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Plotting Component Maps in the Navy/NASA Engine Program (NNEP)—A Method and Its Usage

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PLOTTING COMPONENT MAPS IN THE NAVY/NASA ENGINE PROGRAM (NNEP) -

A METHOD AND ITS USAGE

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SUMMARY

The Navy/NASA Engine Program (NNEP) and the new extended version which handles chemical equilibrium (NNEPEQ) are very general cycle analysis codes that have been used extensively to calculate design and off-design performance of a wide range of turbine engine cycles and configurations. Component maps are used to obtain the off-design engine performance and a "matched engine cycle." This paper describes a method of plotting the scaled NNEP compressor and turbine maps as the user runs the NNEP code as well as plotting the operating line defined by all the cases that were computed in that particular NNEP run. Afterwards, an example demonstrates the use of this capability to help analyze an engine cycle model and then make improvements to that cycle.

INTRODUCTION

The Navy/NASA Engine Program - NNEP (ref. 1) and the new extended version which handles chemical equilibrium - NNEPEQ (ref. 2) are very general cycle analysis codes. These codes have been used extensively to calculate design and off-design (matched) performance of a wide range of turbine engine cycles and configurations ranging from subsonic turboprops to variable cycle engines for supersonic transports. In this paper NNEP will be used to refer to both the original NNEP program as well as the new NNEPEQ program. NNEP's versatility results from the ability of the user to assemble an arbitrary matrix of fans, compressors turbines, ducts, shafts, etc. into a complete gas turbine engine model which NNEP interprets to compute design and off-design thermodynamic performance.

NNEP calculates off-design performance by the use of component maps to obtain a "matched" engine cycle. Although maps can be used to describe the performance of most components, the most commonly used maps are for compressors and turbines.

A typical compressor map (ref. 3) is shown in figure 1. To input this map into NNEP, the map is broken into three separate maps by the use of arbitrary R lines. The R lines are drawn on the compressor map by the user in an arbitrary manner following the general shape of the surge line. R lines must not cross or intersect other R lines. Each R line is assigned an arbitrary value with increasing values from the surge line. The surge line is generally (but not necessarily) defined as an R value of one. The three map properties, pressure ratio, corrected flow, and efficiency can then be defined in tabular form as a function of corrected speed and R value for use by NNEP. Additionally, variable geometry in the compressor may be introduced through the use of stacked maps. Each map in the stack is assigned a third-dimensional argument value which represents the variable geometry. A typical NNEP compressor map table (which corresponds to the example map in fig. 1) is given in table I. These maps are not used in their input form by NNEP but instead must be scaled by NNEP at run time to match the design point pressure ratio, efficiency, and corrected flow of the engine being modeled. The map table data is interpolated using a cubic spline curve fit routine to obtain the off-design component performance. If the required off-design point is outside the table, a linear extrapolation is made of the table data.

A typical turbine map (ref. 4) is shown in figure 2. The two map properties, corrected flow and efficiency, are defined in tabular form as a function of corrected speed and turbine pressure ratio for use by NNEP. As with the compressor, variable geometry may be introduced through the use of stacked maps. Here again, a third-dimensional argument is assigned to each map to represent the variable geometry. A typical NNEP turbine map table (which corresponds to the example map in fig. 2) is given in table II. The turbine maps are also scaled by NNEP at run time to match the design point pressure ratio and efficiency of the engine components being modeled. Like the compressor, the turbine map data is interpolated using cubic spline curve fits unless the desired point is outside the table in which case the table data is linearly extrapolated.

Although preliminary-design map generation computer codes exist (ref. 5), often one set of map tables are used to model a variety of engines. Since maps are scaled, this can give a good representation of off-design performance, provided the component modeled is not too radically different from that of the map being used. However, the user often uses a map without any knowledge of what the map looks like and the design point on the map is picked somewhat arbitrarily. Furthermore, problems can arise getting NNEP to converge when the operating point gets outside the bounds of the tabular map data. When this occurs the map data must be extrapolated to get the required data. However, the user normally has no way of knowing where he is operating on the map. Even if a plot of the original map is available it is of very little use since all its values have been scaled by NNEP. As engine cycles become more complex and engine controls become more sophisticated it is increasingly important to know how the compressors and turbines are operating over a flight path.

This paper describes a method of plotting the scaled NNEP maps as you run the NNEP code as well as plotting the operating line of all cases that were computed in that particular NNEP run. Afterwards, an example demonstrates the use of this capability to help analyze a NNEP engine cycle model and then make improvements to that cycle.

METHOD

Compressor Maps

The problem is to essentially recreate the original map that was used to create the NNEP map tables and scale this map to match the NNEP case that is being run.

First the corrected flow map table data is scanned to get the minimum and maximum values of corrected flow. These minimum and maximum values are used along with the NNEP scale factor on corrected flow to set the bounds of the abscissa on the map. Similarly, the pressure ratio map table data is scanned to obtain the minimum and maximum values of pressure ratio. These minimum and maximum values are used along with the NNEP scale factor on pressure ratio to set the bounds of the ordinate on the map.

The efficiency map data is scanned and scaled by the NNEP efficiency scale factor to get the minimum and maximum efficiency values. The efficiency map data is also scanned to get actual R and corrected speed values used on the map. Subroutine TREAD (the same subroutine that is used in NNEP to interpolate map data) is then used to obtain values of corrected flow versus pressure ratio for lines of constant corrected speed and constant R using the corrected speed and R values that were obtained when scanning the efficiency map. Efficiency values cannot be directly plotted on the corrected flow versus pressure ratio map. Instead, a contouring routine is used to generate lines of constant efficiency values that may be plotted on the map. Efficiency contours with values increasing by 0.05 are obtained between the minimum and maximum efficiency value contours. All of these map values (corrected flow, pressure ratio, and efficiency) are then scaled using NNEP scale factors and are plotted, thus recreating the compressor map as shown in figure 3. Since the same routine interpolates the map table to do the plotting as is used by NNEP when running the engine cycle, the plotted map should accurately represent what NNEP uses to generate the matched engine cycle. R lines (represented as dashed lines) and corrected speed lines (represented as solid lines) are labeled directly at the end of each line. A table of the values of the efficiency contours is printed in the lower right corner of the plot. The label at the top of the plot describes what type of map is plotted (compressor or turbine), gives the value of JCX which is the NNEP component number corresponding to the map, and lists the Z value which is the third-dimensional map argument that corresponds to the map. Once the scaled map is created, the operating line is plotted using the values of corrected flow and pressure ratio that were saved from all the NNEP cases that had been included in that particular NNEP run.

Special consideration must be made for a cycle where the compressor uses variable geometry. When this occurs, there is one map for each value of the third-dimensional argument (in most cases the stator angle). Thus it is not possible to plot the operating line on one map to represent all the conditions that occur along the operating line. There is too much information on any given map to practically represent a three-dimensional plot of a map. To try to handle this problem, the program presents three options from which the user can choose. For the first option, the minimum and maximum third-dimensional arguments that are used along the operating line are found. Then a map representing the minimum value is plotted with the complete operating line and a second map representing the maximum value is plotted with the complete operating line. Although the operating line is not accurately represented on either map, the user may mentally interpolate between the two maps to imagine where the operating points will fall.

Often the variable geometry does not change very much along the operating line. For these cases, the second option is useful. When using this option, the mean value and the standard deviation of the third-dimensional argument along the operating line is calculated. A map is then drawn corresponding to this mean value with the operating line plotted on it. As long as the deviation from the mean value is small, this method should be a good representation of the map and operating line.

Finally, the third option plots each operating point on a separate map with a third-dimensional argument that corresponds to that operating point. This is the only option that will give a truly accurate representation of the location of the operating point on the compressor map. However, since it results in one map for each NNEP case that had been run, it could result in a very lengthy output of maps. Therefore, it is most useful when very accurate spotting of the operating point on the map is necessary and the other two options are not adequate enough because of a large spread in third-dimensional argument values.

Turbine Maps

Turbines are handled similarly to compressors except now the two original turbine maps are used to form NNEP map tables of turbine pressure ratio versus corrected flow and turbine pressure ratio versus efficiency. The data in these maps are scanned in a similar way as the compressor maps to get the minimum and maximum values of efficiency, corrected flow, and pressure ratio on the maps. These minimum and maximum values are then multiplied by their respective NNEP scale factors and then are used to set the bounds on the abscissa and ordinate for the pressure ratio versus corrected flow map and the pressure ratio versus efficiency map. The actual corrected speed line values are obtained from the maps and are multiplied by its NNEP scale factor to obtain the values of the corrected speed lines that are to be plotted on the map. Then subroutine TREAD is used as it was with the compressor to obtain values of pressure ratio versus corrected flow and pressure ratio versus efficiency for the values of constant corrected speed that were found above. These values are then scaled and plotted, thus recreating the turbine map as shown in figure 4. A table of the corrected speed line values is printed in the lower right corner of the plot. The component number (labeled JCX) of the turbine being plotted along with the third-dimensional argument value (labeled Z angle) is printed in the plot header. Once the scaled map is created, the operating line is plotted using the values of pressure ratio, corrected flow, and efficiency that were saved from all the NNEP cases that had been included in that particular NNEP run.

As with the compressor, special consideration must be made for the case where a turbine uses variable geometry. When a third-dimensional argument (in most cases the flow area) is used on the turbine, the program presents the same three options for the user to choose from as for the compressor. See the compressor description for explanation of these three options.

These plotting routines were written to use the NASA Lewis GRAPH3D (Manual G3-1310-V001, 1985) graphics software. Although this software is not available at other sites, the map plotting routines could be easily modified to use other graphics software packages. The appendix gives a brief description of all the graphics subroutines that are used. This should help the potential users determine if their graphics software has equivalent calls that may be substituted for the ones in the current program.

RESULTS

The generation of plots of the component maps can be very useful for understanding how the components match in the NNEP model. An example is now presented which demonstrates the use of the component map plots in analyzing a NNEP engine cycle model. Then modifications are made to the cycle model and corresponding changes to the operating line of each compressor and turbine are shown. This example uses a typical current high bypass ratio subsonic turbofan engine. The NNEP schematic diagram of this engine cycle is shown in figure 5. This two spool engine has a bypass ratio of 4.3 and an overall pressure ratio of 30 at its sea level static design point. The engine employs separate flow nozzles with fixed geometry. Six cases were run at full power to represent a typical constant indicated airspeed climb trajectory from sea level static up to a cruise altitude of 35 000 ft and Mach 0.8 as shown in figure 6. Three additional cases were run to represent a throttle curve at the cruise altitude of 35 000 ft.

The output component maps with the operating line from the above NNEP cases is shown in figures 7 through 11. Figure 7 represents the performance of the fan. The corrected flow into the fan increases substantially as the altitude and Mach number increases up the climb path (points 1 through 6). This causes the fan operating line to move away from the surge line as it goes up the climb path, thereby increasing its corrected flow and corrected speed. When throttled back at constant altitude and Mach number representing cruise conditions, the engine corrected flow decreases. This results in the operating line generally following a constant R line while decreasing its corrected flow and corrected speed (points 7 through 9).

Figure 8 shows the results of the low pressure compressor. Like the fan, the corrected flow of the low pressure compressor increases as the altitude and Mach number are increased (points 1 through 6). Although this compressor has no problems during the climb phase, it runs into surge when it is throttled back (points 7 through 9). With as little as 15 percent thrust reduction (point 7) the compressor is approaching surge.

The operating line on the high pressure compressor (fig. 9) is well within the bounds of the map and well behaved. The operating line on the two turbines (figs. 10 and 11) show very little excursion due to the fact the turbines are operating choked.

The problem the NNEP user now faces is to determine how to vary the engine cycle to avoid surge on the low pressure compressor. A number of options is possible. One option would be to chose a completely different compressor (and thereby a different compressor map). Another option might be to introduce variable geometry into the compressor to control its surge margin. Alternatively, variable geometry may be introduced in the exhaust nozzles. This last option will now be demonstrated in detail.

By introducing variable geometry into the nozzles, this gives the NNEP user two more degrees of freedom with which to match the engine since the flow into the nozzles no longer has to be matched. These two degrees of freedom may be used to control the surge margins on the fan and low speed compressor. NNEP defines surge margin as

$$\text{SURGE MARGIN} = \left(\frac{WC/WC_{SURGE}}{PR/PR_{SURGE}} - 1.0 \right) \times 100.$$

where WC is the corrected weight flow and PR is the compressor pressure ratio for a given point on the map. WC_{SURGE} and PR_{SURGE} are the corresponding values of corrected weight flow and pressure ratio, respectively, at surge (R value = 1) for a constant corrected compressor speed. For this example, the bypass nozzle was varied to maintain a constant surge margin of 5 percent on the fan for all cases (cases 1 through 9) and the core nozzle area was varied to maintain a constant surge margin of 5 percent on the low pressure compressor for cases where the engine is throttled back (cases 7 through 9). This results in the fan and low pressure compressor performance shown in figure 12 and 13, respectively. The compressor and turbine on the high pressure spool shown in figures 14 and 15 changed very little from the previous case. The low pressure turbine (fig. 16) demonstrated a significant change from the previous case. A large change in the low pressure turbine pressure ratio is required to maintain the constant surge margins on the fan and low pressure compressor. Figure 17 shows the fan nozzle area variation required to maintain the surge margin on the fan. The maximum fan nozzle area variation was 12 percent over the range of conditions calculated. The core nozzle area variations are shown in figure 18. The maximum core area variation was also approximately 12 percent.

As can be seen from the example, the user can quickly see the effects various cycle changes have on the operation of the compressors and the turbines. This allows rapid screening of design options to improve the operation of the cycle.

SUMMARY OF RESULTS

The ability to see the operating line on the compressor and turbine maps for NNEP models has proven to be a valuable tool. Not only does it help to understand the operation of new and sometimes complex engine cycles, but it is also very useful as a debugging tool in trying to get NNEP to run a given cycle over a complete flight regime. This helps to pinpoint portions of the flight envelope where the engine could encounter problems.

APPENDIX

REQUIRED GRAPH3D SUBROUTINES

The following subroutines used by the map generation routines are from the NASA Lewis GRAPH3D graphics software package.

CHARS
COPY
CORNER
CONGEN
GINTVL
GPLOT
DISPLA
DISPLC
NUMBER
XAXIS
YAXIS

A brief description of each of these subroutines now follows so that potential users can determine if they have equivalent calls on the particular graphics package in use at their site.

CHARS. Subroutine CHARS allows the user to print character data anywhere on a plot. The routine is used to label a point. The inputs to the subroutine are:

NCHAR - a constant which specifies the number of characters to be printed.

CHAR - the array of characters to be printed.

ORIENT - the angle of orientation from the horizontal.

X - the x-coordinate of the starting position for the character data.

Y - the y-coordinate of the starting position for the character data.

ISIZE- the size code of the character to be printed.

COLOR. The COLOR subroutine allows the user to generate color plots. The inputs to the subroutine are:

NCLRS - the number of colors in this call to COLOR.

NCLR1 - the color code.

NCNT1 - the number of times the color is to be written or exposed.

CONGEN. The CONGEN subroutine produces a graphic display of a function as contour curves at given levels over the arbitrarily defined grid of two variables which is the domain of the function. The grid of two variables must lie in a plane and be transformable to a two-variable orthogonal system. The function must be known at each grid point. The inputs to the subroutine are:

Z - an array of abscissa values at each grid point.

THETA - an array of ordinate values at each grid point.

F - the function to be contoured.

FC - an array of desired contour levels to be plotted.

COPY. The COPY subroutine allows automatic hard-copy after each plot on Tektronix devices.

CORNER. The CORNER subroutine will remove or restore corner marks that define a frame.

DISPLA. The DISPLA subroutine defines the end of a plot and initiates transmission of orders to the device.

DISPLC. The DISPLC subroutine clears the buffers and sets various fields to allow the user to begin a new plot.

GPLOT. The GPLOT subroutine enables the user to plot single or multiple curves or lines as vector, symbol, or vector-symbol plots. The inputs to the subroutine are:

X - an array of x-coordinates of the user data to be plotted.

Y - an array of y-coordinates of the user data to be plotted.

IVARS - a array of codes that communicate the number of points to be plotted, the type of plot (vector, point, symbol, vector-symbol, polar, etc.), the symbol code for a symbol plot, the symbol frequency, and the symbol size.

NUMBER. The NUMBER subroutine allows the user to convert an integer or real number to an array of characters which can be plotted.

XAXIS, YAXIS. The XAXIS and YAXIS subroutines allow the user to draw x and y axes, respectively.

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TABLE I. - EXAMPLE NNEP COMPRESSOR MAP TABLE

1000		EXAMPLE COMPRESSOR MAP						
ANGL	1	0.00						
SPED	10	50.000	60.000	70.000	75.000	80.000	85.000	90.000
		95.000	100.000	110.000				
R	7	1.000	1.100	1.200	1.300	1.400	1.500	1.600
FLOW	7	8.615	8.947	9.144	9.526	9.784	10.203	10.450
FLOW	7	10.914	11.086	11.455	11.984	12.525	13.018	13.315
FLOW	7	13.184	14.179	14.903	15.800	16.502	17.204	17.601
FLOW	7	14.895	16.293	17.435	18.492	19.390	19.983	20.331
FLOW	7	17.682	19.300	20.687	21.807	22.572	23.092	23.466
FLOW	7	21.311	23.260	24.453	25.280	25.766	26.091	26.295
FLOW	7	25.306	27.098	28.060	28.412	28.641	28.747	29.013
FLOW	7	29.718	30.484	30.849	31.103	31.273	31.379	31.424
FLOW	7	33.059	33.258	33.392	33.513	33.561	33.606	33.688
FLOW	7	37.413	37.415	37.501	37.598	37.575	37.621	37.678
EOT								
1001		EXAMPLE COMPRESSOR MAP						
ANGL	1	0.00						
SPED	10	50.000	60.000	70.000	75.000	80.000	85.000	90.000
		95.000	100.000	110.000				
R	7	1.000	1.100	1.200	1.300	1.400	1.500	1.600
EFF	7	0.704	0.705	0.701	0.700	0.695	0.690	0.680
EFF	7	0.725	0.730	0.745	0.755	0.750	0.725	0.700
EFF	7	0.745	0.765	0.780	0.805	0.810	0.795	0.770
EFF	7	0.750	0.780	0.805	0.820	0.825	0.812	0.795
EFF	7	0.780	0.805	0.835	0.849	0.848	0.837	0.820
EFF	7	0.800	0.840	0.855	0.860	0.856	0.845	0.830
EFF	7	0.830	0.852	0.860	0.869	0.859	0.848	0.830
EFF	7	0.850	0.855	0.862	0.869	0.857	0.845	0.828
EFF	7	0.853	0.857	0.859	0.860	0.850	0.830	0.806
EFF	7	0.849	0.848	0.845	0.835	0.820	0.800	0.790
EOT								
1002		EXAMPLE COMPRESSOR MAP						
ANGL	1	0.00						
SPED	10	50.000	60.000	70.000	75.000	80.000	85.000	90.000
		95.000	100.000	110.000				
R	7	1.000	1.100	1.200	1.300	1.400	1.500	1.600
PR	7	1.820	1.775	1.734	1.654	1.587	1.458	1.369
PR	7	2.481	2.456	2.405	2.318	2.229	2.075	1.918
PR	7	3.435	3.445	3.404	3.334	3.168	2.966	2.706
PR	7	4.066	4.135	4.127	4.021	3.833	3.553	3.203
PR	7	4.934	5.070	5.065	4.867	4.565	4.222	3.782
PR	7	6.142	6.334	6.161	5.821	5.285	4.861	4.302
PR	7	7.573	7.623	7.222	6.628	5.988	5.445	4.841
PR	7	9.000	8.668	8.012	7.334	6.589	5.997	5.358
PR	7	9.814	9.570	8.754	7.982	7.124	6.491	5.851
PR	7	10.998	10.834	9.940	9.047	8.034	7.321	6.707
EOT								

TABLE II. - EXAMPLE NNEP TURBINE MAP TABLE

```
 1003       EXAMPLE TURBINE MAP
ANGL  1        0.00
SPED  7       50.000    60.000    70.000    80.000    90.000   100.000   110.000
PR    11       1.217     1.285     1.323     1.363     1.402     1.427     1.495
               1.545     1.600     1.687     1.747
FLOW 11       40.403    44.417    46.653    47.966    48.970    49.544    50.001
              50.081    50.086    50.095    50.090
PR    12       1.231     1.302     1.356     1.404     1.443     1.473     1.525
               1.577     1.635     1.709     1.782     1.845
FLOW 12       40.044    43.754    46.125    47.626    48.513    49.105    49.481
              49.580    49.597    49.624    49.638    49.633
PR    10       1.242     1.328     1.388     1.437     1.528     1.617     1.704
               1.811     1.915     1.979
FLOW 10       39.941    43.795    46.017    47.335    48.795    49.199    49.279
              49.270    49.248    49.230
PR    11       1.244     1.339     1.417     1.465     1.528     1.584     1.692
               1.787     1.899     2.000     2.075
FLOW 11       39.896    43.512    45.914    47.061    48.011    48.558    48.943
              49.042    49.069    49.010    49.046
PR    11       1.245     1.340     1.425     1.492     1.546     1.684     1.748
               1.882     1.987     2.084     2.167
FLOW 11       39.524    42.934    45.686    46.743    47.715    48.670    48.777
              48.836    48.876    48.836    48.845
PR    11       1.251     1.345     1.442     1.521     1.596     1.692     1.849
               1.972     2.100     2.173     2.259
FLOW 11       39.439    43.010    45.556    46.801    47.792    48.388    48.634
              48.670    48.639    48.647    48.625
PR    12       1.248     1.348     1.447     1.516     1.581     1.651     1.749
               1.839     1.930     2.024     2.154     2.242
FLOW 12       39.502    42.849    45.336    46.385    47.312    47.877    48.222
              48.397    48.459    48.482    48.455    48.414
EOT
```

TABLE II. - Concluded.

1004		EXAMPLE TURBINE MAP						
ANGL	1	0.00						
SPED	7	50.000	60.000	70.000	80.000	90.000	100.000	110.000
PR	9	1.224	1.246	1.292	1.387	1.457	1.535	1.610
		1.686	1.743					
EFF	9	0.720	0.754	0.759	0.739	0.714	0.679	0.643
		0.603	0.554					
PR	10	1.237	1.250	1.280	1.369	1.459	1.553	1.629
		1.716	1.799	1.846				
EFF	10	0.716	0.757	0.794	0.819	0.812	0.788	0.761
		0.728	0.692	0.662				
PR	11	1.241	1.255	1.283	1.326	1.401	1.509	1.591
		1.704	1.806	1.913	1.994			
EFF	11	0.629	0.691	0.775	0.831	0.858	0.869	0.859
		0.842	0.816	0.782	0.752			
PR	12	1.250	1.265	1.308	1.364	1.456	1.532	1.637
		1.739	1.851	1.934	2.042	2.085		
EFF	12	0.594	0.668	0.757	0.804	0.857	0.883	0.892
		0.893	0.884	0.865	0.835	0.821		
PR	12	1.281	1.314	1.371	1.425	1.498	1.574	1.647
		1.759	1.878	1.979	2.091	2.180		
EFF	12	0.664	0.720	0.779	0.823	0.858	0.883	0.897
		0.905	0.904	0.896	0.883	0.868		
PR	12	1.252	1.328	1.425	1.544	1.642	1.757	1.873
		2.005	2.100	2.204	2.248	2.280		
EFF	12	0.559	0.610	0.673	0.741	0.788	0.835	0.869
		0.895	0.908	0.899	0.854	0.751		
PR	11	1.382	1.430	1.495	1.586	1.688	1.791	1.887
		1.990	2.079	2.158	2.249			
EFF	11	0.718	0.785	0.824	0.855	0.882	0.900	0.908
		0.906	0.884	0.857	0.804			
EOT								

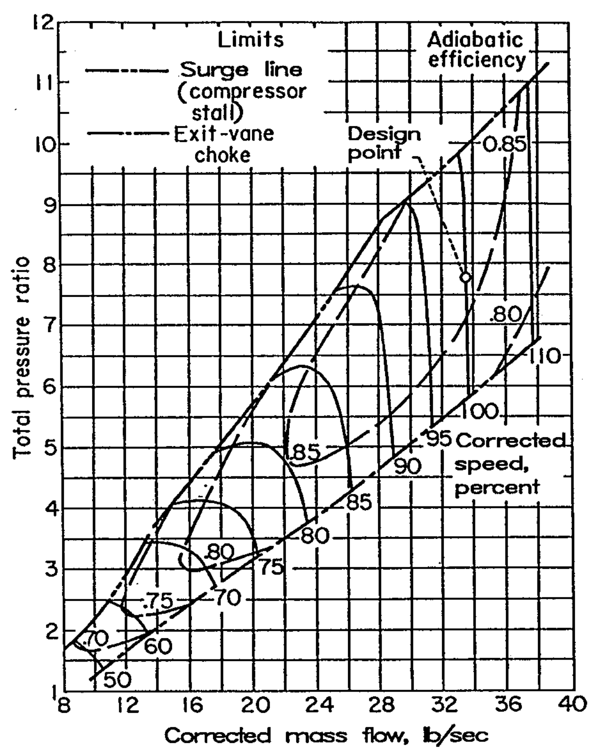

FIGURE 1. - EXAMPLE OF COMPRESSOR MAP.

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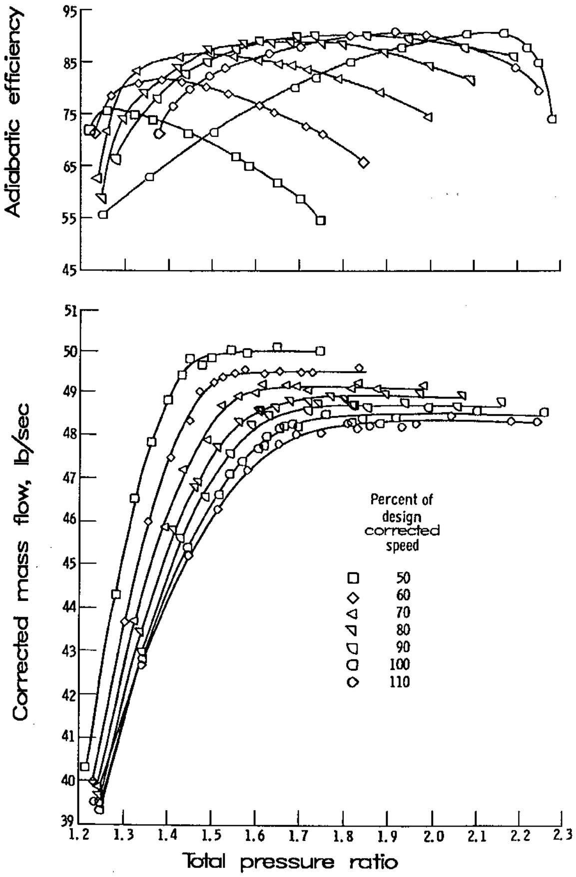

FIGURE 2. - EXAMPLE OF TURBINE MAP.

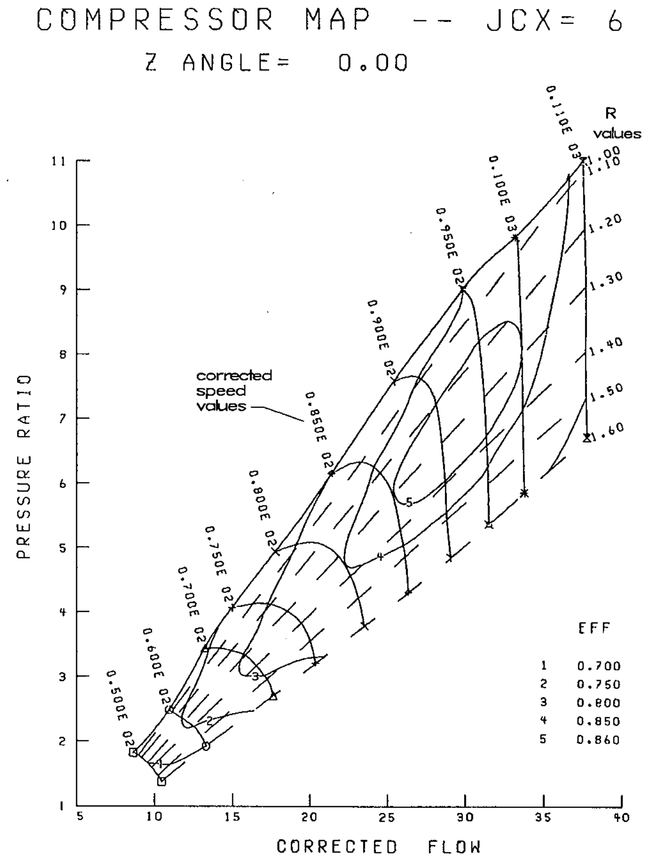

FIGURE 3. - EXAMPLE OF COMPRESSOR MAP RECREATED WITH NNEP MAP PLOTTING ROUTINES.

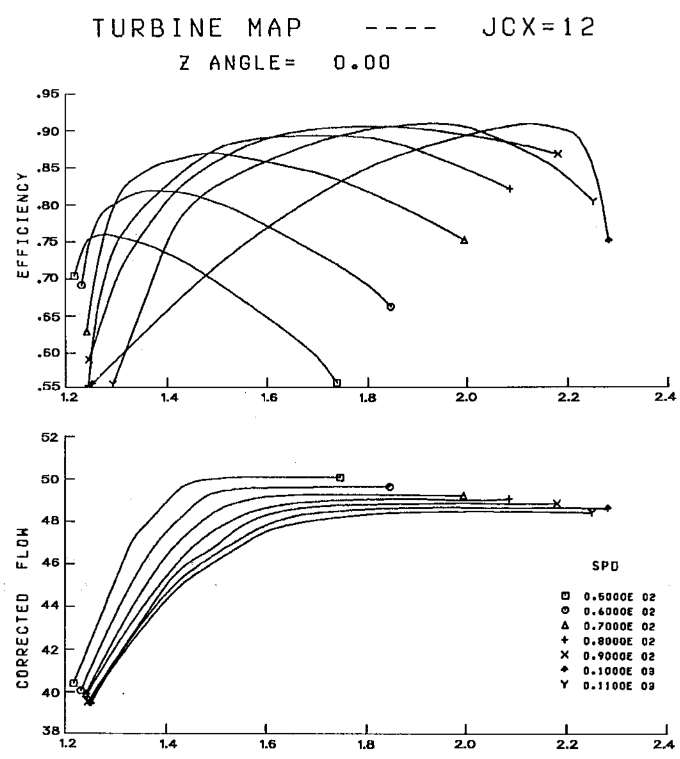

FIGURE 4. - EXAMPLE OF TURBINE MAP RECREATED WITH NNEP MAP PLOTTING ROUTINES.

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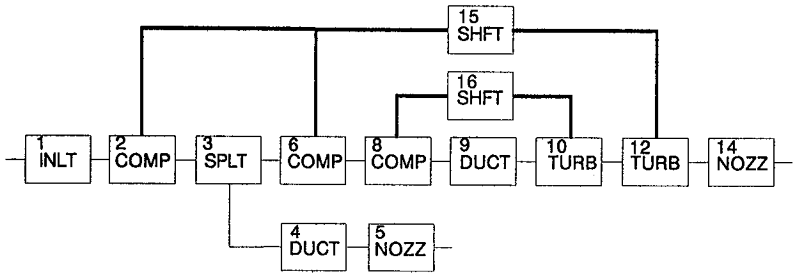

FIGURE 5. - BLOCK DIAGRAM OF EXAMPLE TURBOFAN ENGINE.

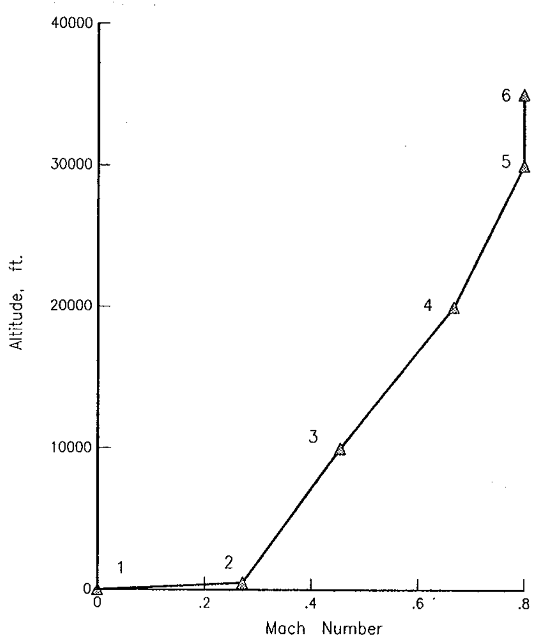

FIGURE 6. - MACH NUMBER VERSUS ALTITUDE FOR EXAMPLE OF CLIMB TRAJECTORY.

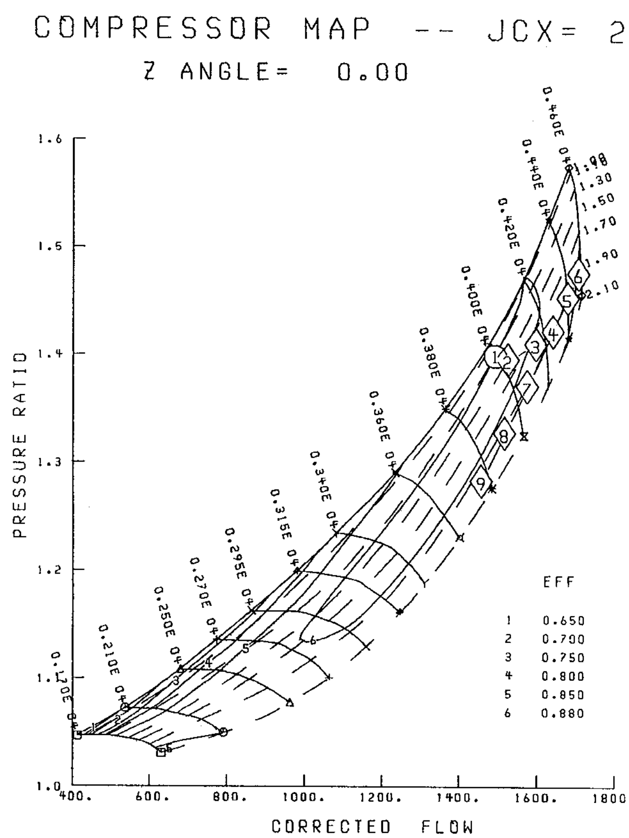

FIGURE 7. - FAN MAP AND OPERATING LINE FOR A TURBOFAN ENGINE WITH FIXED NOZZLE AREAS.

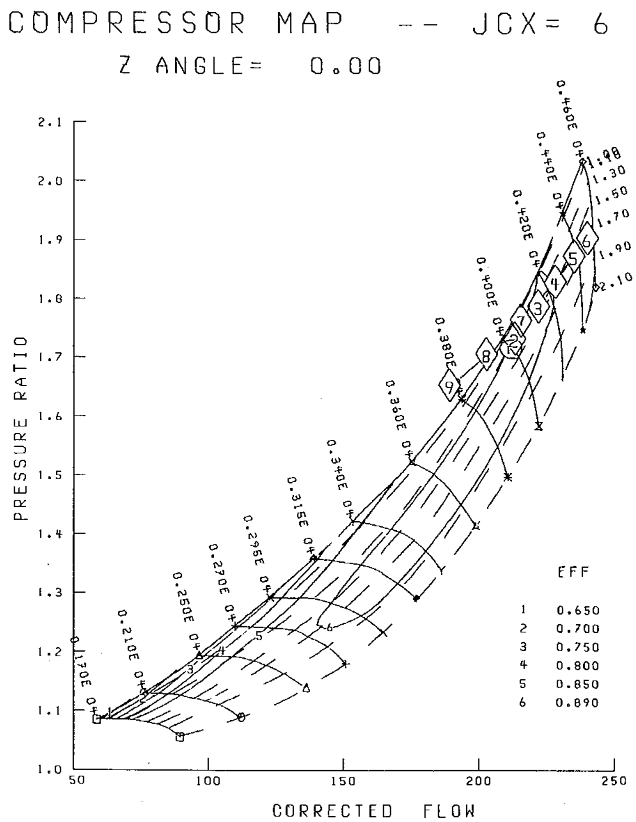

FIGURE 8. - LOW PRESSURE COMPRESSOR MAP AND OPERATING LINE FOR A TURBOFAN ENGINE WITH FIXED NOZZLE AREAS.

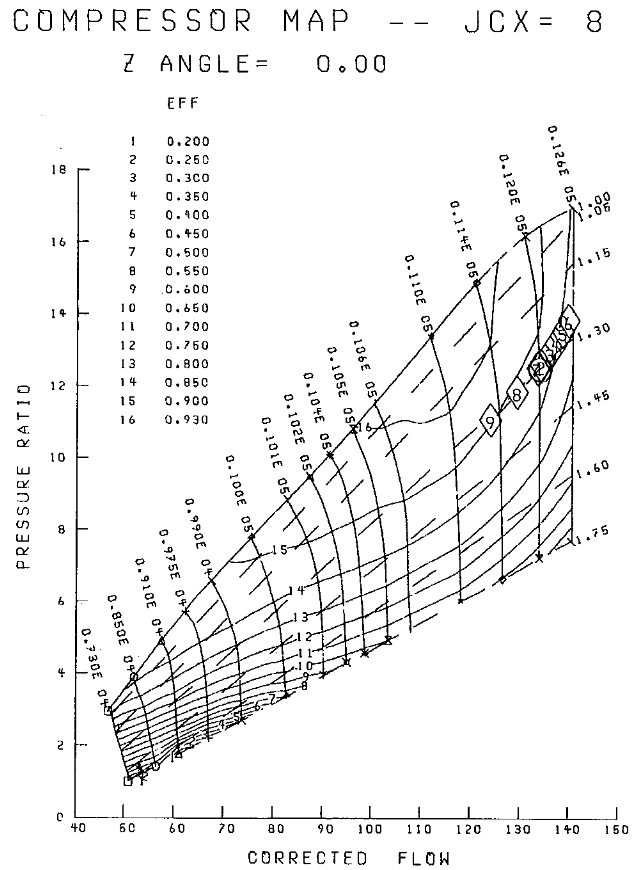

FIGURE 9. - HIGH PRESSURE COMPRESSOR MAP AND OPERATING LINE FOR A TURBOFAN ENGINE WITH FIXED NOZZLE AREAS.

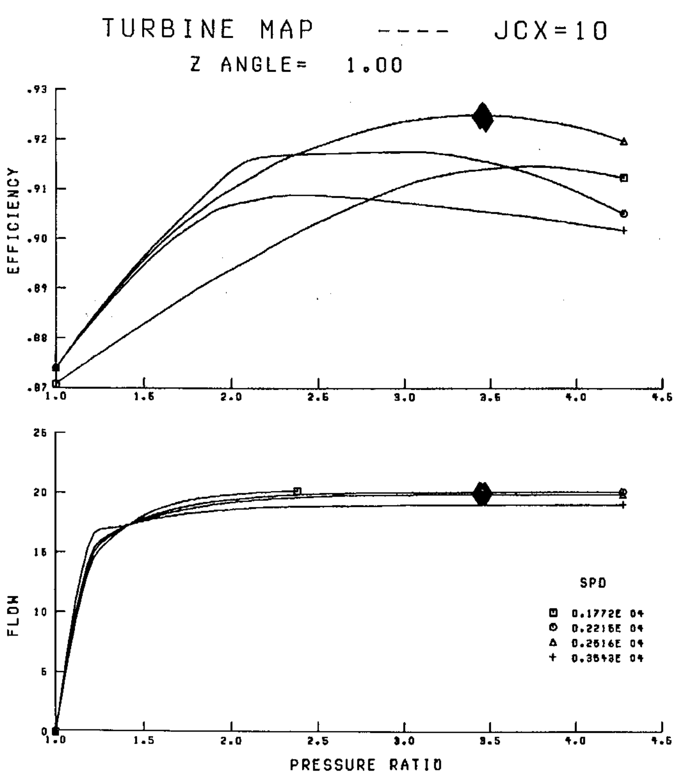

FIGURE 10. - HIGH PRESSURE TURBINE MAP AND OPERATING LINE FOR A TURBOFAN ENGINE WITH FIXED AREA NOZZLES.

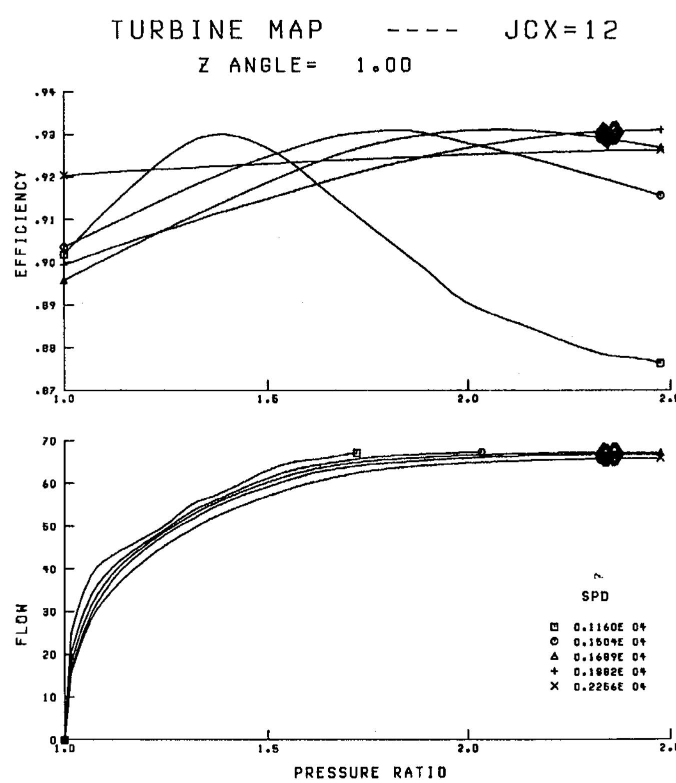

FIGURE 11. - LOW PRESSURE TURBINE MAP AND OPERATING LINE FOR A TURBOFAN ENGINE WITH FIXED AREA NOZZLES.

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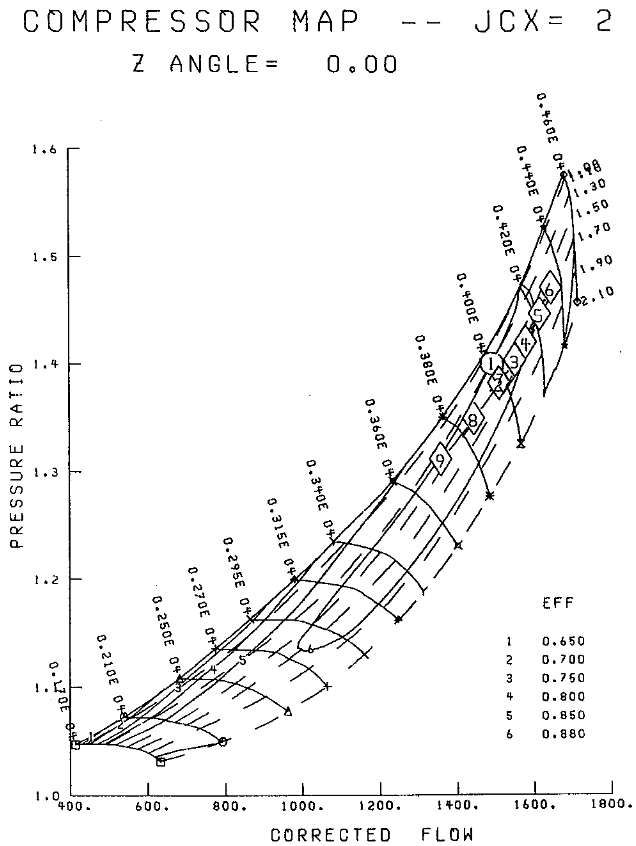

FIGURE 12. - FAN MAP AND OPERATING LINE FOR A TURBOFAN ENGINE WITH VARIABLE AREA NOZZLES.

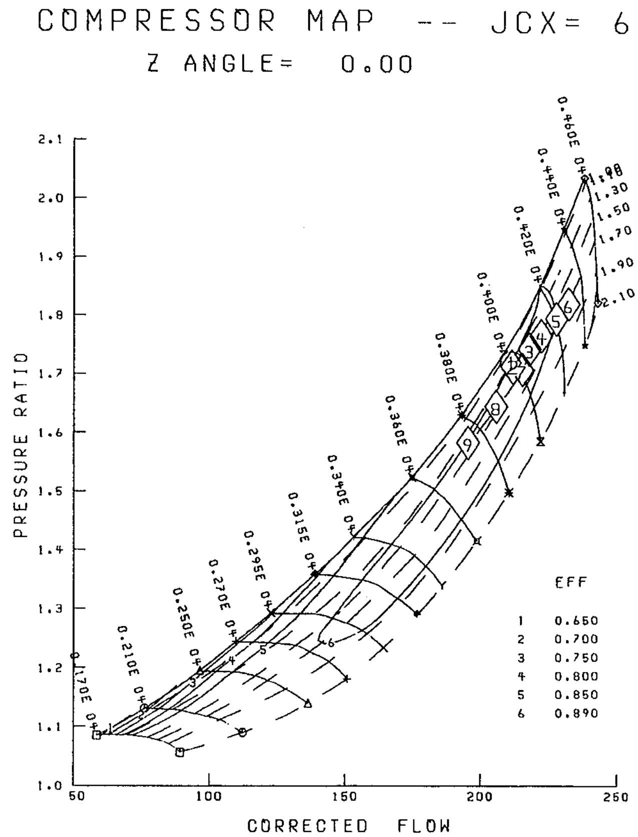

FIGURE 13. - LOW PRESSURE COMPRESSOR MAP AND OPERATING LINE FOR A TURBOFAN ENGINE WITH VARIABLE AREA NOZZLES.

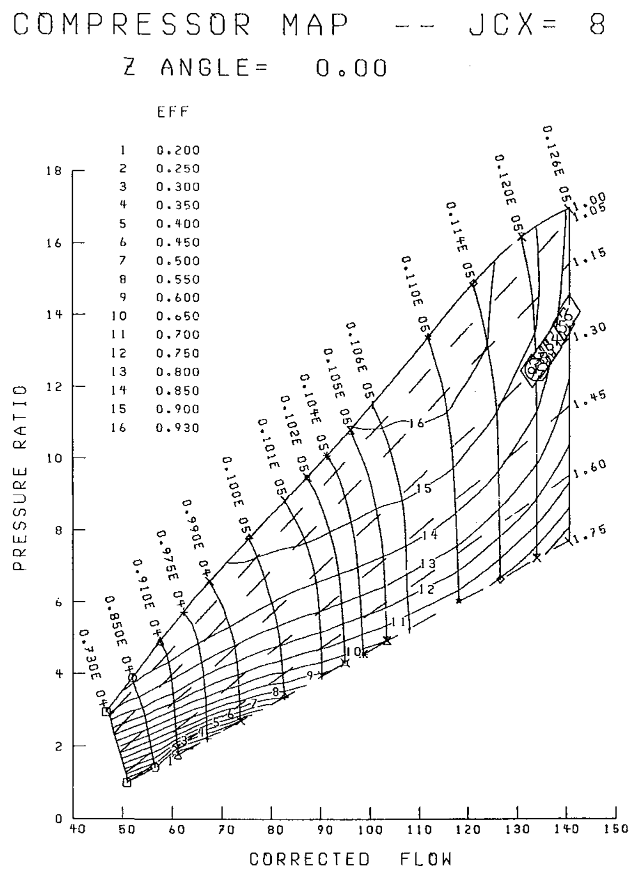

FIGURE 14. - HIGH PRESSURE COMPRESSOR MAP AND OPERATING LINE FOR A TURBOFAN ENGINE WITH VARIABLE AREA NOZZLES.

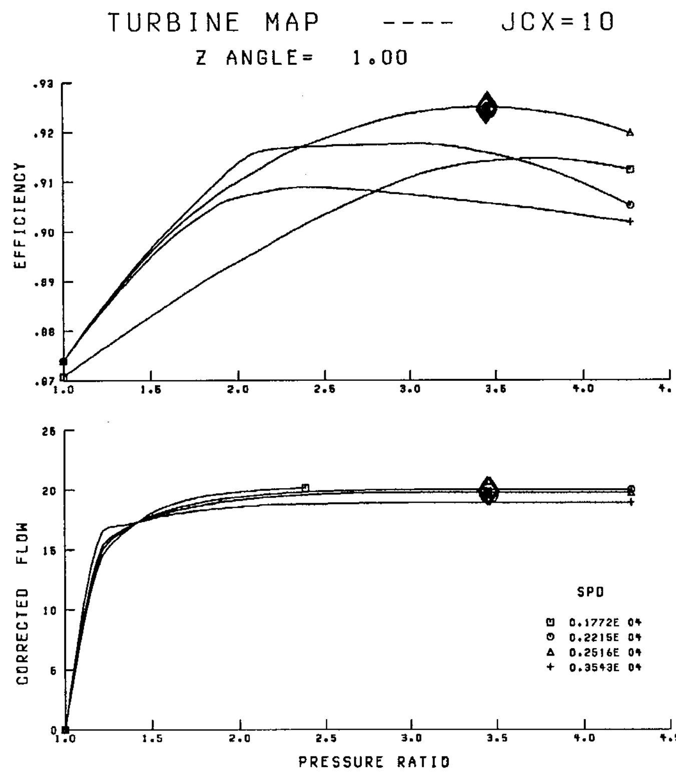

FIGURE 15. - HIGH PRESSURE TURBINE MAP AND OPERATING LINE FOR A TURBOFAN ENGINE WITH VARIABLE AREA NOZZLES.

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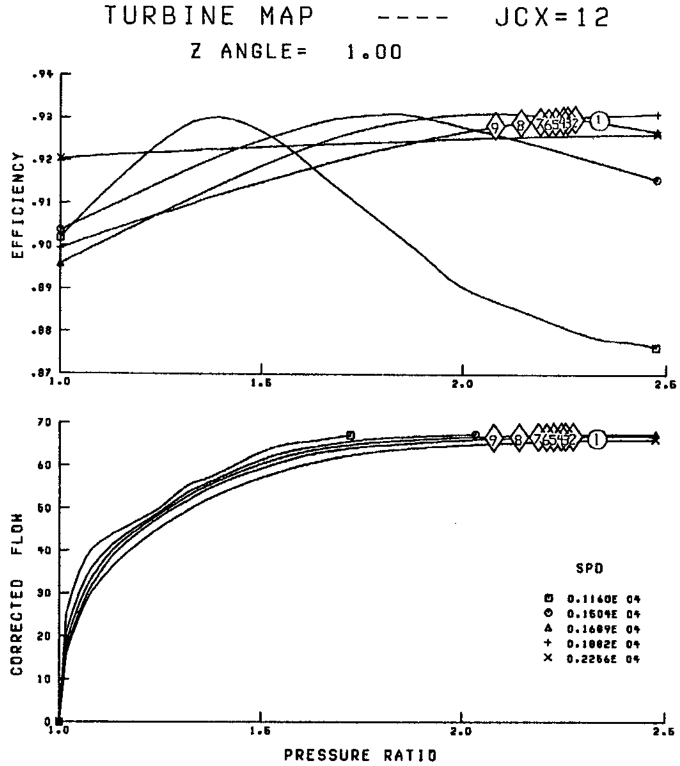

FIGURE 16. - LOW PRESSURE TURBINE MAP AND OPERATING LINE FOR A TURBOFAN ENGINE WITH VARIABLE AREA NOZZLES.

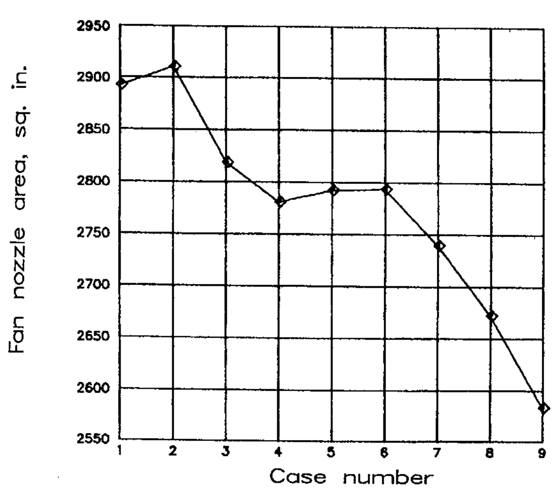

FIGURE 17. - FAN NOZZLE AREA VARIATION.

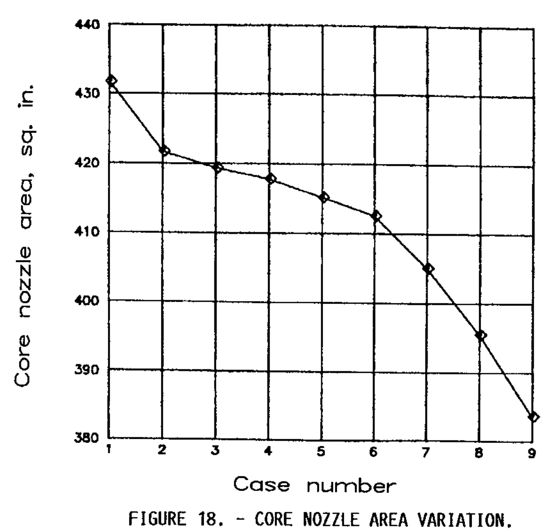

FIGURE 18. - CORE NOZZLE AREA VARIATION.

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15. Supplementary Notes

16. Abstract

The Navy/NASA Engine Program (NNEP) and the new extended version which handles chemical equilibrium (NNEPEQ) are very general cycle analysis codes that have been used extensively to calculate design and off-design performance of a wide range of turbine engine cycles and configurations. Component maps are used to obtain the off-design engine performance and a "matched engine cycle." This paper describes a method of plotting the scaled NNEP compressor and turbine maps as the user runs the NNEP code as well as plotting the operating line defined by all the cases that were computed in that particular NNEP run. Afterwards, an example demonstrates the use of this capability to help analyze an engine cycle model and then make improvements to that cycle.

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