SPMAX(I,J),POMAX
   45 CONTINUE
      JJ=JJ+1
      NP(I,K)=NP(I,K)+1
      XMED(I,JJ,K)=XME(I,J)
      THETLD(I,JJ,K)=THETL(I,J)
   50 CONTINUE
  100 CONTINUE
 1000 CONTINUE
      RETURN
      END


      SUBROUTINE TEST
      DIMENSION XMEDF(5),THLDF(5),AOASF(5),DSTARF(5),SAVE(8)
      COMMON/CO1/GAMAJ,GAMAE,GAMAI,PATM,A,B
      COMMON/CO2/PCMAX,PEPBMN,PC
      COMMON/CO4/SP1(20),PBOPI(20),XMI(20),PI(20)
      COMMON/CO7/SCALE,PEXITD,WMAX,TO
      COMMON/TEST1/XMEL,XMER,THLB,THLT,THUT,THUB,KMAX
      COMMON/TEST2/NNOZF
    1 FORMAT(1H0,1X,'POWER SWEEP OPERATING CHARACTERISTICS FOR EACH OF T
     $HE DESIRED FLIGHT CONDITIONS TO BE SIMULATED IN WIND TUNNEL'/2X,'T
     $ESTS IS PRESENTED BELOW FOR REPRESENTATIVE NOZZLES THAT EXIST IN T
     $HE FINAL ENVELOPE DEFINED ABOVE.')
    2 FORMAT(1H0,11H ITSUB WNC 8E10.5)
    3 FORMAT(1H0,1X,' NOZZLE       MEXIT    LIP ANGLE     MINF      PCMIN
     $ SPMIN      PCNOM      SPNOM      PCMAX      SPMAX    WIND TUNNEL  DSTA
     $R       DEXIT'/105X,'PINF')
    4 FORMAT(1H0)
    5 FORMAT(1X,I5,5X,9E10.5,1X,3E10.5)
    6 FORMAT(1H0,1X,'MJETF IS SUBSONIC AND TEMPORARILY SET = 1.10')
C*    THIS SUBROUTINE DETERMINES THE POWER SWEEP OPERATING CHARACTERIS-
C*    TICS OF REPRESENTATIVE NOZZLES THAT EXIST IN THE FINAL ENVELOPE
C*    FOR EACH OF THE DESIRED FLIGHT CONDITIONS TO BE SIMULATED IN WIND
C*    TUNNEL TESTS.
      WRITE(6,1)
      WRITE(6,3)
      XMEDF(1)=(XMEL+XMER)/2.0
      XMEDF(2)=XMEDF(1)
      XMEDF(3)=XMEDF(1)
      XMEDF(4)=XMEL
      XMEDF(5)=XMER
      THLDF(2)=(THLT+THUT)/2.0
      THLDF(3)=(THLB+THUB)/2.0
      THLDF(1)=(THLDF(2)+THLDF(3))/2.0
      THLDF(4)=(THLB+THLT)/2.0
      THLDF(5)=(THUB+THUT)/2.0
      EXITD=SCALE*PEXITD
      AEXIT=(3.14159*EXITD**2.0)/4.0
      DO 1001 I=1,NNOZF
      WRITE(6,4)
C*    NOZZLE EXIT PLANE AREA RATIO   AE/A*
      CALL ARATIO(GAMAE,XMEDF(I),AOASF(I))
      ASTAR=AEXIT/AOASF(I)
      DSTARF(I)=EXITD/SQRT(AOASF(I))
C*    MAXIMUM ALLOWABLE CHAMBER PRESSURE FOR A GIVEN NOZZLE SUBJECT TO
C*    THE TEST FACILITY MASS FLOW CAPABILITY
```

Subroutine TEST (Cont'd)

```
      POMAX=1.88*WMAX*SQRT(TO)/ASTAR
      DENOMF=XMEDF(I)**A*GAMAJ**B
C*    THE FOLLOWING STATEMENTS CALCULATE SPMIN
C*    NOZZLE LIP ISENTROPIC EXPANSION ANGLE
      CALL PRND(GAMAE,XMEDF(I),PMEF)
C*    NOZZLE EXIT PLANE PRESSURE RATIO   PC/PE
      CALL PRATIO(GAMAE,XMEDF(I),PCOPEF)
      PCLPBF=PCOPEF*PEPBMN
C*    MACH NUMBER ON JET BOUNDARY - MINIMUM
      CALL MACH(GAMAJ,PCLPBF,XMJMNF)
C*    JET BOUNDARY ISENTROPIC EXPANSION ANGLE - MINIMUM
      CALL PRND(GAMAJ,XMJMNF,PMJMNF)
C*    PLUME BOUNDARY INITIAL EXPANSION ANGLE - MINIMUM
      DEJMNF=THLDF(I)+PMJMNF-PMEF
      SPMINF=XMJMNF*DEJMNF/DENOMF
      DO 1000 K=1,KMAX
C*    THE FOLLOWING STATEMENTS CALCULATE SPMAX
      PCOPIF=POMAX/PI(K)
      PCOPBF=PCOPIF/PBOPI(K)
C*    MACH NUMBER ON JET BOUNDARY - MAXIMUM
      CALL MACH(GAMAJ,PCOPBF,XMJMXF)
C*    JET BOUNDARY ISENTROPIC EXPANSION ANGLE - MAXIMUM
      CALL PRND(GAMAJ,XMJMXF,PMJMXF)
C*    PLUME BOUNDARY INITIAL EXPANSION ANGLE - MAXIMUM
      DEJMXF=THLDF(I)+PMJMXF-PMEF
      SPMAXF=XMJMXF*DEJMXF/DENOMF
C*    MINIMUM CHAMBER PRESSURE REQUIRED TO PREVENT FLOW SEPARATION
      POMIN=PCLPBF*PBOPI(K)*PI(K)
C*    THE FOLLOWING STATEMENTS CALCULATE THE REQUIRED CHAMBER PRESSURE
C*    TO SIMULATE THE DESIRED FLIGHT CONDITIONS
      XMJF=1.1*XMEDF(I)
  160 CONTINUE
      SAVE(1)=1.0
      SAVE(2)=.10
      TOL=.05
  170 CONTINUE
C*    JET BOUNDARY ISENTROPIC EXPANSION ANGLE
      CALL PRND(GAMAJ,XMJF,PMJF)
C*    PLUME BOUNDARY INITIAL EXPANSION ANGLE
      DELJF=(SP1(K)/XMJF)*DENOMF
C*    NOZZLE LIP ANGLE
      THETLP=DELJF+PMEF-PMJF
      DTHETL=THLDF(I)-THETLP
      CALL ITSUB(DTHETL,XMJF,SAVE,TOL,199)
      II=IFIX(SAVE(1)+.10)
      NI=IFIX(SAVE(3)+.10)
      IF(XMJF.GT.1.0)GO TO 11
      XMJF=1.10
      WRITE(6,6)
      GO TO 180
   11 CONTINUE
      GO TO(170,170,170,170,180,175),II
  175 CONTINUE
      WRITE(6,2)THLDF(I),THETLP,XMJF,DELJF
  180 CONTINUE
C*    PLUME BOUNDARY PRESSURE RATIO   PC/PB
      CALL PRATIO(GAMAJ,XMJF,PCOPBF)
      PONOM=PCOPBF*PBOPI(K)*PI(K)
      WRITE(6,5)I,XMEDF(I),THLDF(I),XMI(K),POMIN,SPMINF,PONOM,SP1(K),
     $POMAX,SPMAXF,PI(K),DSTARF(I),EXITD
 1000 CONTINUE
 1001 CONTINUE
      RETURN
      END
```

```
      SUBROUTINE XYLIM (SMIN,SMAX,UU,YB,YT,DY,MM,DD,NY)
      COMMON XN,YN,ZN
      REAL INC
      INTEGER UU,DD
      NN=0
      IF(UU.EQ.5)GOTO65
      IF (UU.EQ.1) GO TO 70
      YT=0.0
      YB=0.0
      XINC=(SMAX-SMIN)/10.0
      IF(XINC.LT.1.0.AND.XINC.GE.0.06) GO TO 30
      IF(XINC.LT.0.06) GO TO 65
      DO 10 I=1,50
      NN=I-1
      XN=.5
      IF(2.*10.**(I-1).GT.XINC) GO TO 20
      XN=1.
      IF(5.*10.**(I-1).GT.XINC) GO TO 20
      XN=2.
      IF(1.*10.**(I).GT.XINC) GO TO 20
   10 CONTINUE
   20 INC=XN*10.**NN
      GO TO 60
   30 DIFF=XINC*10.0
      NN=NN+1
      INC=.02
      IF(DIFF.GT.1.5) INC=.05
      IF(DIFF.GT.3.0) INC=.1
      IF(DIFF.GT.7.0) INC=.2
   60 CONTINUE
      YT=SMAX+AMOD(ABS(SMAX),(INC*5.))
      YB=SMIN-AMOD(ABS(SMIN),(INC*5.))
      IF(SMAX.GT.0.0) YT=SMAX+ABS(AMOD(ABS(SMAX),(INC*5.))-(INC*5.))
      IF(SMIN.LT.0.0) YB=SMIN-ABS(AMOD(ABS(SMIN),(INC*5.))-(INC*5.))
      DY=INC
      MM=5
      DD=10
      NY=NN+3
      GO TO 100
   65 CONTINUE
      A=SMAX*10.
      A=IFIX(A)
      YT=A/10.+0.1
      A=SMIN*10.
      A=IFIX(A)
      YB=A/10.
      INC=0.01
      GOTO60
   70 DO 80 I=1,20
C     LOG SCALES
C     THE SMALLEST VALUE FOR SMAX IS 10**-4
      NNN=I-5
   80 IF(SMAX.LT.10.**NNN)GO TO 9
    9 YT=10.0**NNN
      DO 90 I=1,20
      NNN=10-I
C     THE LARGEST VALUE FOR SMIN IS 10**9
   90 IF(SMIN.GT.10.0**NNN)GO TO 91
   91 YB=10.0**NNN
      DY=1.0
      MM=1
      DD=1
      NY=-2
      CALL SMXYV (0,1)
  100 CONTINUE
      RETURN
      END
```