EXTENDED PARAMETRIC REPRESENTATION OF COMPRESSOR FANS AND TURBINES

Volume I - CMGEN User's Manual
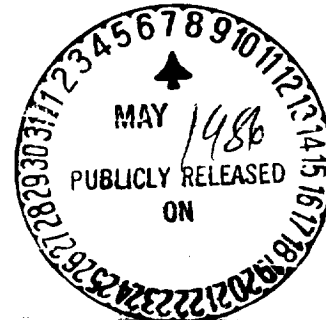
FINAL REPORT

March 1984

By
General Electric Company
Aircraft Engine Business Group
Advanced Technology Programs Dept.
Cincinnati, Ohio 45215

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16. Abstract

A modeling technique for fans, boosters, and compressors has been developed which will enable the user to obtain consistent and rapid off-design performance from design point input. The fans and compressors are assumed to be multi-stage machines incorporating front variable stators. The boosters are assumed to be fixed geometry machines. The modeling technique has been incorporated into a time sharing program to facilitate its use. Because this report contains a description of the input output data, values of typical inputs, and example cases, it is suitable as a user's manual. This report is the first of a three volume set describing the parametric representation of compressors, fans, and turbines. The titles of the three volumes are given below:

(1) Volume I   CMGEN USER's Manual (Parametric Compressor Generator)
(2) Volume II PART USER's Manual (Parametric Turbine)
(3) Volume III MODFAN USER's Manual (Parametric Modulating Flow Fan)

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TABLE OF CONTENTS

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LIST OF TABLES

1.0 INTRODUCTION

The NASA Lewis Research Center employs a general computer program, NNEP, (Reference 1) for calculating the thermodynamic performance of jet propulsion engines. To calcualte off-design engine performance, the user of NNEP must input component maps defining the characteristics of the various components over their full range of operating conditions.

For early cycle analysis of advanced propulsion systems, these map characteristics are not generally known because the geometry of the component has not been specified. Furthermore, the typical user of the program is not sufficiently knowledgeable and/or cannot afford the time to do an extensive design followed by an off-design analysis of the component in question to define the map characteristics. Typically, in this early stage, the user scales some available map.

The available methods for scaling maps can lead to significant errors in component representations. A traditional method of scaling a compressor map retains the flow speed relation of the base map and applies a constant pressure rise scalar calculated at the design point. Direct scaling of flow size is frequently used. The accuracy of such a procedure can be considerably improved by using parametrically generated component maps. A parametric component representation can be a scaling procedure which uses the key design point parameters to impace the fundamental differences in the map characteristics when generating the component maps.

The subject of this report is the parametric multistage compressor/fan program. The key design point parameters in the CMGEN program are:

1. Pressure ratio
2. Inlet corrected flow per unit area (i.e., inlet Mach Number).
3. Stall margin.

A 12 to 1 pressure ratio map generated by the program CMGEN is shown in Figure 1. A series of maps having different design point pressure ratios but identical inlet specific flows was also generated. The lapse rate (i.e., the flow speed variation) was then plotted along the peak efficiency ridge. Figure 2 shows the effect of design point pressure ratio on lapse rate. The variation in the flow speed with design pressure ratio is due to compressibility and associated mis-matching.

1

The above discussion illustrates the importance of having changes in design point parameters reflected by corresponding changes in the off-design characteristics of the performance maps. The more complete the parametric system (i.e., the more design point parameters it includes) the closer the calculated off-design performance representation can be to the actual performance.

The computer program CMGEN is an improved method for representing the off-design characteristics of the compression components when performing off-design performance calculations for advanced air-breathing jet engines. It is applicable to multi-stage fans and compressors having variable stators as well as fixed geometry boosters. It can be applied at any level of inlet corrected flow size.

The program uses design point data and semi-emperical correlations as input to generate off-design values of corrected flow, efficiency, and pressure ratio over a range of corrected speeds and pressure ratio parameters specified by the user.

The computer program CMGEN is compatible in both form and format with the cycle program of Reference 1, and the example map representation of Reference 2.

This report contains a description of the input-output data, values of typical inputs, and sample cases, it is suitable as a user's manual. A description giving the background of the engineering analysis used to generate the program is given near the end of the report.

Low T2 Parametric Compressor P/P = 12.0
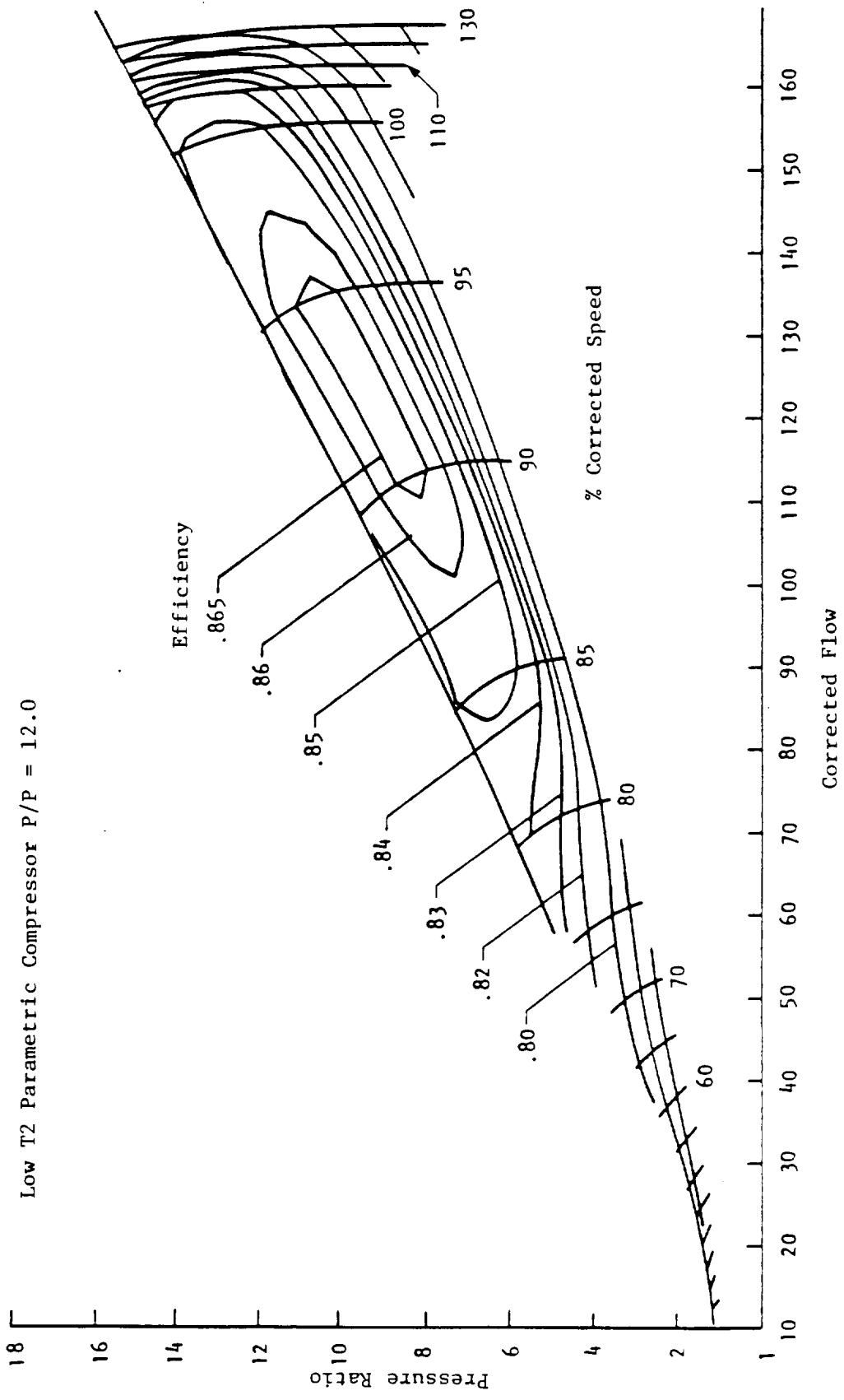
Figure 1. Typical Compressor Map.
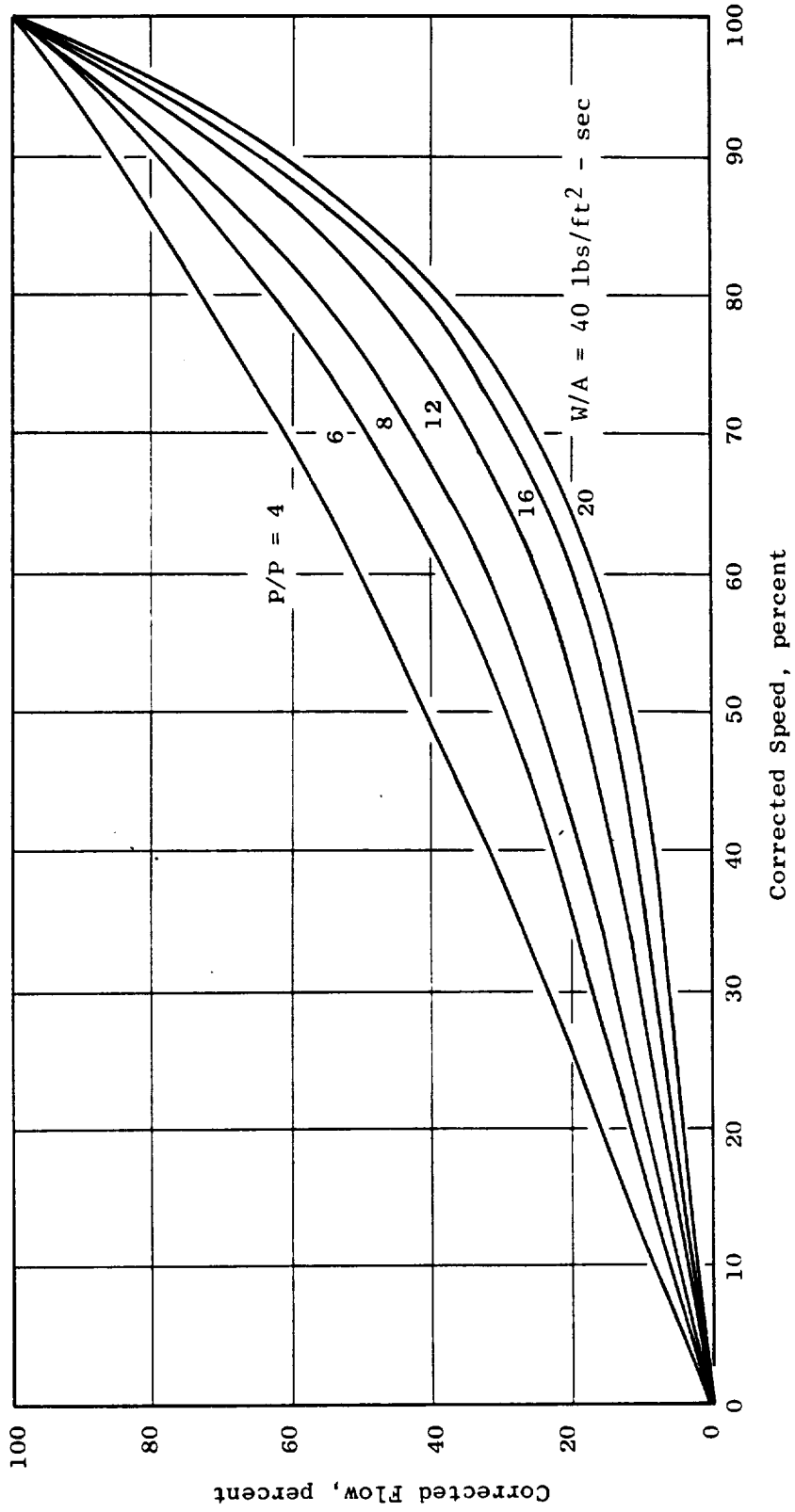
Figure 2. Parametric Map Flow-Speed Relationship (1.0 T2 Schedule).

4

2.0   PROGRAM STRUCTURE

A flow chart showing the flow of control in the computer program CMGEN (Compressor generator) is shown in Figure 3. After the input has been read and processed, the program reads in the set of component base curves selected by the user's setting of the ITYPE switch. These base curves are in NAMELIST form and reside on three external files. The program next carries out a design point calculation in which a number of additional design point values are calculated from the input values. The off-design calculation is then carried out for each value of corrected speed and R selected by the user. This calculation is carried out in the evaluation routine CMPMXX. Finally, the output is written on three files plus an additional output file (File 22) which contains the five base curves discussed in Section 7.1.

Start

Read Namelist Input
* ITYPE, PRDSGN, FLWDGN, WQADGN,
ETADGN, UTRD, STMRGN, NR, AR,
NSPDS, APCNC

Read in
Selected
Component
Correlations

Design Point
Calculation

Off-Design Calculation
* Calculates and Saves the Values of GH
for Constant Speed Stall

(i.e., R = 1 When GH = GHS)

Write Output
File 22 (Base Curves)

Calculate NASA Output
* Calculate GH Values from GHS and R
* Call Evaluation Subroutine to Obtain
Values of Pressure Ratio, Corrected Flow,
and Efficiency (Subroutine CMPMXX)

Write NASA Output
* Subroutine WRTOPT

End

Figure 3. Flow Chart Showing Flow of Control in GMGEN.

6

3.0   PROGRAM INPUTS

All of the CMGEN inputs are of the free-field format (NAMELIST) type, and begin in Column two. There is no specified order to the inputs. The program first gives a brief description of the variables used in the NAMELIST INPUT. The default settings of these variables are then displayed.The user can then enter any changes in the design point values and/or the speed and R arrays. If the user wishes the program to generate a value for the design point efficiency, a zero value should be entered for ETADGN. The program will echo the updated NAMELIST values, then go into execution. Upon completion, the program will display a message to the effect that the NASA output files have been written on file codes 30, 31, and 32. File 22, which is also generated by the program, contains the component base curves which are discussed in section 7.1.

The input variables together with their default settings are listed in TABLE 1.

The first input variable in TABLE 1, ITYPE, is used to determine the type of component desired. The booster is assumed to be a multi-stage fixed geometry machine. Both the fan and compressor are assumed to be multi-stage machines having variable stators. Two sets of flow speed characteristics are generated by the program, a high T2 open stator schedule and a low T2 nominal stator schedule.

The range of design point pressure ratios applicable to each type of is as follows:

ITYPE	Component Type	Pressure Ratio Range	Variable Stator Schedule
1	Fan	2-5	High T2 & Low T2
2	Booster (fixed geometry)	1.2-5	None
3	Core Compressor	4-24	High T2 & Low T2

The next five variables in Table 1 set the key design point parameters. The program will calculate a design point efficiency. A flow size correction is included in the program. The flow size correction was obtained by using the results of a study in which a series of machines differing only in flow size were designed. The efficiency

7

correction is, therefore, an overall correction accounting for all flow sizes effects such as Reynold's number, tip clearance, tolerances, etc.

The last four variables in Table 1 are used to control the number of values of R and speed to be written on the output file. The R values are used to fix a point on a speed line. The R value is unity on the stall line and increases along a constant speed line as the flow increases. The algorithm used in CMGEN forces a value of R equal to two at the min-loss point which is slightly below the peak efficiency on the speed line. The concept of min-loss is discussed in section seven (7).

For example, in the input shown in Figure 4, all of the design point variables have been changed as well as the corrected speed array. The booster map which results is shown in Figure 5. The locus of the R=1 and 2 lines have been indicated on figure 5.

8

TABLE 1.   DEFAULT SETTINGS FOR VARIABLE :
NAMELIST "INPUT"

VARIABLE NAME	UNITS	DEFAULT VALUES	DESCRIPTION
ITYPE	NONE	3	Type of Component 1=Fan, 2=Booster, 3=Compressor
PRDSGN	NONE	12.0	Design point pressure ratio
FLWDGN	pps	155.0	Design point corrected flow
WQADGN	pps/ft^2	40.0	Design point corrected flow per unit annulus area
UTRD	fps	1000.0	Design point corrected first stage rotor tip speed
STMRGN	percent	15.0	Design point constant speed stall margin
NR		11	No.of R values
AR	NONE	1.,1.2,1.4, 1.6,1.8,2.0, 2.2,2.4,2.6, 2.8,3.0	Array of R values
NSPDS		12	No.of corrected speeds
APCNC	NONE	.1,.2,.3,.4, .5,.6,.7,.8, .9,1.0,1.1, 1.2	Array of corrected speeds

PARAMETRIC FAN,BOOSTER,AND COMPRESSOR GENERATOR

VARIABLE NAMES USED IN NAMELIST INPUT

NAME   DESCRIPTION

ITYPE   COMP TYPE:1=FAN,2=BOOSTER,3=COMPRESSOR
            DESIGN POINT VALUE OF:
PRDSGN   PRESSURE RATIO
FLWDGN   CORRECTED FLOW
WQADGN   CORRECTED FLOW PER UNIT ANNULUS AREA
ETADGN   EFFICIENCY
UTRD   CORRECTED FIRST STAGE ROTOR TIP SPEED
STMRGN   CONSTANT SPEED STALL MARGIN

NR   NO OF R VALUES
AR   ARRAY OF R VALUES
NSPDS   NO OF CORRECTED SPEEDS
APCNC   ARRAY OF CORRECTED SPEEDS

NAMELIST   INPUT
 ITYPE=   3
 PRDSGN=   12.██████,   FLWDGN=   1██.██████
 WQADGN=   4█.██████,   ETADGN=   █.861███
 UTRD   =   1███.██████,   STMRGN=   16.██████
 NSPDS =   12,
 APCNC (I)=
    1   █.13████,   █.2█████,   █.3█████,   █.4█████,
    5   █.5█████,   █.6█████,   █.7█████,   █.8█████,
    9   █.9█████,   1.██████,   1.1█████,   1.2█████,
   13   1.3█████,   1.3█████,   1.3█████.
 NR   =   11,
 AR   (I)=
    1   1.██████,   1.2█████,   1.4█████,   1.6█████,
    5   1.8█████,   2.██████,   2.2█████,   2.4█████,
    9   2.6█████,   2.8█████,   3.██████,   3.2█████,
   13   3.2█████,   3.2█████,   3.2█████.
END   NAMELIST
ENTER CHANGES TO NAMELIST INPUT
=$INPUT ITYPE=2,PRDSGN=2.45,FLWDGN=1██.█,WQADGN=33.7,
=ETADGN=█.█,UTRD=869.7,STMRGN=14.34,
=NSPDS/APCNC=.359,.528,.661,.791,.88,.952,1.█,1.█28,1.144$
NAMELIST   INPUT
 ITYPE=   2
 PRDSGN=   2.45████,   FLWDGN=   1██.██████
 WQADGN=   33.7█████,   ETADGN=   █.87█754
 UTRD   =   869.699997,   STMRGN=   14.34████
 NSPDS =   9,
 APCNC (I)=
    1   █.359███,   █.528███,   █.661███,   █.791███,
    5   █.88████,   █.952███,   1.██████,   1.█28███,
    9   1.144███,   1.██████,   1.1█████,   1.2█████,
   13   1.3█████,   1.3█████,   1.3█████,
 NR   =   11,
 AR   (I)=
    1   1.██████,   1.2█████,   1.4█████,   1.6█████,

```
       5        1.800000,       2.000000,        2.200000,        2.400000,
       9        2.600000,       2.800000,        3.000000,        3.200000,
      13        3.200000,       3.200000,        3.200000,
END       NAMELIST
MAP FILE ON TEMP FILE                    22
YOU HAVE CREATED TEMP FILE                        22
NASA OUTPUT ON FILE CODES 30,31,AND 32   &
```

Figure 4. CMGEN Sample Terminal Conversation (Continued).

11
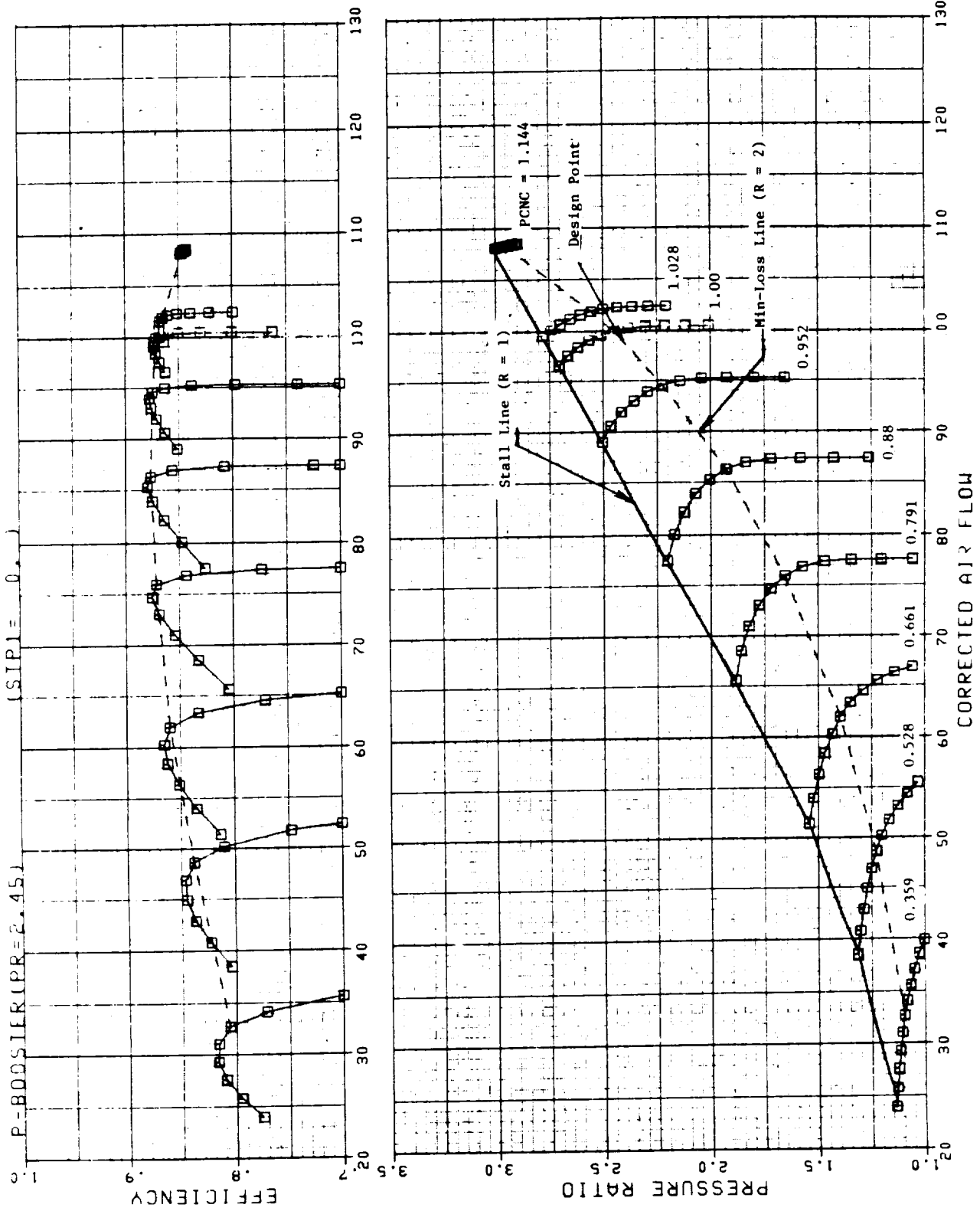
Figure 5. Parametric Booster Performance Map (PR = 2.45).

12

4.0   PROGRAM OUTPUTS

The basic output from the program consists of three tables. These tables show the variation in corrected flow, efficiency, and pressure ratio for each of the stator schedules, R-values, and corrected speeds specified in the input. The low T2 and high T2 stator schedules are written in the output file as pseudo-angle positions of zero and ninety degrees. The output tables for the second default case are shown on pages 19,20, & 21. The table structure is compatible with NASA cycle deck requirements given in Reference 2 (pages A23 and A24).

The output tables can be visualized as three dimensional, composed of a series of planes with each plane assigned a value of pseudo-angle position, ANGL. Then in each ANGL plane, the dependent variable (ordinate axis) is a function of corrected speed, SPED, and R value. The dependent variables are respectively corrected flow, total-to-total efficiency, and pressure ratio.

For example, in the output table on page 24 the 18 lines of the dependent variable correspond to the 9 values of corrected speed, two lines per speed. Within each speed there are 11 R values.

It should be noted that for pressure ratios less than unity the efficiency is negative (see discussion in section 7). These efficiency values are not incorrect, however, the efficiency behavior in this region makes curve fitting and interpolation of efficiency values extremely difficult. For this reason many engine manufacturers use some form of locus or temperature ratio parameter rather than efficiency for interpolation. The solution used here was to simply discard the information below unity pressure ratio and to display the solution for unity pressure ratio for all values of R at which the pressure ratio is less than unity. This means that identical values of pressure ratio (PR=1.0), flow and efficiency (EFF=0.0) will appear in the output table on any speed line where the value of R results in a pressure ratio less than unity.

5.0   PROGRAM DIAGNOSTICS

The CMGEN computer program contains several diagnostic error messages to aid the user in trouble shooting his input. A listing of the error messages and their meanings are given below.

1.   ITERATION COUNTER EXCEEDED, GHS, PQW, PQWS

This fatal error occurs if no stall intersection can be found at the design speed. The program stops. The user should reduce the input value of the stall margin, STMRGN.

2.   FLOW IS ZERO

This fatal error occurs for the same reason as the one above, however, in this case the flow has reached zero before the iteration counter has been exceeded. The input stall margin, STMRGN, should be reduced.

3.   WARNING: NO STALL SOLUTION FOUND AT PCN=, F7.3

This warning error occurs if no stall intersection is found at a speed other than the design speed. Stall is assumed to occur at zero corrected flow. Program continues. The input stall margin should be reduced and/or the range of speeds restricted. If the value of speed displayed by the warning message is outside the range of interest the latter fix can be used.

4.   QIRE CTR ERROR - - (CALLING LINE =, I5)

There is one iteration of this type in the program. This iteration is balanced using the Method of False Position. This method is contained in the subroutine QIREXX. A maximum of 25 passes is allowed for any single iteration to balance. If the iteration does not balance within the specified tolerance, the error message will appear with the statement number of the calling line in the I5 Format field.

This iteration was used to obtain the value of the corrected flow for unity pressure ratio. The value of I5 will be 624. The program will use the largest value of flow obtained in the 25 passes and continue. The user should inspect his output data at

14

unity pressure ratio to see if the flow speed relationship is smooth. The user can restrict the range of R values so that the pressure ratio is always greater than unity.

6.0   EXAMPLE CASES

Two example cases are given in order to illustrate the use of the program. The first case utilizes the default settings to generate the output for a twelve-to-one core compressor. The second case is that of a fixed geometry booster. In both cases the design point is at R=2 and speed=1.

A complete record of the two terminal sessions including a listing of the output tables is given on the following pages. The program inputs and outputs have been discussed in Section 3.0 and 4.0.

PARAMETRIC FAN,BOOSTER,AND COMPRESSOR GENERATOR

VARIABLE NAMES USED IN NAMELIST INPUT

NAME   DESCRIPTION

ITYPE   COMP TYPE:1=FAN,2=BOOSTER,3=COMPRESSOR
            DESIGN POINT VALUE OF:
PRDSGN   PRESSURE RATIO
FLWDGN   CORRECTED FLOW
WQADGN   CORRECTED FLOW PER UNIT ANNULUS AREA
ETADGN   EFFICIENCY
UTRD   CORRECTED FIRST STAGE ROTOR TIP SPEED
STMRGN   CONSTANT SPEED STALL MARGIN

NR   NO OF R VALUES
AR   ARRAY OF R VALUES
NSPDS   NO OF CORRECTED SPEEDS
APCNC   ARRAY OF CORRECTED SPEEDS

NAMELIST   INPUT
 ITYPE=   3
 PRDSGN=   12.000000,   FLWDGN=   155.000000
 WQADGN=   40.000000,   ETADGN=   0.851000
 UTRD   =   1000.000000,   STMRGN=   15.000000
 NSPDS =   12,
 APCNC (I)=
     1   0.100000,   0.200000,   0.300000,   0.400000,
     5   0.500000,   0.600000,   0.700000,   0.800000,
     9   0.900000,   1.000000,   1.100000,   1.200000,
    13   1.300000,   1.300000,   1.300000,
 NR   =   11,
 AR   (I)=
     1   1.000000,   1.200000,   1.400000,   1.600000,
     5   1.800000,   2.000000,   2.200000,   2.400000,
     9   2.600000,   2.800000,   3.000000,   3.200000,
    13   3.200000,   3.200000,   3.200000,
END   NAMELIST
ENTER CHANGES TO NAMELIST INPUT
=$INPUTS
NAMELIST   INPUT
 ITYPE=   3
 PRDSGN=   12.000000,   FLWDGN=   155.000000
 WQADGN=   40.000000,   ETADGN=   0.851000
 UTRD   =   1000.000000,   STMRGN=   15.000000
 NSPDS =   12,
 APCNC (I)=
     1   0.100000,   0.200000,   0.300000,   0.400000,
     5   0.500000,   0.600000,   0.700000,   0.800000,
     9   0.900000,   1.000000,   1.100000,   1.200000,
    13   1.300000,   1.300000,   1.300000,
 NR   =   11,
 AR   (I)=
     1   1.000000,   1.200000,   1.400000,   1.600000,
     5   1.800000,   2.000000,   2.200000,   2.400000,
     9   2.600000,   2.800000,   3.000000,   3.200000,

```
    13       3.200000,      3.200000,       3.200000,
END       NAMELIST
MAP FILE ON TEMP FILE                  22
YOU HAVE CREATED TEMP FILE               22
NASA OUTPUT ON FILE CODES 30,31,AND 32   &
```

18

```
3001        P-COMPRESSOR FLOW VS. R. SPEED. AND ANGL
ANGL  2     0.0        90.000
SPED 12     0.100      0.200      0.300      0.400      0.500      0.600      0.700
SPED 12     0.800      0.900      1.000      1.100      1.200
R    11     1.000      1.200      1.400      1.600      1.800      2.000      2.200
R    11     2.400      2.600      2.800      3.000
FLOW 11     2.4243     2.9874     3.5304     4.0500     4.5433     5.0076     5.4409
FLOW 11     5.4605     5.4605     5.4605     5.4605
FLOW 11     6.9268     7.5854     8.2244     8.8427     9.4389     10.0118    10.5604
FLOW 11     10.9181    10.9181    10.9181    10.9181
FLOW 11     12.4354    13.1153    13.7702    14.3993    15.0017    15.5768    16.1241
FLOW 11     16.6431    17.1334    17.1476    17.1476
FLOW 11     17.8595    18.6732    19.4455    20.1754    20.8623    21.5058    22.1053
FLOW 11     22.6609    23.1725    23.5855    23.5855
FLOW 11     24.1855    25.2298    26.1979    27.0890    27.9027    28.6390    29.2984
FLOW 11     29.8818    30.3903    30.8255    30.9835
FLOW 11     33.6833    34.6643    35.5577    36.3640    37.0838    37.7187    38.2697
FLOW 11     38.7389    39.1283    39.4404    39.6777
FLOW 11     47.3011    48.1558    48.9154    49.5821    50.1577    50.6441    51.0438
FLOW 11     51.3595    51.5938    51.7498    51.8306
FLOW 11     68.6262    69.5158    70.2900    70.9513    71.5025    71.9469    72.2876
FLOW 11     72.5280    72.6721    72.7235    72.7238
FLOW 11     107.5632   108.9274   110.0945   111.0690   111.8568   112.4642   112.8965
FLOW 11     113.1608   113.2641   113.2660   113.2660
FLOW 11     152.8882   153.4332   153.9158   154.3369   154.6978   154.9999   155.2434
FLOW 11     155.4298   155.5605   155.6367   155.6595
FLOW 11     162.7337   162.8315   162.9242   163.0103   163.0921   163.1680   163.2384
FLOW 11     163.3034   163.3629   163.4173   163.4664
FLOW 11     168.3818   168.3885   168.3941   168.4001   168.4058   168.4113   168.4162
FLOW 11     168.4215   168.4262   168.4304   168.4345
SPED 12     0.100      0.200      0.300      0.400      0.500      0.600      0.700
SPED 12     0.800      0.900      1.000      1.100      1.200
R    11     1.000      1.200      1.400      1.600      1.800      2.000      2.200
R    11     2.400      2.600      2.800      3.000
FLOW 11     5.9010     6.4179     6.9201     7.4065     7.8761     8.3284     8.7624
FLOW 11     9.0820     9.0820     9.0820     9.0820
FLOW 11     15.3025    15.7660    16.2153    16.6501    17.0703    17.4756    17.8659
FLOW 11     18.2410    18.6010    18.9455    19.2401
FLOW 11     25.0730    25.2443    25.4121    25.5766    25.7378    25.8956    26.0500
FLOW 11     26.2011    26.3489    26.4933    26.6343
FLOW 11     35.2710    35.6607    36.0294    36.3775    36.7050    37.0123    37.2992
FLOW 11     37.5658    37.8129    38.0403    38.2483
FLOW 11     46.5366    46.9060    47.2493    47.5667    47.8588    48.1257    48.3680
FLOW 11     48.5856    48.7794    48.9494    49.0964
FLOW 11     59.6975    60.0498    60.3728    60.6669    60.9329    61.1710    61.3811
FLOW 11     61.5645    61.7212    61.8518    61.9570
FLOW 11     76.3187    76.7204    77.0834    77.4080    77.6957    77.9466    78.1612
FLOW 11     78.3404    78.4850    78.5957    78.6731
FLOW 11     97.4995    98.0523    98.5455    98.9795    99.3559    99.6760    99.9403
FLOW 11     100.1504   100.3072   100.4128   100.4677
FLOW 11     125.6839   126.5036   127.2202   127.8359   128.3531   128.7742   129.1008
FLOW 11     129.3362   129.4829   129.5431   129.5451
FLOW 11     152.9693   153.4906   153.9540   154.3589   154.7070   154.9999   155.2371
FLOW 11     155.4207   155.5515   155.6309   155.6596
FLOW 11     162.7337   162.8315   162.9242   163.0103   163.0921   163.1680   163.2384
FLOW 11     163.3034   163.3631   163.4173   163.4664
FLOW 11     168.3817   168.3885   168.3941   168.4000   168.4058   168.4113   168.4162
FLOW 11     168.4215   168.4262   168.4304   168.4345
EOT
```

3002   P-COMPRESSOR EFF VS. R. SPEED, AND ANGL

Label	N							
ANGL	2	0.0	90.000					
SPED	12	0.100	0.200	0.300	0.400	0.500	0.600	0.700
SPED	12	0.800	0.900	1.000	1.100	1.200		
R	11	1.000	1.200	1.400	1.600	1.800	2.000	2.200
R	11	2.400	2.600	2.800	3.000			
EFF	11	0.8597	0.8364	0.8039	0.7992	0.7682	0.6713	0.0996
EFF	11	0.0	0.0	0.0	0.0			
EFF	11	0.8086	0.8037	0.7972	0.7797	0.7435	0.6713	0.4499
EFF	11	0.0	0.0	0.0	0.0			
EFF	11	0.7976	0.7897	0.7769	0.7573	0.7280	0.6840	0.5976
EFF	11	0.4126	0.0256	0.0	0.0			
EFF	11	0.7942	0.7857	0.7734	0.7559	0.7315	0.6974	0.6371
EFF	11	0.5221	0.3161	0.0	0.0			
EFF	11	0.7934	0.7864	0.7761	0.7615	0.7413	0.7136	0.6647
EFF	11	0.5729	0.4162	0.1547	0.0			
EFF	11	0.7900	0.7842	0.7763	0.7657	0.7519	0.7342	0.7051
EFF	11	0.6544	0.5759	0.4606	0.2952			
EFF	11	0.7992	0.7953	0.7900	0.7831	0.7743	0.7635	0.7460
EFF	11	0.7163	0.6721	0.6107	0.5286			
EFF	11	0.8286	0.8276	0.8255	0.8222	0.8177	0.8116	0.8002
EFF	11	0.7789	0.7463	0.7012	0.6418			
EFF	11	0.8528	0.8590	0.8632	0.8654	0.8652	0.8626	0.8489
EFF	11	0.8145	0.7575	0.6756	0.5664			
EFF	11	0.8519	0.8532	0.8538	0.8536	0.8527	0.8510	0.8450
EFF	11	0.8347	0.8171	0.7929	0.7617			
EFF	11	0.8088	0.8084	0.8077	0.8067	0.8054	0.8037	0.8008
EFF	11	0.7955	0.7878	0.7776	0.7649			
EFF	11	0.7587	0.7578	0.7569	0.7558	0.7547	0.7534	0.7518
EFF	11	0.7494	0.7462	0.7423	0.7377			
SPED	12	0.100	0.200	0.300	0.400	0.500	0.600	0.700
SPED	12	0.800	0.900	1.000	1.100	1.200		
R	11	1.000	1.200	1.400	1.600	1.800	2.000	2.200
R	11	2.400	2.600	2.800	3.000			
EFF	11	0.8038	0.8030	0.7954	0.7771	0.7410	0.6713	0.4691
EFF	11	0.0	0.0	0.0	0.0			
EFF	11	0.7807	0.7703	0.7569	0.7396	0.7172	0.6884	0.6431
EFF	11	0.5692	0.4509	0.2651	0.0			
EFF	11	0.7411	0.7353	0.7291	0.7225	0.7153	0.7075	0.6986
EFF	11	0.6879	0.6753	0.6605	0.6434			
EFF	11	0.7706	0.7648	0.7583	0.7508	0.7423	0.7328	0.7204
EFF	11	0.7032	0.6805	0.6518	0.6159			
EFF	11	0.7845	0.7804	0.7758	0.7705	0.7646	0.7580	0.7494
EFF	11	0.7372	0.7212	0.7010	0.6761			
EFF	11	0.8053	0.8026	0.7995	0.7960	0.7920	0.7875	0.7811
EFF	11	0.7726	0.7607	0.7457	0.7272			
EFF	11	0.8350	0.8337	0.8320	0.8298	0.8272	0.8241	0.8191
EFF	11	0.8107	0.7989	0.7832	0.7636			
EFF	11	0.8576	0.8582	0.8581	0.8573	0.8558	0.8535	0.8480
EFF	11	0.8367	0.8193	0.7953	0.7645			
EFF	11	0.8611	0.8639	0.8656	0.8661	0.8655	0.8635	0.8560
EFF	11	0.8383	0.8099	0.7699	0.7178			
EFF	11	0.8522	0.8533	0.8538	0.8536	0.8527	0.8510	0.8461
EFF	11	0.8355	0.8189	0.7960	0.7665			
EFF	11	0.8088	0.8084	0.8077	0.8067	0.8054	0.8037	0.8008
EFF	11	0.7955	0.7878	0.7776	0.7649			
EFF	11	0.7587	0.7578	0.7569	0.7558	0.7547	0.7534	0.7518
EFF	11	0.7494	0.7462	0.7423	0.7377			
EOT								

```
3003        P-COMPRESSOR PR VS. R. SPEED. AND ANGL
ANGL  2       0.0         90.000
SPED 12       0.100      0.200      0.300      0.400      0.500      0.600      0.700
SPED 12       0.800      0.900      1.000      1.100      1.200
R    11       1.000      1.200      1.400      1.600      1.800      2.000      2.200
R    11       2.400      2.600      2.800      3.000
PR   11       1.0578     1.0480     1.0384     1.0305     1.0220     1.0128     1.0009
PR   11       1.0000     1.0000     1.0000     1.0000
PR   11       1.1650     1.1431     1.1215     1.0991     1.0759     1.0519     1.0238
PR   11       1.0000     1.0000     1.0000     1.0000
PR   11       1.2962     1.2637     1.2309     1.1977     1.1641     1.1303     1.0933
PR   11       1.0505     1.0023     1.0000     1.0000
PR   11       1.5356     1.4807     1.4259     1.3711     1.3165     1.2622     1.2041
PR   11       1.1387     1.0672     1.0000     1.0000
PR   11       1.9816     1.8846     1.7883     1.6930     1.5988     1.5061     1.4075
PR   11       1.2972     1.1780     1.0527     1.0000
PR   11       2.6731     2.5349     2.3984     2.2637     2.1312     2.0012     1.8640
PR   11       1.7121     1.5493     1.3794     1.2064
PR   11       3.7448     3.5620     3.3810     3.2023     3.0260     2.8527     2.6697
PR   11       2.4670     2.2491     2.0207     1.7870
PR   11       5.4863     5.2552     5.0232     4.7910     4.5592     4.3284     4.0769
PR   11       3.7868     3.4657     3.1218     2.7637
PR   11       9.1205     8.8537     8.5563     8.2309     7.8801     7.5072     7.0115
PR   11       6.3163     5.4701     4.5316     3.5655
PR   11      13.6119    13.3192    13.0106    12.6872    12.3500    12.0000    11.5766
PR   11      11.0268    10.3644     9.6063     8.7719
PR   11      14.6504    14.3973    14.1379    13.8726    13.6018    13.3257    13.0157
PR   11      12.6453    12.2183    11.7393    11.2136
PR   11      15.2538    15.0727    14.8897    14.7050    14.5187    14.3307    14.1305
PR   11      13.9080    13.6640    13.3993    13.1150
SPED 12       0.100      0.200      0.300      0.400      0.500      0.600      0.700
SPED 12       0.800      0.900      1.000      1.100      1.200
R    11       1.000      1.200      1.400      1.600      1.800      2.000      2.200
R    11       2.400      2.600      2.800      3.000
PR   11       1.1080     1.0947     1.0807     1.0663     1.0513     1.0357     1.0175
PR   11       1.0000     1.0000     1.0000     1.0000
PR   11       1.3006     1.2740     1.2473     1.2205     1.1936     1.1667     1.1381
PR   11       1.1066     1.0724     1.0355     1.0000
PR   11       1.4875     1.4698     1.4522     1.4346     1.4171     1.3997     1.3819
PR   11       1.3636     1.3447     1.3253     1.3053
PR   11       2.2703     2.2060     2.1421     2.0788     2.0160     1.9539     1.8900
PR   11       1.8222     1.7508     1.6764     1.5993
PR   11       3.1211     3.0303     2.9402     2.8509     2.7623     2.6746     2.5843
PR   11       2.4880     2.3864     2.2802     2.1701
PR   11       4.1121     4.0014     3.8911     3.7814     3.6725     3.5642     3.4519
PR   11       3.3312     3.2028     3.0677     2.9267
PR   11       5.4241     5.2863     5.1479     5.0091     4.8702     4.7311     4.5828
PR   11       4.4172     4.2359     4.0405     3.8329
PR   11       7.3013     7.1247     6.9431     6.7568     6.5663     6.3720     6.1498
PR   11       5.8782     5.5626     5.2088     4.8237
PR   11      10.4205    10.1680     9.8971     9.6091     9.3052     8.9870     8.5879
PR   11       8.0516     7.3984     6.6530     5.8434
PR   11      13.5715    13.2850    12.9837    12.6685    12.3402    12.0000    11.5904
PR   11      11.0611    10.4246     9.6964     8.8939
PR   11      14.6504    14.3973    14.1379    13.8726    13.6018    13.3257    13.0157
PR   11      12.6453    12.2183    11.7393    11.2136
PR   11      15.2538    15.0727    14.8897    14.7050    14.5187    14.3307    14.1305
PR   11      13.9080    13.6640    13.3993    13.1150
EDT
```

PARAMETRIC FAN,BOOSTER,AND COMPRESSOR GENERATOR

VARIABLE NAMES USED IN NAMELIST INPUT

NAME   DESCRIPTION

ITYPE   COMP TYPE:1=FAN,2=BOOSTER,3=COMPRESSOR
            DESIGN POINT VALUE OF:
PRDSGN   PRESSURE RATIO
FLWDGN   CORRECTED FLOW
WQADGN   CORRECTED FLOW PER UNIT ANNULUS AREA
ETADGN   EFFICIENCY
UTRD   CORRECTED FIRST STAGE ROTOR TIP SPEED
STMRGN   CONSTANT SPEED STALL MARGIN

NR   NO OF R VALUES
AR   ARRAY OF R VALUES
NSPDS   NO OF CORRECTED SPEEDS
APCNC   ARRAY OF CORRECTED SPEEDS

NAMELIST   INPUT
 ITYPE=   3
 PRDSGN=   12.000000,   FLWDGN=   155.000000
 WQADGN=   40.000000,   ETADGN=   0.851000
 UTRD   =   1000.000000,   STMRGN=   16.000000
 NSPDS =   12,
 APCNC (I)=
      1   0.100000,   0.200000,   0.300000,   0.400000,
      6   0.500000,   0.600000,   0.700000,   0.800000,
      9   0.900000,   1.000000,   1.100000,   1.200000,
     13   1.300000,   1.300000,   1.300000,
 NR   =   11,
 AR   (I)=
      1   1.000000,   1.200000,   1.400000,   1.600000,
      5   1.800000,   2.000000,   2.200000,   2.400000,
      9   2.600000,   2.800000,   3.000000,   3.200000,
     13   3.200000,   3.200000,   3.200000,
END   NAMELIST
ENTER CHANGES TO NAMELIST INPUT
=$INPUT ITYPE=2,PRDSGN=2.45,FLWDGN=288.5,WQADGN=33.7,
=ETADGN=.844,UTRD=869.7,STMRGN=14.34,
=NSPDS/APCNC=.359,.528,.661,.791,.88,.952,1.0,1.028,1.144$
NAMELIST   INPUT
 ITYPE=   2
 PRDSGN=   2.450000,   FLWDGN=   288.500000
 WQADGN=   33.700000,   ETADGN=   0.844000
 UTRD   =   869.699997,   STMRGN=   14.340000
 NSPDS =   9,
 APCNC (I)=
      1   0.359000,   0.528000,   0.661000,   0.791000,
      5   0.880000,   0.952000,   1.000000,   1.028000,
      9   1.144000,   1.000000,   1.100000,   1.200000,
     13   1.300000,   1.300000,   1.300000,
 NR   =   11,
 AR   (I)=
      1   1.000000,   1.200000,   1.400000,   1.600000,

22

```
        5        1.000000,        2.000000,            2.200000,            2.400000,
        9        2.600000,        2.800000,            3.000000,            3.200000,
       13        3.200000,        3.200000,            3.200000,
END        NAMELIST
MAP FILE ON TEMP FILE                       22
YOU HAVE CREATED TEMP FILE                       22
NASA OUTPUT ON FILE CODES 30,31,AND 32    &
```

```
2001        P-BOOSTER FLOW VS. R. SPEED. AND ANGL
ANGL   1       0.0
SPED   9       0.359     0.528     0.661     0.791     0.880     0.952     1.000
SPED   9       1.028     1.144
R     11       1.000     1.200     1.400     1.600     1.800     2.000     2.200
R     11       2.400     2.600     2.800     3.000
FLOW  11      69.3296   74.5637   79.6694   84.6391   89.4656   94.1431   98.6653
FLOW  11     103.0265  107.2229  111.2497  114.6824
FLOW  11     111.3183  117.7914  123.9229  129.7021  135.1212  140.1741  144.8552
FLOW  11     149.1636  153.0977  156.6591  159.8508
FLOW  11     148.4324  155.7878  162.4920  168.5404  173.9307  178.6670  182.7580
FLOW  11     186.2159  189.0569  191.3010  192.9713
FLOW  11     189.8559  198.0533  205.0578  210.8891  215.5753  219.1571  221.6829
FLOW  11     223.2093  223.7980  223.8097  223.8097
FLOW  11     224.2483  231.3824  237.3943  242.3121  246.1686  249.0090  250.8790
FLOW  11     251.8331  251.9902  251.9902  251.9902
FLOW  11     257.2646  261.7246  265.4973  268.6003  271.0571  272.8899  274.1228
FLOW  11     274.7837  274.9211  274.9211  274.9211
FLOW  11     279.0522  281.6934  283.9485  285.8279  287.3408  288.4990  289.3119
FLOW  11     289.7942  289.9558  289.9561  289.9561
FLOW  11     287.3101  289.1123  290.6746  292.0032  293.1016  293.9771  294.6343
FLOW  11     295.0789  295.3181  295.3667  295.3667
FLOW  11     311.8733  312.0000  312.1238  312.2412  312.3530  312.4617  312.5637
FLOW  11     312.6604  312.7522  312.8386  312.9202
EOT
```

2002   P-BOOSTER EFF VS. R. SPEED. AND ANGL

ANGL	1	0.0						
SPED	9	0.359	0.528	0.661	0.791	0.880	0.952	1.000
SPED	9	1.028	1.144					
R	11	1.000	1.200	1.400	1.600	1.800	2.000	2.200
R	11	2.400	2.600	2.800	3.000			
EFF	11	0.7584	0.7770	0.7900	0.7963	0.7940	0.7811	0.7430
EFF	11	0.6631	0.5232	0.3001	0.0			
EFF	11	0.7862	0.8037	0.8162	0.8228	0.8220	0.8122	0.7849
EFF	11	0.7153	0.6009	0.4217	0.1514			
EFF	11	0.7948	0.8151	0.8302	0.8392	0.8408	0.8331	0.8043
EFF	11	0.7381	0.6233	0.4430	0.1721			
EFF	11	0.7866	0.8126	0.8328	0.8460	0.8506	0.8447	0.8144
EFF	11	0.7407	0.6108	0.4056	0.0969			
EFF	11	0.8067	0.8266	0.8417	0.8512	0.8542	0.8496	0.8279
EFF	11	0.7774	0.6917	0.5626	0.3792			
EFF	11	0.8303	0.8403	0.8474	0.8513	0.8515	0.8477	0.8354
EFF	11	0.8095	0.7681	0.7091	0.6299			
EFF	11	0.8397	0.8442	0.8470	0.8481	0.8471	0.8440	0.8366
EFF	11	0.8226	0.8012	0.7719	0.7340			
EFF	11	0.8399	0.8419	0.8429	0.8426	0.8412	0.8386	0.8234
EFF	11	0.8243	0.8112	0.7938	0.7716			
EFF	11	0.8223	0.8219	0.8215	0.8210	0.8205	0.8200	0.8195
EFF	11	0.8188	0.8182	0.8174	0.8166			
EOT								

2003		P-BOOSTER PR VS. R. SPEED. AND ANGL						
ANGL	1	0.0						
SPED	9	0.359	0.528	0.661	0.791	0.880	0.952	1.000
SPED	9	1.028	1.144					
R	11	1.000	1.200	1.400	1.600	1.800	2.000	2.200
R	11	2.400	2.600	2.800	3.000			
PR	11	1.1370	1.1316	1.1248	1.1168	1.1074	1.0968	1.0837
PR	11	1.0670	1.0469	1.0235	1.0000			
PR	11	1.3169	1.3042	1.2888	1.2708	1.2503	1.2273	1.1995
PR	11	1.1647	1.1234	1.0762	1.0237			
PR	11	1.5447	1.5245	1.4992	1.4689	1.4339	1.3946	1.3465
PR	11	1.2860	1.2145	1.1334	1.0446			
PR	11	1.8882	1.8616	1.8242	1.7765	1.7191	1.6527	1.5601
PR	11	1.4615	1.3340	1.1913	1.0386			
PR	11	2.2086	2.1738	2.1277	2.0708	2.0038	1.9274	1.8329
PR	11	1.7129	1.5718	1.4141	1.2452			
PR	11	2.5106	2.4677	2.4172	2.3595	2.2950	2.2241	2.1405
PR	11	2.0386	1.9207	1.7890	1.6462			
PR	11	2.7096	2.6663	2.6185	2.5664	2.5101	2.4500	2.3818
PR	11	2.3021	2.2115	2.1113	2.0026			
PR	11	2.7840	2.7435	2.7003	2.6544	2.6060	2.5552	2.4993
PR	11	2.4360	2.3655	2.2885	2.2055			
PR	11	3.0007	2.9912	2.9817	2.9722	2.9625	2.9529	2.9431
PR	11	2.9331	2.9229	2.9126	2.9021			
EOT								

26

7.0   ANALYTICAL BACKGROUND

7.1   COMPRESSOR MAP FITTING SYSTEM

A continuing effort has been conducted by The Aircraft Engine Business Group to obtain more efficient cycle decks. The effort included a search for ways to reduce the size of the computer memory required to represent component maps without compromising the accuracy of the component representations. Meeting both goals was a challenge, for they seemed to call for contrary design approaches. For this reason, new types of component map representations were explored. It was found that maps based on similarity parameters derived from the basic physics of the components produced component maps of equivalent accuracy while requiring less computer memory. Moreover, the use of map "fits" based upon variables obtained from the physics of the component resulted in generally smoother maps and a more meaningful extrapolation to regions not covered by the data. This approach is especially well suited to parametric component representations, for parametric maps can easily occupy a gread deal of computer memory. Parametric compressor maps, for example, require computer memory for storage of the base map and the variations from the base map resulting from changes in the pressure ratio. The larger the range of pressure ratio, the more memory required. Add a second parameter, such as fan inlet guide vane angle, and memory requirements multiply rapidly.

Most of the parametric fan/compressor generating programs currently employedd by AEBG are based on the map fitting procedure to fit fan and compressor performance maps prior to their inclusion in a cycle deck. For this reason, a description of the map fitting procedure currently being used is necessary in order to gain an understanding of the parameteric fan/compressor generating programs.

In the following secions a brief description of the map fitting procedure
will be given. The section also contains sufficient component performance back-
ground information for the reader to gain an understanding of the similarity
parameters employed in the map representation. The relationships required to de-
fine a map in the map fitting system are the specification of flow coefficient,
work coefficient, and loss along the minimum loss locus which forms the "backbone"
of the map; and the loss and flow variations along the speed lines.

7.1.1   DESCRIPTION OF CURRENT COMPRESSOR MAP FITTING PROCEDURE

A typical compressor performance map is shown in Figure 1. Corrected air
flow is the abscissa, and total-to-total pressure ratio is the ordinate. Lines of
constant corrected speed and constant efficiency contours are plotted. In addition
to the map performance parameters, design point values of first stage rotor tip
speed (U Tip, ft/sec) and inlet specific flow (Wcorr/A, lbm/sec/ft^2) are required
in order to fit the map.

Some additional parameters used in the fitting procedure are defined from
the entropy-enthalpy diagram of a compressor stage. These parameters are shown in
Figure 6.

7.1.2   GENERAL BACKGROUND

The compressor stage characteristic serves as the basis for the map fitting
procedure. An analytical expression for the stage characteristic of a constant-pitch,
axial-flow compressor can be obtained by using the steady flow energy and angular
momentum equations, together with a number of relationships from the pitch line
vector diagram. In deriving this equation, it is assumed that the pitch line flow
angle at rotor and stator exit are in-variant and that the axial velocity ratio
across the rotor is constant.

The stage characteristic for a single-stage compressor with the above
assumptions can be written in the form -

$$\psi = 2 - 2\phi \ (\tan \alpha_1 + C_{z2}/C_{z1} \tan \beta_2) \tag{1}$$

The equation is a straight line (ψ vs. ϕ Plot) passing through the point $(\psi = 2, \phi = 0)$.

A typical low speed compressor stage characteristic is shown in Figure 7. In practice, it is found that in the neighborhood of the peak efficiency changes in the absolute air inlet angle and the relative air-outlet angle are small. They can, however, change considerably at extreme operationg conditions. The key point is that in the high efficiency region change in the stage characteristic is nearly linear.

A loss parameter as defined by the difference between the values of the work coefficient and the pressure coefficient is introduced as illustrated in figure 8. Figure 8-A shows an idealized stage characteristic. In Figure 8-B the variation in efficiency with flow coefficient has been shown. Note that the efficiency is zero at unity pressure ratio and has a singularity at the $\psi = 0$ point. This behavior makes the efficiency an inconvenient measure of performance in the neighborhood of zero work. If this behavior is contrasted with that of the loss as shown in Figure 8-C, the reasoning for the use of loss becomes evident. The loss is always positive, finite, and exhibits a minimum value. The map fitting procedure is built around the stage characteristic and the attendant concept of loss. The min-loss point is defined as the "backbone" point on the characteristic.
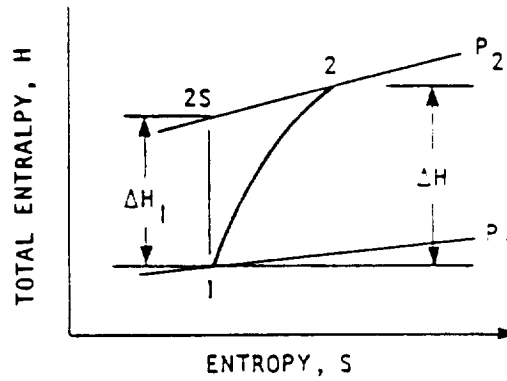
LET: C_{z_1} = AXIAL VELOCITY COMPONENT AT ROTOR INLET

     v   = WHEEL SPEED

DEFINE: 1.   WORK COEFFICIENT, $\psi = \Delta H/(v^2/2g_o J)$

         2.   PRESSURE COEFFICIENT, $\psi_1 = \Delta H_1/(v^2/2g_o J)$

         3.   FLOW COEFFICIENT, $\phi = C_{z_1}/v$

         4.   EFFICIENCY, EFF $= \psi_1/\psi$

         5.   LOSS, XLS $= (\Delta H - \Delta H_1)/(v^2/2g_o J) = \psi - \psi_1$

Since $\eta = \dfrac{\psi'}{\psi}$ and Loss $= \psi - \psi'$

Then Loss $= \psi(1 - \eta)$ or $\eta = 1 - \dfrac{\text{Loss}}{\psi}$

Figure 6.   Dimensionless Compressor Performance Parameters.
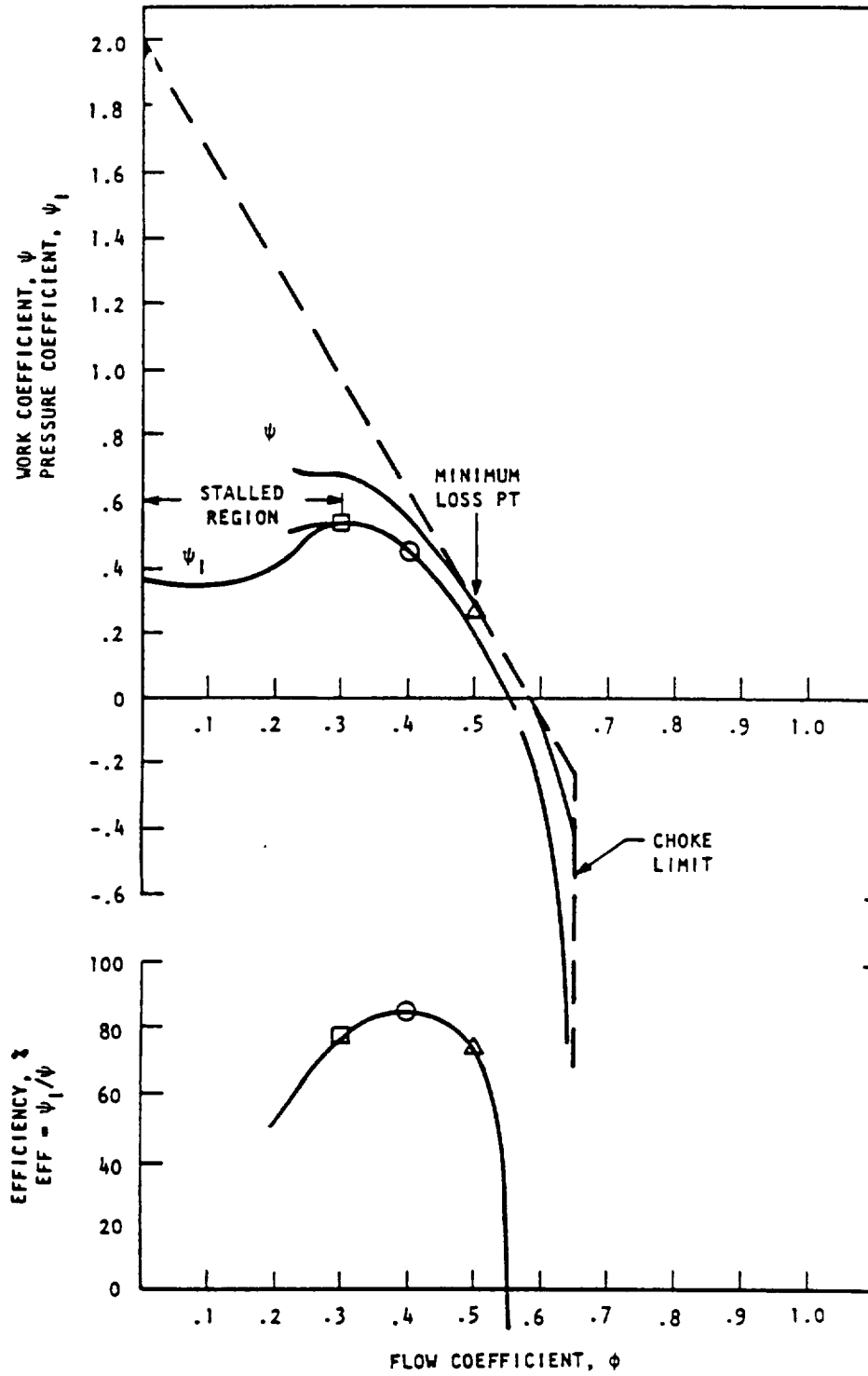
Figure 7. Compressor Stage Characteristic.

7.1.3   COMPRESSOR EFFICIENCY REPRESENTATION

The efficiency representation of the compressor is illustrated by the three sketches shown in Figure 9. For each map speed a plot of loss $(\psi-\psi_I)$ against work coefficient is constructed. Figure 9-A illustrates this type of plot. The values of work coefficient at min-loss (ψ_{ML}) and loss at min-loss $(\psi-\psi_I)ML$ are picked off the curves for each value of speed. The locus of the min-loss points form the "backbone" of the map. The variation of ψ_{ML} and $(\psi-\psi_I)_{ML}$ are then plotted against speed as illustrated in Figure 9-B. The "off-backbone" loss is represented by a plot of the difference between the loss and the min-loss value at a given speed against the difference between the work coefficient and the min-loss work coefficient squared.

The sign of the work coefficient difference is used to plot the two branches of the bi-variate loss representation. When plotted in this fashion the loss correlation is nearly linear over a relatively wide range of work coefficient. However, breaks can occur in the neighborhood of positive stall and/or choking.

These three curves, two univariate and one bi-variate are sufficient to define the compressor efficiency. Since the three curves are fairly linear, a table look up is employed to obtain efficiency values in a cycle deck.

7.1.4   COMPRESSOR FLOW REPRESENTATION

The flow representation begins by calculating the values of the flow coefficient at min-loss. Since the min-loss points on the map are known from the loss calculation, the flow at each min-loss point is known. The value of the inlet flow coefficient is then obtained from the flow-function Mach number relationship, i.e.,

$$(1) \quad \left.\frac{Wcorr}{Ann1}\right|_{ML} = \left.\frac{Wcorr}{Ann1}\right|_{Design} \frac{(Wcorr)ML}{(Wcorr)Design}$$

$$(2) \quad \frac{Wcorr/Ann1}{P_{Tstd}A_{Tstd}cos\alpha_1} = \frac{C_{z1}}{A_{T1}} \frac{1}{cos\alpha_1}\left[1 - \frac{r-1}{2}\left(\frac{C_{z1}}{A_{T1}}\right)^2 \frac{1}{Cos^2\alpha_1}\right]^{\frac{1}{r-1}} \quad \begin{array}{l} Cos\alpha_1 = 0 \\ A_{T1} = \sqrt{rR_g g_o T_1} \end{array}$$
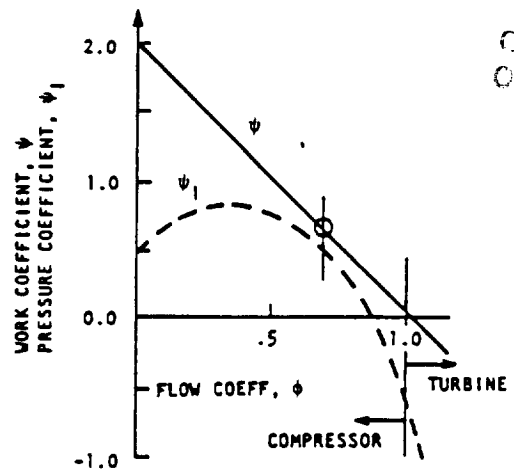
A STAGE CHARACTERISTIC
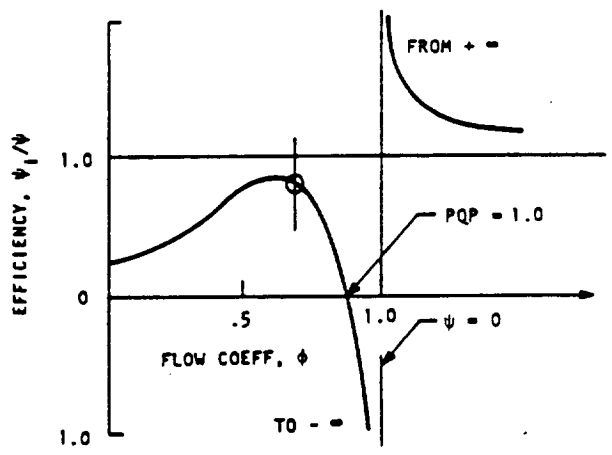
B EFFICIENCY CHARACTERISTIC
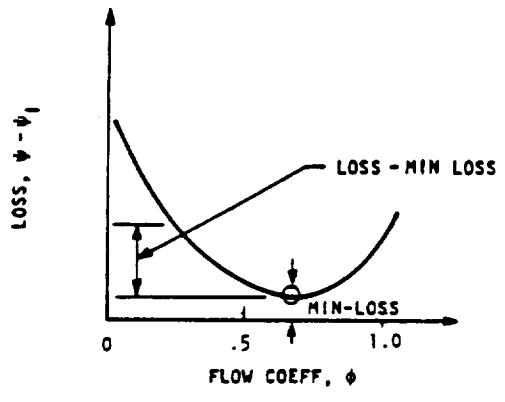
C LOSS CHARACTERISTIC

Figure 8. Compressor Loss Representation.

33

PCNC = A CONSTANT

LOSS, $\psi - \psi_1$

MIN-LOSS
(ψ_{ML})

LOSS - LOSS AT
MIN-LOSS

0

0   1.0   2.0
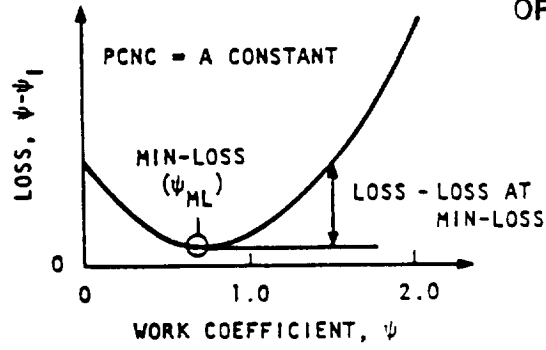
WORK COEFFICIENT, ψ

A. VARIATION OF LOSS WITH WORK COEFF.

WORK COEFF, ψ_{ML}
LOSS, $(\psi - \psi_1)_{ML}$

"BACKBONE CURVES"

ψ_{ML}

$(\psi - \psi_1)_{ML}$

0   1.0
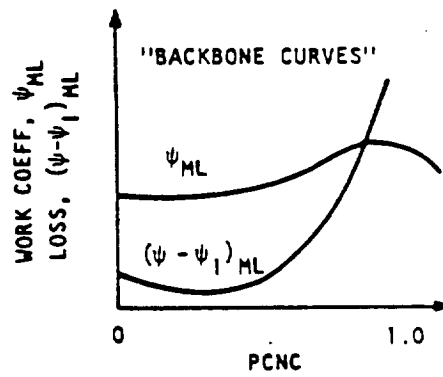
PCNC

B. VARIATION OF MIN-LOSS
WORK COEFF. AND LOSS

LOSS - LOSS AT MIN-LOSS

BREAK
POINT

PCNC = A CONSTANT

-1.0   0.0   +1.0

$(\psi - \psi_{ML}) * | (\psi - \psi_{ML}) |$
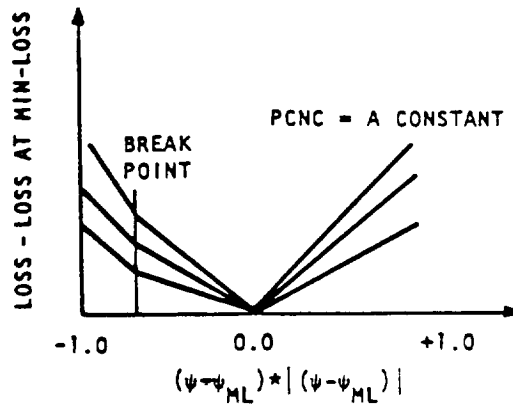
C. LOSS FUNCTION VARIATION

Figure 9.   Stage Efficiency and Loss Characteristics.

34
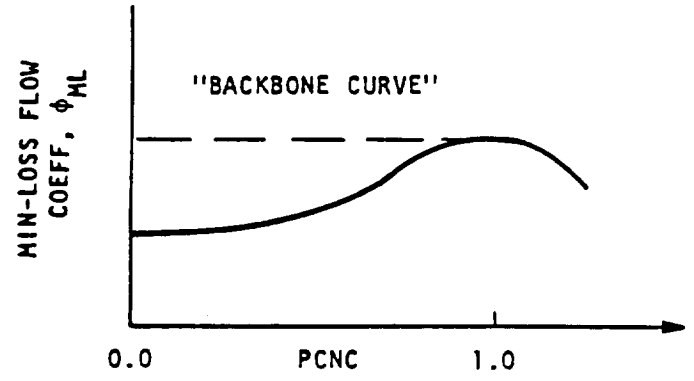
A. VARIATION OF MIN-LOSS FLOW COEFFICIENT
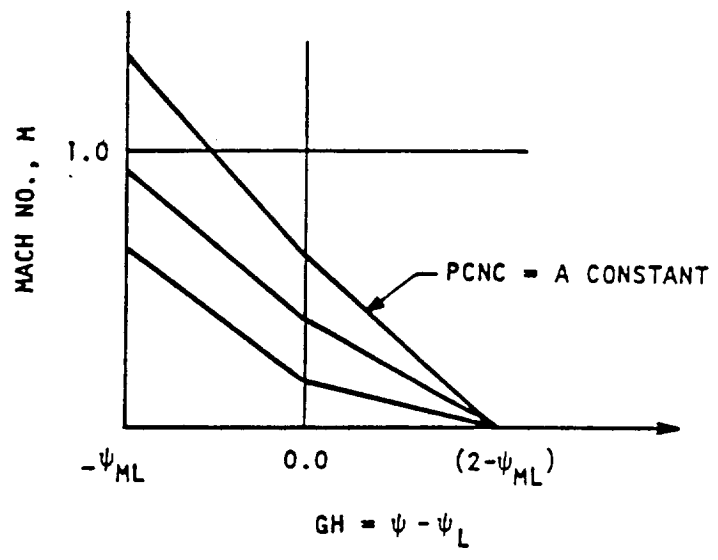
B. MACH NUMBER VARIATION

Figure 10.   Compressor Flow Representation.

(3) $\quad v/A_{T_1} = PCNC \cdot (v/AT_{std})$ Design

(4) $\quad \phi_{ML} = \left(c_{z1}/A_{T1}\right)/\left(v/A_{T1}\right) = c_{z1}/v$

A curve of min-loss flow coefficient as a function of speed as shown in Figure 10-A is then constructed. This univariate curve defines the flow along the "backbone" of the map.

The "off-backbone" flow is then obtained in the following manner. Consider the speed line sketch of Figure 1.

If we assume a pseudo Mach number somewhere in the machine of one at the maximum flow point, then a pseudo critical area can be calculated. If this pseudo area is assumed to remain constant along a speed line, a pseudo-Mach number can be defined at each point on the speed line as follows:

$$W_{corr} \bigg/ W_{corr} \, max = \left[M \bigg/ \left(1 + \left(\frac{r+1}{2}\right) M^2\right)^{\frac{r+1}{2(r-1)}} \right] \left(\frac{r+1}{2}\right)^{\frac{r+1}{2(r-1)}}$$

The Mach number is then plotted at each speed against $(\psi - \psi_{ML})$ as illustrated by Figure 10-B.

These two curves, one univariate and one bi-variate are sufficient to define the flow. As with the efficiency representation, these curves are fairly linear and a table look up is employed in the cycle deck evaluation.

7.1.5 COMPRESSOR BASE CURVES

These five curves, three univariate and two bi-variate are sufficient to define the performance map. These curves are part of the output from the CMGEN program and are written on File 22. They constitute an alternate map representation.
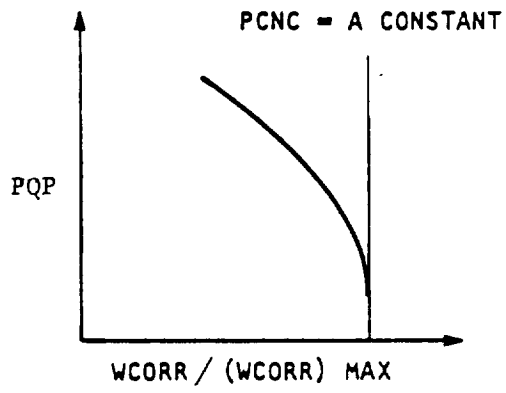
Figure 11.   Speed Line Sketch.

7.2 DISCUSSION OF THE DERIVATION OF THE PARAMETRIC CURVE SETS

The activities of Preliminary Design organizations require the capability
to rapidly generate a wide variety of fan and compressor maps for use in cycle
analysis. The semi-empirical method adopted for the systematic generation of re-
quired maps is the subject of this section.

The approach adapted was to utilize, as directly as possible, the parameters
that AEBG currently uses to fit performance caps. These required inputs to
create a map are the specification of flow coefficient, work coefficient and loss
along the minimum loss "BACKBONE" and the loss variation and flow variation along
the speed lines.

Speed-flow relations have been of interest and the subject of much study
over the years. Use of these relations and correlations from various compressor
tests results in the flow coefficient-speed shown in Figure 12 with pressure ratio
as the independent parameter. The speed-flow implied by Figure 12 for a design
specific flow of 40 lbm/sec/ft^2 is shown in Figure 2. At a given flow coefficient
ratio the percent flow depends upon the level of design Mach number and in this
manner the speed-flow relation is dependent upon the design level of inlet specific
flow, as it should be. This is illustrated in Figure 13, for a pressure ratio 12
design.

Work coefficient-speed relations are not convenient. Work coefficient-flow
coefficient relations are more commonly used and in the early work on the method
this type relation was employed. The work coefficient-speed relation was derived
from the work coefficient-flow coefficient relation and the flow coefficient-speed
relation. Later considerations, particularly hi T_2 stator schedules, favored a
somewhat different approach. This approach was to employ the use of a throttle
coefficient, as a function of flow and design pressure ratio. Throttle coefficient,
can be explained as follows: consider a compressor component operating with an
atmospheric inlet and an isentropic discharge nozzle which expands back to ambient.
The variation of the nozzle throat area required to maintain the compressor on its
minimum loss line, relative to the nozzle throat area at design condition, is the
throttle coefficient. The throttle coefficient employed is shown in Figure 14. A
linear interpolation is used at intermediate pressure ratio. The work coefficient-

38

speed relations is then derived from the throttle coefficient-flow relation and the flow coefficient-speed relation.

The minimum loss-speed relations are again not convenient. In their place an efficiency ratio flow relation is used. The efficiency ratio is the ratio of efficiency to peak efficiency. This is shown in Figure 15. Also employed is the design point efficiency-pressure ratio relation shown in Figure 16. This completed the definition of the map along the minimum loss line. The loss variation and pseudo-Mach number variation, related to flow, along the speed lines are observed to be linear in nature. Advantage is taken of this linearity to specify these variations as slopes and intercepts. In the case of the loss variation, the curves go through the origin by definition which automatically give the intercept. The slope of the loss variation is shown in Figure 17. On the stall side of the compressor map the Figure 17 loss slope is divided by the minimum loss work coefficient at design point. The slope and intercept of the pseudo-Mach number relation is shown in Figures 18 and 19, respectively. The loss and pseudo-Mach number variations which result for a typical pressure ratio are shown in Figures 20 and 21, respectively.

For high T_2 stator schedules a modification is made to the flow coefficient-speed according to Figure 22. A 45° line on Figure 22 results in the hi T_2 schedule being identical to the low T_2 schedule. A linear interpolation between these two lines is available, so that intermediate stator schedules can be generated. All other input remains unchanged. In this manner the minimum loss line on the map is independent of stator schedule, as are the efficiency characteristics, since both of these are functions of flow only. The flow-speed relation for the high T_2 stator schedule in shown in Figure 23.

A typical map which results from this procedure but for the low T_2 schedule was presented in Figure 1.
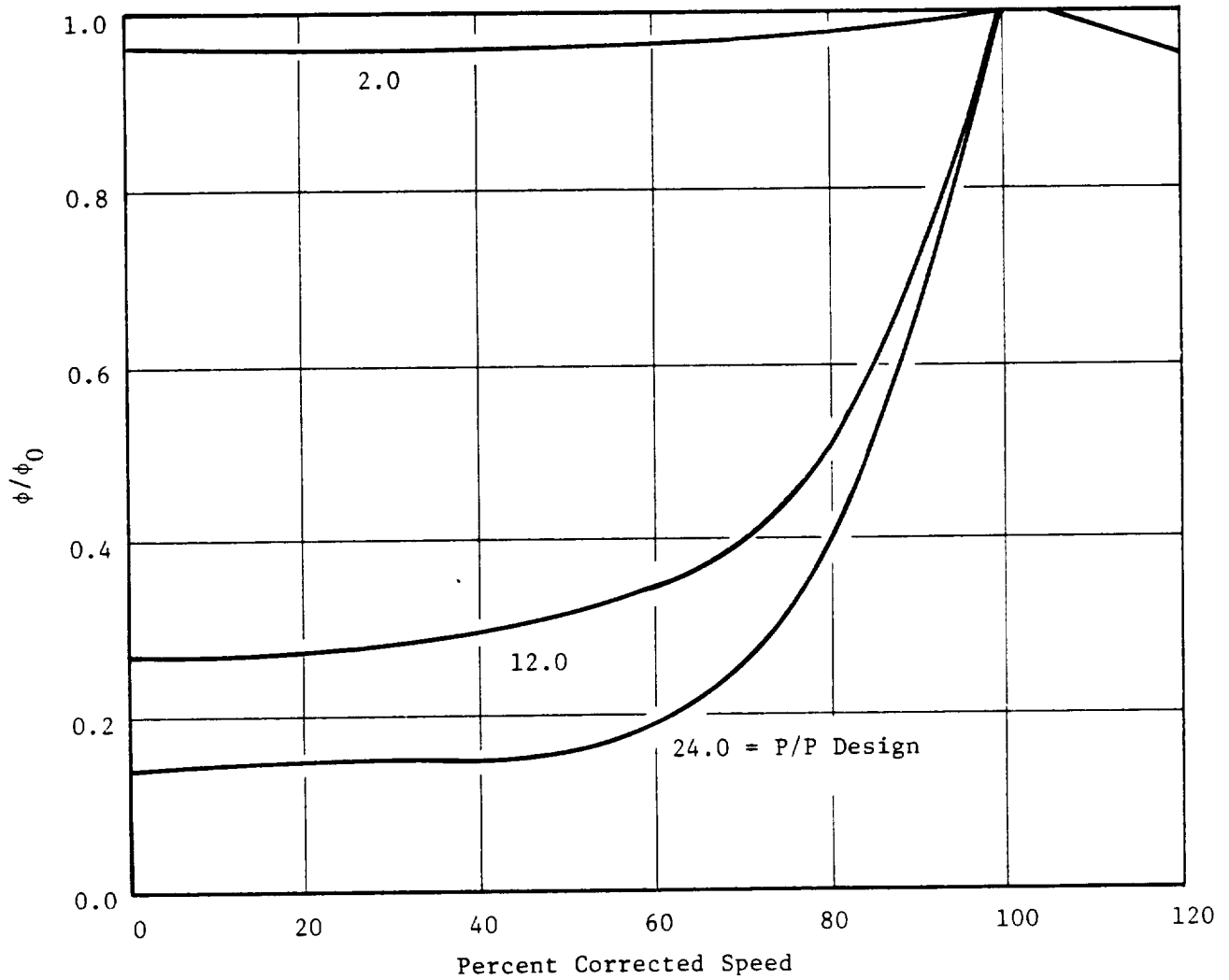
Figure 12.   Normalized Flow Coefficient Variation with Speed and Pressure
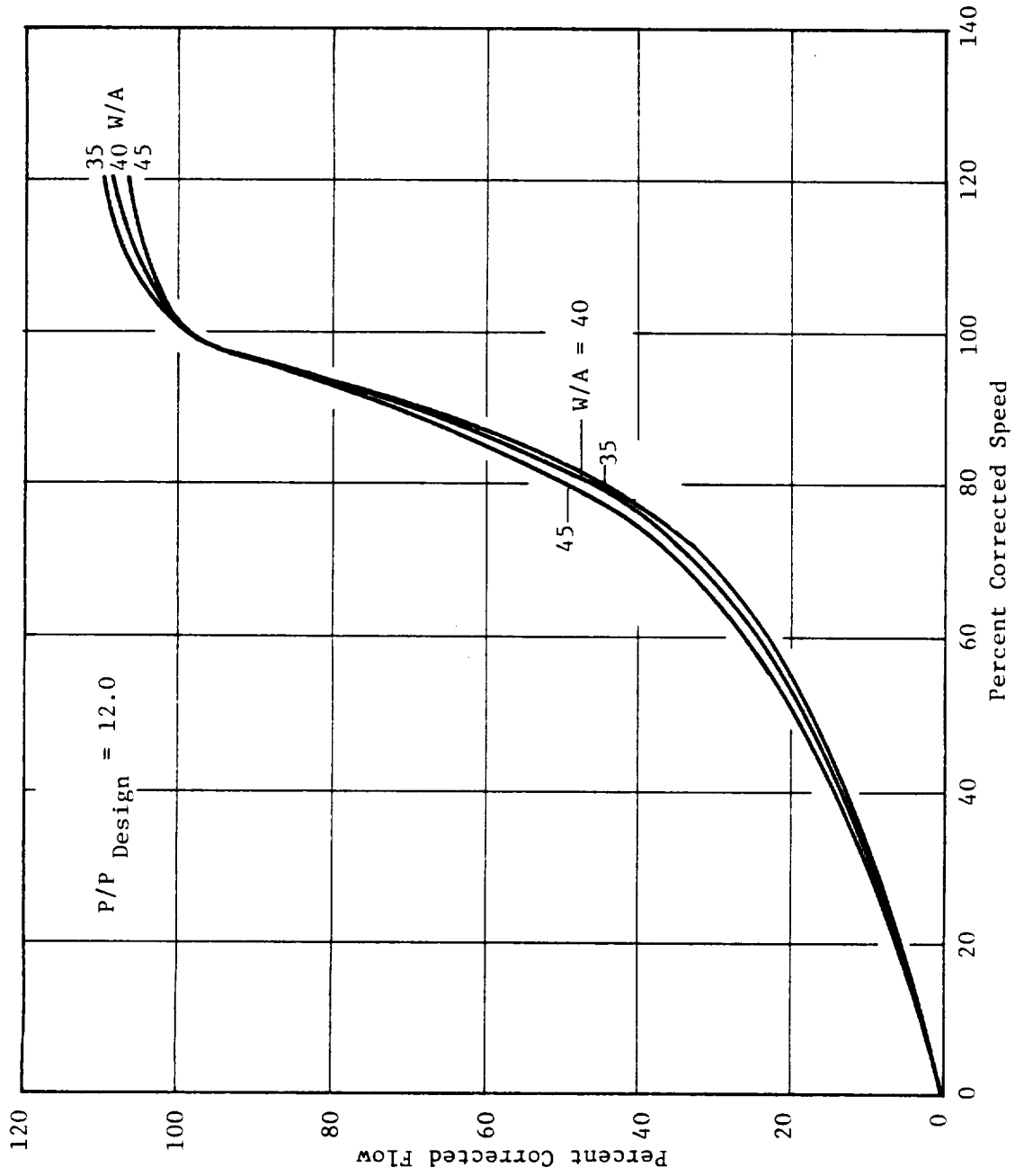   Ratio.

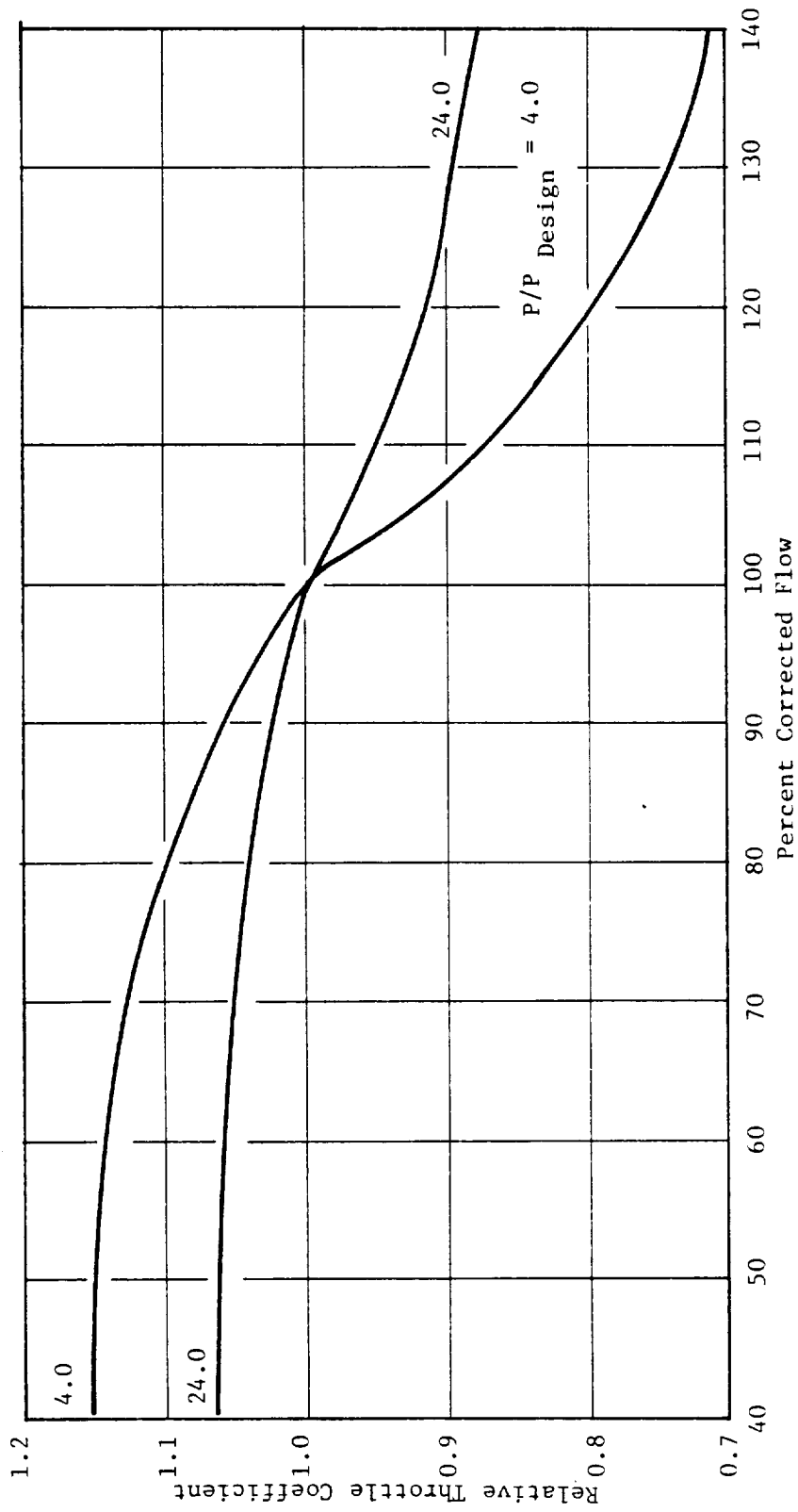Figure 13. Effect of Specified Flow on Backbone Flow-Speed Relationship.

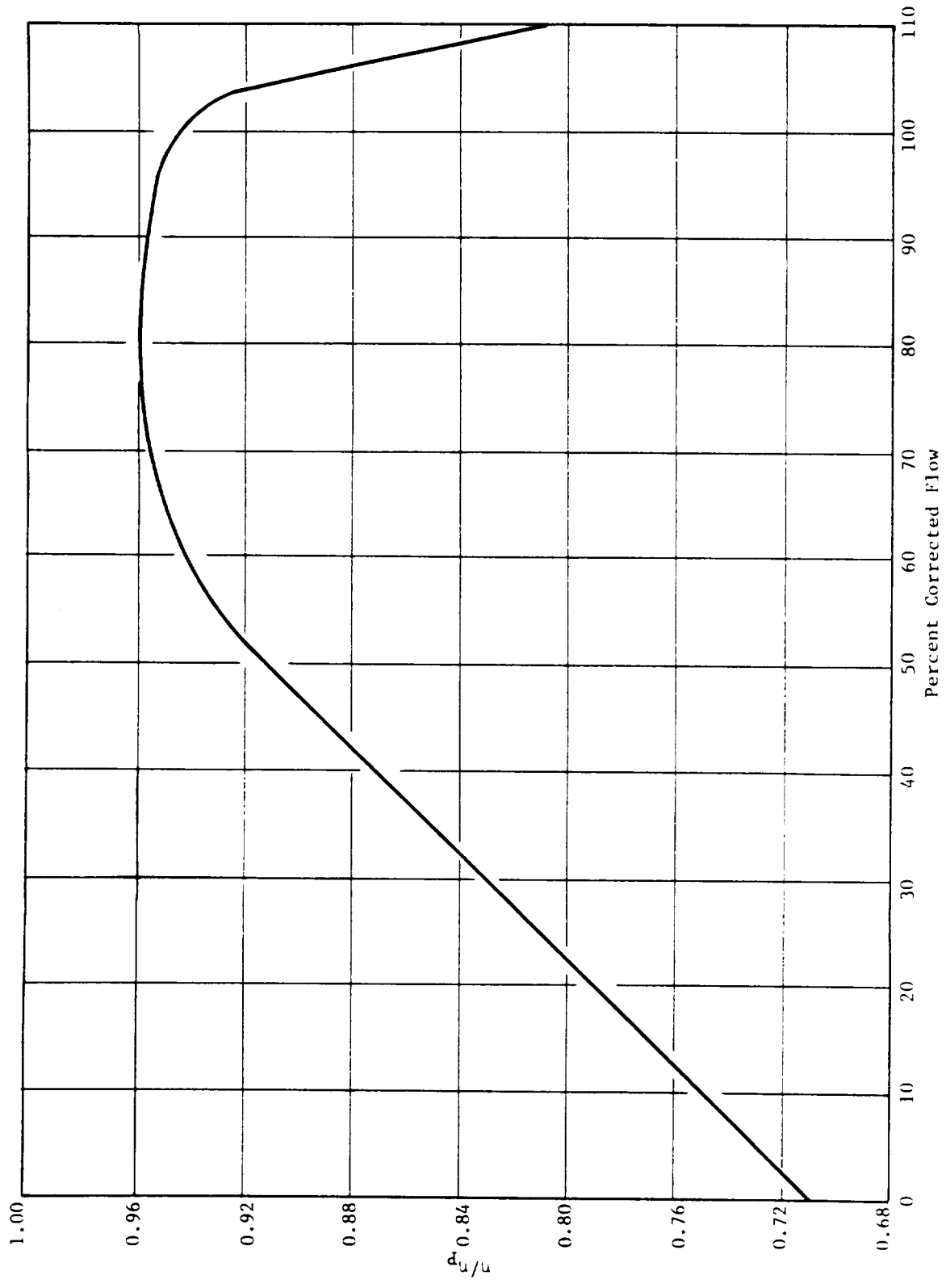Figure 14. Minimum Loss Throttle Coefficient.

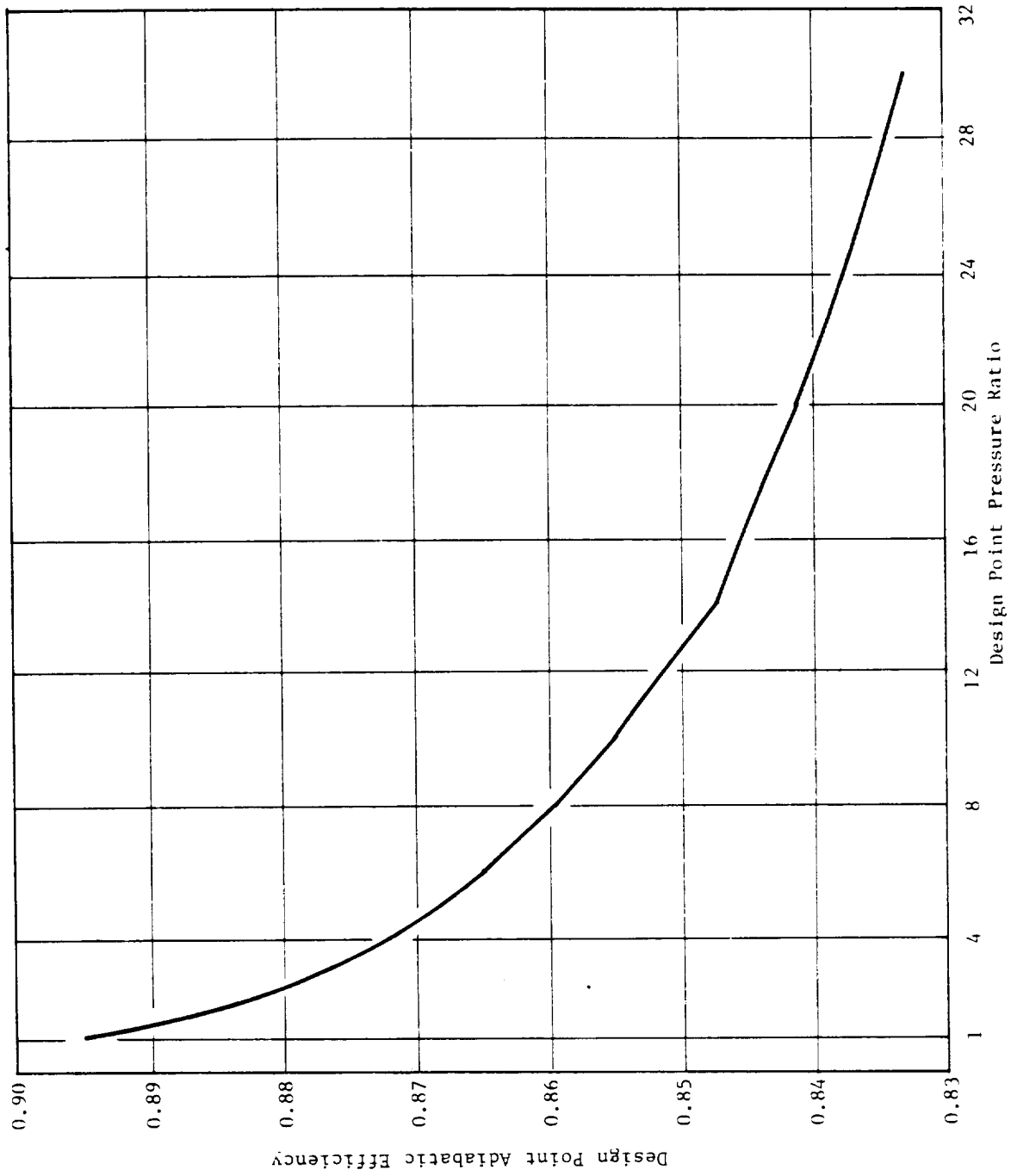Figure 15.   Normalized Minimum Loss Efficiency Distribution.

43

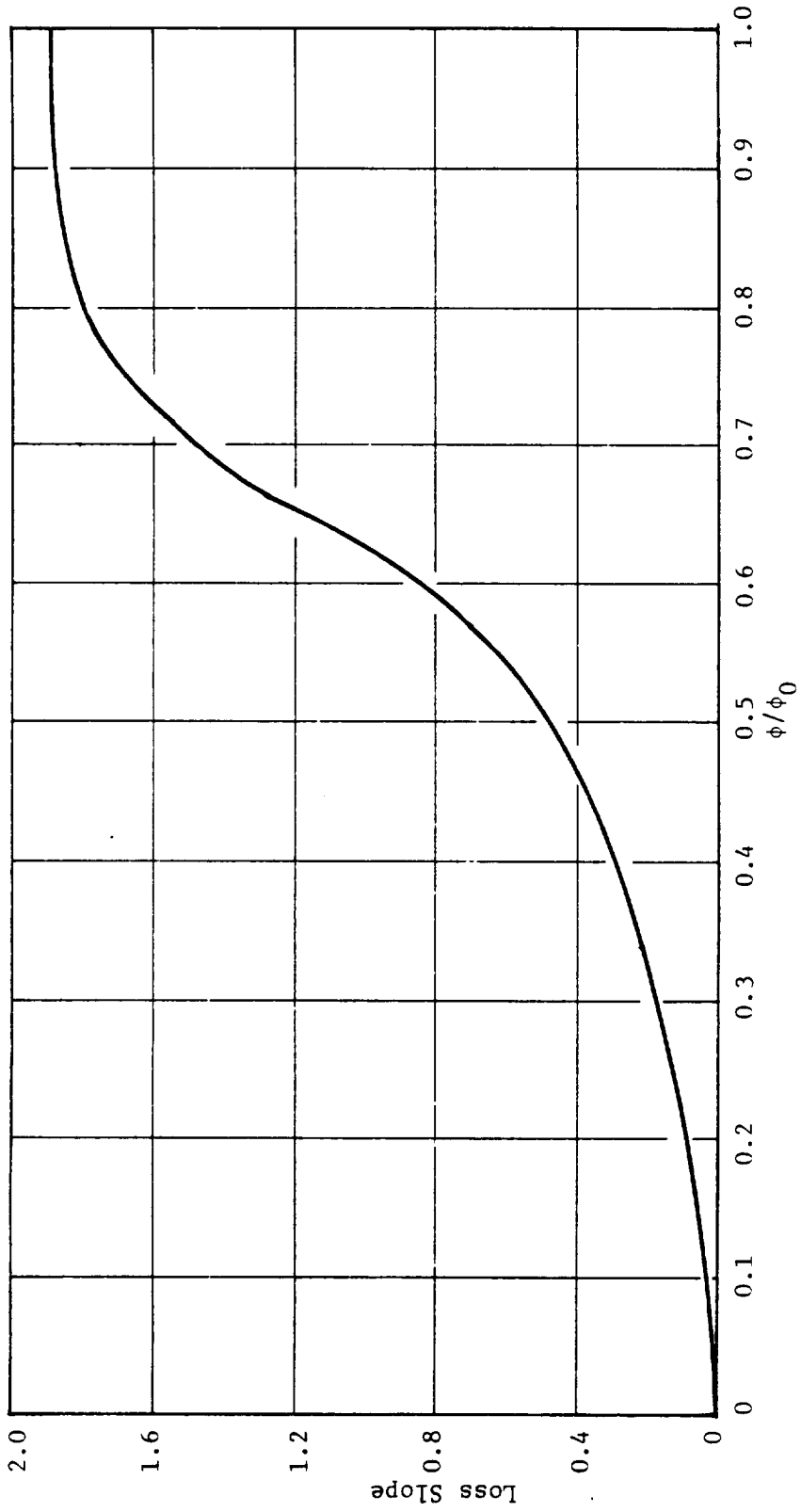Figure 16. Variation of Design Point Efficiency with Pressure Ratio.

44

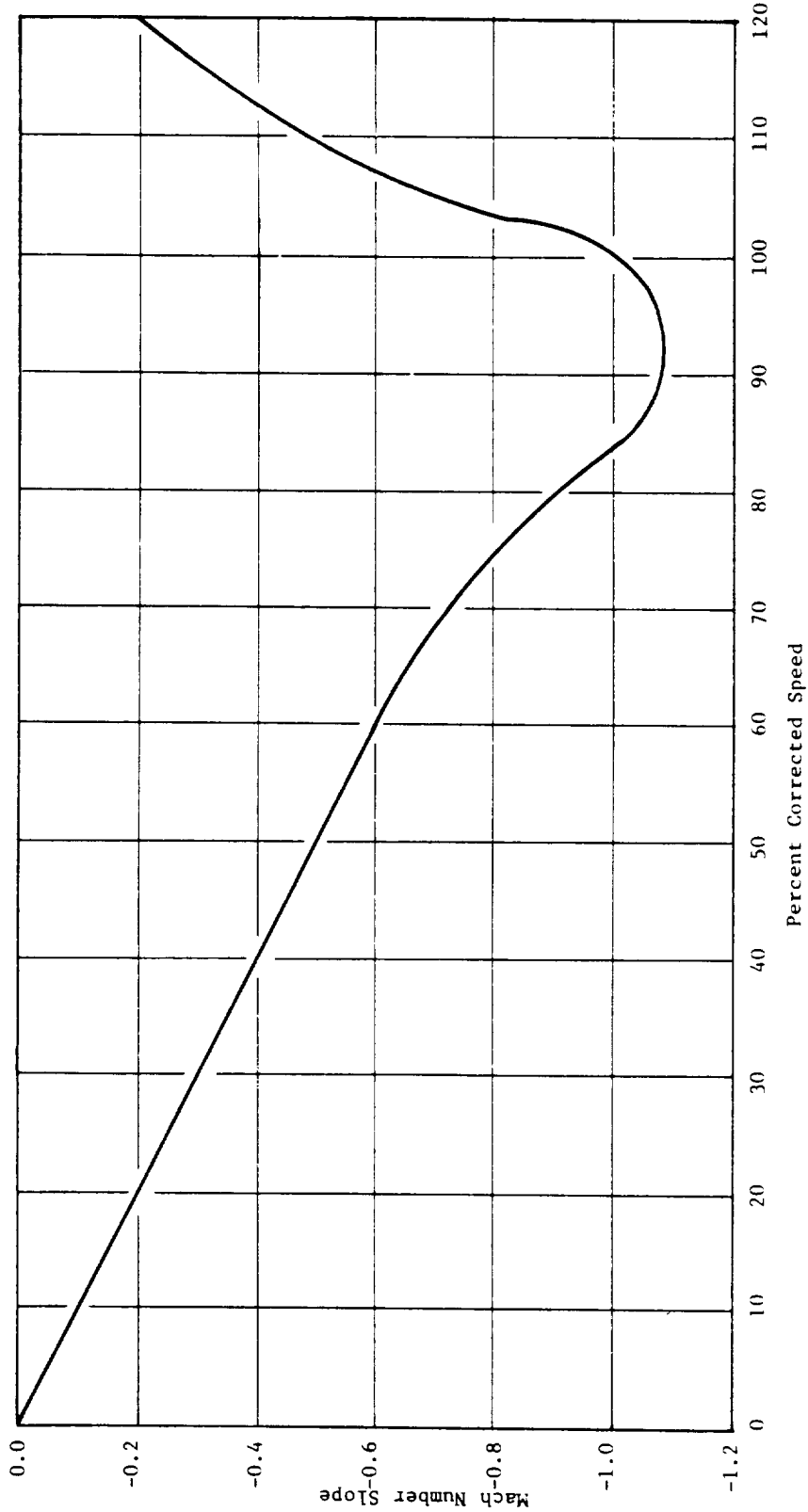Figure 17. Variation of Loss Slope with Normalized Flow Coefficient.
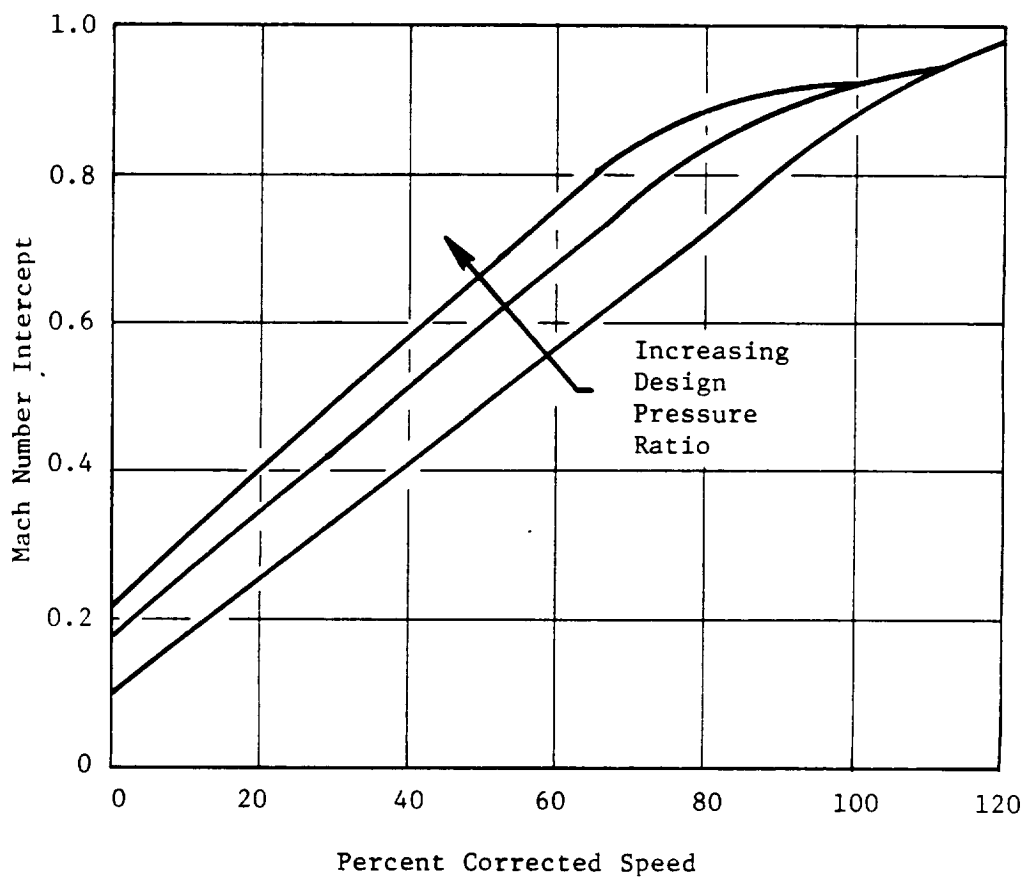
Figure 18. Variation of Mach Number Slope with Speed.

46

Figure 19.   Variation of Mach Number Intercept with Speed and
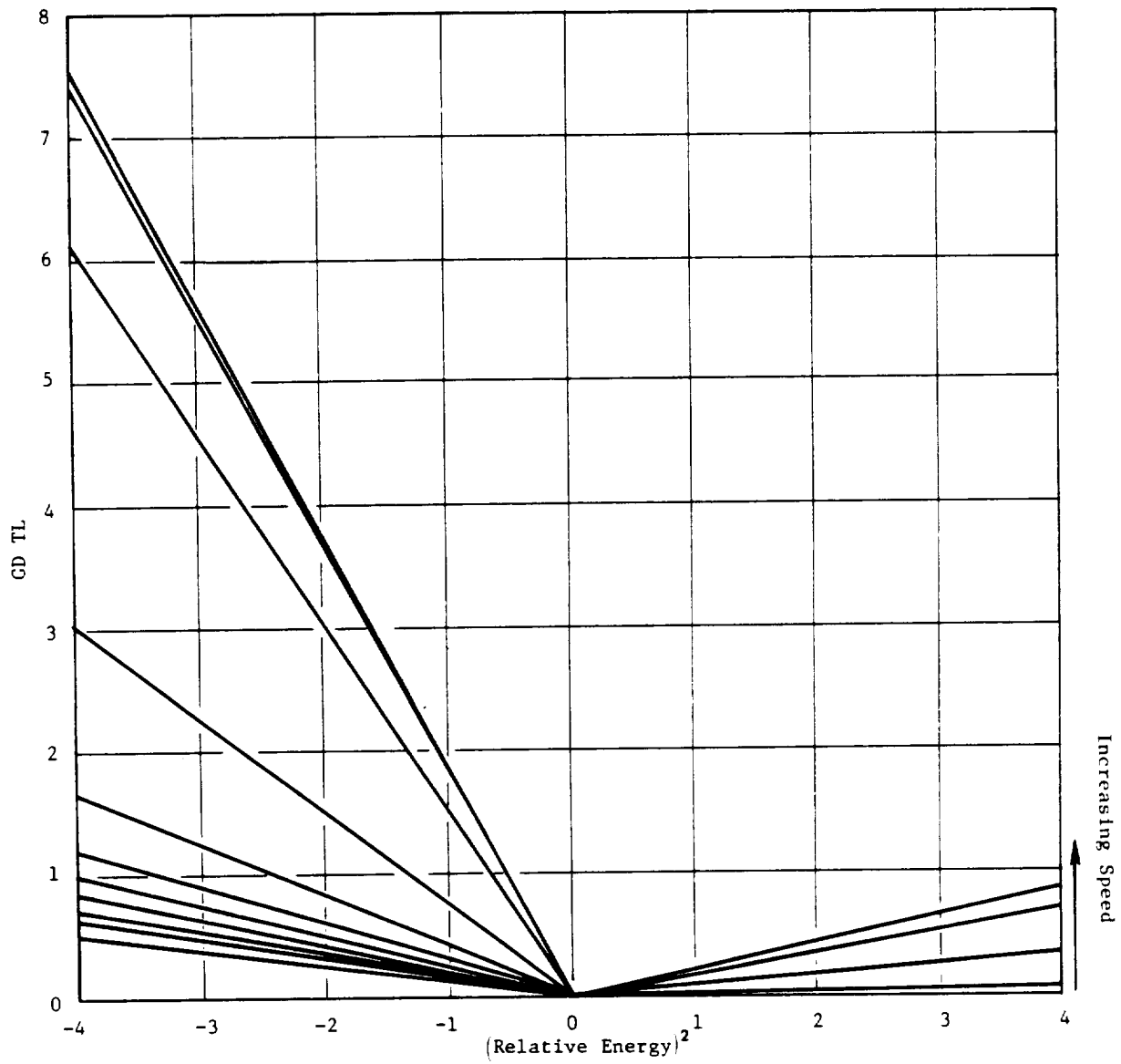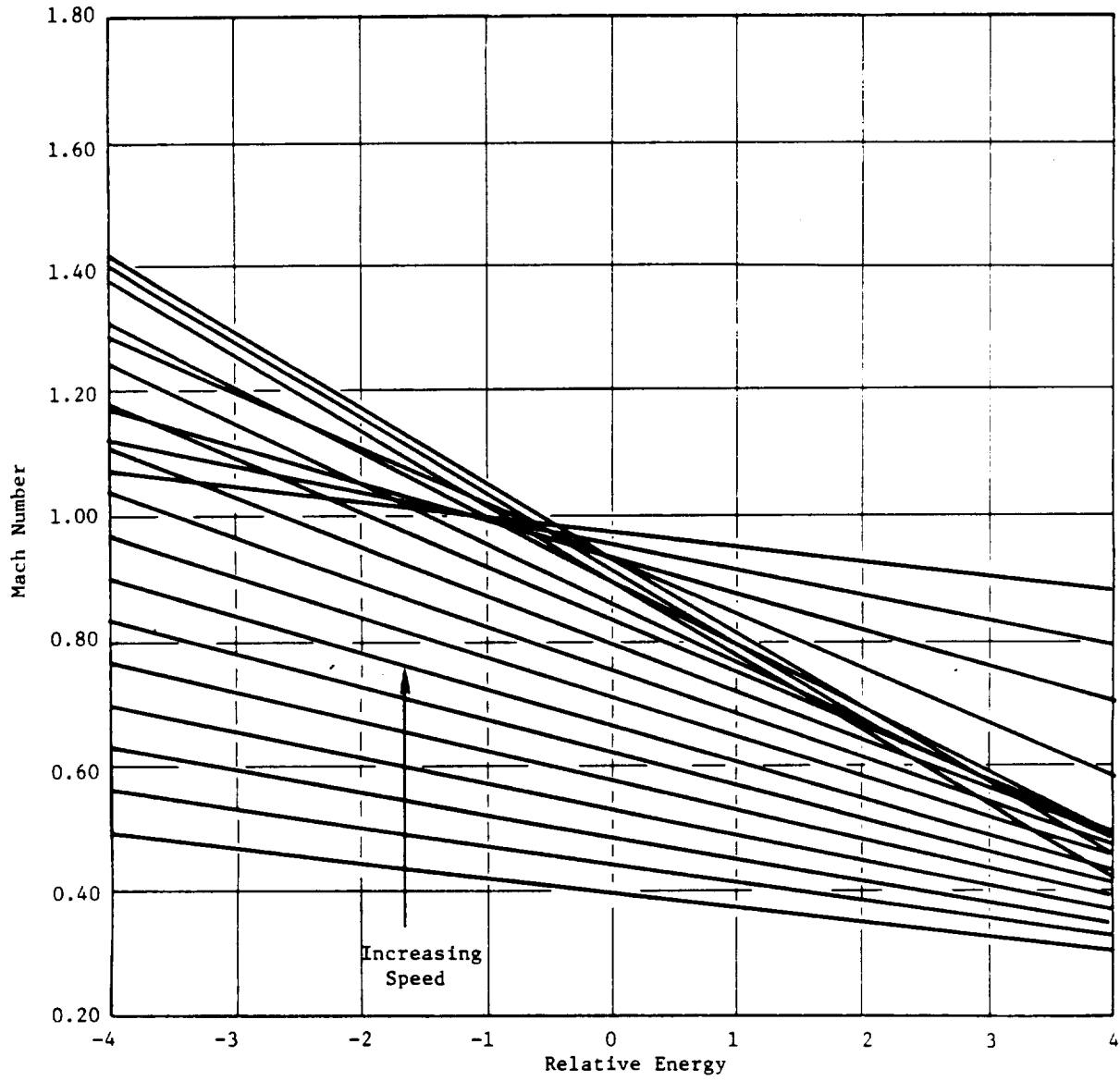   Design Pressure Ratio.

Figure 20. Bivariant Loss Curves.

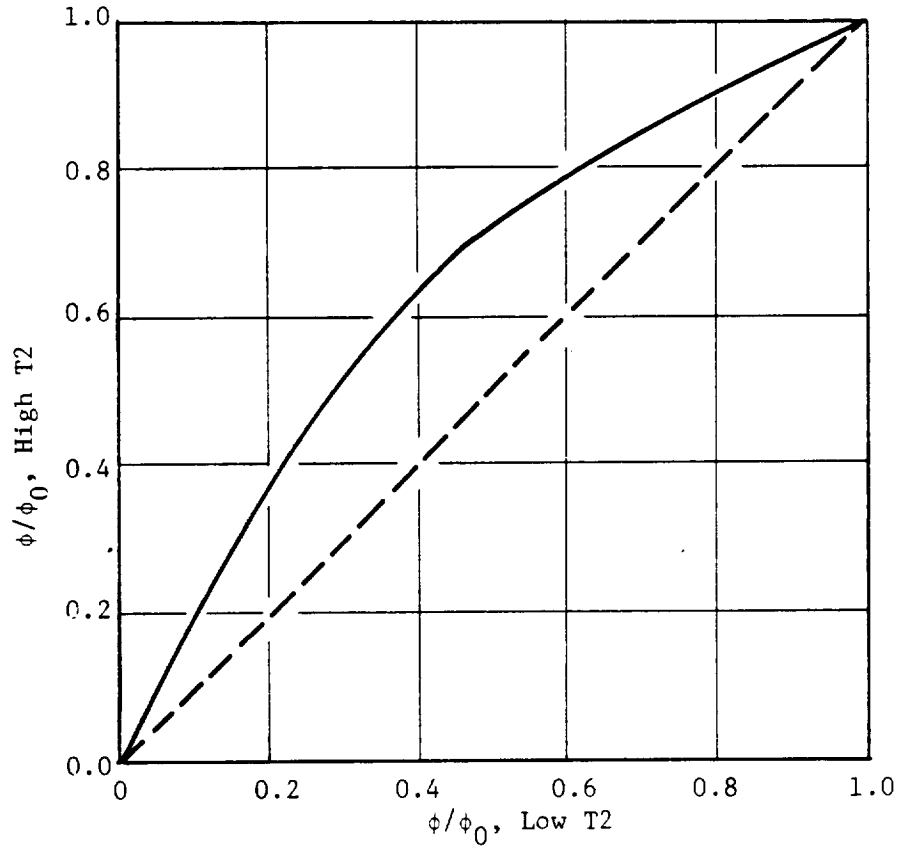Figure 21. Bivariant Flow Curves.

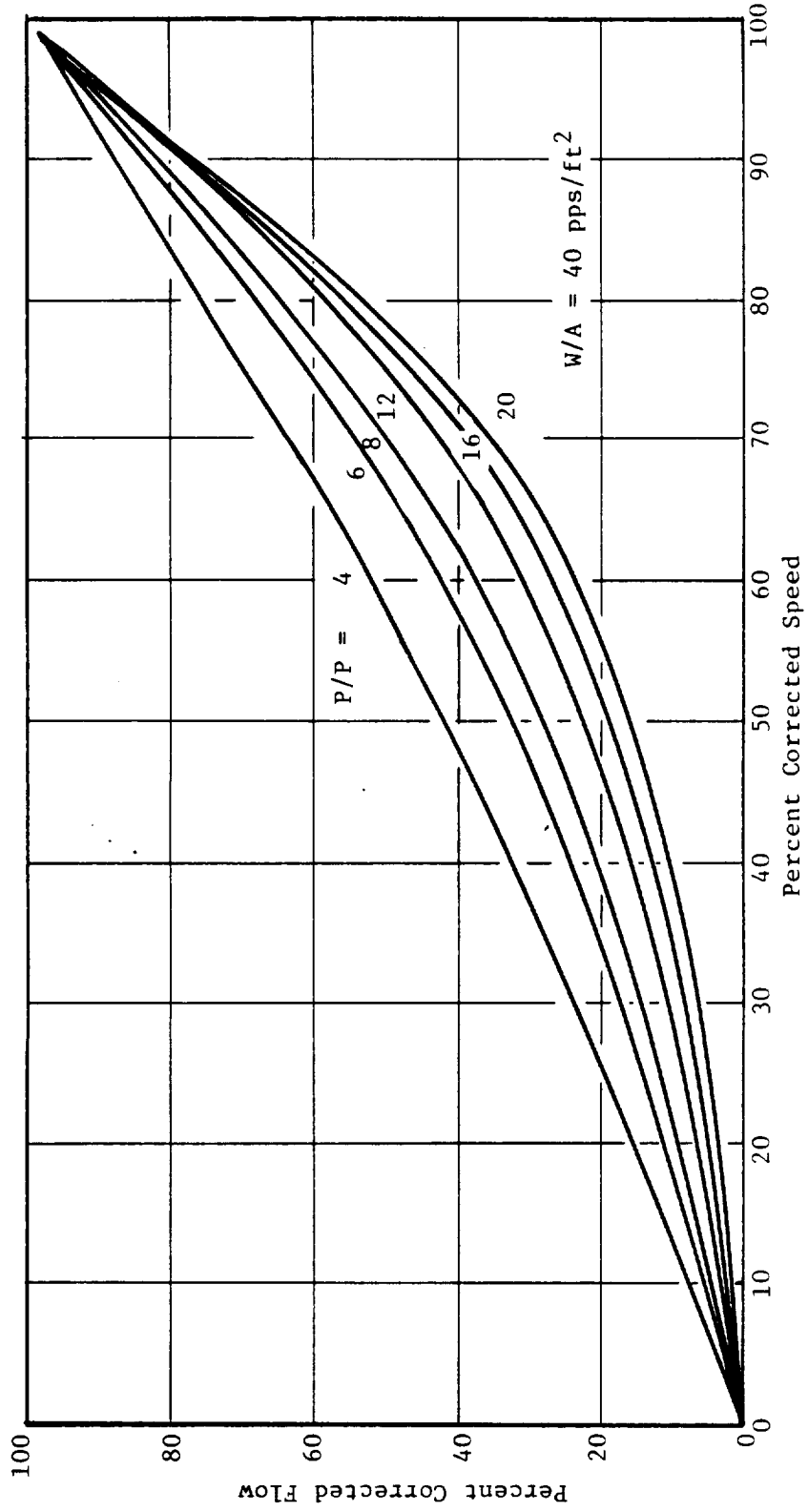Figure 22. Flow Variation for High T2 Schedule.

Figure 23. Parametric Map Flow-Speed Relationships HI T2 Schedule.

51

LIST OF SYMBOLS

A_{T_1} Speed of Sound at Stagnation Temp. fps

A_{NN_1} Inlet Annulus Area, ft^2

P Pressure, psia

C Velocity, fps

T Temperature, ° C

U Wheel Speed, fps

W_{corr} Corrected flow, pps.

α Stator exit angle

β Rotor relative angle

ΔH Change in total enthalpy, BTU/lb_m

ρ Density, lbm/ft^3

ψ Work Coefficient, $\psi = \Delta H / (U^2/2g_oJ)$

ϕ Flow Coefficient, $\phi = c_a/U$

Subscripts

1   Rotor inlet
2   Rotor exit
Design   Design Point
ML   Min-loss point
Std.   Refers to standard day conditions

REFERENCES

1. Fishbach, Laurence H., and Caddy, Michael J., "NNEP: The Navy-NASA Engine Program," NASA TM X-71857, 1975.

2. Fishbach, Laurence H., "Konfig and Rekonfig – Two Interactive Pre-processing Programs to the NAVY/NASA Engine Program (NNEP)," NASA TMX-82636, May 1981.

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