

UNCLASSIFIED

AD NUMBER
AD825197
NEW LIMITATION CHANGE
TO Approved for public release, distribution unlimited
FROM Distribution authorized to U.S. Gov't. agencies and their contractors; Administrative/Operational Use; NOV 1967. Other requests shall be referred to US Air Force Aero Propulsion Laboratory, Attn: Research and Technology Division, Wright-Patterson AFB, OH 45433.
AUTHORITY
AFAPL ltr, 12 Apr 1972

THIS PAGE IS UNCLASSIFIED

AFAPL-TR-67-125
PART I

AD825197

SIMULATION OF TURBOFAN ENGINE

PART I. DESCRIPTION OF METHOD AND BALANCING TECHNIQUE

JOHN S. McKINNEY, CAPTAIN, USAF

TECHNICAL REPORT AFAPL-TR-67-125, PART I

JAN 7 1968

NOVEMBER 1967

~~...is subject to special export controls and is not to be released without
approval of the Air Force Research and Development Command. This is to be
...may be made only with prior approval of the Air Force Research and Development Command.~~

AIR FORCE AERO PROPULSION LABORATORY
RESEARCH AND TECHNOLOGY DIVISION
AIR FORCE SYSTEMS COMMAND
WRIGHT-PATTERSON AIR FORCE BASE, OHIO

NOTICE

~~...corporation, or any other entity, that may in any way be related thereto.~~

SEARCHED	INDEXED
SERIALIZED	FILED
JAN 19 1968	
FBI - NEW YORK	

2

Copies of this report should not be returned unless return is required by security considerations, contractual obligations, or notice on a specific document.

AFAPL-TR-57-125
PART I

SIMULATION OF TURBOFAN ENGINE

PART I. DESCRIPTION OF METHOD AND BALANCING TECHNIQUE

JOHN S. McKINNEY, CAPTAIN, USAF



AFAPL-TR-67-125
Part I

FOREWORD

This report was prepared in the Components Branch (APTC), Turbine Engine Division, Air Force Aero Propulsion Laboratory, Wright-Patterson Air Force Base, Ohio, under Project 3066, "Gas Turbine Technology," Task 306603, "Advanced Engine Studies," with Charles E. Bentz as Project Engineer.

This report covers work conducted within the Components Branch in the time period between July 1965 and June 1967 and was submitted by the author 31 August 1967.

This technical report has been reviewed and is approved.


ERNEST C. SIMPSON
Chief, Turbine Engine Division
Air Force Aero Propulsion Laboratory

ABSTRACT

This report describes a digital computer program titled SMOTE (Simulation of Turbofan Engine). SMOTE is a computer program for balancing-cycle turbofan engines capable of running both design and off-design points. Component performance maps are reduced to Block Data (tabular form) to provide a base for calculating component performance. The design point is run first and map correction factors are calculated to scale the components to the desired performance. These correction factors are then applied to the component performance maps at off-design points. Initially, when the program is running at an off-design point, the cycle is not balanced, and errors (for example, work required by the compressor minus work supplied by the turbine) are generated. Small changes in engine independent variables (for example, compressor speed) then produce small changes in the errors, and these differential changes are loaded into a matrix. The matrix is then solved for the set of independent variables which results in zero errors, thus balancing the cycle. Actually, this process may be repeated several times before it reaches a balanced point because there is a nonlinear relationship between the independent variables and the errors. Sample results are included in this report.

(Distribution of this abstract is unlimited.)

TABLE OF CONTENTS

SECTION	PAGE
I INTRODUCTION	1
II SUMMARY	2
III HISTORY	4
IV METHOD OF ENGINE CALCULATIONS	5
1. Component Maps	5
2. Design Point	7
3. Scaling Factors	7
4. Off-Design Points	7
5. Quadratic Interpolation Routine	11
V BALANCING TECHNIQUE	13
APPENDIX - SAMPLE RESULTS	15
REFERENCES AND BIBLIOGRAPHY	28

ILLUSTRATIONS

FIGURE		PAGE
1.	SMOTE Computer Program Flow Chart	3
2.	Example of Fan-Compressor Map	5
3.	Example of Combustor Map	6
4.	Example of Turbine Map	6
5.	Schematic of Engine Components	9

SYMBOLS

BLF	bleed from fan lost to cycle (leakage)
BLDU	bleed from compressor to duct (leakage)
BLHP	bleed from compressor to high pressure turbine (cooling)
BLLP	bleed from compressor to low pressure turbine (cooling)
BLOB	bleed from compressor overboard for customer use
CN	corrected speed
DHTC	delta-H corrected for temperature
H	enthalpy
PCNC	percent speed of the compressor
PCNF	percent speed of the fan
P	pressure
P2	pressure at the fan face
TFFHP	turbine flow function, high pressure turbine
TFFLP	turbine flow function, low pressure turbine
T	temperature
T2	temperature at the fan face
T21	temperature at the fan exit
T4	main combustor burning temperature
T24	duct-burner burning temperature
T7	afterburner burning temperature
WFA	afterburner fuel flow
WFB	main-combustor fuel flow
WFD	duct-burner fuel flow
WG	gas flow rate
ZC	pressure-ratio ratio of the compressor
ZF	pressure-ratio ratio of the fan

SECTION I

INTRODUCTION

Recent advances in turbine-engine state of the art have increased the requirements for more and better cycle studies. These cycle studies are needed to monitor present engines, determine sensitive or critical areas in near future engines now under development, and to explore the advantages and disadvantages of proposed advanced engine cycles for future aircraft.

Parametric cycle studies, which involve essentially numerous design-point calculations, partially fulfill this need, particularly for optimizing a cycle for a specific single design-point mission. However, with multimission aircraft being emphasized increasingly and with the need for determining off-design performance, the requirement for a balancing cycle computer program (that is, one which simulates a turbine engine at both design and off-design points) becomes definite and essential.

The purpose of this report is to describe a digital computer program for balancing cycle turbofan engines. The program, titled SMOTE (Simulation of Turbofan Engine), was developed in the Components Branch, Turbine Engine Division, Air Force Aero Propulsion Laboratory, to meet the requirements given in the preceding paragraphs. In addition to meeting these requirements, SMOTE is considerably more flexible, requires less computer storage or space, and requires less computer operating time than previous engine cycle decks of comparable sophistication.

Part I of this report describes the method of engine calculations and the balancing technique and gives some sample results. Part II is intended as a user's manual and includes instructions for setting up and running the program, as well as a program listing. The parts may be used independently of one another.

SECTION II

SUMMARY

SMOTE is a computer program for balancing-cycle turbofan engines which presently uses component performance maps for the fan, compressor, combustor, and both turbines to provide the basic performance data, but it can easily be expanded to include additional component performance maps if available. The maps are in Block Data form and are scaled internally to simulate a specific engine. Errors due to an unbalanced cycle are generated at off-design points, and the effects of small changes in independent variables upon the errors are determined. A matrix of differential error equations is then solved to determine the correct values of the independent variables which would produce zero errors. A flow chart of the program is shown in Figure 1.

For a more accurate simulation of a particular engine, performance maps for other components could be added; for example, duct-burner or afterburner maps may be desired. It should also be mentioned that other formats for presenting maps may be used as readily as those presented in this report. Rather than inputting bleed air values at each point or using a constant bleed, a bleed schedule could be used. In addition, if a variable-area nozzle is to be simulated, a nozzle area schedule could be used. Or an engine control system could be used which would set fuel flow, bleeds, and nozzle areas as some function of a power lever angle.

The complexity of an engine cycle can be increased by increasing the size of the matrix (increasing the number of partial differential equations). For example, a basic triple-spool turbofan cycle could be represented using a matrix of nine equations. Or a T-compressor fan engine composed of a fan tip, fan hub, low pressure compressor (running at the same speed as the fan), high pressure compressor, combustor, two turbines, gas mixer, and afterburner could be represented using a matrix of eight equations.

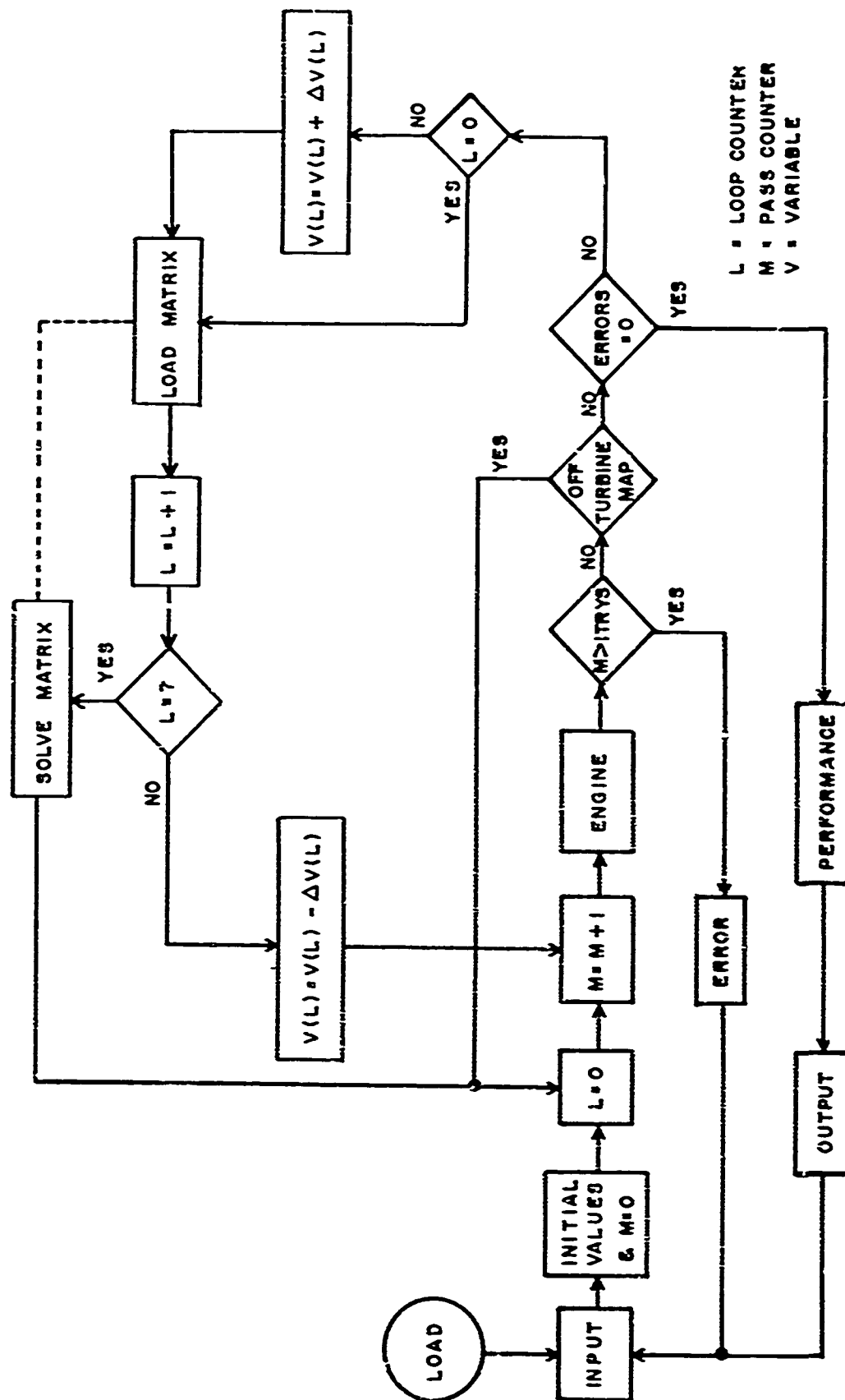


Figure 1. SMOTE Computer Program Flow Chart

SECTION III

HISTORY

Until about six years ago, most general cycle calculations in the Components Branch were done by hand, although some computer programs were available for specific engines. About that time a turbojet, parametric-cycle study program (SPEEDY) was conceived, and, from this program, a more general turbojet or turbofan program (CARPET) with many configuration options was developed. CARPET is still in general use for parametric and optimization studies.

About three years ago, a balancing-cycle turbojet or single-spool computer program (SSPOOL) was developed within the Components Branch. The engine component calculations were based essentially on those in CARPET, and the balancing technique, which depended upon a quadratic interpolation routine (AFQUIR), involved two nested balancing loops. The inner loop was balanced using PCNC as an independent variable and the work difference between compressor and turbine as the dependent variable. The outer loop was balanced using ZC (see Figure 2 for a definition of ZC) and the pressure required by the fixed-area exhaust nozzle. After the inner loop was balanced, the outer loop was changed in an attempt to balance it. Naturally, changes in the outer loop necessitated rebalancing the inner loop. This method, although rather crude, worked well for a turbojet cycle.

The SSPOOL concept was then extended to a turbofan or dual-spool cycle which resulted in a new program called DSPOOL. By logical extension this required four nested loops with four independent variables (PCNF, ZF, PCNC, and ZC) and four dependent variables or errors (two work errors and two nozzle pressure errors for a separate flow cycle; or two work errors, a mixing static pressure error, and a nozzle pressure error for a mixed flow cycle). Although the method worked, computer time was excessive, and various techniques (such as changing the order of the independent variables or using a varying tolerance) were tried in an attempt to shorten the balancing time. These attempts were only partially successful.

Other balancing techniques using various mathematical solutions were experimented with, and the present method was finally developed. This method involves no nested balancing loops; instead, a matrix is loaded with differential errors caused by small changes in the independent variables. The matrix is then solved for the zero error condition. SMOTE reduced computer time by an average factor of about 4 as compared to DSPOOL.

SECTION IV

METHOD OF ENGINE CALCULATIONS

1. COMPONENT MAPS

The performance of the major engine components is based on component maps. These maps are usually obtained from analytical methods or rig-testing and are then converted into Block Data subroutines for use by SMOTE. The maps presently included in SMOTE are very general and do not represent any particular engine or engine components.

The component maps are scaled at the engine design point by SMOTE in order to match their performance to a desired set of performance figures which are input as data. Scaling or correction factors are calculated and then applied to the maps at off-design points. The scaling process is linear; therefore correction factors near unity result in the highest accuracy of component simulation. This means that the component maps used should represent or be similar to the actual components in the engine being simulated. However, with the loss of a little accuracy, maps representing advanced components could be interchanged to determine the effect on the overall cycle.

SMOTE presently includes component maps for the fan, compressor, combustor, and both turbines. Duct burning, duct losses, gas mixing, afterburning, tailpipe losses, and nozzle losses are all calculated or input, but these characteristics could also be included as Block Data if maps were available. Likewise, schedules for bleed air and variable area nozzles could be used.

a. Fan-Compressor Maps

The fan and compressor maps are very similar and are plots of corrected airflow versus pressure ratio with constant corrected speed lines and constant efficiency islands (see Figure 2). Entry to the map is through the corrected speed and Z , where Z is a pressure-ratio ratio, and is defined at a constant corrected speed as shown in Figure 1. It is advantageous to use Z instead of pressure ratio because Z is restrained between the limits of 0 and 1, whereas the limits on the pressure ratio vary depending upon map location and the particular map. Also, an indication that the fan or compressor is approaching surge is given as Z approaches 1.

b. Combustor Map

The combustor map is a plot of temperature rise across the combustor versus efficiency for constant input pressure (see Figure 3). Entry to the map is through temperature rise and input pressure, with efficiency being output.

c. Turbine Map

The turbine map is a plot of turbine corrected speed versus work function with constant turbine flow function lines and constant efficiency islands (see Figure 4). The work function and flow function are defined as

$$DHTC = \frac{H_{IN} - H_{OUT}}{T_{IN}}$$

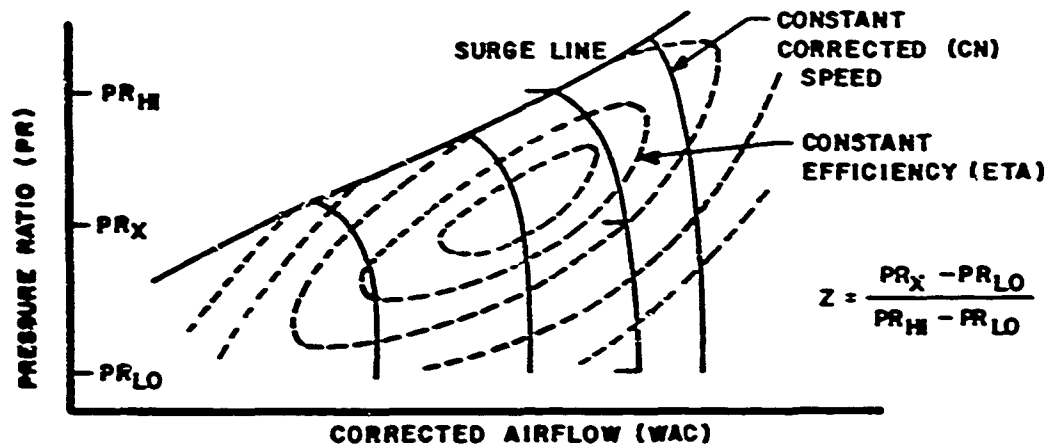


Figure 2. Example of Fan-Compressor Map

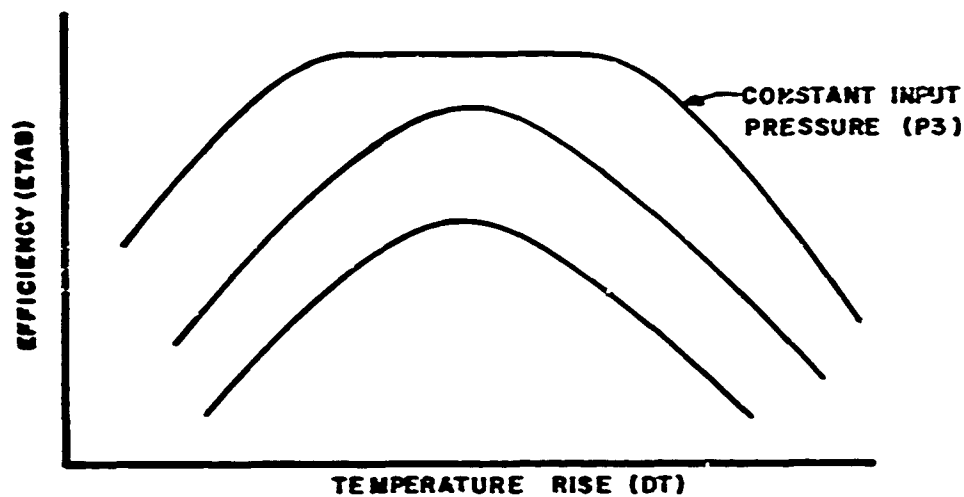


Figure 3. Example of Combustor Map

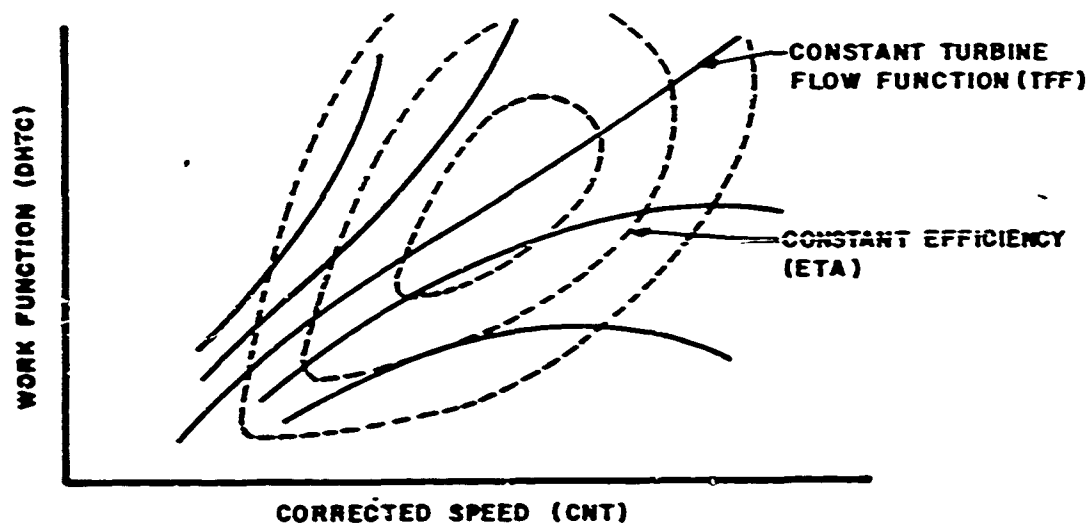


Figure 4. Example of Turbine Map

and

$$TFF = \frac{W_{G_{IN}} \sqrt{T_{IN}}}{P_{IN}}$$

Entry to the map is through corrected speed and turbine flow function, with the work function and efficiency being output.

The work function could have been used as an entry in place of one of the present entries, but, because of the shape of the curves, this could lead to double entry points for one work function. However, if the turbine maps were plotted in a different format, this could be an acceptable method.

2. DESIGN POINT

Once the component maps have been reduced to Block Data form and placed in the program, it is necessary to run a design point. The design point is run at those conditions under which the real engine is designed or sized, usually sea level static. Design parameters necessary to simulate the real engine (for example, airflow, bypass ratio, main burner temperature, various pressure losses, pressure ratios, etc.) are input and a complete thermodynamic cycle calculation is performed. For more details on the cycle calculation see Section IV 4, "Off-Design Points." Scale factors for the component maps are calculated to insure that the input design parameters are met. If the design parameters have been correctly input, the design point will be completed after one pass through the engine calculations (that is, no balancing will occur) because the maps are shifted to reduce the errors to zero.

Other parameters calculated and output at the design point include certain temperatures and airflows, gas mixing areas, and nozzle throat and exit areas.

3. SCALING FACTORS

Scaling or correction factors are calculated at the design point using the following equation:

$$P(\text{correction factor}) = P(\text{design}) / P(\text{map})$$

where P represents a general parameter. One exception to this equation is the equation for calculating fan and compressor pressure correction factors:

$$PR(\text{correction factor}) = [PR(\text{design}) - 1] / [PR(\text{map}) - 1]$$

where PR represents a general pressure ratio.

Theoretically, if the component maps and the input design parameters are exact representations of a particular engine, the correction factors will equal 1. However, this will not be true due to map interpolations, certain assumptions such as ideal and isentropic flow, and tolerances in the thermodynamic calculations. The correction factors should be within 1% of 1. Naturally, if unmatched component maps are used, the correction factors can differ significantly from 1.

4. OFF-DESIGN POINTS

The following discussion pertains particularly to off-design points, although the input and the general cycle calculations are the same for the design point. Throughout the following discussion, it should be remembered that scaling or correction factors (multipliers) are applied to all performance maps (Block Data parameters).

AFAPL-TR-67-125
Part I

For more detailed information on the thermodynamic equations used throughout the cycle calculations, see References 1, 2, and 3 and Part II of this report. A schematic diagram of the engine components and station designations is shown in Figure 5.

a. Input

The program uses a controlled output; that is, the variables desired as output can be selected at the start of a run. This selection is obtained by placing the names of the variables in the first section of input cards. Controls, scaling or correction factors, and operating conditions make up the rest of the input.

The control inputs are used to determine the type of engine: mixed flow or separate flow, afterburning, duct burning, and convergent or convergent-divergent nozzle. The controls are also used to fix the mode of operation: constant PCNC, constant T4, or constant WFB. Other controls determine inlet conditions, title printout, and cycle looping printouts. The correction factors can be input directly, or the designpoint can be run first and the calculated factors will be left in common. The operating conditions include the flight Mach number, altitude, power setting (either PCNC, T4, or WFB), duct burner and afterburner temperatures or fuel flows, bleed, and horsepower extracted.

b. Initial Values

The program uses four primary independent variables: ZF, PCNF, ZC, and PCNC (T4 may be substituted for PCNC, depending upon the mode of operation). Two secondary independent variables (TFFHP and TFFLP) are also used to insure correct entry into the turbine maps. Initial values for these six variables must be obtained to start the program at each point. A subroutine supplies these variables as a function of T2, T21, and some of the variables themselves. It is important to note that the closer the initial values are to the final values at a balanced point, the faster the program will run. Therefore, after a particular engine configuration has been run a few times, it is usually advisable to change the general initial value equations to suit the engine, using the knowledge gained from past runs to estimate more closely the final values of the variables.

c. Inlet

The thermodynamic properties of the atmosphere are found from a 1962 ARDC Atmosphere Tables subroutine. Using conservation of energy and isentropic flow, the conditions at the face of the fan can be found. A ram recovery (total pressure recovery) can be input or, if not input, a ram recovery defined by Mil-E-5008B Specifications will be used. If desired, a T2-P2 direct input mode is available, as are provisions for nonstandard day conditions.

d. Fan and Compressor

Block Data is used to determine the performance characteristics of the fan and compressor. When Z and PCN are known, the pressure ratio, corrected airflow, and efficiency can be found by using a general Block Data interpolation routine named SEARCH. With the pressure ratio known and when the assumption of isentropic compression and the efficiency are used, the thermodynamic conditions at the exit of both the fan and the compressor can be calculated. Bleed for consumer use, leakage, or cooling is accounted for. Actual airflow leaving the fan and the compressor is calculated from the corrected airflow, temperature, pressure, and bleed.

e. Combustor

The pressure drop in the combustor is a function of a design pressure drop and the ratio of corrected airflow to the design corrected airflow. Combustor efficiency is obtained from

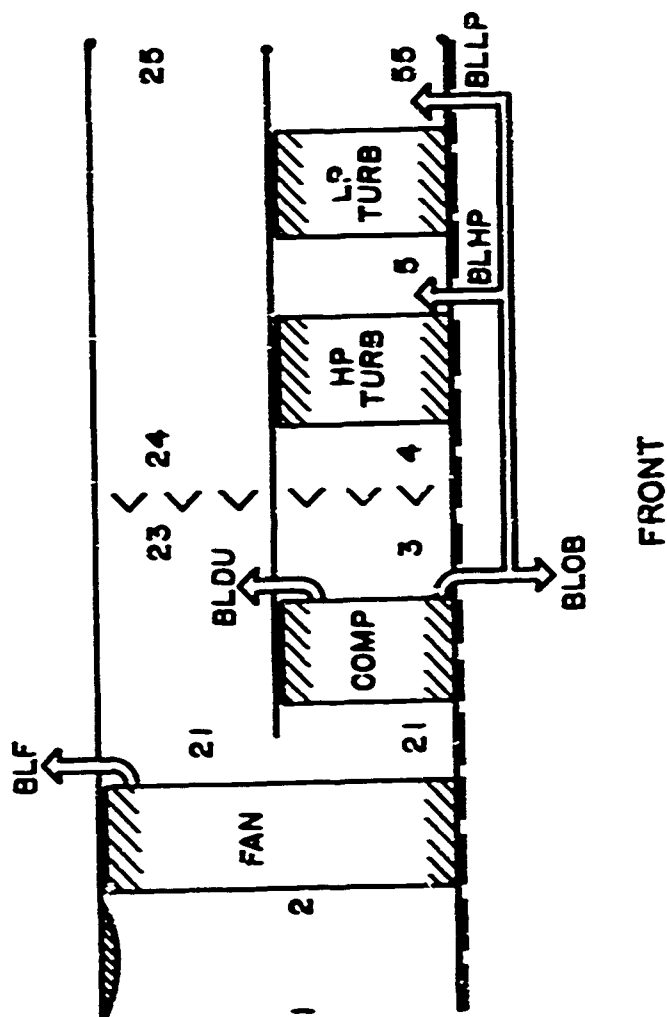
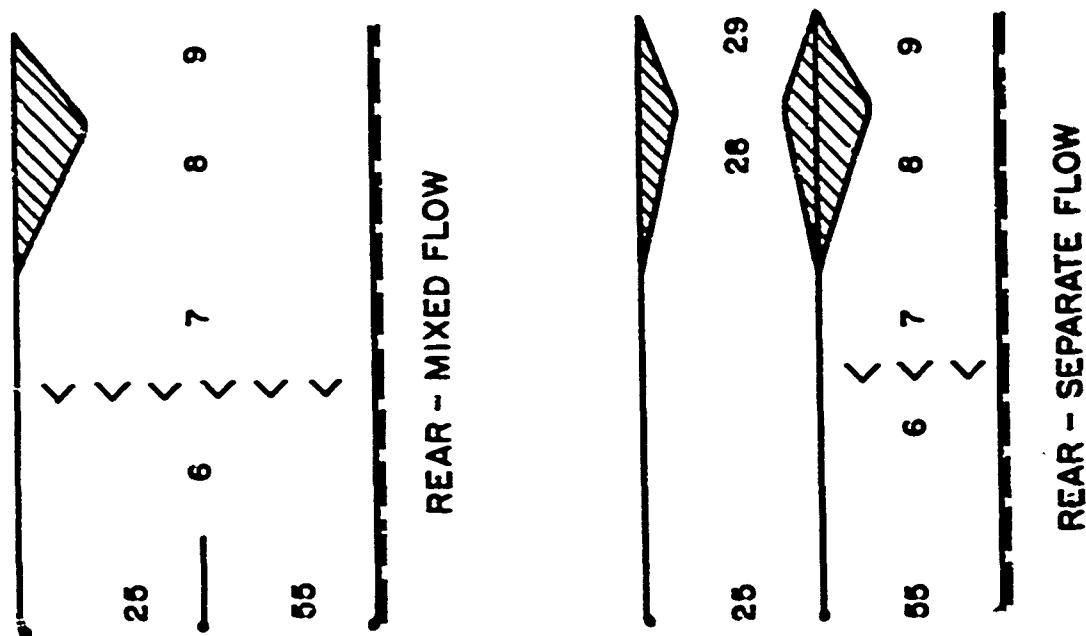


Figure 5. Schematic of Engine Components

Block Data using SEARCH. The fuel used is assumed to be JP-4 (at 59°F), and, with the assumption of adiabatic and constant pressure combustion, a fuel heating value equation as a function of T4 has been derived. Thus the fuel/air ratio, fuel flow, and thermodynamic conditions at the combustor exit can be calculated. If WFB is known instead of T4, a small iteration is necessary.

f. Turbines

Both turbine subroutines use similar logic and obtain their performance characteristics from Block Data using subroutine SEARCH. All three turbine parameters (CN, TFF, DHTC) can be calculated before entering the turbine map, but only two are needed. Therefore, the third parameter obtained from the map is compared with the calculated third parameter, and a balancing error is generated if they are not equal. In this program, CN and TFF are used for map entries, and DHTC is used to generate the error. In addition, the efficiency is also obtained through SEARCH.

In addition, another error will be generated if TFF is not within map limits. The error will be the difference between TFF and the nearest map limit. This error becomes particularly important when the estimated initial values of the independent variables are far from the correct values, and the point is extremely unbalanced. When either TFF or CN is not within map limits, they are set to the nearest map limit, and one of the independent variables is changed in an attempt to rectify the situation. The operating point must appear on all maps before a complete cycle calculation can be accomplished.

Horsepower extraction is accounted for in calculating DHTC of the high pressure turbine. When the efficiency is used and the turbine process is assumed isentropic, the thermodynamic properties at both turbine exits can be calculated. Any bleed airflow for cooling the turbines is treated as if it entered the main stream behind the turbine, and the thermodynamic properties at the turbine exits are recalculated to account for this.

g. Duct

The duct airflow and bypass ratio are calculated from the fan and compressor airflows. The pressure drop in the duct is treated as in the main combustor. For duct-burning, the same fuel heating value equation that was used in the combustor is again used, but the efficiency must be input. As in the combustor, either the temperature (T24) or the fuel flow (WFD) may be input.

If a separate flow engine is being simulated, the duct nozzle calculations are done in this routine, although they are accomplished in the same manner as for the main nozzle.

h. Mixer

The gas mixing areas (duct exit and turbine discharge for a mixed flow engine or just the turbine discharge area for a separate flow engine) are calculated at the design point using either an input static pressure or Mach number. At an off-design point the areas are used to calculate static pressures and Mach numbers.

For a separate flow engine, the thermodynamic conditions entering the afterburner are now known, since they are identical to turbine discharge conditions.

For a mixed flow engine, a set of derived equations based on one-dimensional fluid flow theory and conservation of mass, energy, and momentum is used to determine the thermodynamic conditions after complete mixing of the two gas streams (Reference 4). These equations do not require that the static pressures of the two entering streams be equal. However, for a correct engine balance, the two static pressures must be equal, and a balancing error is generated if they are not equal.

i. Afterburner

The dry loss (cold loss) pressure drop in the afterburner is a function of a design pressure drop and the ratio of corrected gas flow to the design corrected gas flow.

For afterburning, the same equation for the fuel heating value that was used in the combustor is again used, but the efficiency must be input. As in the combustor, either the temperature (T7) or the fuel flow (WFA) may be input. A momentum loss (hot loss) pressure drop is also calculated.

j. Nozzle

The main nozzle program uses fixed effective areas (except when afterburning) calculated at the design point. Either a convergent or a convergent-divergent subroutine may be used depending upon the input controls. If afterburning has been selected, the nozzle areas are allowed to float to obtain optimum performance; however the areas are returned to their original design values after the afterburning point is completed. The duct nozzle behaves identically with the main nozzle, including floating areas if duct-burning has been selected.

Because all thermodynamic properties of the gas stream are known, as well as the amount of flow, nozzle areas, and ambient pressure, there is a redundant parameter. For this program, the total pressure of the gas stream was chosen as the redundant parameter. The nozzle calculations (Reference 5) are made without using the total pressure, and a required total pressure compatible with all other known parameters is calculated. This required pressure is compared with the actual pressure, and a balancing error is generated if they are not equal.

k. Performance and Output

At this point, six errors have been generated after one pass through the engine. Several more passes must be completed under control of the error matrix and engine balancing subroutines. See Section V for a detailed description of the balancing technique used. Eventually, however, the errors will be reduced to zero, and engine performance will be calculated using standard equations. Gross thrust is obtained by summing the momentum term (a nozzle velocity coefficient may be input) and pressure-area term, and net thrust is in turn found by subtracting a ram drag (airflow momentum loss at inlet) term from the gross thrust. Specific fuel consumption is total fuel flow divided by net thrust.

As previously mentioned, a controlled output is used, whereby only selected variables are printed. Each variable is labeled with its name, and provisions have been made for changing the name of a variable. In addition, the values of all variables in common are printed in a close format so that variables other than those selected for a specific run are available later on.

5. QUADRATIC INTERPOLATION ROUTINE

Throughout the program there are many small loops (for example, thermodynamic iterations and table look-up) which require convergence. Trial-and-error methods and linear interpolations can be time-consuming, especially when a tight tolerance is necessary; therefore a general interpolation routine called AFQUIR (Air Force Quadratic Interpolation Routine) was developed.

This routine requires a dummy array dimensioned for nine locations. Also input into the routine through the calling argument are the independent and the dependent variables, the answer or value which the dependent variable is to converge upon, the number of tries at convergence, the tolerance, and a variable called DIR.

AFAPL-TR-67-125
Part I

The DIR is either set or calculated in the calling program and is an initial guess at the direction and percentage change to apply to the first value of the independent variable. If not enough is known about the variables to calculate a DIR, an arbitrary value may be set. This should not affect the final result, but may increase the number of tries at convergence.

The DIR thus establishes the second value of the independent variable. This value is used in the calling program to determine a corresponding second value of the dependent variable and AFQUIR is called a second time with two sets of values. A linear interpolation is made which results in a third value of the independent variable. AFQUIR is then called a third time with the third values of independent and dependent variables and a quadratic interpolation is made. The values of these three sets of variables have been stored in the dummy array, and from here on, quadratic interpolations are made using the three sets which give values closest to the answer. Values farthest from the answer are lost.

Various safeguards are built into AFQUIR to return the interpolation method to DIR or linear if the roots of the quadratic become complex, if the quadratic does not intercept the answer, if the value of the independent variable differs radically from previous values, or if two sets of independent and dependent variables are identical.

Also, it is possible to preload the dummy array and to start directly at the linear or quadratic interpolations if desired.

In summary, AFQUIR is a completely flexible routine which performs quadratic interpolation for quick convergence of general functions.

SECTION V

BALANCING TECHNIQUE

The balancing technique is based upon finding a solution for a set of partial differential equations. For this program, the set is composed of six equations; however, using a set of only three equations will simplify the following discussion. This corresponds to a basic turbo-jet engine simulation. It is relatively easy to expand the set of three equations to one of six, as required in SMOTZ, or even further. For example, a triple-spool turbofan would require nine equations.

As discussed previously, six independent variables were selected (ZF, PCNF, ZC, PCNC or T4, TFFHP, and TFFLP). Once these variables have been given initial values, it is possible to proceed through an entire engine cycle calculation. Six errors are generated as shown in Section IV. These initial values of the six variables and six errors are referred to as base values.

In the following equations, V refers to a variable and E to an error. The basic set of differential equations based on $E = f(V)$ is (Reference 6)

$$dE_1 = \frac{\partial E_{11}}{\partial V_1} dV_1 + \frac{\partial E_{12}}{\partial V_2} dV_2 + \frac{\partial E_{13}}{\partial V_3} dV_3$$

$$dE_2 = \frac{\partial E_{21}}{\partial V_1} dV_1 + \frac{\partial E_{22}}{\partial V_2} dV_2 + \frac{\partial E_{23}}{\partial V_3} dV_3$$

$$dE_3 = \frac{\partial E_{31}}{\partial V_1} dV_1 + \frac{\partial E_{32}}{\partial V_2} dV_2 + \frac{\partial E_{33}}{\partial V_3} dV_3$$

where the single subscripts correspond to three variables and three errors and where the double subscripts indicate the change in a particular error (first subscript) due to a change in a particular variable (second subscript).

Assuming small changes results in the following approximations (where B refers to a base value):

$$dE = E - EB$$

$$dV = V - VB$$

$$\frac{\partial E}{\partial V} = \frac{\Delta E}{\Delta V}$$

With these approximations and the fact that E should be zero when the engine is balanced, the set of partial differential equations reduces to

$$E_1 - EB_1 = \frac{\Delta E_{11}}{\Delta V_1} dV_1 + \frac{\Delta E_{12}}{\Delta V_2} dV_2 + \frac{\Delta E_{13}}{\Delta V_3} dV_3 = -EB_1$$

$$E_2 - EB_2 = \frac{\Delta E_{21}}{\Delta V_1} dV_1 + \frac{\Delta E_{22}}{\Delta V_2} dV_2 + \frac{\Delta E_{23}}{\Delta V_3} dV_3 = -EB_2$$

$$E_3 - EB_3 = \frac{\Delta E_{31}}{\Delta V_1} dV_1 + \frac{\Delta E_{32}}{\Delta V_2} dV_2 + \frac{\Delta E_{33}}{\Delta V_3} dV_3 = -EB_3$$

Three more passes (six for SMOTE) are now made through the engine cycle calculations, and one variable is changed by a small amount (ΔV) for each pass. The change in each error due to the small change in the variables ($\Delta E/\Delta V$) can then be calculated.

The above set of differential equations can now be solved for dV_1 , dV_2 , and dV_3 , and, in general, the new value of each independent variable would be given by

$$V = VB + dV$$

If the engine cycle calculations were linear functions, the engine would balance (errors equal zero) with these new values of the variables. However, this is not the case, and it is usually necessary to repeat the above process (where the new values become the base values) several times before a balance is obtained.

A subroutine to determine the solution of a matrix is used to solve the set of differential equations. After each pass through the engine, a matrix array is loaded with the appropriate values; after seven passes (base value plus six independent variables), the matrix subroutine is called to solve the matrix.

It was found that the "dV's" obtained from the solution of the differential equations were in many cases too large, thus causing the variables to exceed their limits, and to make it practically impossible to balance the cycle. The "dV's" are therefore multiplied by a suppression factor (presently 0.6) which limits the swing of the variables. In addition, if a suppressed "dV" is still greater than 5% of the value of the variable itself, it is reduced to the 5% value. Although this procedure may tend to increase the number of passes before balancing in some cases, it also balances points which previously would not balance. These points are most generally far from the design point, where oscillations of the dependent variables tend to build up.

APPENDIX

SAMPLE RESULTS

The following computer printouts are examples of typical output from SMOTE. The first point is the design point and includes a page of correction (or scaling) factors and a page of values of variables in common. The other points represent conditions throughout a flight envelope and consist of a primary page of output for each point. Not included for these points is a common dump, which normally follows each primary output page and is very similar to the common dump following the design point correction factors.

The engine cycle chosen was a mixed flow turbofan (bypass ratio of 1.4) with a convergent nozzle, a total airflow of 180 pounds a second, and a turbine inlet temperature (T4) of 2400°R. The points were run in a fixed T4 mode; that is, PCNC is an independent variable. Note that the nozzle area is recalculated at each afterburning point for optimum expansion and that no balancing occurs at these points.

AFAPL-TR-87-125
Part I

	SHOTS DESIGN POINT			
FAN DESIGN	PRPCF= 0.10000078 U1	STAPCF= 0.099999998 01	WACCF= 0.100000038 01	72D3= 0.518688208 03
COMPRESSOR DESIGN	PRCCF= 0.995776398 00	STACCF= 0.100004948 01	WACCF= 0.997388858 00	721D3= 0.652249328 03
COMBUSTOR DESIGN	WACCD3= 0.137728738 02	STABCF= 0.099999998 01	OTGOCF= 0.101784538 01	
H.P. TURBINE DESIGN	CHWPCF= 0.999391818 00	THWPCF= 0.100009318 01	ETHPCF= 0.999999998 00	DHHPCF= 0.100042548 01
L.P. TURBINE DESIGN	CHLPCF= 0.100032618 01	THLPCF= 0.100062538 01	ETHPCF= 0.099999998 01	DHLPFCF= 0.990037778 00
DUCT DESIGN	WACCD3= 0.135421018 04			
TURBINE/DUCT AREA DESIGN	AS3= 0.206195598 01	AM55= 0.412985768-00	A25= 0.424503348 01	AM25= 0.174149138-00
WATERBURNER DESIGN	WACCD3= 0.301782388 04			
NOZZLE DESIGN	A8= 0.279600848 01	AM8= 0.099999998 01	59= 0.279600848 01	AM9= 0.099999998 01
MAIN SONIC CONVERGENT NOZZLE	FO= 8314.55	FM= 8314.55		SFC= 0.61205

AFAPL-TR-67-125
Part I

CONVERGED AFTER 1 LOOPS

COMMON	0.833333 00	1.000000 02	0.814598 00	1.000000 02	0.240000 04	0
0.100000 03	0.100000 03	0.240000 04	1.000000 02	-0.000000 -19	0.100000 01	0.100000 01
0.833333 00	0.100000 03	0.200000 01	0.850000 00	0.180000 03	0.100000 01	0.100000 01
0.814598 00	0.100000 03	0.600000 00	0.980000 00	0.137720 02	0.993776 00	0.997389 00
0.240000 04	-0.000000 -19	0.126000 04	0.980000 00	0.137720 02	0.500000 -01	0.100000 01
0.212500 02	0.204000 01	0.890000 00	0.100000 01	0.999392 00	1.000000 00	0.100000 01
0.534100 02	0.228000 01	0.900000 00	0.100000 01	0.100000 01	0.100000 01	0.518688 03
-0.000000 -19	-0.000000 -19	-0.000000 -19	-0.000000 -19	0.135421 04	0.400000 -01	0.652249 03
-0.000000 -19	-0.000000 -19	-0.000000 -19	-0.000000 -19	0.301738 04	0.400000 -01	-0.000000 -19
0.204198 01	0.424306 01	0.630701 01	0.630701 01	0.279601 01	0.279601 01	-0.000000 -19
0.188000 01	0.412966 -00	0.985000 00	0.985000 00	-0.000000 -19	-0.000000 -19	-0.000000 -19
0.518670 03	0.100000 01	0.123918 03	0.159103 01	0.518688 03	0.100000 01	0.159103 01
0.652249 03	0.200000 01	0.155962 03	0.159846 01	0.116209 04	0.120000 01	0.181753 01
0.240000 04	0.114000 02	0.633126 03	0.182714 01	0.192492 04	0.422944 01	0.183080 01
0.165358 04	0.210200 01	0.418454 03	0.183597 01	0.180000 03	0.375000 01	0.
1.000000 00	0.200000 01	0.450000 00	0.180000 03	0.180000 03	0.712500 02	0.198399 -01
0.891739 00	0.600000 01	0.830000 00	0.421027 02	0.750000 02	0.500000 -01	0.111699 04
0.204000 01	0.890000 00	0.540230 -01	0.129655 03	0.300000 01	0.103838 -01	0.
0.228000 01	0.900000 00	0.196015 -01	0.762399 02	0.756636 02	0.190383 -01	0.
0.212500 02	0.	0.100000 01	0.833333 00	0.614598 00	1.000000 02	0.141359 01
0.100000 01	0.534100 02	0.	0.500000 -01	0.	0.800000 00	0.
0.100000 01	0.180000 03	0.750000 02	0.	0.281578 03	0.	0.150983 01
0.857249 03	0.200000 01	0.155962 03	0.159846 01	0.585951 03	0.168538 03	0.160262 01
0.855951 03	0.192000 01	0.158852 03	0.160262 01	0.855951 03	0.158852 03	0.
0.	0.	0.	0.	0.	0.	0.
0.105750 03	0.	0.105750 03	0.	0.400000 -01	0.400000 01	0.
0.	0.	0.	0.	0.	0.	0.
0.145352 04	0.210300 01	0.418454 03	0.183597 01	0.655951 03	0.192000 01	0.160262 01
0.141359 01	0.756636 02	0.190383 -01	0.	0.105750 03	0.	0.
0.109311 04	0.198783 01	0.265954 03	0.172707 01	0.109311 04	0.190383 -01	0.172967 01
0.109311 04	0.190383 01	0.265954 03	0.172967 01	0.109311 04	0.190383 -01	0.172967 01
0.101414 03	0.	0.181414 03	0.785329 -02	0.	0.400000 -01	0.217858 03
0.189908 01	0.412421 03	0.181414 03	0.785329 -02	0.181621 01	0.400000 -01	0.174149 -00
0.919678 03	0.101949 01	0.176298 04	0.100000 01	0.919678 03	0.101545 01	0.100000 01
0.	0.	0.	0.	0.145410 04	0.819210 04	0.115346 03
0.819921 04	0.115346 03	0.141359 01	0.181414 03	0.785329 -02	0.831455 04	0.612051 00

8701 575

AM= 0.	ALTP= 0.	T4= 1750.00	ETAR= 1.0000
PCMP	CMF	ZF	WAF
0.561658 02	0.561658 00	0.594640 06	0.126328 01
PCMC	CNC	ZC	WACC
0.714378 02	0.685898 00	0.690779 00	0.364504 01
T2	P2	T21	P21
0.51 4688 03	0.100000 01	0.562700 03	0.126328 01
PCBLP	BLP	PCBLC	BLC
0.	0.	0.500000 -01	0.170090 01
PCBLNP	BLNP	PCBLLP	BLLP
0.800000 00	0.136072 01	0.	0.
W3	W6	W04	W04
0.323171 02	0.418316 -00	0.327354 02	0.129441 -01
TFFHP	CNHP	DHTCHP	DHTC
0.215719 02	0.170668 01	0.477920 -01	0.867448 02
TFFLP	CNLP	DHTCLP	DHTP
0.486710 02	0.149019 01	0.209477 -01	0.398027 02
PCBL0U	BL0U	T24	P24
0.200000 -00	0.340180 -00	0.564527 03	0.121928 01
WAD	WPD	W024	W024
0.626982 02	0.	0.626982 02	0.
BTAP	BTAC	BTATHP	BTATLP
0.813299 00	0.747810 00	0.876818 00	0.864124 00
T6	P6	P56	AM6
0.836140 03	0.122987 01	0.119938 01	0.190491 -00
T7	WPA	W67	PAR7
0.836140 03	0.	0.967944 02	0.434046 -02
PS8	AMB	V8	PS9
0.100000 01	0.504652 00	0.695767 03	0.100000 01
PS28	AM28	V28	PS29
0.	0.	0.	0.
HYPASS	HYPEXT	WPT	W07
0.103309 01	0.	0.418316 -00	0.967944 02
CVMH02	VJM	CVDH02	VJD
0.984000 00	0.685308 03	0.985000 00	0.
MAIN SUBSONIC CONVERG. NOZZLE			
FNU= 2061.79			PN= 2061.79
			SFC= 0.73040

SLS MILITARY

OUTPUT	AM=	O.	ALTP=	O.	2F	PRR	WAPC	STAR=
PCNF	1.000000	02	1.000000	00	0.633333	00	0.100000	03
PCNC	1.000000	02	0.891730	00	0.814500	00	0.421627	02
T2	0.510668	03	0.100000	01	0.632249	03	0.116209	04
PCULF	0.		0.		0.500000	-01	0.375000	01
PCBLNP	0.800000	00	0.300000	01	0.		0.240000	04
WAS	0.712500	02	0.141350	01	0.726636	02	0.198399	-01
TFRNP	0.212500	02	0.204000	01	0.540830	-01	0.139639	03
YFPLP	0.534100	02	0.228000	01	0.396015	-01	0.762299	02
PCLDU	0.200000	-00	0.750000	00	0.655931	03	0.192000	01
WAD	0.108750	03	0.		0.105750	03	0.	
BTAP	0.850000	00	0.830000	00	0.890000	00	0.900000	00
T6	0.109311	04	0.198870	01	0.189928	01	0.412227	03
T7	0.109311	04	0.		0.161414	03	0.785329	-02
PS6	0.101949	01	0.100000	01	0.147629	04	0.101949	01
PS28	0.		0.		0.		0.	
BYPASS	0.140000	01	0.		0.141359	01	0.101414	03
CVHNO2	0.985000	00	0.145415	04	0.985000	00	0.819921	04
MAIN SONIC CONVERGENT NOZZLE			PO=	0314.55			FN=	0314.55

SL2 TAKE-OFF

NOZZLE DESIGN AS= 0.60324220E 01 AMS= 0.90408222E 00 A9= 0.60324220E 01 AH9= 0.90408222E 00

OUTPUT

AM= 0.	ALTP=	0.	T4= 2400.00	T7= 3200.00	STAR= 1.0000
PCNF	CNF	ZF	PRF	WARC	WAR
1.000000E 02	1.000000E 00	0.833333E 00	0.200000E 01	0.180000E 03	0.180000E 03
PCMC	CNC	ZC	PRC	WACC	WAC
1.000000E 02	0.891739E 00	0.814597E 00	0.600000E 01	0.421627E 02	0.750000E 02
Y2	P2	T21	P21	T3	P3
0.518668E 03	0.100000E 01	0.632249E 03	0.200000E 01	0.116209E 04	0.120000E 02
PCBLF	BLF	PCBLC	BLC	PCBL08	BL08
0.	0.	0.500000E-01	0.375000E 01	0.	0.
PCBLHP	BLHP	PCBLLP	BLLP	T4	P4
0.800000E 00	0.300000E 01	0.	0.	0.240000E 04	0.114000E 02
WAS	WFS	W04	FARA	BTAB	DPCOM
0.712500E 02	0.141399E 01	0.726636E 02	0.198399E-01	0.985000E 00	0.500000E-01
TRHP	CNHP	DHTCHP	DHTC	T5	P5
0.212500E 02	0.204000E 01	0.540230E-01	0.129655E 03	0.192492E 04	0.422944E 01
TFPLP	CNLP	DHTCLP	DHTF	T55	P55
0.394100E 02	0.228000E 01	0.396015E-01	0.762299E 02	0.165332E 04	0.210630E 01
PCBL01	BL01	T24	P24	T25	P25
0.200000E-00	0.750000E 00	0.655951E 03	0.192000E 01	0.655951E 03	0.192000E 01
WAD	WFD	W024	FAR24	BTAD	OPDUC
0.105750E 03	0.	0.105750E 03	0.	0.	0.400000E-01
BTAF	BTAC	BTATHP	BTATLP	AM55	AM23
0.850000E 00	0.830000E 00	0.890000E 00	0.900000E 00	0.412024E-00	0.174134E-00
T6	P6	P56	AM6	V6	W06
0.109311E 04	0.198870E 01	0.189992E 01	0.258644E-00	0.412227E 03	0.181414E 03
T7	WFA	W07	FAR7	BTAA	OPART
0.320000E 04	0.705234E 01	0.188466E 03	0.470330E-01	0.910000E 00	0.399825E-01
P56	AM6	V6	P59	AM9	V9
0.100000E 01	0.904082E 00	0.227120E 04	0.100000E 01	0.904082E 00	0.227120E 04
PS28	AM28	V28	PS29	AM29	V29
0.	0.	0.	0.	0.	0.
BYPASS	HPEXT	HFT	W07	VA	PRO
0.140000E 01	0.	0.846593E 01	0.188466E 03	0.	0.
CVMNO2	VJM	CVDNO2	VJD	PCM	POP
0.985000E 00	0.225713E 04	0.985000E 00	0.	0.131044E 01	0.
MAIN SUBSONIC CONVERG. NOZZLE	FO= 13104.42	FN= 13104.42			SFC= 2.32573

SET-UP LOW ALTITUDE DASH

OUTPUT	AM= 1.200	ALTP= 900.	TA= 2400.00	BTAR= 0.9915
PCNF	0.834548 02	CNF	2F	WAP
0.834548 02	0.736548 00	0.4959358-00	0.136068 01	0.281071E 03
PCMC	0.922888 02	CMC	2C	WACC
0.922888 02	0.7720378 00	0.7374598 00	0.4439428 01	0.8940388 02
T2	0.6658848 03	P2	T21	P3
0.6658848 03	0.2362058 01	0.7411588 03	0.3213918 01	0.142679E 02
PCBLP	0.	BLP	PCBLC	PCULOB
0.	0.	0.5000008-01	0.4470298 01	0.
PCBLHP	0.8000008 00	BLHP	PCBLP	T4
0.8000008 00	0.3576238 01	0.	0.	0.2400008 04
WAS	0.8493558 02	WFS	WGA	BTAD
0.8493558 02	0.1603848 01	0.8653948 02	0.1888308-01	0.9850008 00
TRFHP	0.2132898 02	CNHP	DNTHCP	T5
0.2132898 02	0.1882698 01	0.5170028-01	0.1243338 03	0.5216008 01
TRFLP	0.5183148 02	CNLP	D1TCLP	T55
0.5183148 02	0.1893238 01	0.2907058-01	0.5669568 02	0.3157488 01
PCBLDU	0.2000008-00	BLDU	T24	T25
0.2000008-00	0.8940388 00	0.7434658 03	0.3058828 01	0.3058828 01
WAD	0.1925598 03	WFD	WQ24	UPDUC
0.1925598 03	0.	0.1925598 03	0.	0.4625428-01
RTAP	0.8086248 00	BTAC	BTATHP	AM25
0.8086248 00	0.7809898 00	0.8839808 00	0.8987878 00	0.2140698-00
T6	0.1081268 04	P6	P54	WQ6
0.1081268 04	0.3088468 01	0.2951198 01	0.2578278-00	0.2826758 03
T7	0.1081268 04	I7A	WQ7	DPART
0.1081268 04	0.	0.2826758 03	0.5706168-02	0.3980778-01
P28	0.1578018 01	AM8	V8	V9
0.1578018 01	0.1000008 01	0.1468678 04	0.1578018 01	0.1468678 04
P328	0.	AM28	V28	V29
0.	0.	0.	0.	0.
BVPASS	0.2143778 01	HPERT	WQ7	PRD
0.2143778 01	0.	0.1603848 01	0.2826758 03	0.1168958 05
CVMNOZ	0.9850008 00	VJM	CVONC2	FCM
0.9850008 00	0.1446648 04	0.9850008 00	0.	0.1270998 05
MAIN SONIC CONVERGENT NOZZLE	FC= 16236.07	FN= 4546.59	SFC= 1.26992	

NOZZLE DESIGN		LOW ALTITUDE DASH									
		A8= 0.5987957E 01		A9= 0.0999999E 01		A9= 0.5987957E 01		A9= 0.0999999E 01			
OUTPUT		AM= 1.200		ALTP= 500.		T4= 2400.00		T7= 3200.00		ETAR= 0.9915	
PCNF	0.834554E 02	CHF	0.736546E 00	ZF	0.495935E-00	PRF	0.134065E 01	WAF	0.281071E 03	WAF	0.281071E 03
PCMC	0.922888E 02	GMC	0.772037E 00	IC	0.737459E 00	PRC	0.443942E 01	WACC	0.333410E 02	WAC	0.894058E 02
T2	0.665884E 03	P2	0.236205E 01	T21	0.741158E 03	P21	0.321391E 01	T3	0.122567E 04	P3	0.142679E 02
PCBLF	0.	BLF	0.	PCBLC	0.500000E-01	BLC	0.447029E 01	PCBL08	0.	BL08	0.
PCBLHP	0.800000E 00	BLHP	0.357623E 01	PCBLLP	0.	BLLP	0.	T4	0.240000E 04	P4	0.135333E 02
WAS	0.847355E 02	WFO	0.160384E 01	WG4	0.865394E 02	FAR4	0.188830E-01	ETAB	0.985000E 00	DPCOM	0.514829E-01
TFRHP	0.213285E 02	CHHP	0.188269E 01	DHTCHP	0.517902E-01	DHTC	0.124323E 03	T5	0.194440E 04	P5	0.521690E 01
TFFLP	0.518314E 02	CHLP	0.189323E 01	DHTCLP	0.290705E-01	UHTF	0.366950E 02	T55	0.174336E 04	P55	0.315748E 01
PCBL0U	0.200000E-00	BL0U	0.894038E 00	T24	0.743465E 03	P24	0.305882E 01	T25	0.743465E 03	P25	0.305882E 01
WAD	0.192559E 03	WFD	0.	WQ24	0.192559E 03	FAR24	0.	ETAD	0.	OPDUC	0.482542E-01
ETAF	0.808626E 00	ETAC	0.780989E 00	ETATHP	0.803980E 00	ETATLP	0.899878E 00	AM55	0.324506E-00	AM25	0.214069E-00
T6	0.108126E 04	P6	0.308846E 01	PS6	0.295119E 01	AM6	0.237827E-00	V6	0.409007E 03	WG6	0.282675E 03
T7	0.320000E 04	WFA	0.110345E 02	WGT	0.293729E 03	PAK7	0.450361E-01	ETAA	0.910000E 00	OPAFY	0.398977E-01
PS8	0.140201E 01	AM8	0.100000E 01	V8	0.248577E 04	PS9	0.140201E 01	AM9	0.100000E 01	V9	0.248577E 04
PS28	0.	AM28	0.	V28	0.	PS29	0.	AM29	0.	V29	0.
BYPASS	0.214377E 01	HPEXT	0.	WPT	0.126583E 02	WGT	0.293729E 03	VA	0.133009E 04	PRD	0.116899E 03
CVMNOZ	0.985000E 00	VJM	0.244848E 04	CVNOZ	0.903000E 00	VJD	0.	FGH	0.223532E 05	FGP	0.532154E 04
MAIN SONIC CONVERGENT NOZZLE		PM= 27674.70		PM= 15905.22		SFC= 2.85076					

SUBSONIC CRUISE

OUTPUT	AM= 0.800	ALTP= 36100.	TA= 2100.00	ETAR= 1.0000
PCNR	0.931973E 02	CHP	ZF	WAF
PCNC	0.933169E 02	CNC	PC	WAC
T2	0.440068E 03	P2	T21	P3
PCBLF	0.	BLF	PCBLC	BLNB
PCBLHP	0.800000E 00	BLHP	PCBLLP	P4
WAS	0.271136E 02	WPS	WQ4	OPCOM
TFRHP	0.212356E 02	CNHP	DHTCHP	P5
TFRLP	0.535024E 02	CNLP	DHTCLP	P55
PCBLDU	0.200000E-00	BLDU	T24	P25
WAD	0.392371E 02	WFD	WQ24	DPDUC
BTAF	0.837913E 00	BTAC	BTATHP	AM25
T6	0.942355E 03	P6	PS6	WQ6
T7	0.942355E 03	WFA	WGT	DPART
PS6	0.352897E-00	AMB	V8	V9
PS28	0.	AM28	V28	V29
BYPASS	0.136478E 01	NPEXT	WFT	FRD
CVHNOZ	0.985000E 00	VJM	CVDNOZ	FGH
MAIN SONIC CONVERGENT NOZZLE		P0= 3621.69	PN= 1996.38	SFC= 0.82749

SUPERSONIC AT MILITARY POWER

OUTPUT				AM= 1.200	ALTP= 50000.	Y4= 2400.00	ETAR= 0.9915
PCNF	0.100191E 03	CNF	0.101749E 01	ZF	0.855547E 00	PRF	WAF
PCMC	0.100012E 03	CNC	0.898871E 00	ZC	0.822625E 00	PRC	WACC
T2	0.502712E 03	P2	0.275217E-00	T21	0.642096E 03	P21	T3
PCBLF	0.	BLF	0.	PCBLC	0.500000E-01	BLC	PCBLUD
PCBLMP	0.800000E 00	BLMP	0.872700E 00	PCBLLP	0.	BLLP	T4
W3	0.207265E 02	WFB	0.417850E-00	WQ4	0.211445E 02	PAR4	ETAB
TFHP	0.212515E 02	CNHP	0.204025E 01	DYTCHP	0.541368E-01	DHTC	T5
TFPLP	0.535156E 02	CHLP	0.228507E 01	DHTCLP	0.403460E-01	DHTP	T55
PCBLDU	0.200000E-00	BLDU	0.218175E-00	T24	0.645937E 03	P24	T25
WAD	0.297541E 02	WFD	0.	WQ24	0.297541E 02	PAR24	ETAD
ETAF	0.830473E 00	ETAC	0.827917E 00	ETATHP	0.889763E 00	ETAILP	AM55
T6	0.109268E 04	P6	0.565981E 00	PS6	0.540378E 0	AM6	V6
T7	0.109268E 04	WFA	0.	WQ7	0.517713E 02	PAR7	ETAA
PS8	0.290912E-00	AM8	0.100000E 01	V8	0.147597E 04	PS9	AM9
PS28	0.	AM28	0.	V28	0.	PS29	AM29
BYPASS	0.135377E 01	MPEXT	0.	WFT	0.417850E-00	HGT	VA
CVMNOZ	0.985000E 00	VJM	0.145383E 04	CVMNOZ	0.985000E 00	VJD	FGH
MAIN SONIC CONVERGENT NOZZLE				FG= 3383.44	FM= 1328.45	SFC= 0.98417	

SET-UP SUPERSONIC WITH AFTERBURNER

OUTPUT	AM= 1.600	ALCP= 50000.	T4= 2400.00	ETAR= 0.9624							
PCNF	0.905133E 02	CNF	0.848444E 00	ZF	0.585574E 00	PRF	0.162349E 01	WAPC	0.153578E 00	WAF	0.673905E 02
PCNC	0.970176E 02	CNC	0.838545E 00	ZC	0.780663E 00	P4C	0.525237E 01	WACC	0.380951E 02	MAC	0.249891E 02
T2	0.590294E 03	P2	0.460120E-00	T21	0.694285E 03	P21	0.760024E 00	T3	0.119781E 04	P3	0.399665E 01
PCBLP	0.	BLP	0.	PCBLC	0.500000E-01	ULC	0.124945E 01	PCFLDK	0.	BLDK	0.
PCBLMP	0.800000E 00	BLMP	0.999563E 00	PCBLLP	0.	ULLP	0.	T4	0.240030E 04	P4	0.277739E 01
W3	0.237896E 02	WFB	0.459302E-00	W04	0.241989E 02	FAR4	0.193475E-01	UTAB	0.507829E-01	UPCUM	0.507829E-01
TFRHP	0.212663E 02	CNHP	0.197716E 01	DHTCHP	0.535433E-01	DHTC	0.128631E 03	T5	0.192924E 04	P5	0.141463E 01
TFRLP	0.532579E 02	CNLP	0.206139E 01	DHTCLP	0.346163E-01	DHTF	0.664961E 02	T53	0.169141E 04	P53	0.772359E 00
PCBLDU	0.200000E-00	BLDU	0.249891E-00	T24	0.697309E 03	P24	0.727396E 00	T23	0.697309E 03	P23	0.727656E 00
WAD	0.426013E 02	WFO	0.	W024	0.426513E 02	FAR24	0.	ETAD	0.	UPDUC	0.437198E-01
BTAF	0.844790E 00	BTAC	0.807461E 00	BTATHP	0.867090E 00	BTATLP	0.897886E 00	AM25	0.372028E-00	AM25	0.191041E-00
T6	0.108670E 04	P6	0.743217E 00	P36	0.710188E 00	AM6	0.257923E-00	V6	0.410036E 03	W06	0.678498E 02
Y7	0.108570E 04	WPA	0.	W07	0.678498E 02	P37	0.681352E-02	BTAA	0.	DPAPT	0.398956E-01
P38	0.379947E-00	AK8	0.100000E 01	V8	0.147216E 04	P39	0.379947E-00	AM9	0.100000E 01	V9	0.147216E 04
P328	0.	AM28	0.	V28	0.	P429	0.	AM29	0.	V29	0.
BYPASS	0.169608E 01	HPBXT	0.	WFT	0.459302E-00	WGT	0.678498E 02	VA	0.134959E 04	PRC	0.324571E 04
CVMNO2	0.985000E 00	VJM	0.145007E 04	CVDNO2	0.985000E 00	VJD	0.	FGH	0.305707E 04	FGP	0.157090E 04
MAIN SONIC CONVERGENT NOZZLE		FO= 4628.87				FN= 1383.16				SFC= 1.19344	

SUPERSONIC PARTIAL A70

NOZZLE DESIGN				
AM= 0.36570030 01	AN= 0.09099999 01	AP= 0.36570031 01	AR= 0.50999999 01	
OUTPUT				
AM= 1.600	ALT= 30000.	TA= 3400.00	TT= 1700.00	QYAR= 0.9624
PCNP 0.9051330 02	CHP 0.6852740 00	ZP 0.1623490 01	WAPC 0.1533700 03	WAP 0.6739000 02
PCNC 0.0701700 02	CHC 0.8383450 00	ZC 0.7806630 00	WAPC 0.380410 02	WAC 0.2400410 02
Y2 0.5902940 03	P2 0.4601200 00	Y21 0.6942050 03	T3 0.119731 04	P3 0.3996630 01
PCNLP 0.	BLP 0.	PCNLC 0.5000000 01	PCNLO0 0.	BL00 0.
PCNLLP 0.8000000 00	BLLP 0.9999999 00	PCNLLP 0.	T4 0.2400000 04	P4 0.3793600 01
MA2 0.2373960 02	WFB 0.4593020 00	W04 0.2419000 02	BTAD 0.5827420 00	BTCDM 0.5078290 01
TRNHP 0.2120630 02	CHHP 0.1979160 01	CHTCHP 0.5354330 01	CHTC 0.1246310 01	T5 0.1414630 01
TRFLP 0.5323700 02	CHLP 0.2061390 01	CHTCLP 0.3461630 01	CHTF 0.6689610 02	P55 0.7723590 00
PCBLDU 0.2000000 00	BLDU 0.2400910 00	T24 0.6773090 03	P24 0.7276500 00	Y25 0.7276500 00
WAD 0.4265130 02	WFD 0.	W024 0.4265130 02	PAH24 0.	DDU02 0.4371000 01
UTAF 0.8447900 00	BTAC 0.8076610 00	BTATHP 0.8070900 00	BTATLP 0.8970000 00	AM25 0.1910410 00
T6 0.1006700 04	P6 0.7432170 00	P56 0.7101000 00	AM6 0.2579230 00	W06 0.6784900 02
T7 0.1700000 04	WFA 0.6495740 00	W07 0.6049540 02	PAH7 0.1639510 01	DPAFT 0.3409900 01
PS0 0.3755740 00	AM0 0.1000000 01	V0 0.1031050 04	P30 0.3755740 00	AM9 0.1000000 01
PS20 0.	AM20 0.	V20 0.	P500 0.	V29 0.
BYPASS 0.1696000 01	WFBT 0.1104000 01	W0T 0.6849440 02	VA 0.1549590 04	PRD 0.3247710 04
CUMH02 0.9050000 00	VJM 0.1003900 04	CVDH02 0.9050000 00	VJ0 0.	PGM 0.2020000 04
FO= 3000.43				SFC= 1.52121
MAIN SIMIC CONVERGENT NOZZLE				

SUPERSONIC FULL A/H

NOZZLE DESIGN	ARM 0.59612714E 01	AM0 0.09900000E 01	AV 0.59612714E 01	AM0 0.09900000E 01
OUTPUT	AM 1.600	ALTP 50000.	T4 2400.00	T7 3200.00
PCMP	0.905135E 02	CNF 0.685374E 00	ZF 0.153570E 01	WAF 0.675005E 02
PCMC	0.970170E 02	CNC 0.030545E 00	ZC 0.528237E 01	WACC 0.249891E 02
T4	0.590294E 03	P2 0.460120E-00	T21 0.760924E 00	T3 0.119701E 04
PCOLP	0.	BLP 0.500000E-01	PCOLC 0.124945E 01	PCOL00 0.
PCOLHP	0.000000E 00	BLHP 0.990563E 00	PCOLLP 0.	T4 0.340000E 04
WAS	0.257306E 02	WFB 0.459502E-00	W04 0.241969E 02	ETAB 0.982742E 00
TRHP	0.212653E 02	TRHP 0.197910E 01	DHTCHP 0.555435E-01	DHTC 0.120631E 03
TRHLP	0.532879E 02	CNLP 0.206139E 01	DHTCLP 0.546163E-01	DHTF 0.060961E 02
PCLOU	0.200000E-00	BLDU 0.240991E-00	T24 0.697309E 03	T25 0.169141E 04
WAD	0.426513E 02	WFD 0.	W024 0.426513E 02	T26 0.697309E 03
BTAP	0.844790E 00	BTAC 0.007461E 00	BTATHP 0.887090E 00	BTAD 0.
T6	0.100670E 04	P6 0.745217E 00	PS6 0.710188E 00	AM55 0.372020E-00
T7	0.520000E 04	WFA 0.264604E 01	WGT 0.704958E 02	V6 0.410035E 03
PSR	0.530129E-00	AMB 0.100000E 01	V0 0.240554E 04	BTAA 0.910000E 00
PS20	0.	AM26 0.	V20 0.	AM9 0.240554E 04
BYPASS	0.169680E 01	HPHXT 0.	WHT 0.310834E 01	AM29 0.
CYHNOZ	0.985000E 00	VJM 0.244026E 04	CVDNOZ 0.985000E 00	VA 0.154958E 04
MAIN SONIC CONVERGENT NOZZLE	FO 8186.04	PM 4940.33	VJD 0.	PHD 0.324571E 04
				FGM 0.536432E 04
				FGP 0.262172E 04
				SFC 2.26285

REFERENCES

1. Phillip G. Hill and Carl R. Peterson. Mechanics and Thermodynamics of Propulsion. Addison-Wesley Publishing Company, Inc. 1965.
2. Alexander D. Lewis. Gas Power Dynamics. D. Van Nostrand Company, Inc. 1962.
3. Gordon J. Van Wylen. Thermodynamics. John Wiley & Sons, Inc. 1962.
4. Kervyn D. Mach. "Viscous Mixing of Parallel Gas Streams," Research & Technology Briefs, Vol. III, No. 11. Air Force Systems Command, Bolling Air Force Base, Washington D.C. November 1965.
5. Ascher H. Shapiro. The Dynamics and Thermodynamics of Compressible Fluid Flow. The Ronald Press Company, 1953.
6. Ross R. Middlemiss. Differential and Integral Calculus. McGraw-Hill Book Company, Inc. 1946.

BIBLIOGRAPHY

R.C. Binder. Fluid Mechanics. Prentice-Hall, Inc. 1956.

R.C. Binder. Advanced Fluid Mechanics, Vol. I. Prentice-Hall, Inc. 1958.

Errol G. Blevins. A Turbofan Engine Design and Off-Design Point Computer Program. Technical Memorandum APTC-TM-66-24, Air Force Aero Propulsion Laboratory, Wright-Patterson Air Force Base, Ohio. 1966.

Charles L. Brown. Basic Thermodynamics. McGraw-Hill Book Company, Inc. 1951.

UNCLASSIFIED

Security Classification

DOCUMENT CONTROL DATA - R&D		
(Security classification of title, body of abstract and indexing annotation must be entered when the overall report is classified)		
1. ORIGINATING ACTIVITY (Corporate author) Air Force Aero Propulsion Laboratory Wright-Patterson Air Force Base, Ohio 45433		2a. REPORT SECURITY CLASSIFICATION Unclassified
		2b. GROUP
3. REPORT TITLE SIMULATION OF TURBOFAN ENGINE Part I. Description of Method and Balancing Technique		
4. DESCRIPTIVE NOTES (Type of report and inclusive dates)		
5. AUTHOR(S) (Last name, first name, initial) McKinney, John S. Captain, USAF		
6. REPORT DATE November 1967	7a. TOTAL NO. OF PAGES 38	7c. NO. OF REFS 6
8a. CONTRACT OR GRANT NO.		8b. ORIGINATOR'S REPORT NUMBER(S)
a. PROJECT NO. 3066		AFAPL-TR-67-125, Part I
c. Task No. 306603		
9. OTHER REPORT NUMBER(S) (Any other numbers that may be assigned this report)		
10. AVAILABILITY/LIMITATION NOTICES This document is subject to special export controls and each transmittal to foreign governments or foreign nationals may be made only with prior approval of the Air Force Aero Propulsion Laboratory, Wright-Patterson AFB, Ohio.		
11. SUPPLEMENTARY NOTES		12. SPONSORING MILITARY ACTIVITY Air Force Aero Propulsion Laboratory Wright-Patterson Air Force Base, Ohio 45433
13. ABSTRACT This report describes a digital computer program titled SMOTE (Simulation of Turbofan Engine). SMOTE is a computer program for balancing-cycle turbofan engines capable of running both design and off-design points. Component performance maps are reduced to Block Data (tabular form) to provide a base for calculating component performance. The design point is run first and map correction factors are calculated to scale the components to the desired performance. These correction factors are then applied to the component performance maps at off-design points. Initially, when the program is running at an off-design point, the cycle is not balanced, and errors (for example, work required by the compressor minus work supplied by the turbine) are generated. Small changes in engine independent variables (for example, compressor speed) then produce small changes in the errors, and these differential changes are loaded into a matrix. The matrix is then solved for the set of independent variables which results in zero errors, thus balancing the cycle. Actually, this process may be repeated several times before it reaches a balanced point because there is a non linear relationship between the independent variables and the errors. Sample results are included in this report. (Distribution of this abstract is unlimited.)		

DD FORM 1473
1 JAN 64

UNCLASSIFIED

Security Classification

UNCLASSIFIED

Security Classification

14. KEY WORDS	LINK A		LINK B		LINK C	
	ROLE	WT	ROLE	WT	ROLE	WT
Turbine Engine Simulation						
Turbine Engine Computer Programs						
Turbine Engine Cycle Analysis						

INSTRUCTIONS

1. ORIGINATING ACTIVITY: Enter the name and address of the contractor, subcontractor, grantee, Department of Defense activity or other organization (corporate author) issuing the report.

2a. REPORT SECURITY CLASSIFICATION: Enter the overall security classification of the report. Indicate whether "Restricted Data" is included. Marking is to be in accordance with appropriate security regulations.

2b. GROUP: Automatic downgrading is specified in DoD Directive 5200.10 and Armed Forces Industrial Manual. Enter the group number. Also, when applicable, show that optional markings have been used for Group 3 and Group 4 as authorized.

3. REPORT TITLE: Enter the complete report title in all capital letters. Titles in all cases should be unclassified. If a meaningful title cannot be selected without classification, show title classification in all capitals in parenthesis immediately following the title.

4. DESCRIPTIVE NOTES: If appropriate, enter the type of report, e.g., interim, progress, summary, annual, or final. Give the inclusive dates when a specific reporting period is covered.

5. AUTHOR(S): Enter the name(s) of author(s) as shown on or in the report. Enter last name, first name, middle initial. If military, show rank and branch of service. The name of the principal author is an absolute minimum requirement.

6. REPORT DATE: Enter the date of the report as day, month, year, or month, year. If more than one date appears on the report, use date of publication.

7a. TOTAL NUMBER OF PAGES: The total page count should follow normal pagination procedures, i.e., enter the number of pages containing information.

7b. NUMBER OF REFERENCES: Enter the total number of references cited in the report.

8a. CONTRACT OR GRANT NUMBER: If appropriate, enter the applicable number of the contract or grant under which the report was written.

8b, 8c, & 8d. PROJECT NUMBER: Enter the appropriate military department identification, such as project number, subproject number, system number, task number, etc.

9a. ORIGINATOR'S REPORT NUMBER(S): Enter the official report number by which the document will be identified and controlled by the originating activity. This number must be unique to this report.

9b. OTHER REPORT NUMBER(S): If the report has been assigned any other report numbers (either by the originator or by the sponsor), also enter this number(s).

10. AVAILABILITY/LIMITATION NOTICES: Enter any limitations on further dissemination of the report, other than those

imposed by security classification, using standard statements such as:

- (1) "Qualified requesters may obtain copies of this report from DDC."
- (2) "Foreign announcement and dissemination of this report by DDC is not authorized."
- (3) "U. S. Government agencies may obtain copies of this report directly from DDC. Other qualified DDC users shall request through _____."
- (4) "U. S. military agencies may obtain copies of this report directly from DDC. Other qualified users shall request through _____."
- (5) "All distribution of this report is controlled. Qualified DDC users shall request through _____."

If the report has been furnished to the Office of Technical Services, Department of Commerce, for sale to the public, indicate this fact and enter the price, if known.

11. SUPPLEMENTARY NOTES: Use for additional explanatory notes.

12. SPONSORING MILITARY ACTIVITY: Enter the name of the departmental project office or laboratory sponsoring (paying for) the research and development. Include address.

13. ABSTRACT: Enter an abstract giving a brief and factual summary of the document indicative of the report, even though it may also appear elsewhere in the body of the technical report. If additional space is required, a continuation sheet shall be attached.

It is highly desirable that the abstract of classified reports be unclassified. Each paragraph of the abstract shall end with an indication of the military security classification of the information in the paragraph, represented as (TS), (S), (C), or (U).

There is no limitation on the length of the abstract. However, the suggested length is from 150 to 225 words.

14. KEY WORDS: Key words are technically meaningful terms or short phrases that characterize a report and may be used as index entries for cataloging the report. Key words must be selected so that no security classification is required. Identifiers, such as equipment model designation, trade name, military project code name, geographic location, may be used as key words but will be followed by an indication of technical context. The assignment of links, roles, and weights is optional.

UNCLASSIFIED

Security Classification