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DEVELOPMENT OF AN ENGINE/AIRFRAME  
PERFORMANCE MATCHING SCHEME FOR  
JET ENGINE RETROFIT

THESIS

Alan Lach, Captain , USAF  
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**DEVELOPMENT OF AN ENGINE/AIRFRAME PERFORMANCE  
MATCHING SCHEME FOR JET ENGINE RETROFIT**

**THESIS**

**Presented to the Faculty of the School of Engineering  
of the Air Force Institute of Technology  
Air University  
In Partial Fulfillment of the  
Requirements for the Degree of  
Master of Science in Aeronautical Engineering**

**Alan Lach, B.S.M.E.  
Captain, USAF**

**December 1992**

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## Preface

The purpose of this study was to investigate the engine/airframe matching problem as applied to jet engine retrofit. The intent was to produce a design scheme and explore new analysis techniques for use by students studying jet engine and airframe integration. The general design philosophy presented here, builds on the engine design process outlined in the textbook *Aircraft Engine Design* and assumes that the reader is familiar with those procedures and techniques as well as the computer programs used.

The jet engine design problem confronts the engineer with an infinite number of design variations and their effect on aircraft performance. To develop an effective and efficient engine requires the application of a large number of design tools. Past experience, analysis procedures, and computer programs, all aid the designer in determining the best choices among the variations.

In an effort to reduce the amount of iteration involved, I have explored methods to enhance the engine design process as applied to the academic environment. I devised new techniques for decision making and demonstrated their utility. This thesis introduces new methods for measuring improvements and determining trends as well as the application of empirical model building.

Throughout this research, I received support from a number of people whom I would like to take this opportunity to thank. I am indebted to the authors of *Aircraft Engine Design* for their development of the engine/airframe design process which I used as a road map. I greatly appreciate the support and comments provided throughout the research effort by my faculty advisor, Dr. W. C. Elrod, and committee members Dr. P. I. King and Dr. M. E. Franke. I would also like to thank the GSE students with whom I shared an office. Their discussions led me to the use of modeling techniques which significantly improved the design process. Finally, the greatest amount of thanks goes to my wife, Jan, without whose understanding and support this document would not have been produced.

Alan Lach

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### List of Symbols

|            |                                                           |
|------------|-----------------------------------------------------------|
| A          | - Area                                                    |
| AB         | - Afterburner                                             |
| C          | - Specific fuel consumption                               |
| $C_{DR}$   | - Coefficient of additional drags                         |
| $C_{DRc}$  | - Coefficient of drag for drag chute                      |
| $C_{Do}$   | - Coefficient of drag at zero lift                        |
| $C_L$      | - Coefficient of lift                                     |
| $C_p$      | - Specific heat at constant pressure                      |
| $C_{TO}$   | - Power takeoff power coefficient                         |
| D          | - Drag                                                    |
| e          | - Polytropic efficiency                                   |
| f          | - Fuel-to-air ratio of burner                             |
| $f_s$      | - Fuel specific work                                      |
| F          | - Uninstalled thrust; probability distribution            |
| g          | - Acceleration                                            |
| $g_0$      | - Local acceleration due to gravity                       |
| h          | - Height                                                  |
| $h_{PR}$   | - Heating value of fuel                                   |
| $K_1$      | - Coefficient in lift-drag polar equation                 |
| $K_2$      | - Coefficient in lift-drag polar equation                 |
| $k_{TO}$   | - Velocity ratio at takeoff                               |
| L          | - Lift; length                                            |
| m          | - Mass                                                    |
| $m_0$      | - Mass flow rate                                          |
| M          | - Mach number                                             |
| n          | - Load factor                                             |
| P          | - Pressure                                                |
| $P_s$      | - Weight specific excess power                            |
| q          | - Dynamic pressure                                        |
| $Q_1$ to 3 | - Quality measures                                        |
| R          | - Additional drags                                        |
| S          | - Area; uninstalled thrust specific fuel consumption      |
| T          | - Installed thrust; temperature; probability distribution |
| TSFC       | - Installed thrust specific fuel consumption              |
| t          | - Time                                                    |
| u          | - Total drag-to-thrust ratio                              |
| V          | - Velocity                                                |
| W          | - Weight                                                  |
| $W_E$      | - Empty weight                                            |
| $W_F$      | - Fuel weight                                             |
| $W_P$      | - Payload weight                                          |
| $W_{TO}$   | - Takeoff weight                                          |
| x          | - Independent variable                                    |
| y          | - Dependent variable                                      |

|                        |                                                                |
|------------------------|----------------------------------------------------------------|
| $\alpha$               | - Installed thrust lapse; bypass ratio                         |
| $\beta$                | - Instantaneous weight fraction; coefficient in model equation |
| $\gamma$               | - Ratio of specific heats                                      |
| $\Delta$               | - Change in                                                    |
| $\varepsilon$          | - Error                                                        |
| $\eta$                 | - Efficiency                                                   |
| $\theta$               | - Static temperature ratio                                     |
| $\mu$                  | - Coefficient of friction                                      |
| $\pi$                  | - Total pressure ratio                                         |
| $\tau$                 | - Total temperature ratio                                      |
| $\tau_\lambda$         | - Enthalpy ratio of burner                                     |
| $\phi_{\text{inlet}}$  | - Inlet external loss coefficient                              |
| $\phi_{\text{nozzle}}$ | - Nozzle external loss coefficient                             |

### Subscripts

|           |                                   |
|-----------|-----------------------------------|
| AB        | - Afterburner                     |
| B         | - Braking                         |
| c         | - Compressor                      |
| c'        | - Fan                             |
| FR        | - Free roll                       |
| M         | - Mixer                           |
| max       | - Maximum                         |
| mH        | - Mechanical, high pressure spool |
| mL        | - Mechanical, low pressure spool  |
| R         | - Rotation                        |
| SL        | - Sea-level                       |
| t         | - Turbine; total                  |
| tH        | - High pressure turbine           |
| tL        | - Low pressure turbine            |
| TD        | - Touchdown                       |
| TO        | - Takeoff                         |
| 0 thru 10 | - Station location                |

Abstract

This investigation developed a procedure and new analysis tools for identifying retrofit engine conceptual designs for use in existing airframes. The goal was to find a replacement engine with increased sea-level thrust and reduced fuel consumption for the air-to-air fighter, AAF, developed in the textbook *Aircraft Engine Design*. This paper introduced the ideas of solution surfaces, constraint/thrust diagrams, quality measures and linear regression analysis for the engine design problem. It considered the application of the jet engine design software ACSYS, MISS, and ONX along with statistical analysis software, SAS. Modeling techniques and linear regression analysis were used to minimize iteration while searching the maximum range of design variables. Improvements to the design point engine selection were made through the development of quality measures for selecting appropriate values for bypass ratio and compressor pressure ratio. The analysis tools were assembled into a design scheme for engine retrofit. The design scheme was then demonstrated with a two-variable and a six-variable design example. The result of the study determined a new baseline engine design for the AAF with a 16% increase in thrust and a 3% decrease in overall mission fuel consumption. This design process was developed for use by engine design students in the academic environment.

# **I. Introduction**

## **1.1. Background**

Modern aviation ventures require the investment of a great number of resources to introduce a new aircraft. It costs billions of dollars to bring a new aircraft to the market; the failure of a design can be a disaster for the corporation. With so much at stake it is imperative that aircraft designers create the most economical and best performing vehicle possible.

Due to the considerable cost involved in developing entirely new aircraft, many older designs have seen extended service via engine retrofit. Possibly the most obvious use of engine retrofit for existing aircraft is by the military. Almost every aircraft which has endured a long life in military service has done so because of its ability to be updated with better performing engines and equipment. The KC-135 is one example of an old airframe with new engines. The F-15 fighter has seen the use of three different engines over the past twenty years. New engines have taken these aircraft beyond their original design life span and given them new capability and performance.

While the initial airframe and engine design seeks to develop an aircraft with the best blend of design variables, if the aircraft is successful it will most likely become a candidate for engine retrofit in the future. While engine retrofit is a common method of extending the life of an airframe, there is little in the literature that examines this problem in detail. The textbooks to date do not address the retrofit situation specifically, as it is a special case of the overall aircraft design process.

Anyone who has taken an engine design course quickly realizes the enormous task in synthesizing multiple design variables into a viable airframe/engine. There is no single correct answer since design is a continual process of modification, evaluation and compromise.

Engine conceptual design considers the selection of various engine characteristics and design parameters to provide the required thrust while minimizing fuel consumption. The lightest and most cost effective aircraft will be produced by

minimizing the fuel load, since fuel cost is the primary driver of the life cycle cost of an aircraft (12:525).

This design process is iterative, and seeks the best compromise among all variables to achieve the performance goals. The textbook, *Aircraft Engine Design*, was developed to provide a systematic approach to the solution of airframe and engine integration problems.

Along with this approach, the computer programs ACSYS, MISS, ONX and OFFX, References 5, 8 and 9, were developed by Dr. Jack D. Mattingly to facilitate engine design courses in order to alleviate the burden of constant calculation and recalculation for each design option. These programs provide a quick and efficient method for analyzing variations in design parameters and determining their effects on the overall aircraft system.

Airframe and engine matching is essential in the design of an aircraft system. Optimization and trend analyses play a major role in making design choices. Most textbooks concentrate on the airframe design or the propulsion design and stop short of actually performing any optimization or trend analysis. A paper titled, *Airplane Engine Selection by Optimization on Surface Fit Approximations*, Reference 4, outlines the use of some of these optimization methods in the design environment. The method described develops a procedure which can account for numerous variables and optimize designs using surface fit methods (4:595). Engine retrofit is an ideal application for some of the ideas described in the paper.

This thesis examines the engine retrofit problem and the author introduces new methods of data preparation, presentation, and trend analysis to enhance the design process. It introduces the concept of using multivariable linear regression for determining interactions between design variables by developing a link between the overall engine and airframe performance and the component design choices. The computer programs ACSYS, ONX, MISS, and SAS are applied to the retrofit problem.

## **1.2. Problem Statement**

The need exists for a method to identify new jet engine conceptual designs for retrofit in an existing airframe. The development of such a scheme would provide a tool for

engineering students to determine the tradeoffs between various candidate engine designs and select the best choice. The problem proposed requires that a new engine be designed for the air-to-air fighter, AAF, developed in *Aircraft Engine Design*. This is an engine retrofit problem, since the airframe particulars will remain constant while new engine design points are considered to improve the aircraft's overall performance.

### **1.3. Scope**

This investigation developed a procedure for using small sampling and trend analysis in determining the appropriate engine design for retrofit. It covered the engine design process from the selection of design variables to determining the baseline engine. New methods of data presentation and analysis were developed to assist in selecting the best design choices. This study inspired new methods for comparing the overall improvement of each engine design and the use of modeling to reduce the iteration involved in choosing the design point.

### **1.4. Plan of Development**

The jet engine retrofit procedure is developed in the following sections of this paper.

Section 2. The design tools are introduced and tailored to the jet engine retrofit problem. New analysis methods consisting of constraint/thrust diagrams, solution surfaces, quality measures, and modeling are explained. These tools are then assembled into a design scheme which applies the analysis fundamentals and explains the assumptions made.

Section 3. A two-variable and six-variable design analysis is performed to demonstrate the usefulness of the design scheme in selecting alternative design point engines for the AAF fighter. The candidate engine designs are compared and the best design selected as the new baseline.

Section 4. Conclusions are presented and recommendations made for improving the design process.

## **II. Analysis Fundamentals**

This section develops the background information needed to perform the retrofit engine design analysis. It explains the new methods and procedures developed during this research effort and assembles them into a retrofit design scheme.

### **2.1. Engine and Airframe Analysis**

Successful engine design requires matching an appropriate engine cycle to an airframe in order to achieve the desired mission performance from the aircraft. This performance is usually specified by a mission profile and some maximum performance requirements, such as the maximum Mach number or minimum cruise range. The mission may consist of takeoff, climb, cruise, descend, and land as in the case of an airliner, or be much more complicated, including high speed turns, supersonic accelerations and weapons delivery, as in the case of a modern fighter. Once the flight characteristics of the aircraft have been determined the goal is to develop an engine design which will produce adequate thrust throughout the mission flight envelope.

### **2.2. Constraint Analysis**

The constraint analysis allows the designer to determine the appropriate relationship between an aircraft's wing loading and thrust loading based on the required performance. The thrust loading is the ratio of the sea-level thrust to the aircraft takeoff weight ( $T_{SL}/W_{TO}$ ). The wing loading is the ratio of the takeoff weight to the wing area ( $W_{TO}/S$ ).

Depending upon the mission, maximum performance objectives, and the constraints placed on the aircraft, a design will emerge which is the best compromise of the wing and thrust loading. The basic aircraft performance requirements and the effect of wing loading and thrust loading have been summarized below.

**Airfield Performance**

Landing and takeoff considerations are driven by the lifting ability of the wing. A low wing loading is desirable to obtain reasonable landing distances. The thrust loading and wing loading will determine the takeoff distance of the aircraft.

**Subsonic cruise and loiter**

The distance an aircraft is required to fly and loiter is of major importance for some missions. The contributing factor for an aircraft's range is its wing loading. Medium wing loading is desirable.

**Subsonic sustained turn rate**

The turn rate is limited by balancing the thrust and drag for the maneuver. A low wing loading results in the best performance.

**Instantaneous turn rate**

Instantaneous turn rate is limited by the maximum lift attainable. A low wing loading is necessary.

**Supersonic maneuvering**

Relatively large wing area of low aspect ratio is desirable.

**Max Mach number**

Tendency is toward lower wing loading for modern fighter aircraft.

**Subsonic specific excess power (SEP)**

A measure of an aircraft's ability to increase energy (rate of climb) rapidly,  $(T-D)V/W$ . The thrust to weight ratio is the dominating factor.

The various factors influencing the choice of wing and thrust loading are not complementary. The conditions required for the airfield, cruise and loiter, and

maneuverability are in opposition to those for maximum speed and low altitude strike. An aircraft designed for high maneuverability will have low wing loading and high thrust to weight ratio, whereas a low altitude bomber will exhibit the opposite trend (14:38-39, 12:84-100).

In order to arrive at reasonable estimates for the wing loading and thrust loading, a relationship between these two design parameters can be developed. This relationship may be used to produce constraint diagrams for determining the combinations of wing loading and thrust loading needed to perform the required maneuvers.

### 2.2.1. Constraint Diagram Generation

For an aircraft in flight, a force balance can be used to develop an equation which relates  $T_{SL}/W_{TO}$  and  $W_{TO}/S$ . The generalized force diagram for an aircraft is presented in Figure 1, where  $D+R$  are the drag components,  $L$  is the lift,  $W$  is the aircraft weight, and  $T$  is the installed thrust.

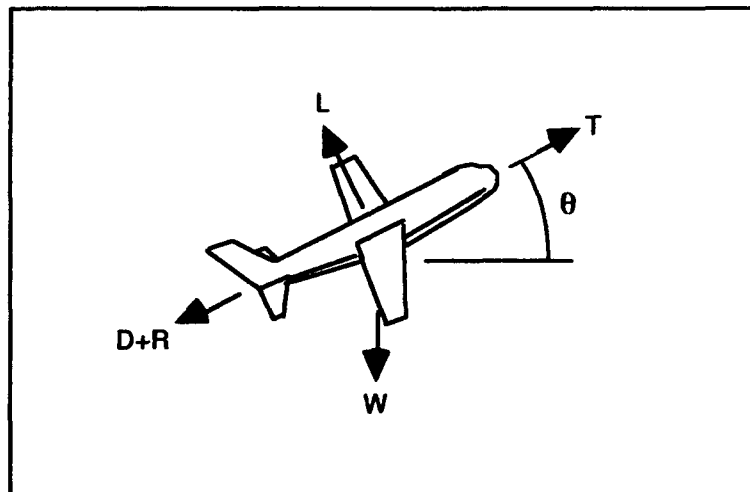


Figure 1. Aircraft Force Diagram

The summation of forces along the flight path is

$$T - (D + R) - W \sin \theta - \frac{W}{g_o} \frac{dV}{dt} = 0 \quad (1)$$

where the last term represents the force due to the aircraft's acceleration along the flight path. The aircraft's change in altitude with respect to time can be written as

$$\frac{dh}{dt} = V \sin \theta \quad (2)$$

Solving Eq (2) for  $\sin \theta$  and substituting into Eq (1), the force balance becomes

$$T - (D + R) - W \frac{1}{V} \frac{dh}{dt} - \frac{W}{g_o} \frac{dV}{dt} = 0 \quad (3)$$

Multiplying Eq (3) through by  $V$  and rearranging results in

$$\{T - (D + R)\}V = W \frac{dh}{dt} + \frac{1}{2} \frac{W}{g_o} \frac{dV^2}{dt} \quad (4)$$

The term to the left of the equals sign represents the rate of mechanical energy added to the system while the first term on the right is the potential energy and the second term is the kinetic energy of the system.

Eq (4) forms the basis for developing the various performance constraints for the aircraft at each condition in the flight. The thrust and weight can be corrected to  $T_{SL}$  and  $W_{TO}$  by defining the installed thrust  $T$ , as

$$T = \alpha T_{SL}$$

where  $\alpha$  is the installed full throttle thrust lapse, and the instantaneous weight,  $W$ , as

$$W = \beta W_{TO}$$

where  $\beta$  is the weight fraction. Eq (4) can be rewritten using  $\alpha$  and  $\beta$  along with the traditional lift and drag definitions to arrive at the working form of the equation

$$\frac{T_{SL}}{W_{TO}} = \frac{\beta}{\alpha} \left\{ \frac{qS}{\beta W_{TO}} \left[ K_1 \left( \frac{n\beta W_{TO}}{q S} \right)^2 + K_2 \left( \frac{n\beta W_{TO}}{q S} \right) + C_{DO} + \frac{R}{qS} \right] + \frac{1}{V} \frac{d}{dt} \left( h + \frac{V^2}{2g_o} \right) \right\} \quad (5)$$

This equation provides the functional relationship between  $T_{SL}/W_{TO}$  and  $W_{TO}/S$  and can be modified for the various flight conditions. The complete development of this equation can be found in Reference 6.

The last term in Eq (5) includes the weight specific excess power and is defined as

$$P_s = \frac{d}{dt} \left\{ h + \frac{V^2}{2g_0} \right\}$$

$P_s$  is a measure of the instantaneous change in potential and kinetic energy of the aircraft and combines the dynamic effects of both climb and acceleration. Using Eq (5), the following flight conditions have been developed in Reference 6 for the constraint analysis.

- Constant Altitude/Speed Cruise ( $P_s=0$ )
- Constant Altitude/Speed Turn ( $P_s=0$ )
- Constant Speed Climb ( $P_s=dh/dt$ )
- Service Ceiling ( $P_s=dh/dt$ )
- Horizontal Acceleration ( $P_s=VdV/g_0dt$ )
- Takeoff Ground Roll (with or without obstacle)
- Braking Roll (with or without obstacle)

These flight conditions form the basis of the ACSYS computer program, Reference 5, which allows for easy generation of constraint boundary diagrams. These constraint diagrams are generated in order to determine the values for the wing and thrust loading which lie within the solution space.

Using ACSYS, Figure 2 was produced and shows a completed constraint analysis diagram. The region indicated as the solution space, bounded by the landing,  $M=0.9$  turn, and supercruise constraint lines, represents all possible combinations of wing loading and thrust loading which will successfully perform all the maneuvers specified. More information on the program ACSYS is presented in Appendix A.

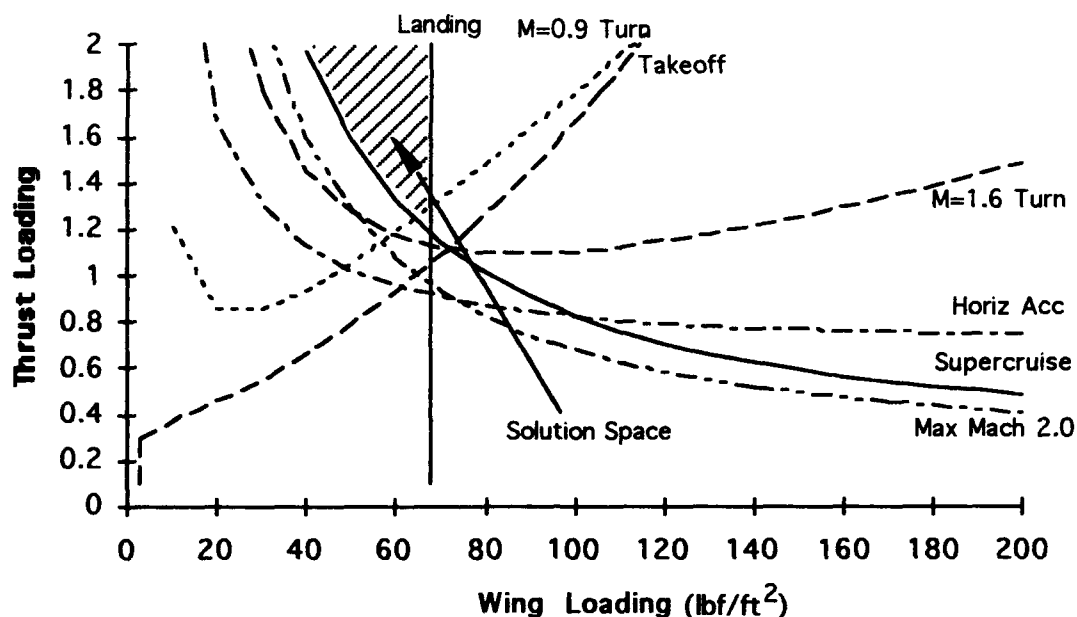


Figure 2. Constraint Analysis Diagram

### 2.2.2. Constraint/Thrust Diagrams for Engine Retrofit

The constraint diagram was transformed from a device for selecting the design point wing and thrust loading into a method for evaluating various engines that are required to perform specific maneuvers. Constraint/thrust diagrams were developed to provide a means to quickly compare the performance advantages of one engine over another. This was possible due to the fixed wing area which allows lines of constant  $T_{SL}$  to be plotted on the constraint diagram.

For the case of an engine retrofit problem, the aircraft particulars are known and can be used to help construct a wing and thrust loading plot for values of constant thrust. A relationship between  $T_{SL}/W_{TO}$  and  $W_{TO}/S$  was developed and can be represented by the equation

$$\frac{T_{SL}}{W_{TO}} = \frac{T_{SL}}{S \frac{W_{TO}}{S}}$$

Since the aircraft's wing area,  $S$ , is known, for any given  $T_{SL}$ ,  $T_{SL}/W_{TO}$  can be evaluated at the various values of  $W_{TO}/S$ . Constant thrust lines can be plotted for the values of  $T_{SL}$  in which the designer is interested. This resulted in the plot of Figure 3, which presents lines of constant thrust based on an aircraft's wing area of 381 ft<sup>2</sup>.

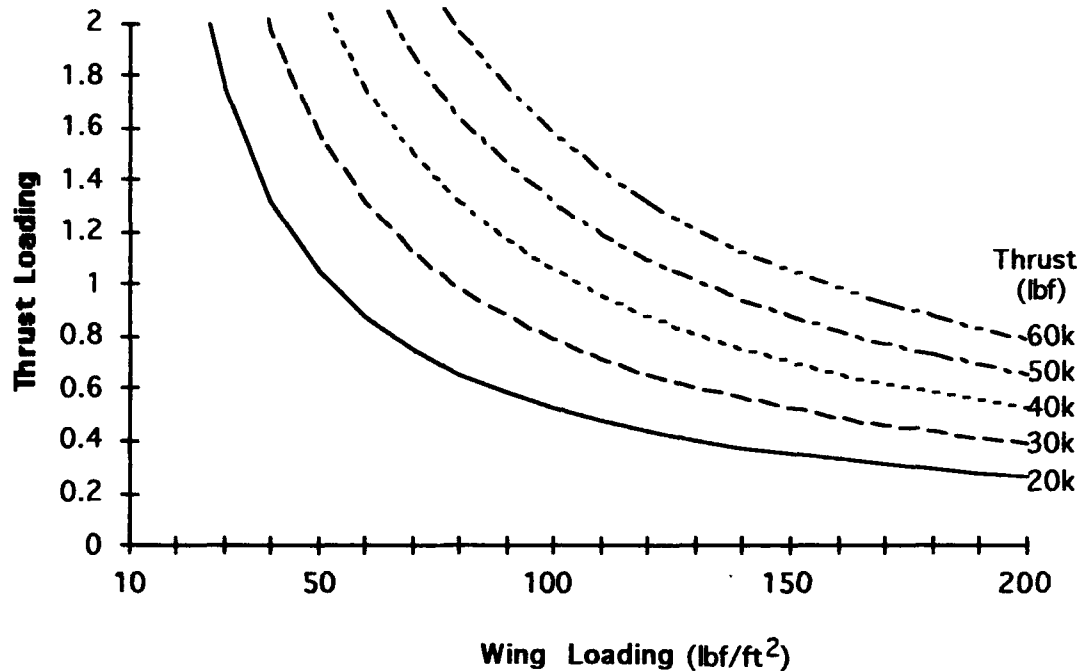


Figure 3. Thrust Loading vs Wing Loading and Lines of Constant Thrust

When a particular flight maneuver or condition is desired, a constraint diagram for various values of  $\beta$  can be created. For example, if the aircraft is required to negotiate a  $M=0.9$ ,  $5g$  turn at 30,000 ft, the thrust loading and wing loading requirements at various values of  $\beta$  are plotted as shown in Figure 4.

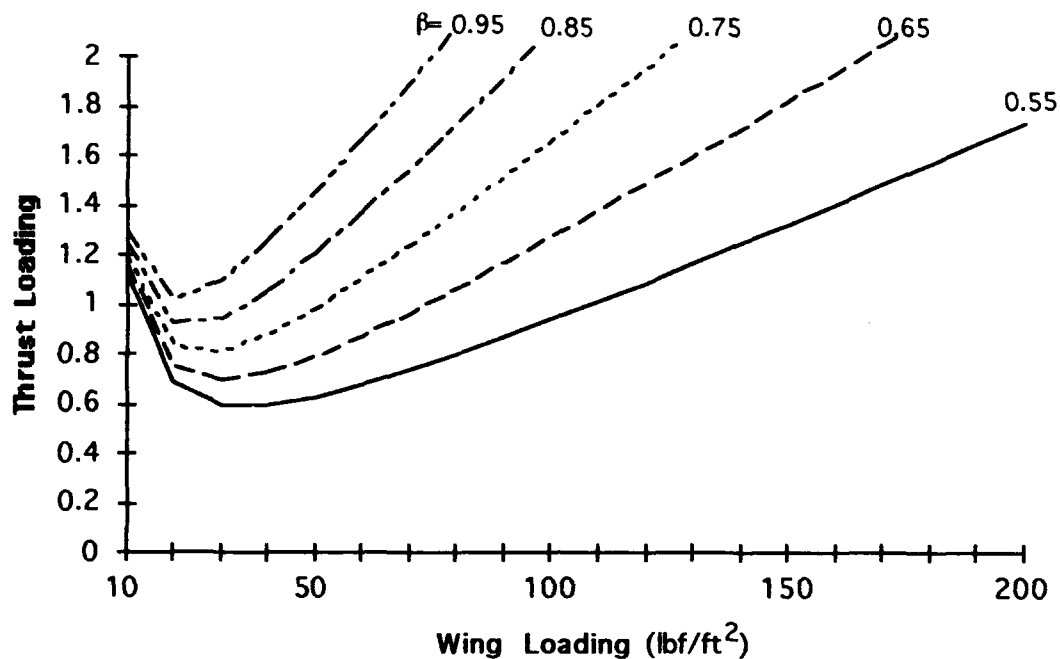


Figure 4. Thrust Loading vs Wing Loading  $M=0.9$ , 5g Turn, 30k ft

By combining Figures 3 and 4, a new diagram called the constraint/thrust diagram was created. Figure 5 presents the constraint/thrust diagram and shows the constraint boundary for various  $\beta$  values along with the lines of constant thrust. The solution boundaries of this chart are read below the lines of constant  $T_{SL}$ . All combinations of  $\beta$ , wing loading and thrust loading are solutions if they lie below the thrust curve. Any combination above the thrust curve will not be possible. From this diagram the minimum sea-level thrust needed for negotiating the turn at various weight fractions can be determined.

For example, if the desire is to fly an aircraft with a wing loading of 90 and a thrust loading of 0.9 while negotiating this turn at  $\beta=0.55$  then the required  $T_{SL}$  would be 30,000 lbf. This would be the design goal, to develop an engine or engines to produce 30,000 lbf of installed thrust at sea level.

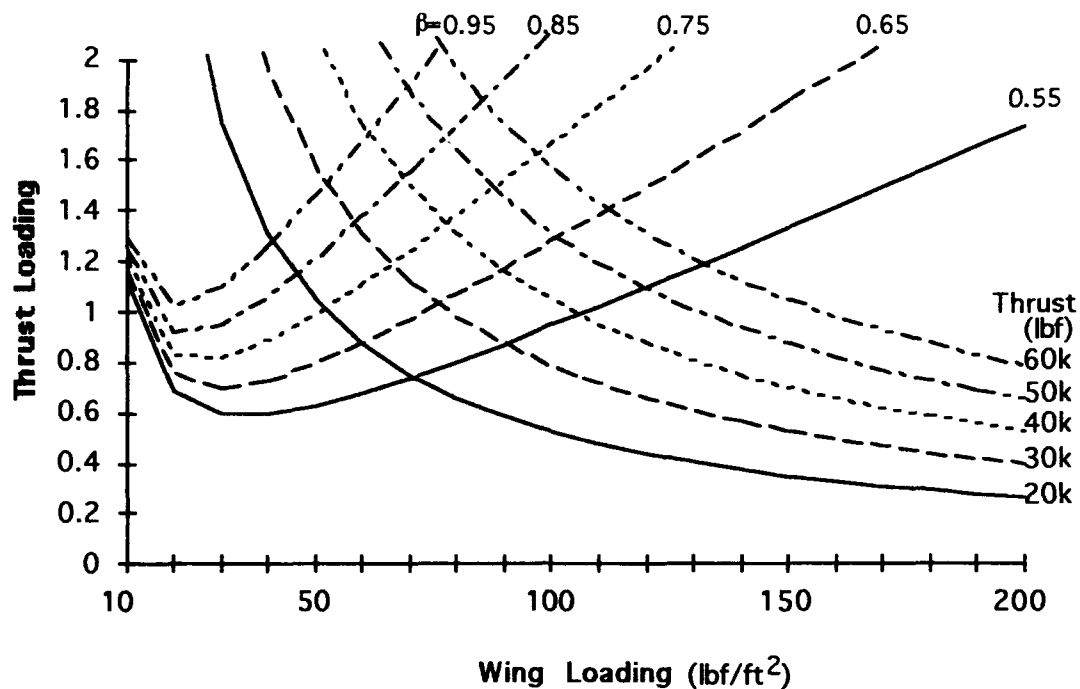


Figure 5. Constraint/Thrust Diagram,  $M=0.9$ , 5g Turn, 30k ft

This plot can also be used to determine the range of performance of an aircraft if the sea-level thrust is known. Using Figure 5, if the available thrust is 30,000 lbf and the wing loading is 70, the aircraft will only be able to negotiate a  $M=0.9$  turn for weight fractions below approximately 0.7. With the lines of constant  $T_{SL}$  plotted, any engine whose  $T_{SL}$  is known, can be evaluated to determine the aircraft weight fraction at which the various maneuvers can be performed.

For engine retrofit, the original aircraft wing loading is kept the same, since it is based on the aircraft's takeoff weight (the retrofit engine weight change is ignored) and wing area which are known. The desire is to move along a constant wing loading line with the various engine designs and evaluate their performance.

This concept can be extended to evaluate new takeoff weights and wing loading for the retrofit aircraft. Since all combinations of wing loading, thrust loading and  $\beta$  below the constant thrust line are possible, new combinations may be selected which will allow performance at higher  $\beta$  values.

The constraint/thrust diagram converts the constraint diagram into a flexible analysis tool upon which to place the attributes of each engine design and analyze its effectiveness for performing various maneuvers. As the retrofit aircraft performance is being determined, the designer can shift the wing loading to gain insight into the maneuverability of the aircraft at various takeoff weights and weight fractions. This analysis allows the aircraft designer to compare new engine designs to see how the changes in  $T_{SL}$  will affect each maneuver and not just a specific mission.

### 2.3. Mission Analysis

The mission analysis portion of the design process, as developed in chapter 3 of Reference 6, uses the wing and thrust loading values selected from the constraint diagram to determine an acceptable takeoff weight for the aircraft.

The aircraft weight is simply a combination of the empty weight, fuel weight and payload weight

$$W_{TO} = W_E + W_F + W_P$$

The rate of change of the aircraft weight as a function of the fuel consumption is

$$\frac{dW}{dt} = -\frac{dW_F}{dt} = -TSFC \times T$$

where TSFC is the installed thrust specific fuel consumption and T is the installed thrust. This equation can be rewritten as

$$\frac{dW}{W} = -TSFC \frac{T}{W} dt \quad (6)$$

The desire is to determine appropriate expressions for various legs of the mission which relate the initial and final weights for that phase. These expressions are of the form

$$\frac{W_f}{W_i} \leq 1$$

and Eq (6) is used to develop the weight fraction equations which correspond to flight regimes where  $P_S > 0$  (type A), or  $P_S = 0$  (type B). Type A behavior is exhibited during constant speed climb, horizontal acceleration, climb and acceleration, and takeoff acceleration. Type B behavior relates to constant altitude/speed cruise and turn, best cruise Mach number and altitude, loiter, warmup, takeoff rotation, and constant energy height maneuvers. The developed equations are

Type A:

$$\frac{W_f}{W_i} = \exp \left\{ - \frac{C\sqrt{\theta}}{V(1-u)} \Delta \left( h + \frac{V^2}{2g_0} \right) \right\}$$

Type B:

$$\frac{W_f}{W_i} = \exp \left\{ - C\sqrt{\theta} \left( \frac{D+R}{W} \right) \Delta t \right\}$$

Where C is the specific fuel consumption,  $\theta$  is the static temperature ratio, and u is the total drag-to-thrust ratio. These equations are used in the computer program MISS, Reference 8, to calculate the weight fractions for any given mission leg. More information on the MISS computer program is provided in Appendix B.

For the engine retrofit problem, the design takeoff weight is known and the mission analysis is used to evaluate the overall fuel consumption of each new engine design.

## **2.4. On-Design Analysis**

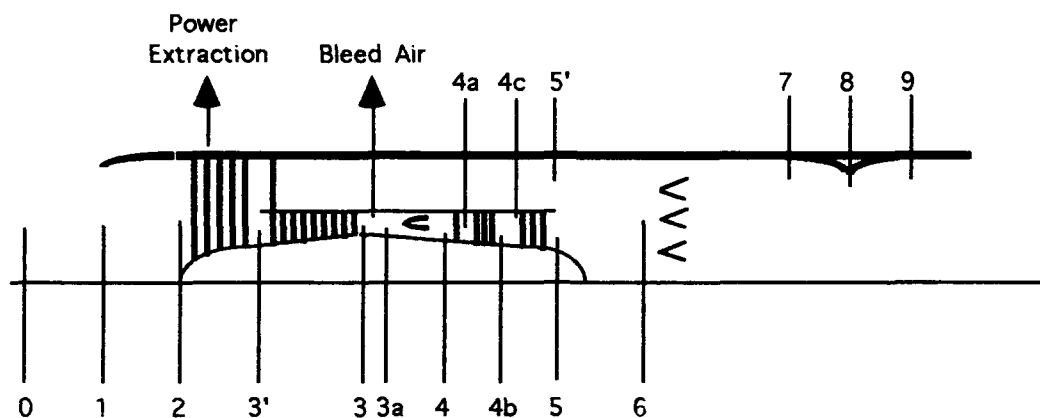
### **2.4.1. On-Design Solution**

The on-design cycle analysis was used to select a reasonable range for the engine design variables at the design point. This analysis, which will be referred to as the parametric analysis in future papers by Mattingly and Heiser (7:2), allows the engine designer to select a design point and calculate engine performance. In particular, values for the two most important design characteristics at this point, the uninstalled specific thrust,  $F/m_0$ , and the uninstalled thrust specific fuel consumption,  $S$ , can be determined. The engines developed with the on-design analysis are referred to as the design point engines.

In order to calculate  $F/m_0$  and  $S$ , a closed form solution for the on-design analysis can be achieved by solving the series of equations presented in Appendix E of Reference 6. The inputs and outputs to these equations are presented in Table 1. Figure 6 illustrates the reference station numbering for a mixed-stream turbofan engine. Each reference station number pertains to the locations of the mass flow as it migrates through the engine.

To begin the analysis, the design altitude and Mach number are selected. These values are usually based on that leg of the mission which is the most demanding or best encompasses the range of mission requirements. Judgement is required when selecting this starting point but some general comments can be made.

If an aircraft will subsonically cruise for long distances, then the engine performance at the cruise altitude and Mach number is going to be most important. Fuel economy should be the best at this cruise condition for the engine design. On the other hand, if the design calls for an aircraft which must perform at a high Mach number and supercruise then the design altitude and Mach number should reflect the best blend of these conditions (6:129)



| <u>Station</u> | <u>Location</u>                                 | <u>Station</u> | <u>Location</u>                          |
|----------------|-------------------------------------------------|----------------|------------------------------------------|
| 0              | Far upstream                                    | 4b             | High pressure turbine exit               |
| 1              | Inlet or Diffuser                               | 4c             | Low pressure turbine entry               |
| 2              | Inlet or diffuser exit<br>Fan entry             | 5              | Low pressure turbine exit<br>Mixer entry |
| 3'             | Fan exit<br>High pressure compressor entry      | 5'             | Fan bypass mixer entry                   |
| 3              | High pressure compressor exit                   | 6              | Mixer exit<br>Afterburner entry          |
| 3a             | Burner exit                                     | 7              | Afterburner exit<br>Exhaust nozzle entry |
| 4              | Burner exit<br>Nozzle vanes entry               | 8              | Exhaust nozzle throat                    |
| 4a             | Nozzle vane exit<br>High pressure turbine entry | 9              | Exhaust nozzle exit                      |

Figure 6. Engine Reference Stations (6:99)

Table 1. On-Design Solution Inputs and Outputs (6:467)

| <u>Inputs</u>               |                                                                                                                                                                                              |
|-----------------------------|----------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|
| Flight parameters:          | $M_0, T_0(R), P_0(\text{psia})$                                                                                                                                                              |
| Aircraft system parameters: | $\beta, C_{TO}$                                                                                                                                                                              |
| Design limitations:         |                                                                                                                                                                                              |
| Perfect gas constants:      | $\gamma_C, \gamma_t, \gamma_{AB}, C_{pC}, C_{pt}, C_{pAB} \text{ (BTU/lbm-R)}$                                                                                                               |
| Fuel heating value:         | $h_{PR} \text{ (BTU/lbm)}$                                                                                                                                                                   |
| Component figures of merit: | $\epsilon_1, \epsilon_2$                                                                                                                                                                     |
|                             | $\pi_b, \pi_{dmax}, \pi_{Mmax}, \pi_{AB}, \pi_n$                                                                                                                                             |
|                             | $e_c', e_{cH}, e_{tH}, e_{tL}$                                                                                                                                                               |
|                             | $\eta_b, \eta_{AB}, \eta_{mL}, \eta_{mP}, \eta_{mH}$                                                                                                                                         |
| Design choices:             | $\pi_c', \pi_c, \alpha, T_{t4} \text{ and } T_{t7} (^{\circ}R), M_5, P_0/P_9$                                                                                                                |
| <u>Outputs</u>              |                                                                                                                                                                                              |
| Overall performance:        | $F/m_0 \text{ (lbf/lbm/s)}, S \text{ (1/h)}, f_0,$<br>$\eta_P, \eta_{TH}, V_9/V_0, P_{t9}/P_9, T_9/T_0$                                                                                      |
| Component behavior:         | $\pi_{tH}, \pi_{tL}, \pi_M,$<br>$\tau_c', \tau_{cH}, \tau_{tL}, \tau_{tH}, \tau_\lambda, \tau_{\lambda AB}$<br>$f_{AB}, f$<br>$\eta_c', \eta_{cH}, \eta_{tH}, \eta_{tL}$<br>$M_5', M_6, M_9$ |

Once the altitude and Mach number have been selected, the on-design analysis is used to generate solution surfaces and trend plots from which to select the best design point engine values for further analysis. At this point in the design scheme the engine is considered to be a "rubber engine" with variable size and thrust which can be stretched and shaped to fit the performance requirements (12:101).

The computer program ONX provides an efficient tool for generating the on-design data. A complete description of this program can be found in Reference 9.

### 2.4.2. Carpet Plots and Solution Surfaces

The on-design calculations produce data used to generate plots of  $F/m_0$  and  $S$  based on various combinations of design variables. These plots are used to select reasonable ranges for the design variables by seeking those combinations which maximize  $F/m_0$  and minimize  $S$ . The most useful representation presents the effect of the compressor pressure ratio,  $\pi_c$ , and the bypass ratio,  $\alpha$ , on  $F/m_0$  and  $S$ . This results in a typical carpet plot as shown in Figure 7, where each data point represents the value of  $F/m_0$  and  $S$  at a particular combination of  $\pi_c$  and  $\alpha$ .

Carpet plots are produced for various combinations of Mach number, altitude, turbine inlet temperature, etc. and are used to select a suitable range for the compressor pressure ratio and bypass ratio. This is done by looking below the knee of the constant  $\alpha$  curves and choosing the  $\pi_c$  and  $\alpha$  values which will reduce  $S$  while minimizing the reduction in  $F/m_0$ .

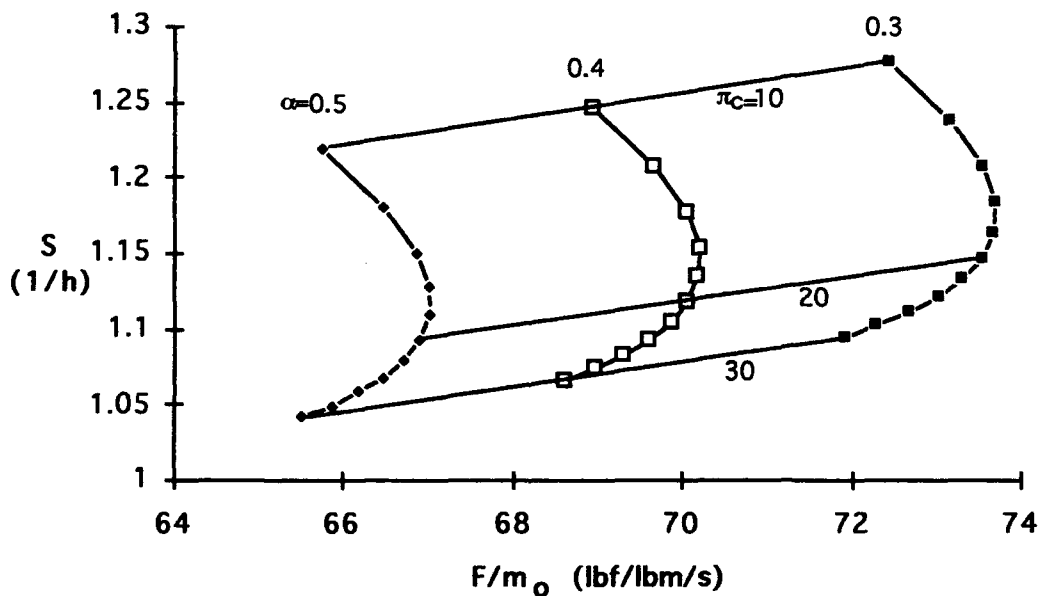


Figure 7. Carpet Plot,  $M=0.9$ ,  $h=35$  k ft,  $T_{t4}=3200$  R

The mixer of a mixed stream turbofan engine plays an important role in the engine's overall performance. The Mach number of the airflows leaving stations 5 and 5' influence the temperatures and pressures of all the rotating components and must

be compatible to allow for proper mixing at station 6. Since  $M_5$  and  $M_5'$  will change for various flight conditions, it is prudent to select only those combinations of  $\pi_c$  and  $\alpha$  for which  $M_5$  and  $M_5'$  lie between 0.4 and 0.6 at the design point (6:123). The results presented in the carpet plots are therefore misleading, since the plot presents a large number of compressor pressure ratios and bypass ratios where a useful solution does not exist.

Using ONX, a series of on-design calculations were made by varying  $\pi_c$  from 6 to 30 and  $\alpha$  from 0.2 to 0.6 for  $M=1.5$  at an altitude of 35,000 ft and  $T_{t4}=3200$  R. After extracting those combinations of  $\pi_c$  and  $\alpha$  which result in an  $M_5$  and  $M_5'$  between 0.4 and 0.6, the carpet plot shown in Figure 8 was generated. Unlike the carpet plot of Figure 7, there are large gaps in the useful combinations of  $\pi_c$  and  $\alpha$ . There is no value for  $\pi_c$  which will extend from the lowest  $\alpha$  to the highest and include all  $\alpha$  values. Also, at this design point, the lines of constant  $\alpha$  do not form a knee. These conditions make selecting design point ranges for  $\pi_c$  and  $\alpha$  more difficult.

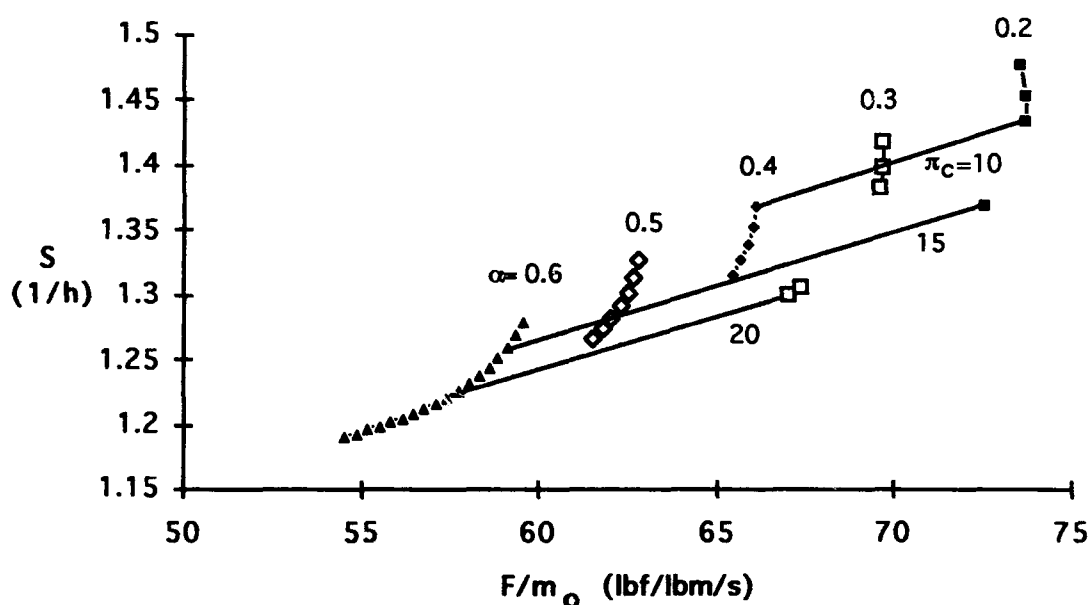


Figure 8. Carpet Plot,  $M=1.5$ , 35k ft,  $T_{t4}=3200$  R,  
 $M_5$  and  $M_5'$  between 0.4 and 0.6

A new method for displaying and interpreting this information was developed through the use of surface plots. For the same on-design condition as used in Figure 8, the  $F/m_0$  and  $S$  surface plots have been generated and are presented in Figures 9 and 10. Anywhere the surface is above the arbitrary minimum  $F/m_0$  and  $S$  of 50 and 1.2 respectively, and within or along the heavy block border, is a possible combination of  $\pi_c$  and  $\alpha$  which should perform well at off-design conditions and can be considered a solution for off-design operation. This plot will be called the solution surface since it represents all acceptable candidate engines for the given design condition and limits. It is this surface which presents the acceptable solutions and graphically demonstrates the influence of the two design variables,  $\pi_c$  and  $\alpha$ , on  $F/m_0$  and  $S$ .

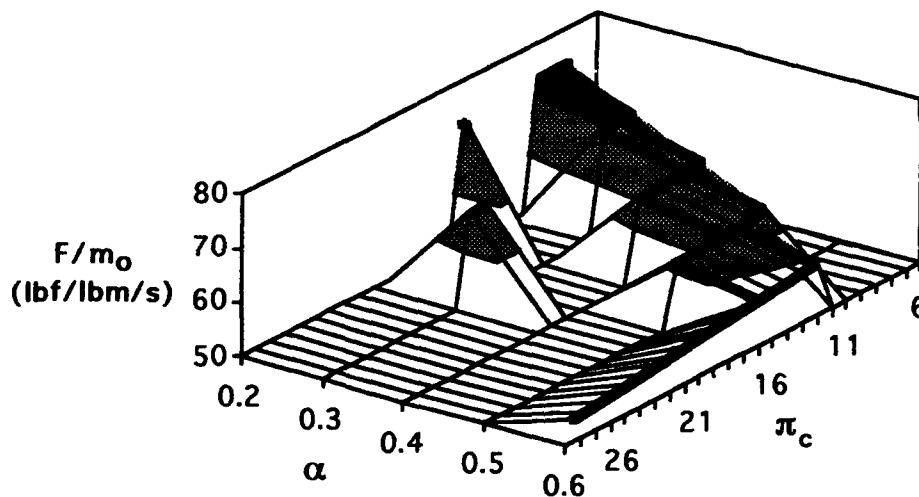


Figure 9. Uninstalled Specific Thrust ( $F/m_0$ ) Solution Surface

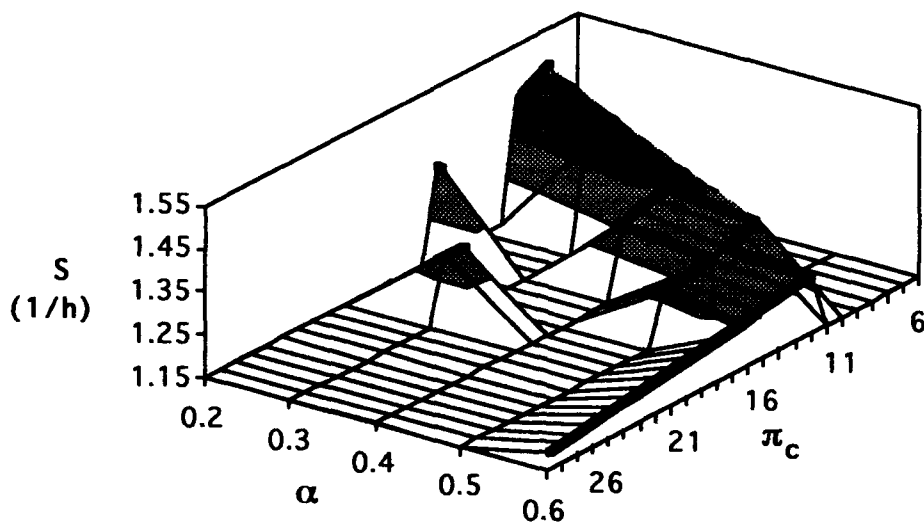


Figure 10. Uninstalled Thrust Specific Fuel Consumption (S) Solution Surface

The impact of the solution surface diagrams is quite striking in that they provide a visual clue as to where the majority of solutions lie. Two points should be made about the solution surfaces. First, the regions which are represented by sharp peaks may or may not contain a reasonable solution. These points emerge when the values for  $M_5$  and  $M_5'$  just fall within limits. Second, some solutions may lie off the solution surface where  $M_5$  and  $M_5'$  just fall outside the limits. Neither of these conditions can be relied upon to produce a strong candidate engine and the solution surface is meant to represent the best choices of design variable combinations for off-design operation.

To verify the validity of the solution surface analogy and limiting  $M_5$  and  $M_5'$ , an off-design analysis on all combinations of  $\pi_c$  and  $\alpha$  in Figures 9 and 10 was accomplished. If an engine with a particular combination of  $\pi_c$  and  $\alpha$  performed successfully at off-design conditions it represents a design point solution and is indicated on Figure 11 by a square. The mixer limited solutions, from the solution surfaces, are represented by a dot on Figure 11. This figure shows that the majority of the mixer limited solutions fall within the region of mixer unlimited solutions. Figure 11 also indicates that a solution does not exist where the spikes were present in Figures 9 and 10 and that the mixer unlimited solutions extend over a slightly larger area.

Since the majority of the mixer limited solutions, 92%, fall within the mixer unlimited region, it may be concluded that limiting the Mach number at station 5 and 5' results in an acceptable number of possible solutions for selecting the design point engine and that the solution surface is a valid representation of this information.

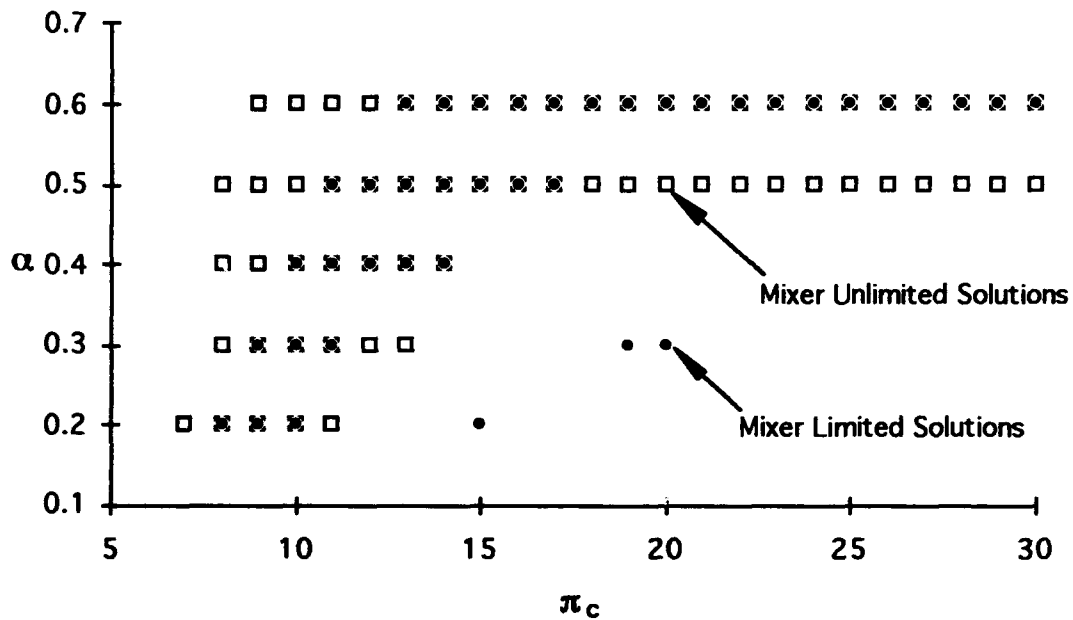


Figure 11. Mixer Limited and Mixer Unlimited Solutions

### 2.4.3. Generation of Trend Data

The solution surface representation of the uninstalled specific thrust and uninstalled thrust specific fuel consumption provides information as to where possible solutions exist. It is necessary that a measure be developed with which to evaluate the various combinations.

The method developed here is based on the changes in  $F/m_o$  and  $S$  from one compressor pressure ratio to the next along a line of constant  $\alpha$ . For each incremental change in  $\pi_c$ , the fractional change in  $F/m_o$  and  $S$  can be calculated. The change in  $F/m_o$  can be represented by the equation

$$Q_1 = \frac{\left(\frac{F}{m_o}\right)_{i+1} - \left(\frac{F}{m_o}\right)_i}{\left(\frac{F}{m_o}\right)_i}$$

where  $i$  varies from 1 to  $n-1$ , and  $n$  is the number of  $\pi_c$  values evaluated along the line of constant  $\alpha$ . A similar equation for  $S$  is

$$Q_2 = \frac{S_{i+1} - S_i}{S_i}$$

The quantities  $Q_1$  and  $Q_2$  are defined as quality measures as they establish a characteristic measure for  $F/m_o$  and  $S$ .

As an example, the quality measures were calculated for the same on-design data represented in Figures 9 and 10 in the previous section. After calculating the various quantities for  $Q_1$  and  $Q_2$ , the two measures can be plotted against  $\pi_c$  to generate the plot shown in Figure 12.

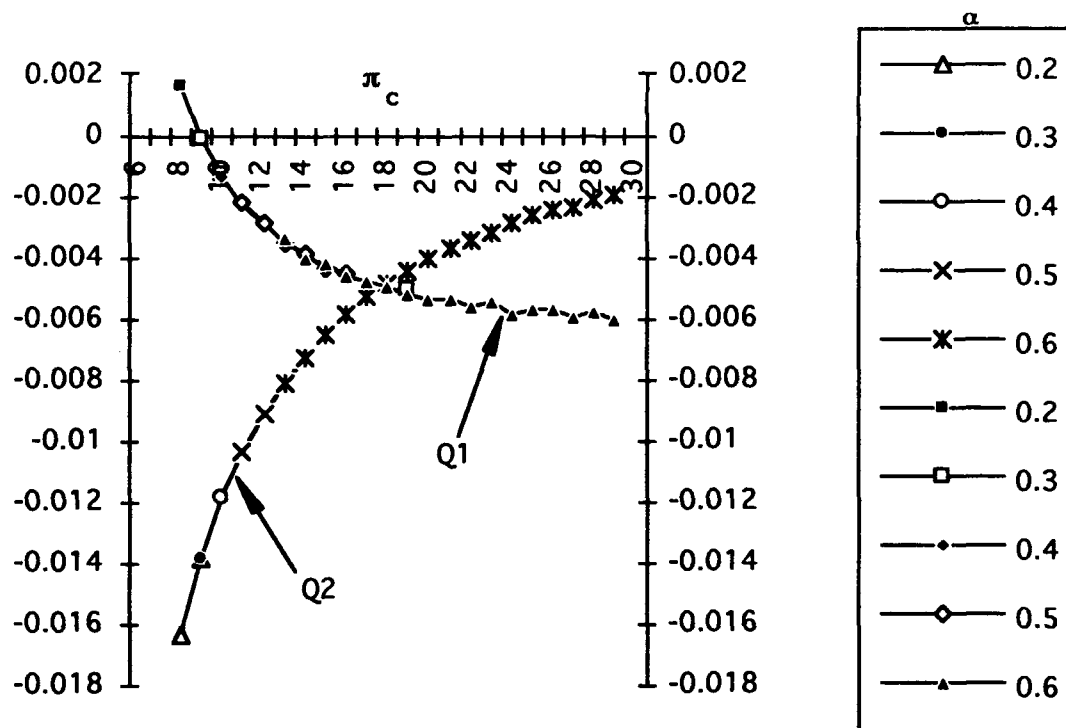


Figure 12. Quality Measures  $Q_1$  and  $Q_2$  for  $M=1.5$ , 35 k ft

The negative value on the y-axis, indicates that  $F/m_0$  and  $S$  are being reduced for every increment of  $\pi_c$ , a positive value would indicate an increase. For this case, there was an increase in  $F/m_0$  at  $\pi_c=8$ . The rest of the plot shows that there is a steady decline in both  $F/m_0$  and  $S$  as the compressor pressure ratio is increased. The decrease in  $F/m_0$  is small at first, as indicated by the small negative values, and grows to -0.006.  $S$  starts out with large improvements in fuel consumption at the low pressure ratios and drops to very small gains at the higher pressure ratios. The portions of the curves which tend to flatten out indicate a constant rate of change from one pressure ratio to the next.

A final measure can be developed which presents the two measures above plotted in a single relationship.

$$Q_3 = \frac{Q_1}{Q_2}$$

This quality measure presents the relationship between the fractional change in  $F/m_0$  and the fractional change in  $S$  between subsequent values of  $\pi_c$ . If the fractional

change in  $F/m_0$  decreased by 0.1 while  $S$  decreased by 0.05 the result is 2, which indicates that  $F/m_0$  decreased more rapidly than the corresponding decrease in  $S$  between the two pressure ratios. The plot of  $Q_3$  for the values of  $Q_1$  and  $Q_2$  previously calculated is presented in Figure 13.

This plot indicates that at the high  $\pi_c$  values,  $F/m_0$  decreases more quickly than the corresponding decrease in  $S$ . At  $Q_3=1$ , both values are changing at the same rate. Below 1,  $S$  is changing more rapidly, and above 1,  $F/m_0$  changes more rapidly.

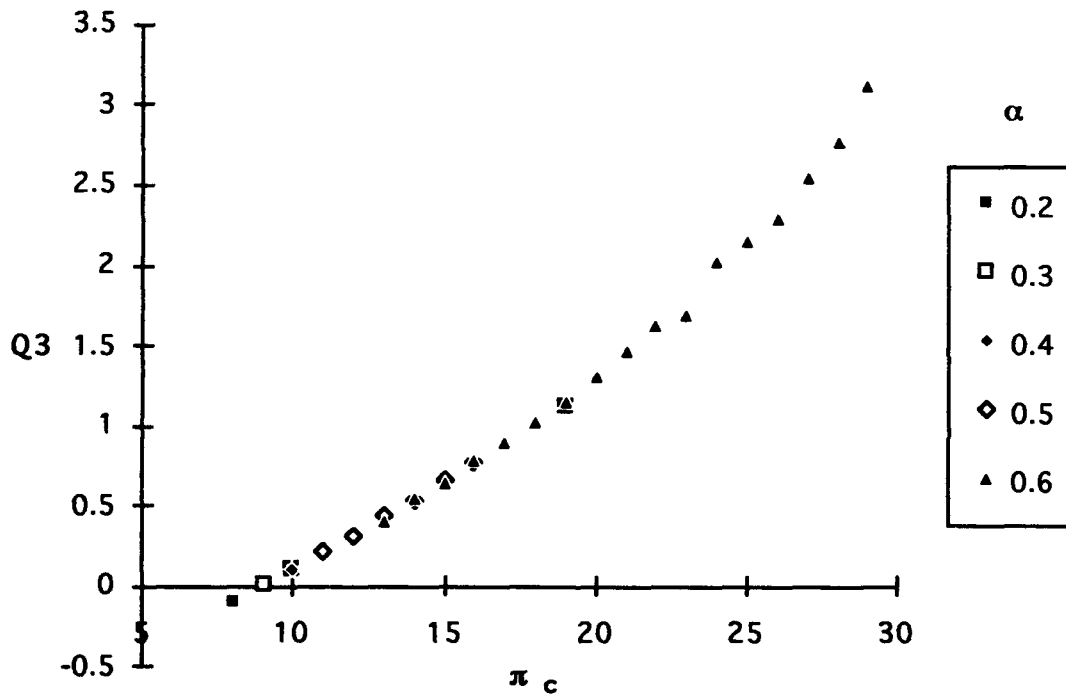


Figure 13. Quality Measure  $Q_3$  for  $M=1.5$ , 35k ft

These three quality measures assist the designer by presenting the fractional changes in  $F/m_0$  and  $S$  when considering various flight altitudes and conditions for the design point engine. The quality measures are used, rather than the simple difference in  $F/m_0$  or  $S$  per  $\pi_c$  increment, in order to allow comparison between the two quantities and across various Mach numbers and altitudes.

For example, plots of the quality measures were created for exactly the same engine parameters as Figures 12 and 13 but at  $M=1.5$  and an altitude of 25,000 ft. The results

are presented in Figures 14 and 15. Figure 14 shows that both  $F/m_0$  and  $S$  are changing at the same rate when  $\pi_c$  is 14 whereas the same condition occurs at a  $\pi_c$  of approximately 18 for the 35,000 ft case. This indicates that at the lower altitude the combinations of  $\pi_c$  and  $\alpha$  which will minimize  $S$  while maximizing  $F/m_0$  begin at lower values of  $\pi_c$ . Also, the intersection for the 25,000 ft case occurs at a higher fraction but a lower  $\pi_c$  than for the 35,000 ft case. Figure 15 indicates that, for any  $\pi_c$ , the decrease in  $F/m_0$  is much higher than the change in  $S$  when compared to Figure 13.

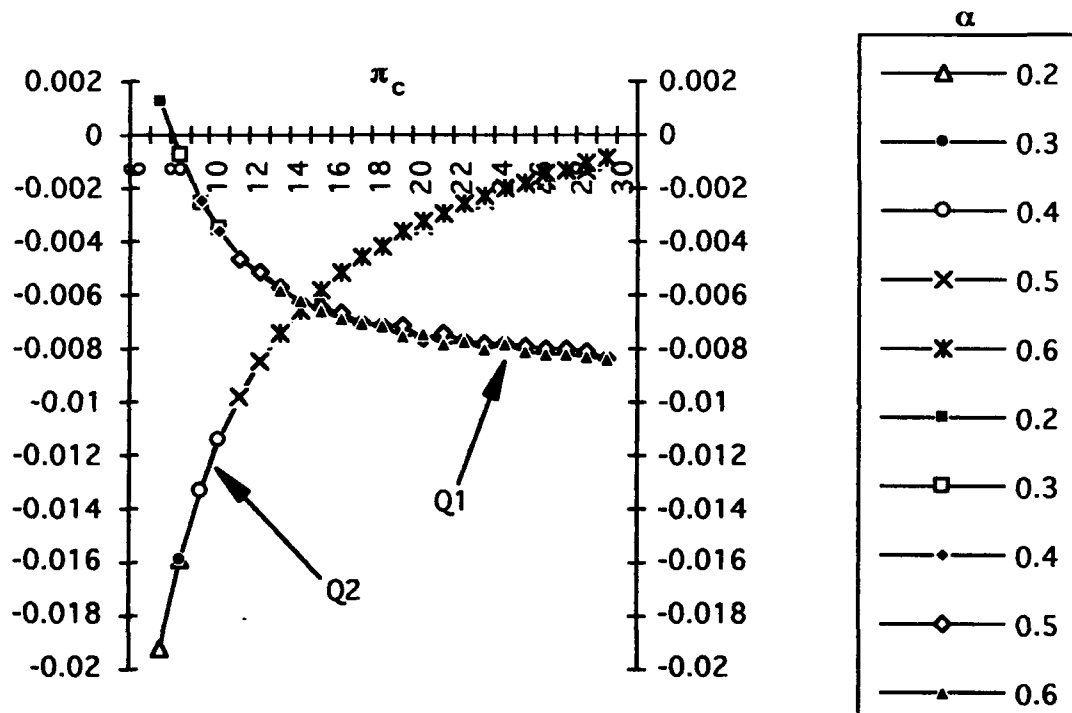


Figure 14. Quality Measures  $Q_1$  and  $Q_2$  for  $M=1.5$ , 25 k ft

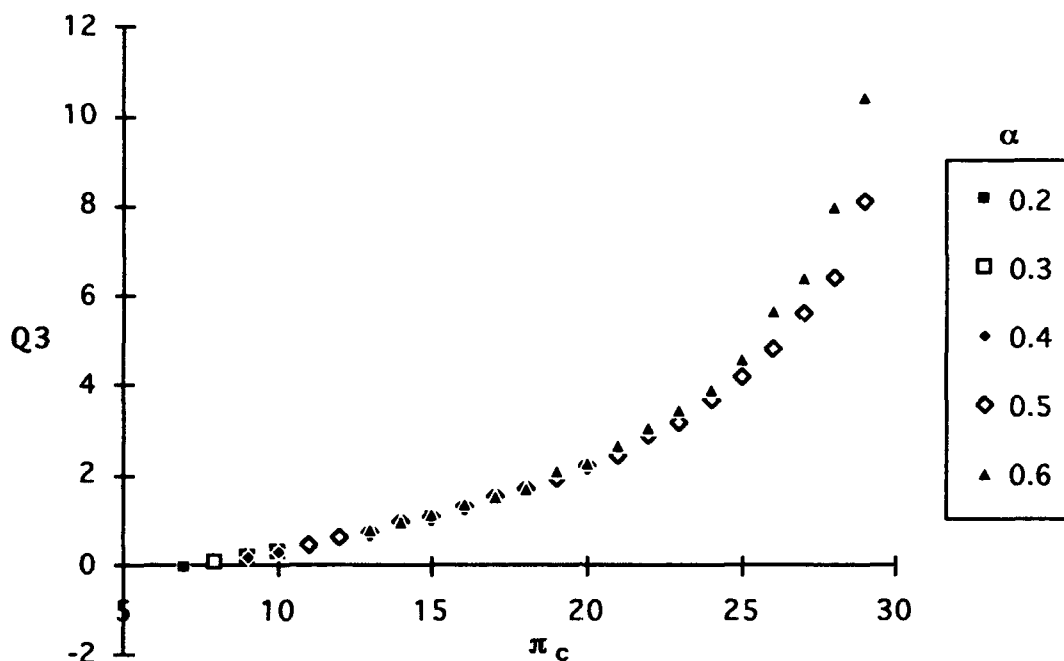


Figure 15. Quality Measure Q3 for M=1.5, 25k ft

Figures 12 and 14 are used to determine the points where the tradeoff between maximum  $F/m_0$  and minimum  $S$  is acceptable. For a pure performance application, as in a high performance test vehicle, the choice would be to select a range for  $\pi_c$  and  $\alpha$  to the left of the intersection. If fuel economy is the primary concern, the choice would be to move as far to the right of the intersection as possible. For a high performance fighter aircraft, the best of both worlds is desirable, and choices should be made just to the right of the intersection.

Figures 13 and 15 show that the ratio of change in  $F/m_0$  to change in  $S$  is much greater for the 25,000 ft case. This would result in selecting a narrower range of  $\pi_c$  values for an investigation of design point engines at 25,000 ft.

These quality measures create an analysis tool for displaying the interactions between  $F/m_0$ ,  $S$ ,  $\pi_c$ , and  $\alpha$ . This analysis and plot generation was used in the engine retrofit effort to select the range of values for  $\pi_c$  and  $\alpha$  which should yield design point engines with good fuel economy and adequate thrust.

## **2.5. Off-Design Analysis**

The off-design cycle analysis provides a means to operate the design point engine at various flight conditions. The solution to the off-design problem is presented in Chapter 5 of Reference 6 and results in 14 dependent variables and 14 independent equations. In order to solve this system of equations, an iterative approach is used. This approach brings all variables within their specified operating limits to calculate the uninstalled thrust,  $F$ , and fuel consumption,  $S$ . The analysis produces uninstalled engine data over various in-flight operating conditions.

The off-design analysis provides a tool for determining the baseline engine design. The baseline engine is the engine which has been selected due to its ability to successfully complete all mission and performance requirements while minimizing the fuel consumed.

The program OFFX, allows rapid iteration and calculation of the engine performance at off-design conditions. It can be used to make adjustments to the design variables by examining any off-design set of conditions more critically. Additional information on the OFFX program and its various uses can be found in Reference 9.

The off-design analysis is mentioned here because a derivative of it is used in the computer program MISS. MISS is capable of generating off-design performance data for specific mission legs and was used to evaluate each design point engine in an off-design scenario. Additional information on MISS is presented in Appendix B.

## **2.6. Modeling Techniques**

In order to reduce the amount of iteration necessary when developing new design point engines, empirical modeling was used. The purpose of empirical modeling is to take a related group of predictor values and generate a response to them. A group of independent variables or input values is developed into a model which predicts the dependent variable or output value. The method of multivariable linear regression and the application of statistical analysis for empirical model building will be discussed here.

If the response to a given set of inputs can be demonstrated by a simple relationship it is referred to as a deterministic or mechanistic model. For example, if the response to an input,  $x$ , follows the rule

$$y = 3x + 6$$

it is a mechanistic model since it predicts with very little error and it is a simple matter to predict the outcome of any input,  $x$  (1:11). When systems become more complex and their behavior cannot be modeled using a simple equation, then other means must be used to achieve a useful predictor of future outcomes.

The creation of a model which relies on observations or experience without considering the theoretical aspect of the analysis, is the foundation of empirical modeling. Each observation of the response to a certain set of input variables is an experiment. The prediction of other outputs can be made based on careful analysis of the results. Of interest here are functions of more than one variable, where

$$y = f(x_1, x_2, \dots, x_k)$$

If each of the  $x_i$ 's are thought of as vector components, then this equation can be simply stated as

$$y = f(\mathbf{x})$$

where  $\mathbf{x}$  is a one dimensional column vector representing the input variables. Usually, a set of physical parameters,  $\theta_1, \theta_2, \dots, \theta_p$ , define this functional relationship between the input and output. The result is

$$y = f(\mathbf{x}, \theta)$$

If the functional relationship linking the inputs to the output are precisely known, a mechanistic model is formed. When the relationship between the input and output is unknown, the response may be approximated if the functional relationship is assumed

smooth. This relationship can be written as

$$y \approx f(\mathbf{x}, \boldsymbol{\beta})$$

where the vector  $\boldsymbol{\beta}$ , refers to the approximate values of the physical parameters  $\theta$ . Thus, the empirical model relates the input to the output through an approximation. Since the result of this calculation is an approximation, there is some error,  $\varepsilon$ , which is a random variable associated with the particular set of independent variables. The linear model

$$y = \beta_0 + \beta_1 x_1 + \beta_2 x_2 + \dots + \beta_k x_k + \varepsilon$$

relates the behavior of the dependent variable  $y$  to the independent variables  $x_i$ 's with an error term  $\varepsilon$ .

In matrix notation, letting  $y_i$ ,  $x_{ij}$ , and  $\varepsilon_i$  be the values for  $y$ ,  $x_j$ , and  $\varepsilon$  in the  $i^{\text{th}}$  experiment, and defining the  $\mathbf{Y}$  vector, the  $\mathbf{X}$  matrix, the  $\boldsymbol{\beta}$  vector, and the  $\boldsymbol{\varepsilon}$  vector as

$$\mathbf{Y} = \begin{bmatrix} y_1 \\ \vdots \\ y_n \end{bmatrix}, \quad \mathbf{X} = \begin{bmatrix} 1 & x_{11} & \dots & x_{1k} \\ \vdots & \vdots & & \vdots \\ 1 & x_{n1} & \dots & x_{nk} \end{bmatrix}, \quad \boldsymbol{\beta} = \begin{bmatrix} \beta_0 \\ \vdots \\ \beta_k \end{bmatrix}, \quad \boldsymbol{\varepsilon} = \begin{bmatrix} \varepsilon_1 \\ \vdots \\ \varepsilon_n \end{bmatrix}$$

the model becomes

$$\mathbf{Y} = \mathbf{X}\boldsymbol{\beta} + \boldsymbol{\varepsilon}$$

where the number of experiments or observations is  $n$  and the number of variables is  $k$ .

After experiments are performed using various input levels for the independent variables, the information can be used to develop an approximation to the actual function. Despite the fact that this is an approximation, a well developed model allows general statements to be made about the interactions between the input variables and assess their impact on the output.

After making  $n$  observations of the  $y$  variable using  $k$  independent variables, estimates for the values of  $\beta$  can be made. The resulting equation is

$$\hat{y} = \hat{\beta}_0 + \hat{\beta}_1 x_1 + \dots + \hat{\beta}_k x_k$$

The least squares estimate for  $\hat{\beta}' = (\hat{\beta}_0, \hat{\beta}_1, \dots, \hat{\beta}_k)$ , is found by solving

$$\hat{\beta} = (X'X)^{-1} X'Y$$

After solving for the values of  $\hat{\beta}$ , the model must be examined to see how well it conforms to the data being modeled. The process is an iterative one using various statistical methods for determining how well the model fits the data (1:34-35, 3:9, 10:493-500).

When modeling, there is no requirement that all the terms in the input have to be used in the model, since some of the terms may not produce significant changes in the result. The terms can be second order, third order, exponential, etc., as long as the model accurately characterizes the data within the region of interest (2:218-224). Second order approximations of the form

$$g(\mathbf{x}, \beta) = \beta_0 + \beta_1 x_1 + \beta_2 x_2 + \beta_{11} x_1^2 + \beta_{22} x_2^2 + \beta_{12} x_1 x_2$$

were used to develop the models in this investigation.

The computer program SAS, Reference 13, was used extensively for creating the models, determining how well they fit the data, and making predictions for the sea-level thrust and the mission fuel consumption. How suitably the model fits the data can be determined using statistical analysis techniques. The specific tests used for linear regression as applied to the SAS environment are discussed in Appendix C on SAS programming.

## **2.7. Engine Retrofit Design Scheme**

The engine retrofit problem differs from the aircraft and engine design problem outlined in Reference 6, in that the goal was to find a new baseline engine which improved the performance of an existing aircraft design. If this was a new aircraft development program, the best engine and airframe integration would be produced using any of the procedures outlined in References 6, 11 or 12, since both the airframe and engine design variables are flexible in the design process. By keeping the airframe constant, the design scheme can be simplified to a certain degree and new analysis and comparison methods demonstrated.

The two major measures of improvement for the retrofit problem were the overall fuel consumption and the available sea-level thrust. The search can be for improved fuel economy while maintaining the same thrust, increased thrust without regard to fuel economy, or search for improvement in both thrust and fuel economy. For the first case, the amount of fuel which the aircraft will have to carry will be reduced. The benefit is increased range or increased payload equal to the reduction in fuel weight. The second case relates to a pure performance improvement, as in a high performance test application, where fuel economy is not a concern. The final case results in an overall improvement in performance across the board. This case is applicable to a fighter type aircraft and was the focus of this investigation.

The problem was to search for trends and make inferences by testing a minimum number of alternative engine designs. The procedure outlined in this section presents the process used for selecting appropriate engine design parameters when designing a new engine for an existing airframe. It incorporates existing computer programs to generate performance data while developing methods to weigh the various outputs in a manner which will lead the investigator toward a feasible design.

Items A through H below, describe the analysis approach developed in this investigation. They present a brief description of the process along with the assumptions and methods involved in its use. The technique described in Reference 6, was very useful as a road map in planning the retrofit analysis.

**A. Assemble the design point information.**

The existing engine and airframe have a design point. This is where the initial information for the search was found. Since the retrofit aircraft was known, information on the drag characteristics, the effective wing area, and the design thrust loading and wing loading was available. This information was used to develop the baseline airframe upon which to hang candidate engines and evaluate their performance.

The allowable space for the engine is fixed and the engine inlet sized by the restriction of the fuselage. It was assumed that the existing inlet area and the length and diameter of the nozzle would remain constant.

With the inlet area determined, the mass flow rate is limited to a maximum for each engine design. This is critical in the search for the new engine since the performance at off-design flight conditions depends on the available airflow.

The existing baseline engine was the first source of information for defining the new engine design. It already performs all aspects of the mission and provides acceptable fuel economy. The retrofit engine design may incorporate changes for component efficiencies, fuel heating value, or any of the numerous input design variables for the design point engine.

**B. Develop constraint/thrust diagrams for the required flight maneuvers.**

Use the computer program ACSYS to determine the solution space for the thrust and wing loading and to produce constraint/thrust diagrams. For engine retrofit the wing surface area,  $S$ , is fixed which allows lines of constant thrust to be plotted against the wing loading and thrust loading variables. When the aircraft performance requirements are plotted, the amount of sea-level thrust that the engine must produce in order to fly the maneuver can be determined.

**C. Identify an appropriate mission to judge the fuel consumption improvements of each candidate engine.**

The aircraft is "flown" using the mission analysis program MISS, to simulate the off-design characteristics of the engine and determine its fuel consumption. It

identifies shortcomings and whether or not the mission can be flown. MISS is a useful tool when testing candidate engines because it reports if the off-design solution fails to converge and why, as well as warn the user of an engine inlet which has to be resized to accommodate the incoming mass flow.

The mission analysis forms the basis for comparing the aircraft's overall fuel consumption while performing a baseline mission. The mission the aircraft will fly can either be modeled after its current mission profile or a new mission. If a change in the mission is required, then the aircraft can be flown in the new environment, but the overall engine characteristics may change considerably. The assumption was made that the aircraft's original mission profile was still valid for this investigation and that the engine was being redesigned to allow greater mission flexibility and fuel economy.

The output from MISS is used to compare weight fractions, overall fuel consumption, and whether or not the engine power is adequate for the aircraft without increased mass flow requirements. This last item refers to the fact that a baseline engine can be specified which produces much higher thrust than the one currently in use, but the space available in the airframe may not be large enough to accommodate it.

**D. Generate solution surfaces and trend analyses for selecting candidate design point engines.**

After selecting a design point Mach number and altitude, generate solution surfaces and perform trend analyses. This is accomplished using the ONX computer program to generate the design point data over ranges of compressor pressure ratio and bypass ratio. The solution surfaces and quality measures are then developed to relate the changes in  $F/m_0$  and  $S$  at the design point.

By creating plots at different altitudes and Mach number, specific candidate engine designs can be selected for testing and to develop trends within the range of design variables.

**E. Test the candidate engines using MISS.**

A single point file is created using the ONX computer program for each candidate engine. This information is loaded into MISS along with the aircraft design point data. The engine's sea-level thrust and fuel consumption are obtained and the engine's position on the constraint/thrust diagrams determined. The fuel consumption is another indicator of the efficiency of the new design point and therefore an additional check on the improvement of one design over another.

**F. Use linear regression to build the models.**

The candidate design point engines tested represent only a small sample of all available solutions. In order to perform a thorough check of the solution surface all variations of design variables must be calculated in order to choose the best combination. A better method is to use linear regression analysis techniques to model the response.

Properly constructed models reduce the computer intensive work of running a mission analysis for each design point engine. Models are created which relate the design variables to the fuel consumption and sea-level thrust using the SAS software. From the models, and depending upon the number of variables, new engine designs are selected using any one or all of the following methods.

**2 variables:**

Generate surfaces which visually represent the effect of the two variables on the dependent variable and make selections.

**Any number of variables:**

- a. Use SAS predicted values to rank the engines and make selections.
- b. Identify the effect of each independent variable on the dependent variable and make selections.

The selected engines are then "flown" using MISS to see if the desired improvement was obtained. This in effect tests the validity of the model. If there is considerable error between the SAS predicted values and the MISS values, the

data base can be expanded with the new MISS observations until enough data points have been sampled to correctly characterize the response.

Through modeling, trends can be established and inferences made concerning the influence of one variable over another. This allows selection of a minimum number of design choices, since the trend established is based on the fit of the model to the data. This model only provides approximate solutions to any given set of design variables and care must be used in building the model as well as interpreting the results.

**G. Produce the best candidate engines and plot their performance on constraint/thrust diagrams.**

The constraint/thrust diagrams are used to present the changes in capability produced by the new engines while performing various maneuvers. The aircraft's takeoff performance, maneuverability, and max performance requirements can be evaluated with constraint/thrust diagrams. These diagrams provide a method for evaluating the merits of each design.

**H. Select the new engine design point.**

The final engine choice is based on the performance improvements indicated by the constraint/thrust comparisons and/or the ability to accomplish the mission with improved fuel economy. This engine is referred to as the baseline engine and is used to begin the design of the individual engine components.

This section has discussed the analysis tools used and the design scheme developed for jet engine retrofit. The next section will consider two applications of the process to demonstrate its utility. The process described above is outlined in the flow chart shown in Figure 16.

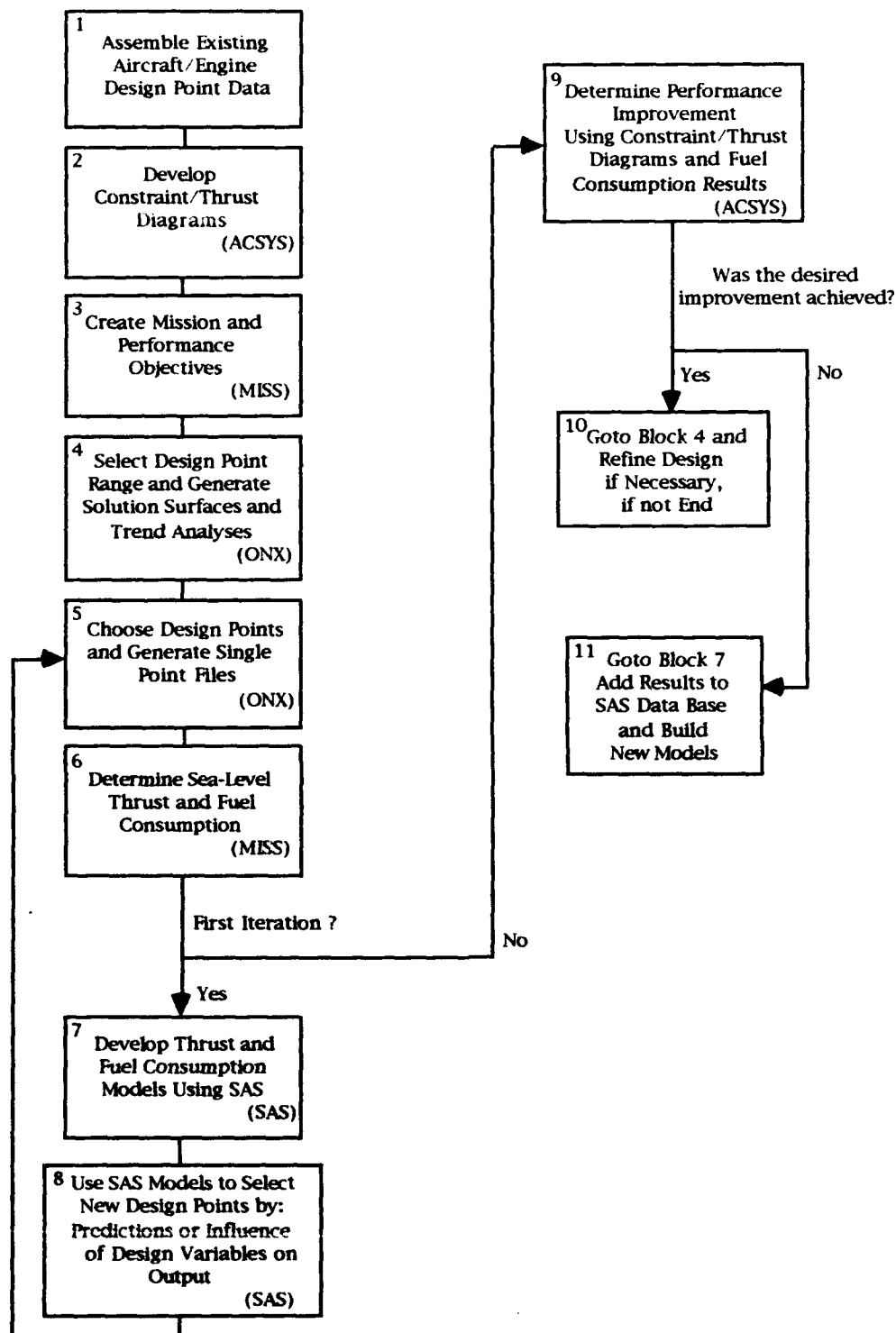


Figure 16. Solution Scheme Flow Chart

### **III. Example Analysis**

The two engine retrofit examples presented in this section, used the Air-to-Air Fighter, AAF, developed in Reference 6 Chapters 1 through 6. This particular engine, airframe, and mission combination was selected in order to provide a reference against which to make comparisons and point out the performance improvements, compromises and disappointments.

The new engine may be designed to perform any of a number of parts of the mission better than its predecessor. Since the engine retrofit problem is based on a high performance fighter aircraft, the goal of these design examples was to identify engines which will increase the sea-level thrust and decrease the fuel consumption. If an engine can fulfill both of these requirements while simultaneously satisfying any other new mission requirement, then it is a standout candidate for retrofit.

The first example demonstrates the use of the design scheme when examining the impact of two variables on the engine design. This analysis would be most useful when searching a small region for optimizing the final baseline engine. This search focused on the compressor pressure ratio and the bypass ratio.

The second example considers applying the design scheme to a multivariable problem. This method is most useful when the search is to be conducted over a wide range of design variables and the intent is to rapidly reduce the limit of possible choices. This example considered variations in Mach number, altitude, compressor pressure ratio, bypass ratio, fan pressure ratio, and mass flow rate..

Preliminary information for the examples is developed in sections 3.1 through 3.3. Section 3.4 contains the analysis of the two-variable design approach and section 3.5 contains the six-variable design approach. The engines developed by the two approaches are then compared in Section 3.6.

### 3.1. Design Point Airframe and Engine

The search for the new engine began after extracting the appropriate data from the existing AAF design developed in Chapters 1 through 6 of Reference 6. This information consists of the mission and performance specification for the AAF along with the airframe and baseline engine design parameters. The information extracted from the design is outlined below:

#### A. Aircraft Performance and General Information

The existing performance requirements and mission for the AAF were used to develop the constraint diagrams, constraint/thrust diagrams, and mission analysis. The performance requirements are:

|                                            |                                                                |
|--------------------------------------------|----------------------------------------------------------------|
| Takeoff distance                           | 1500 ft                                                        |
| Landing distance                           | 1500 ft                                                        |
| Max Mach number at maneuver weight         | M=2.0/40,000 ft                                                |
| Supercruise requirement at maneuver weight | M=1.5/30,000 ft                                                |
| Acceleration at maneuver weight            | M=0.8 to 1.6/30,000 ft in $t \leq 50$ s                        |
| Sustained g level at maneuver weight       | $n \geq 5$ at M=0.9/30,000 ft<br>$n \geq 5$ at M=1.6/30,000 ft |

The maneuver weight of this aircraft was defined as the aircraft's weight when carrying two AIM-9L missiles, 250 rounds of ammo, and 50% of internal fuel. The weight of the armament and stores is:

**Armament/Stores**

|                           |          |
|---------------------------|----------|
| AIM-9L Sidewinder Missile | 191 lb   |
| AMRAAM                    | 326 lb   |
| 25mm Cannon               |          |
| Cannon weight             | 270 lb   |
| Rate of fire              | 3600 rpm |
| Ammunition feed system    | 405 lbs  |
| weight (500 rounds)       |          |
| Ammunition (25mm)         |          |
| Weight (fired rounds)     | 550 lb   |
| Casings weight (returned) | 198 lb   |

The aircraft design weight of 24,400 lbs was used with a wing loading of 64 and thrust loading of 1.2. These values were used for the mission analysis phase of the engine design.

The aircraft weight fractions were kept the same as those used in the original analysis for the AAF. These were 1.0 for takeoff, 0.58 for landing, and 0.78 for maneuvers.

For the aircraft performance analysis, the engine thrust model and TSFC model for the low bypass ratio mixed turbofan of the ACSYS program are assumed adequate to model the engine for this part of the development.

The aircraft drag model used was the default future fighter model in the programs ACSYS and MISS. Even though a user input model could have been used, it was considered unnecessary since the intent is to provide insight into the effect of various engine designs on performance. As long as there is consistent use of a particular drag model, the analysis is considered valid.

The following is a list of additional design information for the aircraft used with the computer programs throughout this analysis:

| <u>Takeoff</u>  | <u>Landing</u>   | <u>Miscellaneous</u>              |
|-----------------|------------------|-----------------------------------|
| $k_{TO}=1.2$    | $k_{TD}=1.15$    | $C_{Lmax}=2.0$                    |
| $\mu_{TO}=0.05$ | $\mu_B=0.18$     | $n=5$                             |
| $t_R=3$ s       | $C_{DRc}=0.5348$ | $q_{max}=2133$ lb/ft <sup>2</sup> |
|                 | $t_{FR}=3$ s     |                                   |

This summarizes the information used from the existing airframe design and performance requirements.

#### B. Baseline Engine Information

The baseline engine data for the AAF engine developed in Reference 6 is presented below and will be used as the starting point for the design search.

Table 2. Baseline AAF Engine Design Point Data (6:207)

|               |                  |                                |
|---------------|------------------|--------------------------------|
| $M_0=1.6$     | $M_5=0.4$        | $C_{TO}=0.016$                 |
| $h=35,000$ ft | $T_{t4}=3200$ R  | $A_1=3.287$ ft <sup>2</sup>    |
| $\pi_c=20$    | $T_{t7}=3600$ R  | $A_{10}=4.028$ ft <sup>2</sup> |
| $\pi_c'=3.7$  | $m_0=94.5$ lbm/s | $L=4.087$ ft                   |
| $\alpha=0.55$ |                  |                                |

The engine diameters and nozzle length will be held constant to insure a fit in the airframe. The maximum operating limits on  $T_{t4}$  and  $T_{t7}$  were fixed at 3200 R and 3700 R respectively, to minimize the number of variables and to identify a design point which does not require increased temperatures to improve performance. Any increase in turbine inlet temperature leads to an increase in fuel consumption and no benefit is achieved. (6.133)

Since the idea behind the retrofit is to find a comparable engine which will perform adequately, the search was limited to engines with the same design performance parameters as the AAF. This allowed direct comparison of the proposed engines to the existing AAF design without having to account for the influence of the component efficiencies or any of the other values. The engine design performance parameters used are presented in Table 3.

Table 3. Component Design Performance Parameters (6:125)

| <u>Description</u>                                           | <u>Design Value</u>                                  |
|--------------------------------------------------------------|------------------------------------------------------|
| <b>Polytropic Efficiency</b>                                 |                                                      |
| Fan ( $e_c'$ )                                               | 0.89                                                 |
| High Pressure Compressor ( $e_c$ )                           | 0.90                                                 |
| High Pressure Turbine ( $e_{th}$ )                           | 0.89                                                 |
| Low Pressure Turbine ( $e_{tl}$ )                            | 0.91                                                 |
| <b>Total Pressure Ratios</b>                                 |                                                      |
| Inlet ( $\pi_{dmax}$ )                                       | 0.97                                                 |
| Burner ( $\pi_b$ )                                           | 0.97                                                 |
| Mixer ( $\pi_{Mmax}$ )                                       | 0.97                                                 |
| Afterburner ( $\pi_{AB}$ )                                   | 0.96                                                 |
| Nozzle ( $\pi_n$ )                                           | 0.98                                                 |
| <b>Component Efficiency</b>                                  |                                                      |
| Burner ( $\eta_b$ )                                          | 0.98                                                 |
| Afterburner ( $\eta_{AB}$ )                                  | 0.97                                                 |
| <b>Mechanical</b>                                            |                                                      |
| Low Pressure Spool ( $\eta_{mL}$ )                           | 0.99                                                 |
| High Pressure Spool ( $\eta_{mH}$ )                          | 0.98                                                 |
| Power Takeoff ( $\eta_{mP}$ )                                | 0.98                                                 |
| <b>Fuel Heating Value (<math>h_{PR}</math>)</b>              |                                                      |
|                                                              | 18,000 BTU/lbm                                       |
| <b>Afterburner Total Temperature (<math>T_{tmax}</math>)</b> |                                                      |
|                                                              | 3600 R                                               |
| <b>Turbine Cooling Air</b>                                   |                                                      |
| $T_{t4} > 2400$ R                                            | $\epsilon_1 = \epsilon_2 = (T_{t4} - 2400) / 16,000$ |
| $T_{t4} \leq 2400$ R                                         | $\epsilon_1 = \epsilon_2 = 0$                        |

Required inputs to MISS are the design values for the conditions at engine station #3. The values for  $\pi_{c\max}$ , total pressure,  $P_{t3}$ , total temperature,  $T_{t3}$ , and the low and high pressure spool rpm are determined by knowledge of the design considerations behind each term.

The total temperature at station 3 is dictated by the maximum design temperature allowable based on the material properties at this location. A rule of thumb is that the compressor discharge temperature upper limit is approximately 1660 R (6:288). The engines in a future fighter should be able to exceed this temperature and so a reasonable value for the new engine was selected at a temperature of 1760 R.

The total pressure at station 3, is a function of both the maximum pressure which the burner can accept, for structural design reasons and to maintain combustion stability, as well as the maximum pressure which can be successfully raised by the compressor. The value of 350 psia was selected based on comparison with previous engines using similar design temperatures and should provide a reasonable estimate for the AAF (6:303).

The max spool rpm is based on the efficiency of the compressor and turbine as a function of engine speed. The efficiency of turbomachinery is typically nearly constant between 70% and 100% of engine speed rpm. The efficiency tends to drop off steadily at values above 110% and below 60%. For the maximum allowable rpm select 110% to allow for some migration during the high speed maneuvers away from the 100% limit. The assumption of constant efficiency would not apply to regions of the flight envelope requiring high altitude and low Mach number or low altitude and high Mach number flight (6:166).

Setting a maximum design value for  $\pi_c$  forces the engine to lower  $T_{t4}$  to keep this limit from being exceeded. The result is a decrease in available thrust during any flight condition for which the limiting value of  $\pi_c$  would be exceeded. The effect of this limitation is illustrated by the OFFX computer program output for three calculations presented below.

| <u>Setting</u>    | <u>F (lbf)</u> | <u>Limitation</u> | <u><math>T_{t4}</math> (R)</u> | <u><math>\pi_c</math></u> |
|-------------------|----------------|-------------------|--------------------------------|---------------------------|
| $P_{t3}=300$ psia | 9458           | LP spool rpm      | 2888.7                         | 26.35                     |
| $\pi_c=26.35$     | 9459           | LP spool rpm      | 2888.8                         |                           |
| $\pi_c=20$        | 7329           | $\pi_c$ max       | 2580.8                         |                           |

The first calculation used a value for  $P_{t3}$  of 300 psia and the limit for the calculation was the low pressure, LP, spool rpm. The value for the compressor pressure ratio was 26.35 with an uninstalled thrust of 9458 lbf and a turbine inlet temperature of 2888.7 R. When the limit on  $P_{t3}$  was removed and a limit of 26.35 placed on  $\pi_c$ , the results were the same, and the limiting factor was the LP spool rpm. When  $\pi_c$  was reduced to 20 the engine required a reduction in  $T_{t4}$  in order to keep  $\pi_c$  from being exceeded. The result of this reduction was an over 2000 lbf reduction in available thrust. Lowering the ratio of turbine inlet temperature to compressor inlet temperature, i.e. decreasing  $T_{t4}$ , reduces the compressor flow rate, speed, and pressure ratio resulting in a reduction of available thrust and engine efficiency (11:50). The larger the engine temperature ratio, the higher the engine efficiency and specific excess power.

The final selection of limits for the design values at station 3 are:

$\pi_c = \text{none}$

$P_{t3} = 350$  psia

$T_{t3} = 1760$  R

LP Spool RPM = 110 %

HP Spool RPM = 110 %

The engine design values described in this section were used for the remainder of the analysis.

### **3.2. Constraint Diagrams**

The constraint diagram and constraint/thrust diagrams for the AAF were constructed to determine the approximate thrust levels required for the new engine design. The constraint information used with ACSYS to generate the plots are presented in Table 4.

The constraint diagram produced with this data is presented as Figure 17. The design point for the AAF aircraft developed in Reference 6 is noted on the diagram and the solution space presented. The usefulness of this diagram was enhanced by adding a line of constant sea-level thrust of 30,000 lbf as shown in Figure 18. The required TSL is therefore a little over 30,000 lbf to power the aircraft through the maneuvers at the weight fractions selected.

Table 4. Constraint Analysis Information

|                                |                              |
|--------------------------------|------------------------------|
| Takeoff (No Obstacle)          | Landing (No Obstacle)        |
| $\beta=1.0$                    | $\beta=0.56$                 |
| Altitude=2000 ft               | Altitude=2000 ft             |
| $C_{DR}=0.1$                   | $C_{DR}=.5348$               |
| Mach # during roll=0.1         | Fraction of $C_{Lmax}$ for   |
| $C_{Lmax}=2.0$                 | braking=0.61                 |
| $k_{TO}=1.2$                   | $C_{Lmax}=2.0$               |
| $\mu_{TO}=0.05$                | $k_{TD}=1.15$                |
| $t_R=3.0$ s                    | $\mu_{TD}=0.18$              |
| $S_{TO}=1500$ ft               | $t_{FR}=3.0$ s               |
| Afterburner=ON                 | $S_{LD}=1500$ ft             |
|                                | Drag Chute                   |
| Constant Altitude/Speed Cruise | Constant Altitude/Speed Turn |
| $\beta=0.78$                   | $\beta=0.78$                 |
| $M=1.5$                        | $M=0.9$                      |
| Altitude=30,000 ft             | Altitude=30,000 ft           |
| Afterburner=OFF                | 5g's                         |
|                                | Afterburner=ON               |
| Constant Altitude/Speed Cruise | Constant Altitude/Speed Turn |
| $\beta=0.78$                   | $\beta=0.78$                 |
| $M=2.0$                        | $M=1.6$                      |
| Altitude=40,000 ft             | Altitude=30,000 ft           |
| Afterburner=ON                 | 5g's                         |
|                                | Afterburner=ON               |
| Horizontal Acceleration        |                              |
| $\beta=0.78$                   |                              |
| Altitude=30,000 ft             |                              |
| $dV/dt=15.9$                   |                              |
| Afterburner=ON                 |                              |

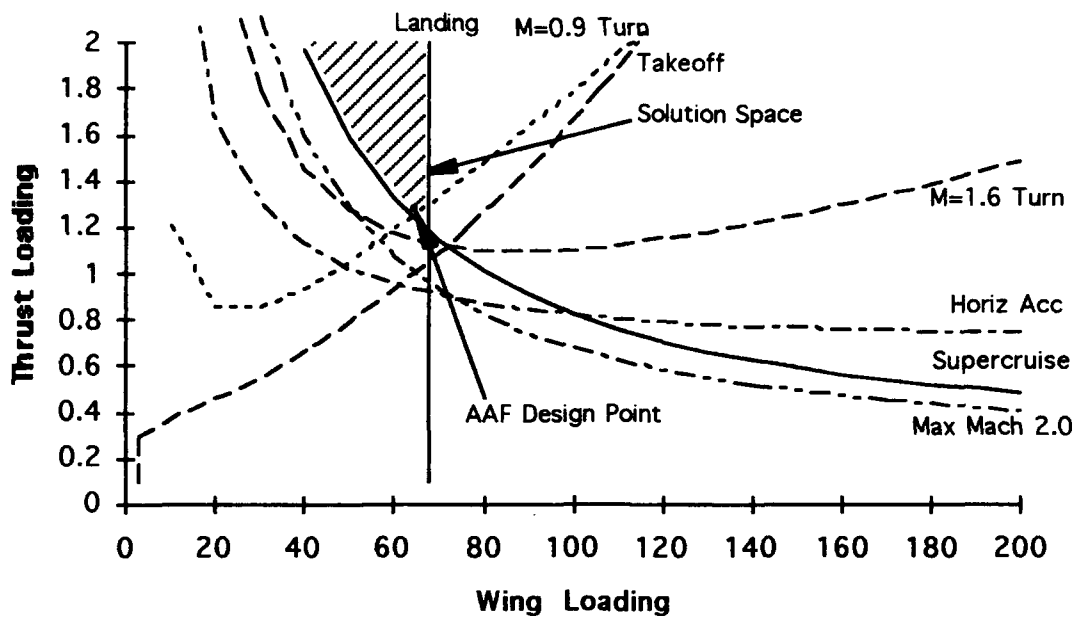


Figure 17. AAF Constraint Diagram

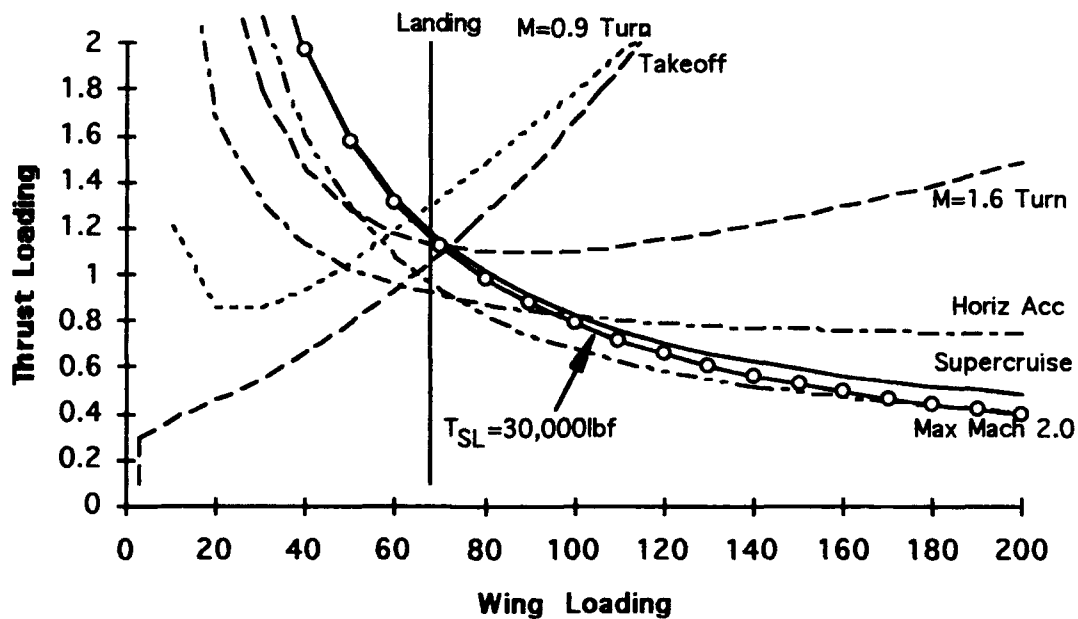


Figure 18. AAF Constraint Diagram with Constant Thrust Line

Constraint/thrust diagrams were constructed for the two maneuvers which border the solution space as shown in Figure 17 and the M=1.6 turn. The M=1.6 turn, M=0.9 turn and supercruise diagrams are shown in Figures 19 through 21. An additional constraint/thrust diagram, Figure 22, was developed to show, that for this particular aircraft, the subsonic cruise, M=0.9, leg will not have an impact on the solution for any pair of engines which produce more than 20,000 lbf (total) of thrust, since the constraint lines lie well below the lowest thrust line (for the wing loadings being considered).

Note from the constraint/thrust diagrams, Figures 19 through 22, that at a wing loading of 64 and a maneuvering  $\beta$  of 0.78, the engines will have to produce a minimum  $T_{SL}$  of 30,000 lbf (total) in order to perform as required. This information will be used later in selecting the best choice.

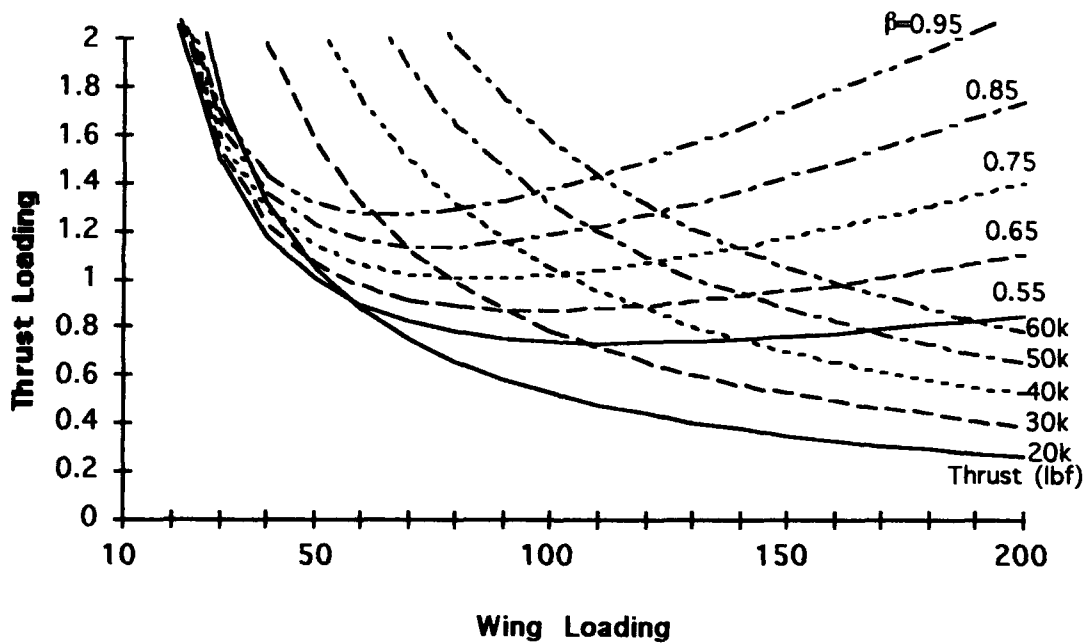


Figure 19. Constraint/Thrust Diagram, M=1.6, 30k ft, 5g Turn

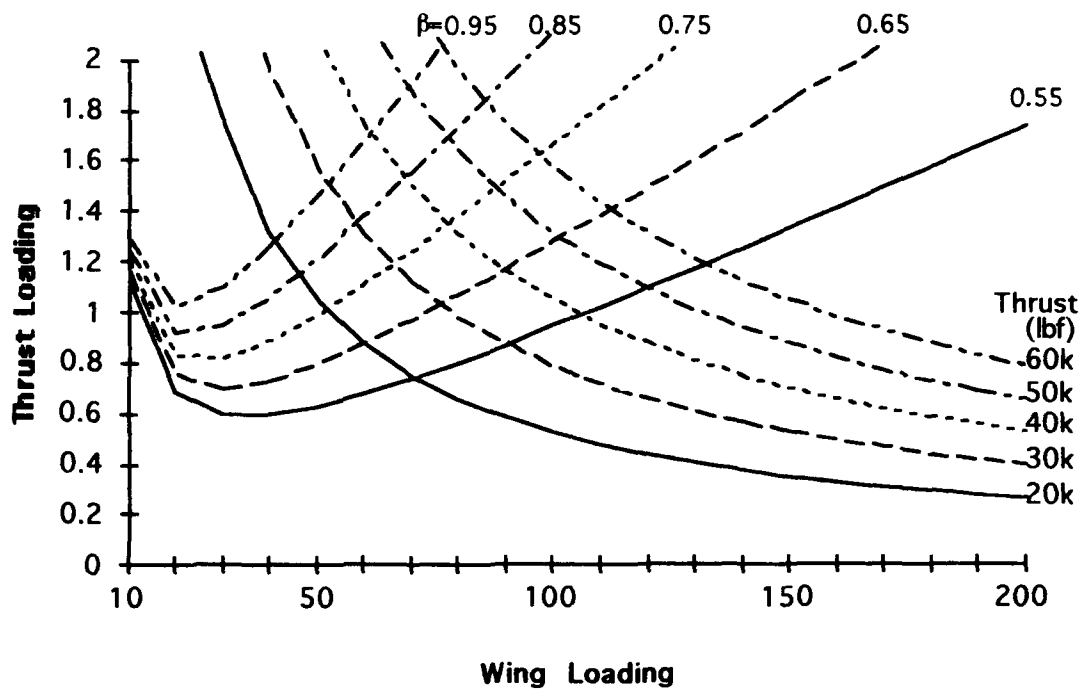


Figure 20. Constraint/Thrust Diagram,  $M=0.9$ , 30k ft, 5g Turn

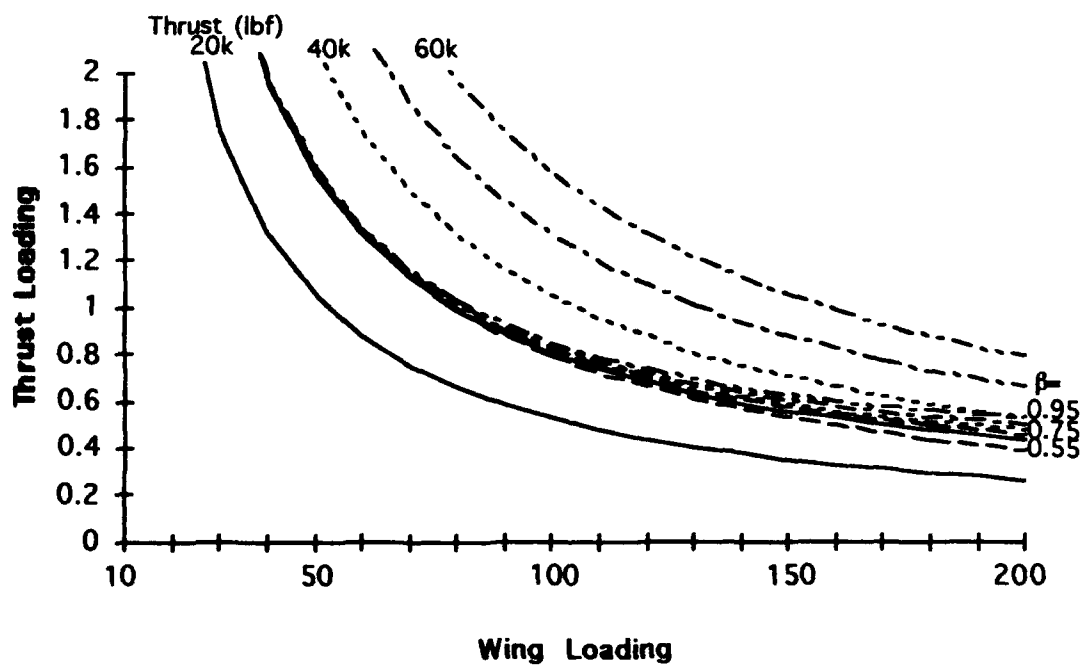


Figure 21. Constraint/Thrust Diagram,  $M=1.5$  Cruise, 30k ft

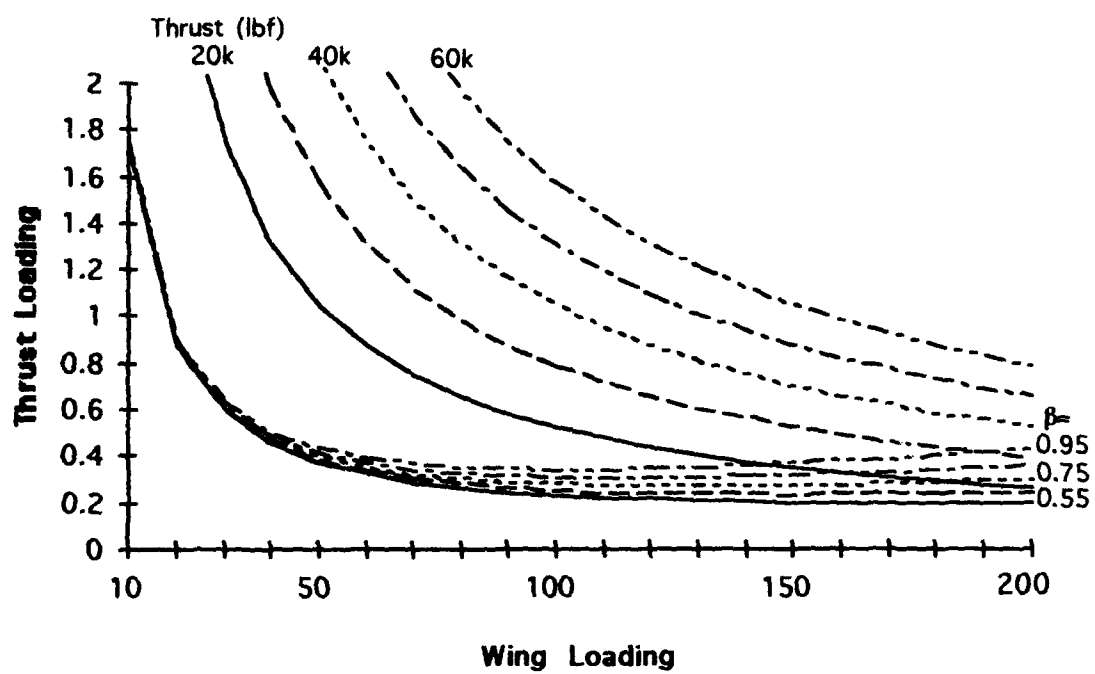


Figure 22. Constraint/Thrust Diagram, M=0.9 Cruise, 30k ft

### 3.3. Mission Development

The aircraft was "flown" using the computer program MISS to simulate the mission. MISS performs an off-design analysis to determine whether or not the engine has acceptable off-design performance characteristics while calculating the fuel consumption over the length of the mission. This analysis will be used when the new engine design points are selected and is presented here as a preliminary step in preparing for evaluating the design point engines.

The mission particulars were taken directly from the AAF request for proposal presented in Chapter 1 of Reference 6. The following mission legs were used:

- |                                 |                                      |
|---------------------------------|--------------------------------------|
| 1. Warmup                       | 9. Constant Alt/Speed<br>Cruise      |
| 2. Takeoff Acceleration         | 10. Constant Alt/Speed Turns<br>(2)  |
| 3. Takeoff Rotation             | 11. Horizontal Acc                   |
| 4. Horizontal Acc               | 12. Deliver Expendables              |
| 5. Climb and Acc Legs (4)       | 13. Constant Alt/Speed<br>Cruise     |
| 6. Constant Alt/Speed<br>Cruise | 14. Constant Speed Climb<br>Legs (2) |
| 7. Loiter                       | 15. Constant Alt/Speed<br>Cruise     |
| 8. Horizontal Acc               | 16. Loiter                           |

The mission leg data and airframe data loaded into the program are presented for each leg in Appendix D. All candidate engines can now be input to the program MISS using an on-design single point reference file from ONX as described in Reference 9.

The mission outlined above was used for determining the fuel consumption of each engine for each leg and for the complete mission. The sea-level thrust was determined by performing a single calculation at max power using the warm-up leg.

### 3.4. Two-Variable Analysis

#### 3.4.1. Generation of Solution Surfaces

The preliminary information for "flying" and comparing the engines has been assembled and the search for possible new engines can begin. This section covers the construction of the solution surfaces for the two-variable problem.

The design point of the existing AAF engine was presented in Table 2 and was selected as the best point to begin the design search in order to identify if any improvements could be made at this design condition.

Using the ONX computer program, multiple calculations for uninstalled specific thrust,  $F/m_0$ , and uninstalled specific fuel consumption,  $S$ , were made by varying  $\pi_c$  from 10 to 30 while  $\alpha$  varied from 0.4 to 0.65; the results are presented in Appendix E. The solution surfaces were generated by eliminating those combinations of  $\pi_c$  and  $\alpha$  which failed to meet the criteria that  $M_5$  and  $M_5'$  lie between 0.4 to 0.6. This generated two plots, one of  $F/m_0$ , and another of  $S$ , see Figures 23 and 24.

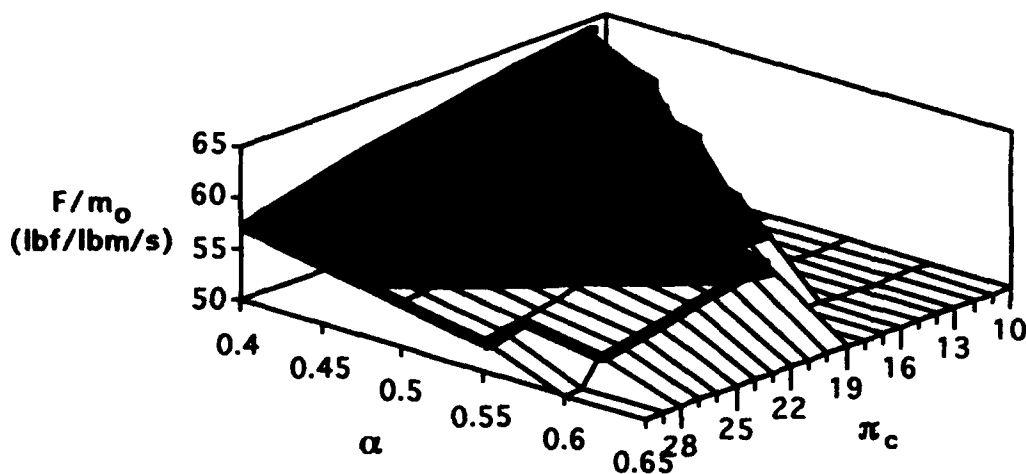


Figure 23.  $F/m_0$  Solution Surface,  $M=1.6$ , 35k ft

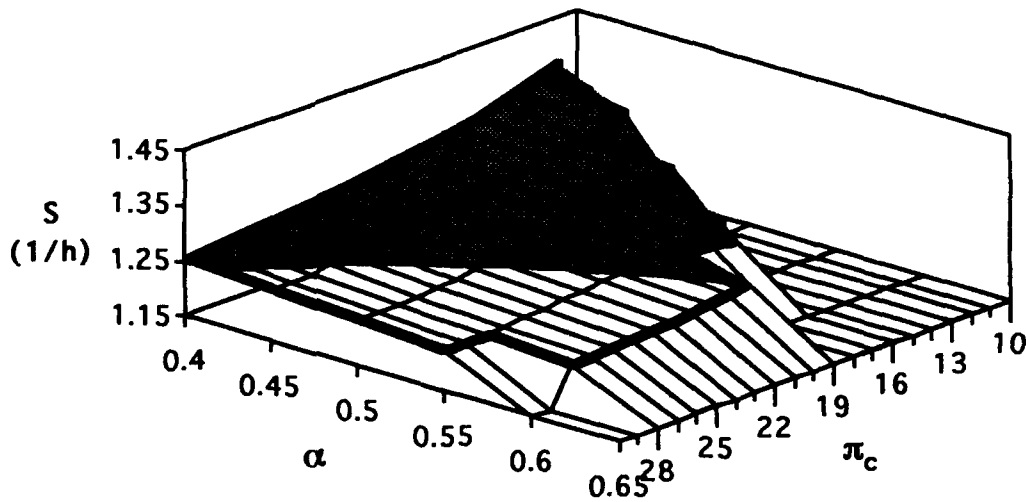


Figure 24. S Solution Surface,  $M=1.6$ , 35k ft

The heavy black border outlines the solution surface and represents the best set of possible solutions. The shading corresponds to the areas which lie between the plotted values on the dependent variable axis.

The solution surface is used to provide a visual indication of the available solution space after all restrictions have been imposed (both surfaces represent the same set of solutions but they are plotted against a different variable). The search is restricted to those combinations of  $\pi_c$  and  $\alpha$  within the bordered region since searching in the lower regions outside the border will likely result in a poor engine choice.

Once the solution surfaces were plotted, the next step was to determine the values of the quality measures associated with the surfaces.

### 3.4.2. Generation of ONX Trend Data

The solution surface data was collected for the ranges of  $\pi_c$  and  $\alpha$ , see Appendix E, and from this information the trend analysis plots were constructed. These plots provide insight into the tradeoffs between  $F/m_0$  and  $S$ .

The AAF engine plots for the quality measures  $Q_1$ ,  $Q_2$ , and  $Q_3$  are shown in Figures 25 and 26. Figure 25 indicates that as the compressor pressure ratio and bypass ratio are increased, there is a continual decrease in both  $F/m_0$  and  $S$ .  $F/m_0$  tends toward a constant decrease of between 0.006 and 0.007 for every unit increase in  $\pi_c$  while  $S$  continues to decrease but at a slower rate. For a fuel efficient engine the tendency would be to move toward increasing values of  $\pi_c$ , but for every decrease in fuel consumption of -0.002 to -0.003, there is a correspondingly large decrease in thrust between -0.006 and -0.007. This plot shows the impact of each increase in  $\pi_c$  or change in  $\alpha$ .

Figure 26 was used as another gage of the rate at which the change in  $\pi_c$  would effect the changes in  $F/m_0$  and  $S$ . The decrease in thrust is much larger than the decrease in fuel consumption at the higher compressor pressure ratios. The thrust is decreasing twice as fast as the decrease in fuel consumption for  $\pi_c$  above 22. At  $Q_3=1$ , both quantities are changing at the same rate.

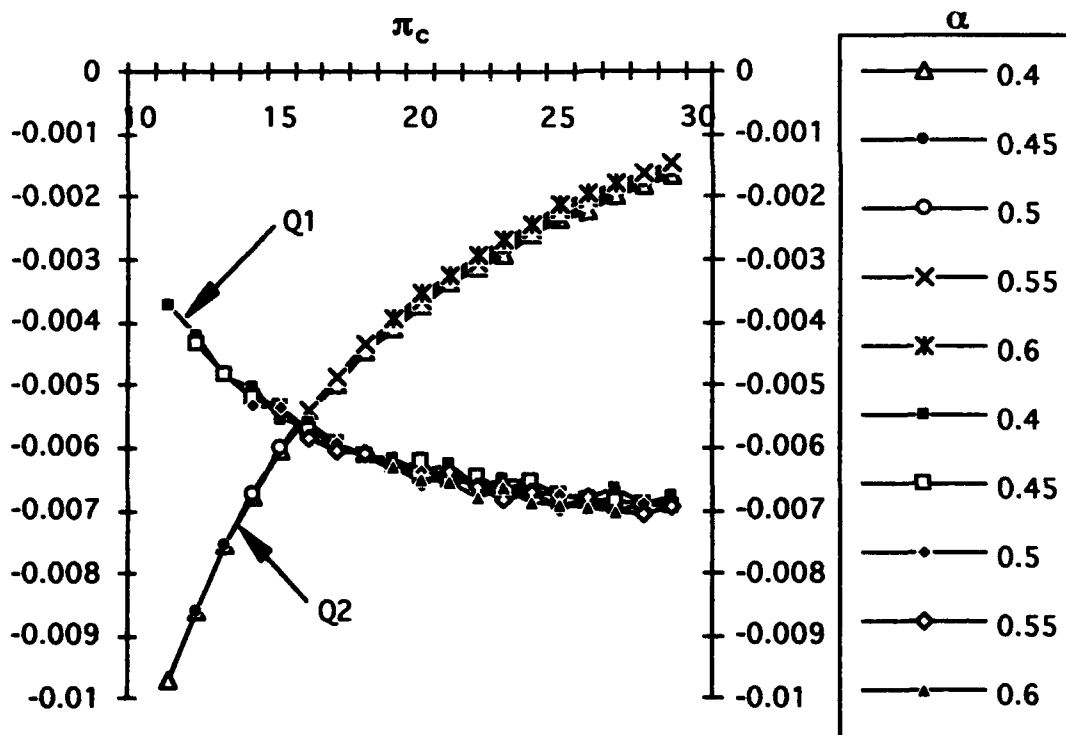


Figure 25. Quality Measures  $Q_1$  and  $Q_2$  for  $M=1.6$ , 35k ft

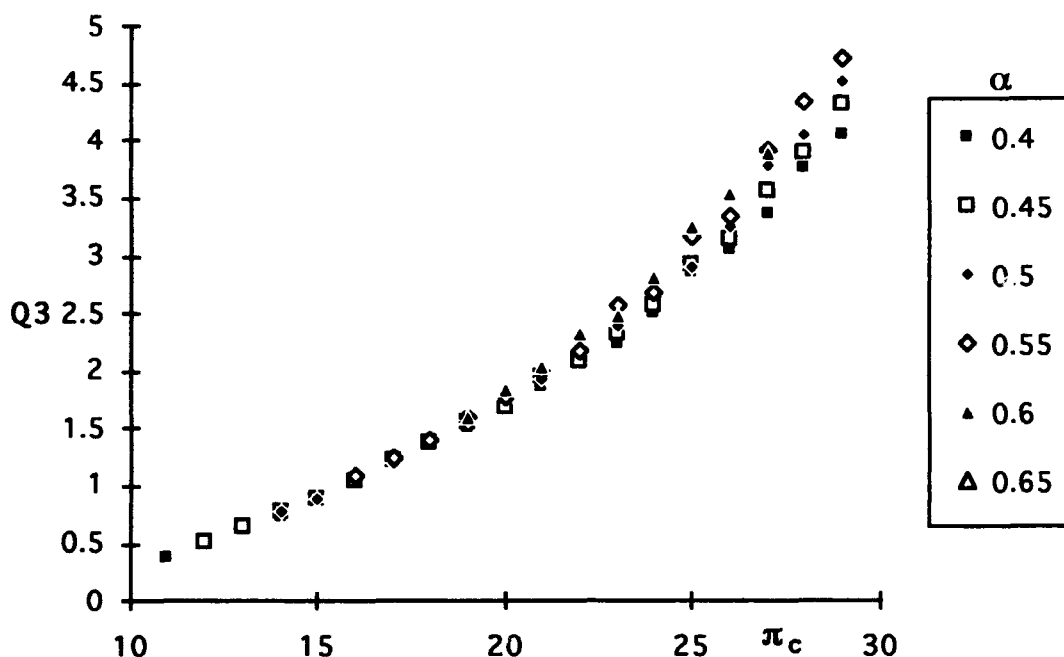


Figure 26. Quality Measure  $Q_3$  for  $M=1.6$ , 35k ft

Selecting the appropriate design point ranges required careful examination of the solution surface and the trend data above. It can be seen that when comparing any two bypass ratios at the same compressor pressure ratio there is little change in the measures  $Q_1$  or  $Q_2$ . This indicates that  $F/m_0$  and  $S$  are dependent upon  $\pi_c$  rather than  $\alpha$ .

Toward compressor pressure ratios to the left of the intersection of Figure 25, the fuel consumption is changing rapidly while the thrust is changing at a slower rate. Engines in this region will produce higher thrust levels with higher fuel consumption. This engine choice would suit a high performance requirement. Engines to the right of the intersection begin to exhibit increased fuel economy but at a loss of thrust. An engine at the far right would only be slightly more fuel efficient than those in the middle since fuel consumption is not changing very rapidly. The best choice for improving overall performance of the AAF is to select a range where the change in thrust is still small while the maximum change in fuel consumption has dropped to a reasonable value. This tradeoff occurs to the right of the intersection.

The quality measure  $Q_3$ , Figure 26, was used for limiting the range of design variables to those where the change in thrust is no more than twice the change in fuel consumption. This was an arbitrary choice made for this investigation and, when combined with the observations made from Figure 25, results in limiting possible engine combinations to those between compressor pressure ratios of 15 and 22 with bypass ratios of 0.4 to 0.6. Also, the selected range for the design variables falls on the solution surfaces of Figures 23 and 24 where off-design solutions should be plentiful.

Using the solution surfaces to guide the choice of design points, a sampling was made which would characterize the engines performance over this region. The selected combinations of  $\pi_c$  and  $\alpha$  were:

| $\pi_c$ | $\alpha$ |
|---------|----------|
| 15      | 0.4      |
| 16      | 0.5      |
| 18      | 0.45     |
| 18      | 0.55     |
| 20      | 0.5      |
| 20      | 0.6      |
| 22      | 0.55     |

The selection so far has centered around minimizing  $S$  while maximizing  $F/m_0$ . The solution surface has been generated to locate the possible solution areas and the quality measures have been used to examine the relative changes between the thrust and fuel consumption.

The selected engines were "flown" using MISS to determine their mission fuel consumption and sea-level thrust. The mass flow rate had to be increased from the AAF baseline engine design point value of 94.5 lbm/s to 100 lbm/s in order to meet all performance requirements. This will become the standard mass flow rate used in this analysis.

The next step was to build a model to characterize all possible combinations of  $\pi_c$  and  $\alpha$  over the selected ranges.

### 3.4.3. Modeling Analysis

After the candidate design point engines were selected they were “flown” to see if they perform the off-design mission. All candidates performed well and their max power sea-level thrust, T<sub>SL</sub>, and mission fuel consumption were determined. The results of operating the selected engines is shown below:

| $\pi_c$ | $\alpha$ | T <sub>SL</sub> | Fuel Consumption |
|---------|----------|-----------------|------------------|
| 15      | 0.4      | 14,539          | 8579             |
| 16      | 0.5      | 14,400          | 8410             |
| 18      | 0.45     | 14,465          | 8314             |
| 18      | 0.55     | 14,375          | 8268             |
| 20      | 0.5      | 14,394          | 8243             |
| 20      | 0.6      | 14,166          | 8159             |
| 22      | 0.55     | 13,079          | 8143             |

The change in T<sub>SL</sub> and fuel consumption over the range selected appears to indicate that the best choice is somewhere in the middle. The options at this point are either to run all the design combinations around the middle values of  $\pi_c=18$  and  $\alpha=0.5$  or use modeling to help select the next best choice.

The results above were used with the SAS modeling software to develop 6 models, 3 for thrust and 3 for fuel consumption, by using various combinations of the independent variables  $\pi_c$  and  $\alpha$ , see Appendix F. The equations for the thrust and fuel consumption models determined by SAS are presented below.

$$Thrust_1 = 498.7\pi_c + 22357\alpha - 67.77\pi_c^2\alpha^2$$

$$Thrust_2 = 2221.18\pi_c - 17745\alpha - 75.6\pi_c^2 + 882.24\pi_c\alpha$$

$$Thrust_3 = 2266.2\pi_c - 19381\alpha - 64.63\pi_c^2 + 17425\alpha^2$$

$$Fuel_4 = 11472 - 235.76\pi_c - 1749.84\alpha + 4.39\pi_c^2 + 58.1\pi_c\alpha$$

$$Fuel_5 = 11496 - 236.1\pi_c - 1833\alpha + 5.2\pi_c^2 + 1126.12\alpha^2$$

$$Fuel_6 = 17739 - 758.24\pi_c - 17795\alpha + 6.45\pi_c^2 + 1487.02\pi_c\alpha - 28.95\pi_c^2\alpha^2$$

The thrust models were produced without an intercept since this resulted in the best fit of the data, see Appendix C. The statistics used to evaluate the fit of each model and the influence of the variables are presented below.

|                                |                    |                    |
|--------------------------------|--------------------|--------------------|
| Model 1 (Thrust <sub>1</sub> ) | F Value=2034.14    | Prob>F=0.0001      |
|                                | <u>Variables</u>   | <u>Prob&gt; T </u> |
|                                | $\pi_c$            | 0.0087             |
|                                | $\alpha$           | 0.004              |
|                                | $\pi_c^2 \alpha^2$ | 0.0005             |
|                                | R-Square           | 0.9993             |
| Model 2 (Thrust <sub>2</sub> ) | F Value=8470.513   | Prob>F=0.0001      |
|                                | <u>Variables</u>   | <u>Prob&gt; T </u> |
|                                | $\pi_c$            | 0.0161             |
|                                | $\alpha$           | 0.3635             |
|                                | $\pi_c^2$          | 0.0509             |
|                                | $\pi_c \alpha$     | 0.3938             |
| Model 3 (Thrust <sub>3</sub> ) | F Value=8273.967   | Prob>F=0.0001      |
|                                | <u>Variables</u>   | <u>Prob&gt; T </u> |
|                                | $\pi_c$            | 0.0224             |
|                                | $\alpha$           | 0.3861             |
|                                | $\alpha^2$         | 0.4142             |
|                                | $\pi_c^2$          | 0.0177             |
| Model 4 (Fuel <sub>4</sub> )   | F Value=61.723     | Prob>F=0.016       |
|                                | <u>Variables</u>   | <u>Prob&gt; T </u> |
|                                | Intercept          | 0.0038             |
|                                | $\pi_c$            | 0.0925             |
|                                | $\alpha$           | 0.2703             |
|                                | $\pi_c^2$          | 0.2703             |
| Model 5 (Fuel <sub>5</sub> )   | F Value=60.128     | Prob>F=0.0164      |
|                                | <u>Variables</u>   | <u>Prob&gt; T </u> |
|                                | Intercept          | 0.0043             |
|                                | $\pi_c$            | 0.0957             |
|                                | $\alpha$           | 0.543              |
|                                | $\alpha^2$         | 0.6924             |
| Model 6 (Fuel <sub>6</sub> )   | F Value=89.844     | Prob>F=.0799       |
|                                | <u>Variables</u>   | <u>Prob&gt; T </u> |
|                                | Intercept          | 0.1381             |
|                                | $\pi_c$            | 0.2599             |
|                                | $\alpha$           | 0.3269             |
|                                | $\pi_c^2$          | 0.2362             |
|                                | $\pi_c \alpha$     | 0.3424             |
|                                | $\pi_c^2 \alpha^2$ | 0.3524             |
|                                | R-Square           | 0.9978             |

To evaluate the fit of the data and select the best models, the F Value, Prob>F, and the R-Square statistics were used. Large F Values indicate that the mean of the data did not happen by chance while Prob>F values close to 0.0001 indicate that the model explains a significant portion of the variation in the data. The R-Square value measures the fraction of the total variation due to the variables and the closer this value is to 1.0 the better the model is at accounting for variation in the data.

The Prob>F statistic for models 1 through 3 indicate that all models explain a significant portion of the variation in the data. Therefore, the best models were selected based on the largest F Values and the R-Square values which were closest to 1.0. This resulted in selecting thrust models 2 and 3 as the best fit of the data.

For models 4 through 6, the Prob>F values vary from 0.016 to 0.0799 and indicate that models 4 and 5 appear to be the best fit of the data. The F Value, on the other hand, indicates that models 4 and 6 are the best. The final choice was made by comparing the R-Square values which are closest to 1.0 for models 4 and 6. The best fit to the data for the thrust and fuel consumption was therefore achieved with models 2, 3, 4 and 6.

The fit statistics also indicate the influence of each variable on the output. This is determined by the Prob>|T| value which tests to see if the slope of the data is zero for that variable. The closer this measure is to 1.0 indicates that the variable has very little influence on the output.

The fit statistics show that  $\pi_c$  has a stronger influence on the output of most models, since the Prob>|T| is lower for the  $\pi_c$  terms than the  $\alpha$  terms. For the fuel consumption models, the Prob>|T| indicated the strongest influence for all the models was due to the intercept. This is to be expected since the intercept value is derived from the lack of fit of the model and is tailored to account for any residual error. This results in the strong influence.

The best way to show the influence of the two variables is to plot each model over the range of  $\pi_c$  and  $\alpha$  values under consideration. The equations for models 2, 3, 4 and 6 were used to generate surfaces over the range of  $\pi_c$  from 15 to 22 and  $\alpha$  from 0.4 to 0.6. These surfaces are presented in Figures 27 through 30.

Figure 27 presents the modeled sea-level thrust determined by the equation Thrust<sub>2</sub>. It indicates that the maximum thrust is achieved at compressor pressure ratios around 18 and bypass ratios of 0.4 while the minimum thrust occurs at the compressor pressure ratio of 22 and bypass ratio of 0.4. Figure 28, model Thrust<sub>3</sub>, shows a similar trend but indicates less influence by the bypass ratio as indicated by the small slope along lines of constant  $\pi_c$ . These two surfaces provide insight into the engine's sea-level off-design performance at various combinations of  $\pi_c$  and  $\alpha$ .

Figure 29 presents the modeled fuel consumption determined by equation Fuel<sub>4</sub>. It indicates that the maximum fuel consumption will occur at a compressor pressure ratio of 15 and bypass ratio of 0.4 while the minimum fuel consumption occurs at a compressor pressure ratio of 22 and bypass ratio of 0.6. Figure 30, model Fuel<sub>6</sub>, indicates less influence on the fuel consumption by the bypass ratio but still follows the same general trend as Figure 29. These two surfaces show how the mission fuel consumption varies with various combinations of  $\pi_c$  and  $\alpha$ .

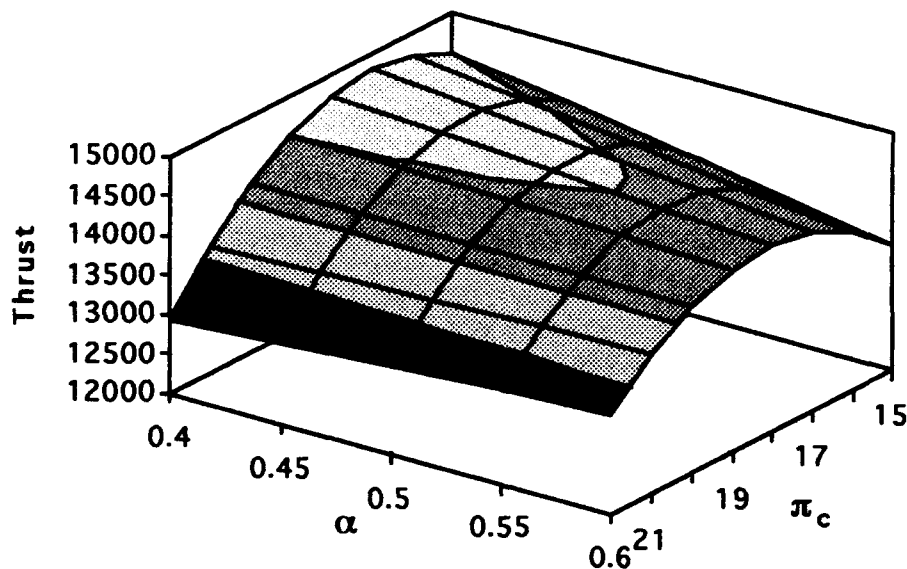


Figure 27. Model #2 Surface

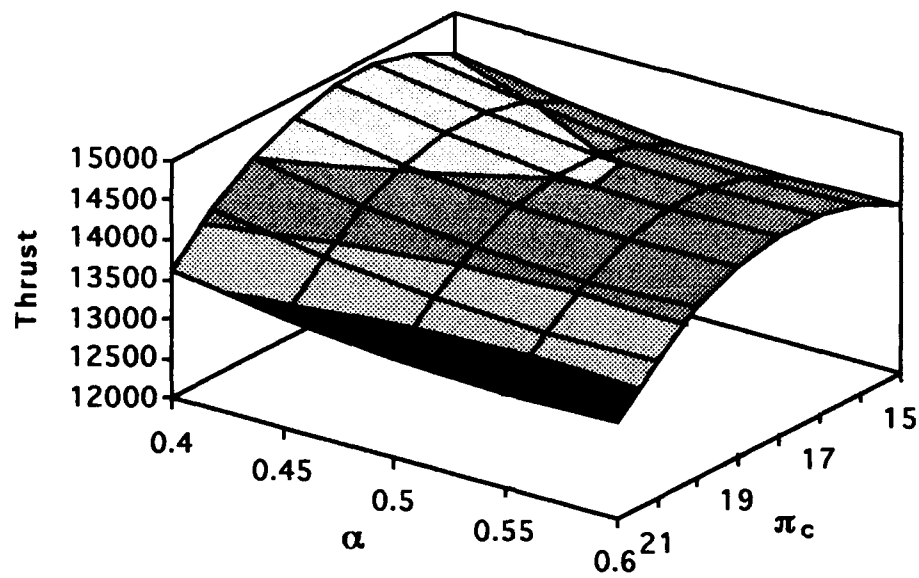


Figure 28. Model #3 Surface

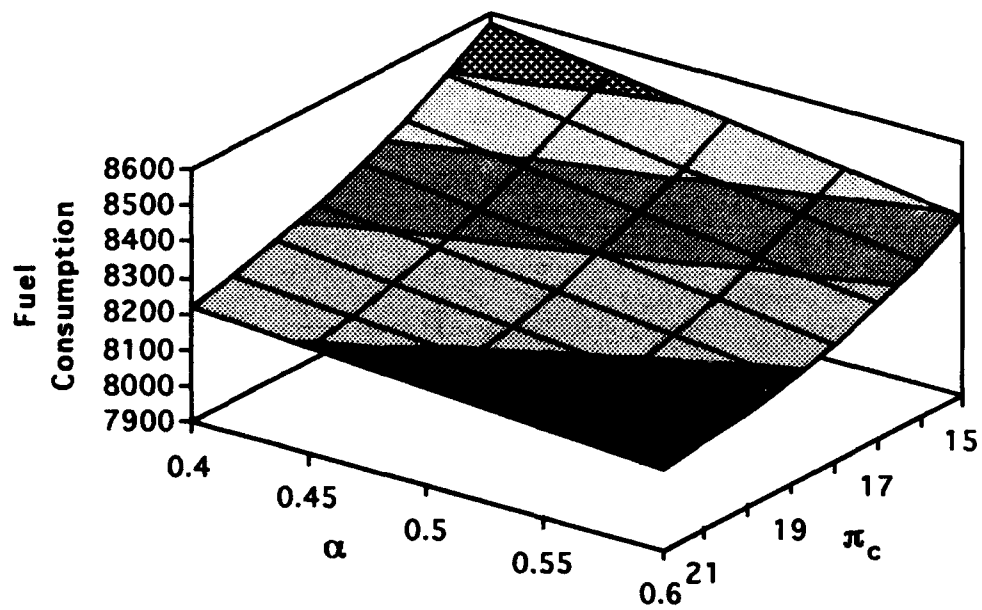


Figure 29. Model #4 Surface

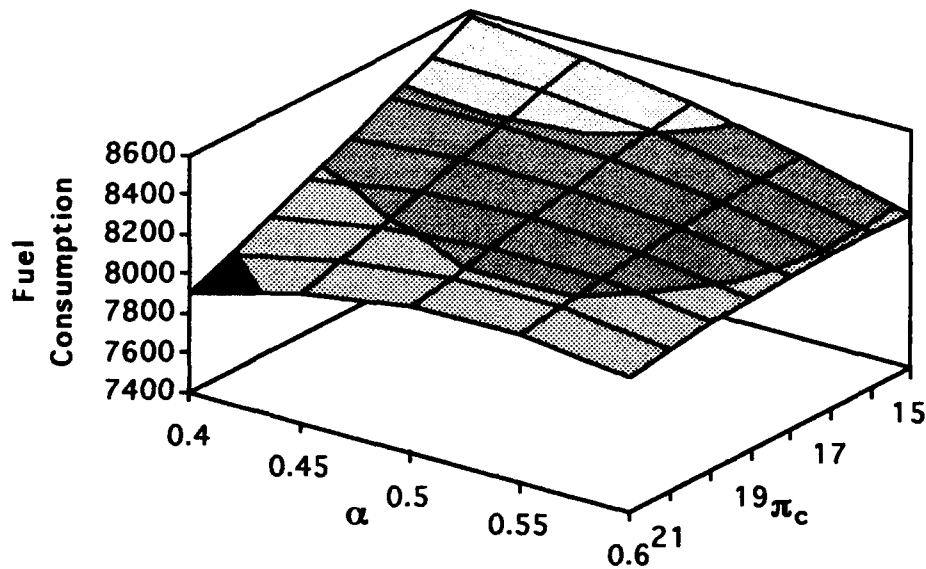


Figure 30. Model #6 Surface

After viewing these surfaces, the thrust levels tend to be highest at a  $\pi_c$  of about 18 and tend to level off at  $\alpha$  about 0.5. The fuel consumption is high in this region but tends to decrease at high  $\pi_c$  and high  $\alpha$  values for model 4 while decreasing at high  $\pi_c$  and low  $\alpha$  values for model 6. Since the trends in thrust and fuel consumption are not complementary, the choice was made to continue to search for a design point engine at  $\pi_c$  values between 18 to 20 and  $\alpha$  between 0.5 and 0.6.

Now that the models have been developed, the search is trivial and was accomplished using the SAS program rather than running another set of ONX single point files and MISS analyses. The SAS program took about 4 minutes to run a check on a wide range of possible engines in the new design range and determine what the predicted values would be. Twenty three combinations of  $\pi_c$  and  $\alpha$  were used with SAS to calculate the fuel consumption and sea-level thrust. The following engines are numbered starting at 8 since the first seven engines form the initial data base. The SAS results are presented in Appendix F.

| <u>Number</u> | $\pi_c$ | $\alpha$ | <u>Number</u> | $\pi_c$ | $\alpha$ |
|---------------|---------|----------|---------------|---------|----------|
| 8             | 22      | 0.65     | 16            | 19      | 0.6      |
| 9             | 22      | 0.45     | 17            | 19      | 0.45     |
| 10            | 21      | 0.6      | 18            | 17.5    | 0.5      |
| 11            | 21      | 0.55     | 19            | 17      | 0.6      |
| 12            | 21      | 0.4      | 20            | 17      | 0.4      |
| 13            | 20      | 0.65     | 21            | 16      | 0.6      |
| 14            | 20      | 0.55     | 22            | 16      | 0.45     |
| 15            | 20      | 0.45     | 23            | 15      | 0.6      |

After running the SAS program these engines were ordered according to the predicted values of each model. They were arranged from lowest to highest for the thrust and highest to lowest for the fuel consumption and included engines 1 through 7 which were used to build the model. This arrangement allows the list to be split in half and only those engines appearing on the high thrust and low fuel consumption side were considered. The results, shown below, indicated that only engines number 15 and 16 were candidates with low fuel consumption and high thrust.

#### Thrust Model #2

Low High

9 7 8 23 12 11 10 21 13 6 14 | 5 15 19 16 2 4 17 1 22 18 3 20

#### Thrust Model #3

7 8 9 11 10 14 23 6 12 5 13 | 15 21 16 2 4 1 19 22 18 17 3 20

#### Fuel Model #4

High Low

1 22 20 2 23 3 21 18 17 19 4 | 15 12 5 9 16 14 11 6 7 10 13 8

#### Fuel Model #6

1 22 2 20 18 3 4 17 5 14 19 | 21 11 15 23 16 6 7 10 9 13 12 8

These engines were then “flown” using MISS to calculate the actual TSL and fuel consumption. The results are shown below along with the best predicted value from the SAS results for models 2,3,4 and 6 in parentheses.

| <u>Engine</u> | <u>TSL (lbf)</u> | <u>Fuel consumed</u> |
|---------------|------------------|----------------------|
| AAF           | 14,280           | 8199                 |
| 15            | 14,509 (14,277)  | 8292 (8249)          |
| 16            | 14,308 (14,319)  | 8190 (8190)          |

This process quickly identified two acceptable engine designs. Engine 16 is better than the AAF engine for both thrust and fuel economy. Engine 15 gives a 229 lbf increase in thrust with a penalty in fuel economy of 93 lbs.

Comparing these engines against the constraint diagrams will determine if any real performance advantage has been achieved. This will be accomplished in Section 3.6 after the six-variable design analysis has been demonstrated.

### 3.5. Six-Variable Analysis

The two variable example showed the detailed procedure used to generate alternative design point engines. This next example was developed to show how the modeling technique can be used when considering more than two variables.

When only two variables were involved, surface plots could be generated of each model to display the effect of the two variables on the dependent variable. The problem is not as easily visualized for more than two variables and the information provided from the SAS program provided insight into the effect of each variable on the outcome.

A six variable analysis was completed to show the utility of the modeling technique when searching for the best set of design values. For this case the Mach number, altitude,  $\pi_c$ ,  $\alpha$ ,  $\pi_c'$ , and mass flow rate are the variables.

Proceeding as in the two variable analysis, choices of Mach number and altitude were made to begin the search. The decision was to concentrate on altitudes between 25,000 and 40,000 ft and Mach numbers between 1.4 and 1.7. This decision is quite arbitrary but it should reflect the leg of the mission where the aircraft will burn the most fuel.

Solution surfaces and trend analyses were performed at various combinations of Mach number and altitude. For example, Figure 9 in section 2.4.3 shows the solution surface for  $M=1.5$  and 35,000 ft. This surface was based on the average value of  $\pi_c'=3.7$  over the selected range of  $\pi_c$  and  $\alpha$ . Figures 10 and 11 show the trend analyses and, from these three figures, the best range for  $\pi_c$  was selected to be between 19 and 24 with an  $\alpha$  of 0.6. In this range the decrease in  $F/m_0$  is reasonably constant while  $S$  continues to decrease.

From the design point ranges described above, a  $\pi_c$  of 19 and  $\alpha$  of 0.6 were selected. The same mission described in section 3.3 and engine design performance values in Table 3 were used to calculate the fuel consumption and  $T_{SL}$  of the engine. After running MISS it was found that a mass flow of 105 lbm/s was adequate to fly the mission without requiring changes to the engine diameter. For this design point the result was  $T_{SL}=16,469$  lbf and fuel consumption=8048 lbf.

After generating additional solution surfaces and trend analyses at various Mach numbers, altitudes,  $\pi_c$ ,  $\alpha$ ,  $\pi_c'$ , and mass flow, additional design points were selected. The choice of engine design points were selected at random as long as they fell on the solution surfaces and exhibited trend analyses which predicted good performance and low fuel consumption. The following design point engine information was collected:

| Mach # | Alt<br>(k ft) | $\pi_c'$ | $\pi_c$ | $\alpha$ | mass flow<br>(lbm/s) | TSL<br>(lbf) | Fuel<br>Req'd |
|--------|---------------|----------|---------|----------|----------------------|--------------|---------------|
| 1.4    | 25            | 3.6      | 22      | 0.6      | 130                  | 14,161       | 8130          |
| 1.4    | 30            | 3.5      | 18      | 0.55     | 120                  | 17,004       | 8118          |
| 1.4    | 35            | 3.7      | 17      | 0.7      | 110                  | 18,288       | 7997          |
| 1.5    | 25            | 3.3      | 21      | 0.5      | 130                  | 12,904       | 8268          |
| 1.5    | 30            | 3.6      | 20      | 0.5      | 115                  | 14,972       | 8203          |
| 1.5    | 35            | 3.7      | 19      | 0.6      | 105                  | 16,469       | 8048          |
| 1.5    | 40            | 3.7      | 20      | 0.6      | 90                   | 17,653       | 7911          |
| 1.6    | 35            | 3.7      | 15      | 0.4      | 100                  | 14,539       | 8579          |
| 1.6    | 35            | 3.7      | 19      | 0.6      | 100                  | 14,308       | 8190          |
| 1.6    | 35            | 3.7      | 20      | 0.45     | 100                  | 14,509       | 8292          |
| 1.6    | 35            | 3.7      | 22      | 0.65     | 100                  | 12,855       | 8071          |
| 1.6    | 38            | 3.7      | 22      | 0.5      | 120                  | 17,710       | 7895          |
| 1.7    | 30            | 3.4      | 18      | 0.5      | 120                  | 12,820       | 8393          |
| 1.7    | 35            | 3.6      | 18      | 0.7      | 120                  | 15,029       | 7784          |

Five models were constructed using the above data and the SAS results are presented in Appendix G. After reviewing the fit statistics, SAS models 2 and 3 for fuel consumption and models 4 and 5 for thrust were selected as the best fits. This selection was based on the F value, Prob>F, and the Root MSE. The Root MSE was used to judge the fit by looking for a low value which indicates small residuals. The following four SAS models resulted

$$Fuel_2 = 899.93M - 51.08h + 555.16\pi_c + 5563.41\alpha - 15.98\pi_c^2 - 6437.67\alpha^2 + 205.96(\pi_c')^2$$

$$Fuel_3 = 102.96M - 6.99h + 1136.83\pi_c - 36.02\pi_c^2 - 7577.5\alpha^2 + 17.38\pi_c^2\alpha^2 + 0.012\dot{m}^2$$

$$Thrust_4 = -9830.4 - 15210M + 609.07h + 2443.92\pi_c + 5084.65\alpha - 69.71\pi_c^2 - 7317.43\alpha^2 + 0.555\dot{m}^2$$

$$Thrust_5 = -12995 - 15495M + 623.38h + 2988.16\pi_c - 86.48\pi_c^2 - 6092.48\alpha^2 + 8.82\pi_c^2\alpha^2 + 0.582\dot{m}^2$$

where the subscript indicates the model number.

From these models it was not immediately obvious which variables significantly affect the dependent variables. This information was necessary to determine which direction to search for the candidate engine designs. More than one model was used to obtain a consensus for determining the influence and the SAS program provided the information needed.

The Prob>|T| statistic gave insight into the influence of each variable on the outcome. The closer this value was to 0.0001 the stronger the influence this variable has on the outcome. Arbitrarily selecting only those variables with Prob>|T| of 0.2 or below as showing significant influence in the model, the independent variables' effects can be determined. This determination was made by looking at both the model itself and the T for HO statistic.

The T for HO statistic indicates the dependence on the output by this variable: the larger it is in absolute value the greater the dependence. T for HO also indicates the direction of the influence on the dependent variable.

For the model, *Fuel*<sub>2</sub>, there is dependence upon the Mach number, altitude,  $\pi_c^2$ , and  $(\pi_c')^2$ . The effect of each variable is summarized below where an up arrow indicates increase and a down arrow indicates a decrease.

$$\begin{aligned} M \uparrow &\Rightarrow \text{Fuel} \uparrow \\ h \uparrow &\Rightarrow \text{Fuel} \downarrow \\ \pi_c^2 \uparrow &\Rightarrow \text{Fuel} \downarrow \\ (\pi_c')^2 \uparrow &\Rightarrow \text{Fuel} \uparrow \end{aligned}$$

These results show that for model 2, the fuel consumption can be decreased by lowering the Mach number, increasing the altitude, increasing the compressor pressure ratio, and decreasing the fan pressure ratio.

For the model, *Fuel3*, the following dependence was observed:

$$\pi_c \uparrow \Rightarrow Fuel \uparrow$$

$$\pi_c^2 \uparrow \Rightarrow Fuel \downarrow$$

$$\alpha^2 \uparrow \Rightarrow Fuel \downarrow$$

$$\pi_c^2 \alpha^2 \uparrow \Rightarrow Fuel \uparrow$$

There appears to be a contradiction of the effect of  $\pi_c$  on the output since  $\pi_c$  terms increase the fuel consumption and  $\pi_c^2$  terms decrease the fuel consumption. In order to determine the effect of  $\pi_c$  the coefficients of the model are used to determine the influence of each of these terms subtracted from one another. In this case the tendency was toward an overall increase in the fuel consumption for an increase in  $\pi_c$ . The  $\pi_c^2 \alpha^2$  term has the effect that any increase in  $\pi_c$  or  $\alpha$  will increase the fuel consumption.

The primary influences on models 4 and 5, *Thrust4* and *Thrust5*, are presented below. The overall effect of  $\pi_c$  for either model will be an increase in thrust.

*Thrust4:*

$$M \uparrow \Rightarrow T_{SL} \downarrow$$

$$h \uparrow \Rightarrow T_{SL} \uparrow$$

$$\pi_c \uparrow \Rightarrow T_{SL} \uparrow$$

$$\pi_c^2 \uparrow \Rightarrow T_{SL} \downarrow$$

$$\dot{m}^2 \uparrow \Rightarrow T_{SL} \uparrow$$

*Thrust5:*

$$M \uparrow \Rightarrow T_{SL} \downarrow$$

$$h \uparrow \Rightarrow T_{SL} \uparrow$$

$$\pi_c \uparrow \Rightarrow T_{SL} \uparrow$$

$$\pi_c^2 \uparrow \Rightarrow T_{SL} \downarrow$$

$$\dot{m}^2 \uparrow \Rightarrow T_{SL} \uparrow$$

As a result of this investigation, the effect of the design variables on the fuel consumption and  $T_{SL}$  can be summarized as follows

$$M \uparrow \Rightarrow Fuel \uparrow T_{SL} \downarrow$$

$$h \uparrow \Rightarrow Fuel \downarrow T_{SL} \uparrow$$

$$\pi_c \uparrow \Rightarrow Fuel \uparrow T_{SL} \uparrow$$

$$\alpha \uparrow \Rightarrow Fuel \downarrow$$

$$\dot{m} \uparrow \Rightarrow T_{SL} \uparrow$$

$$\pi_c' \uparrow \Rightarrow Fuel \uparrow$$

The Mach number, altitude, and compressor pressure ratio have the most effect on both the fuel consumption and  $T_{SL}$  whereas the bypass ratio, mass flow rate, and fan pressure ratio showed a stronger influence on either fuel consumption or  $T_{SL}$  but not both.

The best choice for seeking new design points with improved fuel economy and increased sea-level thrust would be at lower Mach numbers and fan pressure ratios, while raising the altitudes, bypass ratios and mass flows. Since  $\pi_c$  raises both  $T_{SL}$  and fuel consumption its influence would have to be checked at each design point Mach number and altitude to determine the best  $\pi_c$  as in the two variable analysis of section 3.4.

These models have produced sufficient trend data to select the next best design point away from the existing AAF baseline design point engine. The information gathered thus far considered only 14 design points and covered a wide range for the design variables. Using this information, along with the models and the results for the design point engines used to build the models, the new design points are selected.

The Mach numbers 1.4 and 1.5 were chosen since decreasing the Mach number will produce both a decrease in fuel consumption and an increase in  $T_{SL}$ . An increase in altitude will also improve overall performance but increasing the altitude too much can cause poor performance for lower altitude maneuvers, as in loiter phases. The altitude selected should not vary much from the original design point if it represents a good compromise between the high altitude requirement and the majority of the low altitude maneuvers. The value of 35,000 ft is still a good design point and will be retained.

Increasing  $\pi_c$  increases both the dependent variables and an average  $\pi_c$  (representing the range of  $\pi_c$  values used for the modeling) should provide good results. Selecting values of 18 and 19 for  $\pi_c$  will produce some variation in the engines for comparison with the candidate retrofit engine designs already discussed.

For  $\alpha$ , a fairly high bypass ratio was selected to keep fuel consumption down. A value of 0.65 reflects an acceptable compromise among the design point engines used for the models. A mass flow rate of 110 lbm/s was chosen which represents a 10% increase over the existing retrofit designs.

Engine performance can be very sensitive to  $\pi_c'$  when negotiating a particular maneuver. It should be selected based on the results of the analysis at the design point Mach number and altitude. This was previously accomplished when collecting the data for the models and a value of 3.7 will be used.

These decisions resulted in the following proposed design points which were "flown" using MISS to determine their  $T_{SL}$  and fuel consumption:

|               | <u>Altitude</u> |          |         |          | <u>mass flow*</u> | <u><math>T_{SL}</math></u> | <u>Fuel Req'd</u> |
|---------------|-----------------|----------|---------|----------|-------------------|----------------------------|-------------------|
| <u>Mach #</u> | (k ft)          | $\pi_c'$ | $\pi_c$ | $\alpha$ | (lbm/s)           | (lbf)                      | (lbf)             |
| 1.4           | 35              | 3.7      | 18      | 0.65     | 100               | 16,986                     | 8056              |
| 1.4           | 35              | 3.7      | 19      | 0.65     | 100               | 17,056                     | 8008              |
| 1.5           | 35              | 3.7      | 18      | 0.65     | 110               | 17,015                     | 8010              |
| 1.5           | 35              | 3.7      | 19      | 0.65     | 110               | 17,050                     | 7966              |

\*It was found during the MISS analysis that the inlet had to be resized for  $M=1.4$ , therefore the mass flow was reduced to 100 lbm/s

These results showed that the modeling scheme determined the proper direction to move when selecting the next choice for each design variable. The thrust has been significantly increased over that of the AAF and fuel has been saved in the process. This was an excellent result considering the amount of data points used (18 including these last 4 engines) and the improvements achieved. Further refinement of these engines could be made by using only the  $M=1.4$  and  $M=1.5$  values, over small ranges of  $\pi_c$ ,  $\alpha$ , or any other design variable and constructing new models. This then becomes the same type of search as was presented in the two-variable example.

These engines will now be checked against the constraint/thrust diagrams to view the performance improvements from the two-variable search and the six-variable search. The new baseline engine will also be selected.

### 3.6. Engine Comparisons Using Constraint/Thrust Diagrams

The two-variable and six-variable analyses identified six candidate baseline engine designs for use in the retrofit effort. These engines were compared using the constraint/thrust diagrams generated in the section on constraint diagrams. The method used was to take the existing constraint/performance diagrams and determine the relative position of each engine on the plot. The M=0.9 turn, M=1.6 turn and supercruise flight conditions were compared.

The candidate baseline engines are summarized below for easy reference

| Engine | Mach # | Altitude<br>(k ft) | $\pi_c$ | $\alpha$ | $\pi_c'$ | mass<br>flow<br>(lbm/s) | T <sub>SL</sub><br>(lbf) | Fuel<br>Req'd<br>(lbf) |
|--------|--------|--------------------|---------|----------|----------|-------------------------|--------------------------|------------------------|
| A      | 1.6    | 35                 | 20      | 0.55     | 3.7      | 100                     | 14,280                   | 8199                   |
| B      | 1.6    | 35                 | 20      | 0.45     | 3.7      | 100                     | 14,509                   | 8292                   |
| C      | 1.6    | 35                 | 19      | 0.6      | 3.7      | 100                     | 14,308                   | 8190                   |
| D      | 1.4    | 35                 | 18      | 0.65     | 3.7      | 100                     | 16,986                   | 8056                   |
| E      | 1.4    | 35                 | 19      | 0.65     | 3.7      | 100                     | 17,056                   | 8008                   |
| F      | 1.5    | 35                 | 18      | 0.65     | 3.7      | 110                     | 17,015                   | 8010                   |
| G      | 1.5    | 35                 | 19      | 0.65     | 3.7      | 110                     | 17,050                   | 7966                   |

In order to judge the performance improvement of each engine, a line representing the AAF wing loading value of 64 was drawn on each of the constraint/thrust diagrams. The AAF is a two engine aircraft, therefore the sea-level thrust of each engine is multiplied by two for the total aircraft T<sub>SL</sub>. By plotting the total sea-level thrust along this line, the performance advantage of one engine design over the other can be seen. The engines were broken up into two groups since the change in thrust among members of either group was not significant and represent the same point on the constraint/thrust diagram. These diagrams are presented in Figures 31, 32 and 33.

Figure 31 indicates that engines A, B, and C allow the AAF to negotiate a M=0.9 turn for a  $\beta$  of 0.77, whereas engines D, E, F, and G allow the maneuver at a  $\beta$  of 0.83. In comparison to the weight of the aircraft at this maneuver, the first set of engines produces enough thrust for the aircraft to maneuver at a weight of 18,788 lbf vs. 20,252 lbf for the second set. This is a significant improvement which would allow the aircraft to maneuver with additional fuel or munitions on board.

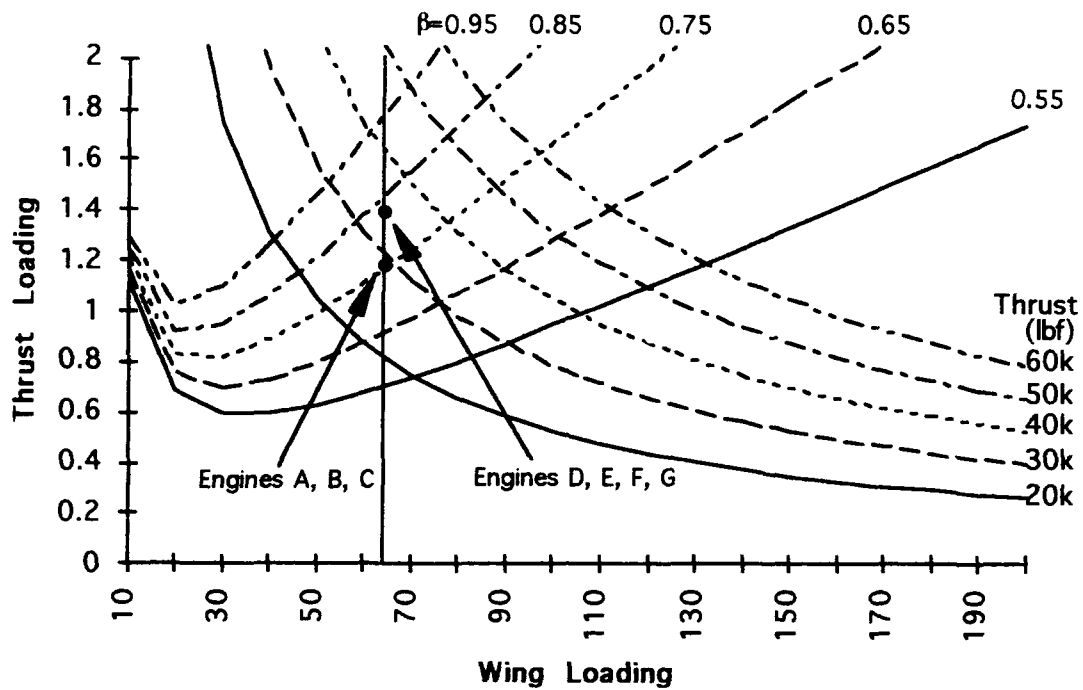


Figure 31. M=0.9 Turn Constraint/Thrust Diagram Showing Baseline Engine Thrust

Figure 32 presents a similar improvement. Engines D, E, F, and G will power the aircraft through a M=1.6, 5 g turn at a weight above 23,180 lbf ( $\beta=0.95$ ), an improvement in weight of at least 1400 lbf over the other engines.

The supercruise requirement, Figure 33, indicated that the aircraft will easily perform supercruise at a  $\beta$  of 0.95 with engines D, E, F, and G. The other engines were barely adequate to perform this maneuver.

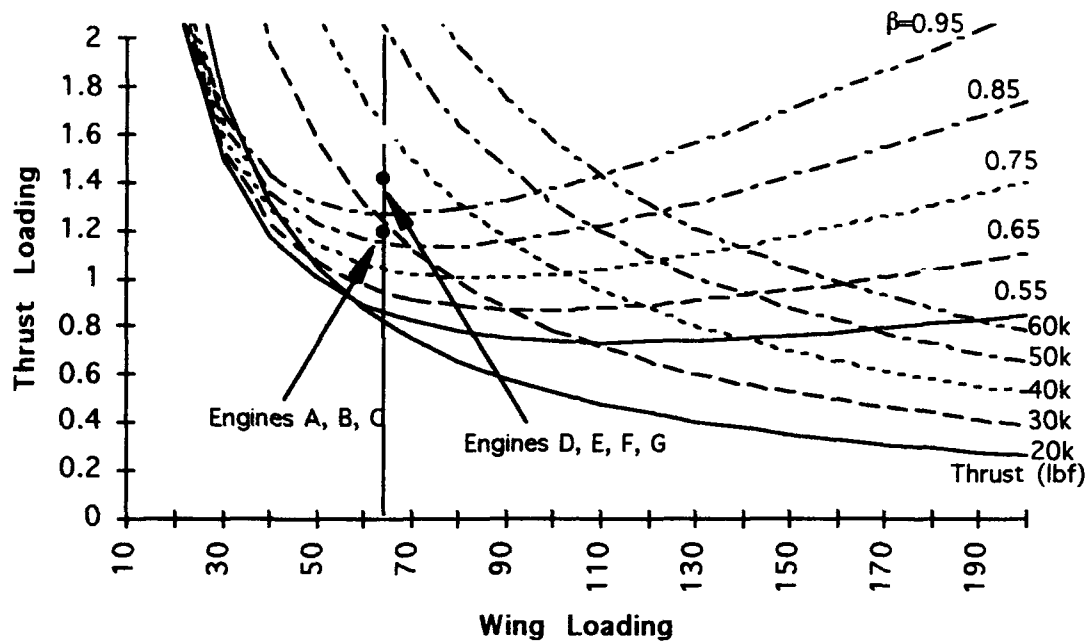


Figure 32. M=1.6 Turn Constraint/Thrust Diagram Showing Baseline Engine Thrust

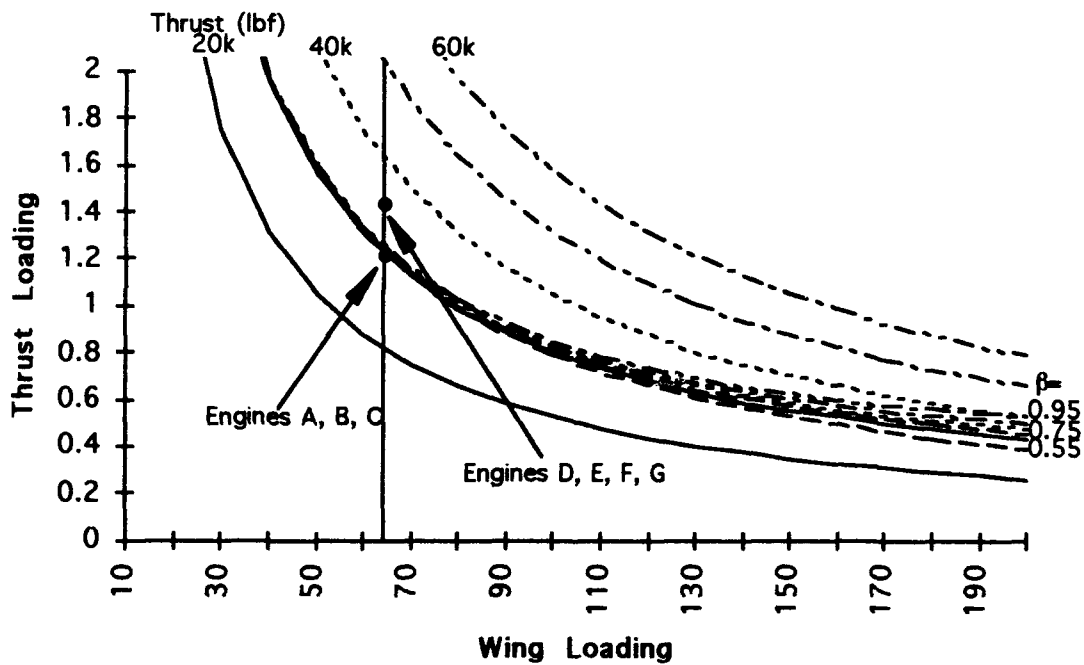


Figure 33. Supercruise Constraint/Thrust Diagram Showing Baseline Engine Thrust

Since the change in engine thrust within the groups was small , there is very little to compare. Each engine performed the mission and negotiated the maneuvers at the required weight fractions. The advantage is in the improvement which was made with the second group of engines.

The last issue to examine was the fuel consumption. Among the possible candidates, engines D, E, F, and G all showed improved fuel economy over engines A, B, and C. Therefore, these engines represent both an improvement in performance as well as an improvement in fuel economy.

From these results, the new baseline design point engine selected was engine G. This engine has the lowest fuel consumption of all candidates and a  $T_{SL}$  of only 6 lbf less than the highest  $T_{SL}$  in the group. The original AAF engine and the new engine are presented below for comparison.

| <u>Engine</u> | <u>Mach #</u> | <u>Altitude</u><br>(k ft) | $\pi_c$ | $\alpha$ | $\pi_c'$ | <u>mass</u><br><u>flow</u><br>(lbm/s) | <u><math>T_{SL}</math></u><br>(lbf) | <u>Fuel</u><br><u>Req'd</u><br>(lbf) |
|---------------|---------------|---------------------------|---------|----------|----------|---------------------------------------|-------------------------------------|--------------------------------------|
| AAF           | 1.6           | 35                        | 20      | 0.55     | 3.7      | 100                                   | 14,280                              | 8199                                 |
| G             | 1.5           | 35                        | 19      | 0.65     | 3.7      | 110                                   | 17,050                              | 7966                                 |

Maximum maneuver weights were determined based on the intersections of the thrust line, the wing loading line, and the constraint line for the particular maneuver.

The application of empirical modeling and statistical analysis in the engine search greatly enhanced the ability to detect trends and make inferences between the engine design variables, the total fuel consumption, and sea-level thrust. This tool eliminates the need to test each new choice by producing a model by which to judge the influence of each independent variable on the dependent variable. The modeling technique quickly narrowed the choice of ranges for the design variables.

The modeling method required a minimum number of observations to produce acceptable results. The AAF design point engine analysis was based on only 7 observations and resulted in accurate results. The six-variable analysis used 14 observations and resulted in a rapid convergence on the influence of each design variable.

The two-variable analysis resulted in two new designs. The best of these improved the sea-level thrust by 0.2% and the fuel consumption by 0.1%. This indicated that the original AAF engine was nearly optimum for the design point conditions and very little improvement could be made.

The six-variable analysis covered a much wider range of design choices and resulted in a significant improvement over the AAF engine. The thrust was increased by 16% and the fuel consumption was reduced by 3%. The real advantage to the new engine design was the increase in thrust which enabled the aircraft to perform the same maneuvers at higher aircraft weight.

A final conclusion is that the design scheme presents a method which will reduce the amount of iteration by using the quality measures and modeling technique. A good model eliminates the need to test each new design point choice with MISS therefore reduces the amount of computer time required.

Further research into the modeling scheme should address the following areas:

1. The search for better models and the introduction of optimization techniques could greatly enhance the engine design process.

2. Incorporation of the effect of throttle ratio into this analysis scheme should be explored.
3. Integration of this procedure into the AFIT design course to provide feedback and test the design scheme on a wide range of aircraft engine retrofit scenarios. This could be accomplished by introducing the SAS modeling technique as applied specifically to engine design and following the design scheme outlined in this investigation to augment the textbook *Aircraft Engine Design*.

## Appendix A: ACSYS Computer Program

The ACSYS program performs two major functions. It can perform a constraint analysis to generate constraint diagrams as well as produce  $P_S/f_S$  contour plots. This appendix contains excerpts from the ACSYS program user guide, Reference 5. It provides a brief overview of the program components used in this research.

The constraint analysis is based on the constraint equations of Chapter 2, Reference 6. This analysis was used extensively to generate the design data for constructing the constraint diagrams and constraint/thrust diagrams. The program is capable of analyzing nine constraint types, seven aircraft drag models, and six engine thrust models. Once the constraint analysis has been calculated the constraint lines can be plotted on the screen.

The program is organized with the following menus and sub-menus

- Constraint Analysis
  - Select Constraints
  - Constraint Data
  - Range of W/S and T/W
  - Perform Calculations
  - Plot Constraint Diagram
- $P_S/f_S$  Contour Plot
  - Select Calculation Desired (1= $P_S$  or 2= $f_S$ )
  - Aircraft System Design Point
  - Range of Velocities and Altitudes
  - Calculate and Plot Contours
- Input Data (Read or Save Input Data File)
- Aircraft (Six Models plus One User Input Model)
- Engine Thrust (Four Models plus Two User Input Models)
- Engine TSFC (Four Models plus One User Input Model)
- Output Devices (Screen, Printer, or Both)
- Screen Resolution (Hi Res B&W, CGA, EGA)
- Exit Program

The information needed to perform a constraint analysis is input to the program using the sub-menus which consist of the following options:

#### **Constraints**

A-Constant Altitude Speed Cruise  
B-Constant Speed Climb  
C-Constant Altitude Speed Turn  
D-Horizontal Acceleration  
E-Service Ceiling  
F-Takeoff (No Obstacle)  
G-Takeoff  
H-Landing (No Obstacle)  
I-Landing

#### **Engine Thrust Models**

--High Bypass Ratio Turbofan  
--Low Bypass Ratio Mixed Turbofan  
--Advanced Turbojet  
--Advanced Turboprop  
--User Input Thrust Model  
--User Input Alpha Values

#### **Drag Models**

--Cargo/Passenger-TProp (Low Drag)  
--Cargo/Passenger-TProp (High Drag)  
--Cargo/Passenger-TFan (Low Drag)  
--Cargo/Passenger-TFan (High Drag)  
--Future Fighter  
--Current Fighter  
--User Input Drag Model

#### **Engine TSFC Models**

--High Bypass Ratio Turbofan  
--Low Bypass Ratio Mixed Turbofan  
--Advanced Turbojet  
--Advanced Turboprop  
--User Input TSFC Model,  $C=f(M)$

Various information must be input for each constraint type to perform the calculation. The data item and constraint it corresponds to are summarized below.

| <u>Data Item</u>               | <u>Constraint</u> | <u>Data Item</u>                   | <u>Constraint</u>            |
|--------------------------------|-------------------|------------------------------------|------------------------------|
| - $\beta$ (Weight Fraction)    | A thru I          | - $dh/dt$ (ft/s)                   | B                            |
| - Temperature (R)              | A thru I          | - Number of g's                    | C                            |
| - Altitude (ft)                | A thru I          | - $dV/dt$ (ft/s <sup>2</sup> )     | D                            |
| - CDR                          | A thru I          | - $P_S$ (ft/s)                     | E                            |
| - Velocity (ft/s)              | A thru E          | - Total landing distance (ft)      | H, I                         |
| - Fraction of max thrust       | A thru E          | - Fraction $C_{Lmax}$ for braking  | H, I                         |
| - $C_{Lmax}$                   | F thru I          | - $k_{TD}$                         | H, I                         |
| - Mach # during takeoff roll   | F, G              | - Thrust reverser ( $-\alpha$ )    | H, I                         |
| - Takeoff Friction Coefficient | F, G              | - Free roll time (s)               | H, I                         |
| - Total takeoff distance (ft)  | F, G              | - Braking friction coefficient     | H, I                         |
| - Rotation time (s)            | F, G              | - Landing obstacle height (ft)     | I                            |
| - $k_{TO}$                     | F, G              | - $k_{obs}$                        | I                            |
| - Takeoff obstacle height (ft) | G                 | - Engine thrust lapse ( $\alpha$ ) | A thru G (user input engine) |
| - Engine AB (1=ON)             | A thru G          |                                    |                              |

After loading the appropriate information for each constraint, the program will generate the constraint data and the constraint diagram. To receive a printout of the constraint diagram, the program EGADMP.COM can be used. This is most convenient for producing a diagram for use in reports or comparison analysis.

## Appendix B: MISS Computer Program

The MISS computer program performs a multitude of functions in analyzing the off-design performance of an engine. It can perform a mission analysis to obtain estimates of the aircraft's takeoff weight, fuel usage, and engine thrust. It may also be used to perform a thrust/drag analysis at a given Mach number and altitude to obtain variations in  $P_s$  and  $f_s$ . This appendix contains excerpts from the MISS program user guide, Reference 8. It provides a brief overview of the program components used in this research.

The program consists of the following menus and sub-menus:

### MISSION:

- Define Legs
- View/Change Data
- Input/Save Data

### SYSTEM:

- Aircraft Drag Model
- Engine Model
  - Engine Thrust Models
  - Engine TSFC Models
  - Engine Model 7
    - Number of Engines
    - Engine Operating Limits
    - Installation Loss Model
- Aircraft Drag Model

### CALCULATION:

- Mission Analysis
- Thrust/Drag Analysis

### OTHER:

- Select Output Devices
- Exit Program

The mission section asks the user to define the mission legs, of which there are thirteen types. The aircraft's mission profile is loaded into the program by ordering the legs of the mission as they are expected to be performed. The possible choices for mission legs are listed below

- A-Constant Speed Climb
- B-Horizontal Acceleration
- C-Climb and Acceleration
- D-Takeoff Acceleration
- E-Constant Altitude/Speed Cruise
- F-Constant Altitude/Speed Turn
- G-Best Cruise Mach and Altitude
- H-Loiter
- I-Warm-up
- J-Takeoff Rotation
- K-Constant Energy Height Maneuver
- L-Deliver Expendables
- M-Descend ( $P_s=0$ )

Once the mission has been defined, the mission data for each leg is input.

| <u>Mission Data</u>       | <u>Mission Type</u>             | <u>Mission Data</u>                     | <u>Mission Type</u>                                |
|---------------------------|---------------------------------|-----------------------------------------|----------------------------------------------------|
| - Altitude                | B, D, E, F, H, I, J             | - Fraction of avg vel in vertical       | K                                                  |
| - Initial altitude        | A, C, K, M                      | - Angle of descent                      | M                                                  |
| - Temperature             | A, B, C, D, E, F, H, I, J, K, M | - kTO                                   | D, J                                               |
| - Velocity                | A, E, F, J                      | - Takeoff friction coefficient          | D                                                  |
| - Initial velocity        | B, C, K, M                      | - Rotation time                         | J                                                  |
| - Mach number             | A, E, F, J                      | - Distance                              | E, G                                               |
| - Initial Mach number     | B, C, K, M                      | - Time                                  | H, I                                               |
| - Best cruise Mach number | G                               | - Legs included in distance calculation | E, G                                               |
| - Final altitude          | A, C, K, M                      | - Engine thrust lapse                   | A, B, C, D, F, I, J, K, M (user input $\alpha$ 's) |
| - Final velocity          | B, C, K, M                      | - Engine AB (1=ON)                      | A, B, C, D, F, I, J, K, M                          |
| - Final Mach number       | B, C, K, M                      | - Engine TSFC                           | A thru K, M (user input)                           |
| - Number of g's           | F                               | - Maximum $T_{t4}$                      | A thru K, M                                        |
| - Avg Mach number         | B, C, M                         | - Engine C                              | A thru K, M                                        |
| - Number of turns         | F                               | - Maximum $T_{t7}$                      | A thru K, M                                        |
| - CDR                     | A thru K, M                     | - Payload expended                      | L                                                  |
| - $C_{Lmax}$              | D, J                            | - Total inlet/nozzle installation loss  | A thru K, M                                        |

The aircraft wing loading, thrust loading, weight fraction, and takeoff weight are input to define the particular aircraft design point. The aircraft and engine model is completed by selecting from the available options indicated below.

#### **Drag Models**

- Cargo/Passenger-TProp (Low Drag)
- Cargo/Passenger-TProp (High Drag)
- Cargo/Passenger-TFan (Low Drag)
- Cargo/Passenger-TFan (High Drag)
- Future Fighter
- Current Fighter
- User Input Drag Model

#### **Engine Models**

- Basic Engine Model (consists of a thrust model and TSFC model)

##### **Engine Thrust Models**

- High Bypass Ratio Turbofan
- Low Bypass Ratio Mixed Turbofan
- Advanced Turbojet
- Advanced Turboprop
- User Input Thrust Model
- User Input Alpha Values

##### **Engine TSFC Models**

- High Bypass Ratio Turbofan
- Low Bypass Ratio Mixed Turbofan
- Advanced Turbojet
- Advanced Turboprop
- User Input Model
- User Input TSFC or C Values

- Advanced Engine Model (reads a single point reference data file from ONX or OFFX)

The advanced engine model requires the user to set the number of engines, the engine operating limits, and the installation loss model. The engine operating limits, which are determined by the material properties and to ensure proper mixing at the burner, consist of

Max Compressor Pressure Ratio  
Max Pressure at Station 3  
Max Temperature at Station 3

Max % Ref RPM - L<sub>1</sub> Spool  
Max % Ref RPM - HP Spool

The installation loss model, which is made up of the following inputs, accounts for the inlet and nozzle dimensions and their associated losses. The inlet capture area, nozzle

area, and nozzle length may be input.

Constant loss for all mission legs

Different losses for each mission leg

Loss model of chapter 6

After all the mission, aircraft, and engine data have been loaded, the mission can be executed. The analysis provides a leg by leg accounting of the changes in the weight fraction of the aircraft as the fuel is burned. It provides an accounting for each leg of the engine's performance including the required thrust, losses, and temperatures, while warning the user if the off-design solution fails to converge or the inlet size is too small.

This program is most useful in evaluating an engine over a wide range of operating conditions. It also allows the student designer to try all types of engines and aircraft designs, compare how well they perform the mission, and make intelligent choices as to which is the best design combination.

### Appendix C: SAS Software

In this investigation, the modeling tool used is multivariable linear regression with statistical analysis. This method takes a group of input and output data and attempts to build a model to fit the output based on the input conditions. The SAS software has been developed to provide the data analyst with a tool for applying various statistical analyses when building models or performing optimization studies. This appendix is based on the information in Reference 13.

The SAS program is a self contained analysis tool which uses a two step process for analyzing the data. The first step is a data step, wherein the data is organized. The second step is a process step, which tells SAS how to operate on the data (13:19). The program portion of the analysis implies a command file containing SAS instructions and data which is input to the SAS environment. This file is built by the analyst and reflects the type of analysis requested. A typical SAS program file for this paper is presented below.

```
TITLE 'MODELING MISSION FUEL CONSUMPTION AND THRUST AT SEA LEVEL';
DATA ENGINES;
    INPUT FUEL THRUST MACH ALT PIC ALPHA PICSQ MDOT
    PICSQ=PIC**2
    ALPHASQ=ALPHA**2
    B=PIC*ALPHA
    D=PIC**2*ALPHA**2
CARDS;
8579 14539 1.6 35 15 .4 3.7 100
8268 14375 1.6 35 18 .55 3.7 100
8143 13079 1.6 35 22 .55 3.7 100
8410 14400 1.6 35 16 .5 3.7 100
8159 14166 1.6 35 20 .6 3.7 100
8335 14452 1.6 35 17.5 .5 3.7 100
.. 1.6 35 22 .65 3.7 100
.. 1.6 35 20 .45 3.7 100
.. 1.6 35 16 .6 3.7 100
;
PROC PRINT;
PROC REG SIMPLE;
    MODEL THRUST=PIC ALPHA D/CLI NOINT;
    MODEL FUEL=PIC ALPHA PICSQ B/CLI;
```

The first line of the program produces a title for the output pages. The next section under DATA ENGINES; creates the order in which the dependent and independent variables will be read from the CARDS section and defines the terms used in the model. If a quadratic term of the variable PIC is required, then a new variable PICSQ=PIC\*\*2 must be defined.

The CARDS section of the program contains the input data. This data is entered in the same order as defined in the portion of the program under DATA ENGINES. The PROC PRINT statement allows the output to be formatted for printing and the last section of the program contains the information for SAS to construct the model. The semicolon indicates the end of a SAS statement.

The process is PROC REG SIMPLE or simple regression analysis. Each model begins with the word MODEL. The value to be modeled is listed next with an equals sign indicating which variables the model should be based on. A slash indicates the end of the variables and the beginning of any special instructions to be used by SAS. The term CLI after the slash tells SAS to produce an output which includes the predicted values and the 95% prediction limits for the model. The last command, NOINT, tells SAS to build the model forcing the intercept through the origin. There will be no residual terms when all the input variables are entered as zero. If an intercept is desired delete the command.

The program output for a typical SAS analysis is presented at the end of this appendix (Note: SAS output pages 1 and 2 have been combined on one page, and SAS output pages 3 and 4 been combined on one page). Page 1 of SAS output shows the values for all the input variables. The second page provides the descriptive statistics for the variables including the sum, mean, uncorrected sum of squares, variance, and standard deviation.

Page 3 contains the output titled Analysis of Variance which provides statistical information for the model's fit to the data. The degrees of freedom for the model, DF, is equal to the number of variables used for the model. The DF of the error is the difference between the Model DF and the U Total DF, which is equal to the sample size for models without an intercept, or the C Total DF, which is one less than the sample size for models with an intercept.

The sum of squares, SS, separates the variation in the data into portions which can be attributed to the model and to the error. The sum of squares is equal to

$$SS = \sum_{i=1}^n (y_i - \bar{y})^2$$

where  $y_i$  is the observed response and  $\bar{y}$  is the mean response. The Total SS=Model SS+Error SS where the Error SS is the sum of the residuals squared.

The mean square, MS, is the sum of squares divided by the degrees of freedom. The Error MS estimates the variance of a population to a given set of independent variables.

The F Value is a test statistic which is calculated by taking the MS for the model and dividing it by the MS of the error. This statistic is the first indication of how good the model is. The value for F tests the hypothesis that the model explains a significant portion of the variation in the data.

$$F > F_{\alpha}$$

This is a test of the null hypothesis which, if the value of F is larger than the value of  $F_{\alpha}$ , indicates that the mean of the data did not happen by chance. The value for  $F_{\alpha}$  is found in tables and is based upon the DF for the model and the DF for the error and is written as  $F(\alpha, \text{DF model}, \text{DF error})$  where  $\alpha$  represents the error probability, normally 0.05.

The value Prob>F is the p-value associated with the same test and indicates whether or not the model explains a significant portion of the variation in the data. If the choice for  $\alpha$  is greater than the value of p then the null hypothesis is rejected. This measure provides an indication of the extent to which the observed data disagrees with the null hypothesis. If the p-value is 0.0001 then the model is called a significant model.

The Root MSE is equal to the square root of the Error SS divided by the DF of the error or, the square root of the mean squared error, MSE. The Dep Mean, is simply the mean value of the dependent variable. The value C.V. is the coefficient of variation and is calculated by taking the Root MSE divided by the dependent mean and multiplying

by 100. This is the Root MSE expressed as a percentage of the dependent mean. The smaller this value is the smaller the Root MSE and the smaller the residuals of the model.

R-Square is the coefficient of multiple determination and represents the fraction of the total variation due to the variables in the model and can range from 0 to 1. It represents the correlation between  $y$  and  $\hat{y}$  and is equal to

$$RSquare = \frac{\sum_{i=1}^n (\hat{y}_i - \bar{y})^2}{\sum_{i=1}^n (y_i - \bar{y})^2}$$

where  $\hat{y}_i$  is the approximate response. It is equal to the Model SS/Total SS and the closer this value is to 1, the better the model is at accounting for variation in the data.

The next section of the SAS output presents the parameter estimates and gives the coefficients for each of the independent variables and indicates their relative importance in the model.

The degree of freedom for each parameter should be 1. The standard error is an indicator for how much the parameter estimates would vary from one set of data to the next. This can be used to attain confidence intervals around the parameter estimates.

The T for  $H_0: \text{Parameter}=0$ , presents the t-value for testing the null hypothesis that the parameter is 0 using the t-distribution. The t-value is calculated by taking the parameter estimate and dividing by the standard error. If there is very little dependence on the output by this variable, then this value will be small indicating it can be dropped from the analysis. Another important analysis tool to determine the relative worth of a particular variable is by using the Prob>|T| which gives the p-value for the t-value of the parameter. If this value is close to 1 then it indicates that the slope of the data is zero for that parameter. In other words there is very little change to the data based upon that parameter. If the value is close to 0.0001 it indicates that the slope is not zero and that the data is dependent upon that variable.

The last page of SAS output summarizes the model by presenting the dependent variable, the predicted value, standard error predicted, lower and upper 95% predicted value, and the residuals. Most of these columns are self explanatory. The Standard Err Predict is a measure of how much the predicted value estimate would vary from one set of data to the next. The Lower and Upper 95% Predict gives the prediction limits. This means that you can be 95% confident that the actual value lies somewhere between the upper and lower values. The Residual is the error between the predicted and the actual value.

Once a model has been built it is easy to obtain new predictions for different input variables. This is accomplished by placing a period in place of the dependent variable and listing the new input variables the same way as the model data. The predicted values and their confidence interval can be used to make inferences about new values for design variables. For this model, observations 7, 8, and 9 show predictions based on the input conditions.

There are additional tests which may be used to determine how well the regression model fits the data. These tests are explained in detail in Chapter 6 of Reference 2 and Chapter 10 of Reference 13.

## MODELING MISSION FUEL CONSUMPTION AND THRUST AT SEA LEVEL

Page 1

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| OBS | FUEL | THRUST | MACH | ALT | PIC  | ALPHA | PICP | MDOT | PICSQ  |
|-----|------|--------|------|-----|------|-------|------|------|--------|
| 1   | 8579 | 14539  | 1.6  | 35  | 15.0 | 0.40  | 3.7  | 100  | 225.00 |
| 2   | 8268 | 14375  | 1.6  | 35  | 18.0 | 0.55  | 3.7  | 100  | 324.00 |
| 3   | 8143 | 13079  | 1.6  | 35  | 22.0 | 0.55  | 3.7  | 100  | 484.00 |
| 4   | 8410 | 14400  | 1.6  | 35  | 16.0 | 0.50  | 3.7  | 100  | 256.00 |
| 5   | 8159 | 14166  | 1.6  | 35  | 20.0 | 0.60  | 3.7  | 100  | 400.00 |
| 6   | 8335 | 14452  | 1.6  | 35  | 17.5 | 0.50  | 3.7  | 100  | 306.25 |
| 7   | .    | .      | 1.6  | 35  | 22.0 | 0.65  | 3.7  | 100  | 484.00 |
| 8   | .    | .      | 1.6  | 35  | 20.0 | 0.45  | 3.7  | 100  | 400.00 |
| 9   | .    | .      | 1.6  | 35  | 16.0 | 0.60  | 3.7  | 100  | 256.00 |

| OBS | ALPHASQ | B     | D      |
|-----|---------|-------|--------|
| 1   | 0.1600  | 6.00  | 36.00  |
| 2   | 0.3025  | 9.90  | 98.01  |
| 3   | 0.3025  | 12.10 | 146.41 |
| 4   | 0.2500  | 8.00  | 64.00  |
| 5   | 0.3600  | 12.00 | 144.00 |
| 6   | 0.2500  | 8.75  | 76.563 |
| 7   | 0.4225  | 14.30 | 204.49 |
| 8   | 0.2025  | 9.00  | 81.00  |
| 9   | 0.3600  | 9.60  | 92.16  |

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## MODELING MISSION FUEL CONSUMPTION AND THRUST AT SEA LEVEL

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## Descriptive Statistics

| Variables | Sum      | Mean         | Uncorrected SS |
|-----------|----------|--------------|----------------|
| INTERCEP  | 6        | 1            | 6              |
| PIC       | 108.5    | 18.083333333 | 1995.25        |
| ALPHA     | 3.1      | 0.516666667  | 1.625          |
| D         | 564.9825 | 94.16375     | 63031.664606   |
| THRUST    | 85011    | 14168.5      | 1205979247     |
| PICSQ     | 1995.25  | 332.54166667 | 709182.0625    |
| B         | 56.75    | 9.4583333333 | 564.9825       |
| FUEL      | 49894    | 8315.6666667 | 415037120      |

| Variables | Variance     | Std Deviation |
|-----------|--------------|---------------|
| INTERCEP  | 0            | 0             |
| PIC       | 6.641666667  | 2.5771431211  |
| ALPHA     | 0.004666667  | 0.0683130051  |
| D         | 1966.1587444 | 44.341388616  |
| THRUST    | 300178.7     | 547.88566324  |
| PICSQ     | 9135.6604167 | 95.580648756  |
| B         | 5.6444166667 | 2.3757981115  |
| FUEL      | 27049.466667 | 164.46722064  |

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Model: MODEL1

NOTE: No intercept in model. R-square is redefined

Dependent Variable: THRUST

## Analysis of Variance

| Source   | DF | Sum of Squares | Mean Square  | F Value  | Prob>F |
|----------|----|----------------|--------------|----------|--------|
| Model    | 3  | 1205007724.5   | 401669241.51 | 1240.329 | 0.0001 |
| Error    | 3  | 971522.45528   | 323840.81843 |          |        |
| U Total  | 6  | 1205979247     |              |          |        |
| Root MSE |    | 569.07013      | R-Square     | 0.9992   |        |
| Dep Mean |    | 14168.50000    | Adj R-sq     | 0.9984   |        |
| C.V.     |    | 4.01645        |              |          |        |

## Parameter Estimates

| Variable | DF | Parameter Estimate | Standard Error | T for HO: Parameter=0 | Prob> T |
|----------|----|--------------------|----------------|-----------------------|---------|
| PIC      | 1  | 515.240497         | 167.1484383    | 3.083                 | 0.0540  |
| ALPHA    | 1  | 21711              | 5486.284904    | 3.957                 | 0.0288  |
| D        | 1  | -67.685055         | 8.17087135     | -8.284                | 0.0037  |

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| Obs                        | Dep Var | Predict Value | Std Err Predict | Lower 95% Predict | Upper 95% Predict | Residual |
|----------------------------|---------|---------------|-----------------|-------------------|-------------------|----------|
| 1                          | THRUST  | 13976.2       | 452.098         | 11663.1           | 16289.2           | 562.8    |
| 2                          |         | 14581.3       | 310.633         | 12518.0           | 16644.6           | -206.3   |
| 3                          |         | 13366.3       | 531.121         | 10889.0           | 15843.6           | -287.3   |
| 4                          |         | 14767.3       | 354.911         | 12632.9           | 16901.7           | -367.3   |
| 5                          |         | 13584.5       | 437.889         | 11299.3           | 15869.7           | 581.5    |
| 6                          |         | 14689.8       | 266.157         | 12690.5           | 16689.2           | -237.8   |
| 7                          | .       | 11606.2       | 779.265         | 8535.3            | 14677.1           | .        |
| 8                          | .       | 14592.1       | 754.641         | 11584.1           | 17600.0           | .        |
| 9                          | .       | 15032.3       | 827.072         | 11837.3           | 18227.3           | .        |
| Sum of Residuals           |         | 45.62706      |                 |                   |                   |          |
| Sum of Squared Residuals   |         | 971522.4553   |                 |                   |                   |          |
| Predicted Resid SS (Press) |         | 9867627.6973  |                 |                   |                   |          |

#### Appendix D: MISS Analysis Data

This appendix contains an example result from a mission analysis. This example is representative of all the MISS program calculations used in this paper. From this data the particular attributes assigned for each mission leg can be determined.

## MISSION ANALYSIS CALCULATIONS

MISSION DATA FILE: MISSION5.DAT

MODELS: AIRCRAFT # 5 THRUST # 7 TSFC # 7

ENGINE DATA FILE: AAFSP100.DAT

NUMBER OF ENGINES 2  
 MAX PRESSURE AT STATION 3 350.0 psia  
 MAX TEMPERATURE AT STATION 3 1760.0 R  
 MAX % REF RPM - LP SPOOL 110.0 %  
 MAX % REF RPM - HP SPOOL 110.0 %  
 Area 1 = 3.29 Area 10 = 4.03 N Length = 4.09

## CURRENT SELECTION:

WING LOADING (W/S) 64.00 psf  
 THRUST LOADING (T/W) 1.20  
 WEIGHT FRACTION (BETA) 1.0000  
 AIRCRAFT GROSS TAKEOFF WEIGHT 24400.1b

## MISSION LEG # 1 NAME: WARMUP TYPE: I - WARM-UP

1 - Altitude (ft) - - - - - 2000.  
 2 - Temperature (R) - - - - - 511.60  
 Speed of Sound (A0 - ft/sec) - 1108.7  
 10 - CDR - - - - - .0000  
 16 - Time (sec) - - - - - 60.0  
 18 - Engine AB (1-ON/0-OFF) - - - - 0  
 19 - Maximum TT4 (R) - - - - - 3200.

----- RESULTS -----  
 Thrust = 17059.1b TSFC = .9892 1/hr  
 TT4 = 3017.R Limit = %RPM LP Spool  
 Area 0\* = 2.60 ft2 Area 9 = 1.56 ft2  
 IMS Noz = .1420 CD Noz = .0005  
 Phi I = .1025 Phi N = .0000  
 C = .9960 1/hr PI = .9885  
 Beta 1 = 1.0000 Beta 2 = .9885

## MISSION LEG # 2 NAME: TOACC TYPE: D - TAKEOFF ACCELERATION

1 - Altitude (ft) - - - - - 2000.  
 2 - Temperature (R) - - - - - 511.60  
 Speed of Sound (A0 - ft/sec) - 1108.7  
 4 - Mach Number - - - - - .1800  
 10 - CDR - - - - - .0700  
 11 - CL max - - - - - 2.0000  
 12 - kTO - - - - - 1.2000  
 13 - TO Friction Coeff - - - - - .0500  
 18 - Engine AB (1-ON/0-OFF) - - - - 1  
 19 - Maximum TT4 (R) - - - - - 3200.  
 20 - Maximum TT7 (R) - - - - - 3600.

----- RESULTS -----  
 TO Mach = .1819 TO Vel = 201.6 ft/sec  
 Distance = 669. ft Distance = .1101 n mi  
 CL = 1.3889 CD = .46780  
 Etta TO = .3984 Thrust = 27601.1b  
 TT4 = 3031.R Limit = %RPM LP Spool  
 TT7 = 3600.R  
 Area 0\* = 2.60 ft2 Area 9 = 2.48 ft2  
 IMS Noz = .0462 CD Noz = .0002  
 Phi I = .0296 Phi N = .0000  
 u = .2943 C = 1.8394 1/hr  
 TSFC = 1.8267 1/hr PI = .9955  
 Beta 2 = .9885 Beta 3 = .9840

## MISSION LEG # 3 NAME: TOROT TYPE: J - TAKEOFF ROTATION

1 - Altitude (ft) - - - - - 2000.  
 2 - Temperature (R) - - - - - 511.60  
 Speed of Sound (A0 - ft/sec) - 1108.7  
 14 - Rotation Time - tR (sec) - - 3.0  
 18 - Engine AB (1-ON/0-OFF) - - - 1  
 19 - Maximum TT4 (R) - - - - - 3200.  
 20 - Maximum TT7 (R) - - - - - 3600.

## ----- RESULTS -----

|            |             |            |               |
|------------|-------------|------------|---------------|
| Distance - | 605. ft     | Distance - | .0995 n mi    |
| Thrust -   | 27608.1b    | TSFC -     | 1.8269 1/hr   |
| TT4 -      | 3031.R      | Limit -    | 8RPM LP Spool |
| TT7 -      | 3600.R      |            |               |
| Area 0* -  | 2.60 ft2    | Area 9 -   | 2.48 ft2      |
| IMS Noz -  | .0462       | CD Noz -   | .0002         |
| Phi I -    | .0292       | Phi N -    | .0000         |
| C -        | 1.8395 1/hr | PI -       | .9982         |
| Beta 3 -   | .9840       | Beta 4 -   | .9823         |

## MISSION LEG # 4 NAME: ACC TYPE: B - HORIZONTAL ACCELERATION

1 - Altitude (ft) - - - - - 2000.  
 2 - Temperature (R) - - - - - 511.60  
 Speed of Sound (A0 - ft/sec) - 1108.7  
 3 - Initial Velocity (ft/sec) - - 200.9  
 4 - Initial Mach Number - - - - .1812  
 6 - Final Velocity (ft/sec) - - - 811.7  
 7 - Final Mach Number - - - - .7000  
 10 - CDR - - - - - .0000  
 18 - Engine AB (1-ON/0-OFF) - - - 0  
 19 - Maximum TT4 (R) - - - - - 3200.

## ----- RESULTS -----

|            |             |            |              |
|------------|-------------|------------|--------------|
| Avg Mach - | .4406       | Avg Vel -  | 488.5 ft/sec |
| Time -     | 32.6 sec    | Distance - | 2.62 n mi    |
| CL -       | .2351       | CD -       | .02306       |
| CD/CL -    | .0981       | Thrust -   | 16835.1b     |
| TT4 -      | 3031.R      | Limit -    | Pt3 Max      |
| Area 0* -  | 2.47 ft2    | Area 9 -   | 1.60 ft2     |
| IMS Noz -  | .1357       | CD Noz -   | .0005        |
| Phi I -    | .0015       | Phi N -    | .0000        |
| u -        | .1396       | C -        | 1.0614 1/hr  |
| TSFC -     | 1.0541 1/hr | PI -       | .9933        |
| Beta 4 -   | .9823       | Beta 5 -   | .9758        |

MISSION LEG # 5 NAME: C&A1 TYPE: C - CLIMB AND ACCELERATION

1 - Initial Altitude (ft) - - - - 2000.  
 2 - Temperature (R) - - - - - 511.60  
     Speed of Sound (A0 - ft/sec) - 1108.7  
 3 - Initial Velocity (ft/sec) - - 776.1  
 4 - Initial Mach Number - - - - - .7000  
 5 - Final Altitude (ft) - - - - - 9000.  
 6 - Final Velocity (ft/sec) - - - 897.5  
 7 - Final Mach Number - - - - - .8300  
 8 - Average Mach Number - - - - - .7700  
 10 - CDR - - - - - .0000  
 18 - Engine AB (1=ON/0=OFF) - - - - 0  
 19 - Maximum TT4 (R) - - - - - 3200.

----- RESULTS -----  
 Avg Mach = .7700      Avg Vel = 843.2 ft/sec  
 Time = 26.4 sec      Distance = 3.66 n mi  
 Delta ze = 10157 ft  
 CL = .0871      CD = .01352  
 CD/CL = .1553      Thrust = 14567.1b  
 TT4 = 3015.R      Limit = Pt3 Max  
 Area 0\* = 2.27 ft2      Area 9 = 1.72 ft2  
 IMS Noz = .1202      CD Noz = .0004  
 Phi I = .0378      Phi N = .0001  
 u = .2538      C = 1.2272 1/hr  
 TSFC = 1.2038 1/hr      PI = .9946  
 Beta 5 = .9758      Beta 6 = .9705

MISSION LEG # 6 NAME: C&A2 TYPE: C - CLIMB AND ACCELERATION

1 - Initial Altitude (ft) - - - - 9000.  
 2 - Temperature (R) - - - - - 486.60  
     Speed of Sound (A0 - ft/sec) - 1081.3  
 3 - Initial Velocity (ft/sec) - - 897.5  
 4 - Initial Mach Number - - - - - .8300  
 5 - Final Altitude (ft) - - - - - 16000.  
 6 - Final Velocity (ft/sec) - - - 895.3  
 7 - Final Mach Number - - - - - .8500  
 8 - Average Mach Number - - - - - .8400  
 10 - CDR - - - - - .0000  
 18 - Engine AB (1=ON/0=OFF) - - - - 0  
 19 - Maximum TT4 (R) - - - - - 3200.

----- RESULTS -----  
 Avg Mach = .8400      Avg Vel = 896.6 ft/sec  
 Time = 16.3 sec      Distance = 2.41 n mi  
 Delta ze = 6939 ft  
 CL = .0953      CD = .01488  
 CD/CL = .1562      Thrust = 14915.1b  
 TT4 = 3143.R      Limit = 8RPM LP Spool  
 Area 0\* = 2.54 ft2      Area 9 = 1.92 ft2  
 IMS Noz = .0953      CD Noz = .0180  
 Phi I = .0235      Phi N = .0062  
 u = .2480      C = 1.2397 1/hr  
 TSFC = 1.1853 1/hr      PI = .9966  
 Beta 6 = .9705      Beta 7 = .9672

MISSION LEG # 7 NAME: C&A3 TYPE: C - CLIMB AND ACCELERATION

1 - Initial Altitude (ft) - - - - 16000.  
 2 - Temperature (R) - - - - - 461.70  
     Speed of Sound (A0 - ft/sec) - 1053.3  
 3 - Initial Velocity (ft/sec) - - - 895.3  
 4 - Initial Mach Number - - - - - .8500  
 5 - Final Altitude (ft) - - - - - 23000.  
 6 - Final Velocity (ft/sec) - - - - 851.9  
 7 - Final Mach Number - - - - - .8800  
 8 - Average Mach Number - - - - - .8650  
 10 - CDR - - - - - .0000  
 18 - Engine AB (1-ON/0-OFF) - - - - 0  
 19 - Maximum TT4 (R) - - - - - 3200.

----- RESULTS -----  
 Avg Mach - .8650                      Avg Vel - 898.7 ft/sec  
 Time - 17.6 sec                      Distance - 2.60 n mi  
 Delta ze - 5821 ft  
 CL - .1189                      CD - .01656  
 CD/CL - .1393                      Thrust - 11964.1b  
 TT4 - 3043.R                      Limit - %RPM LP Spool  
 Area 0\* - 2.59 ft2                      Area 9 - 1.98 ft2  
 IMS Noz - .0894                      CD Noz - .0177  
 Phi I - .0225                      Phi N - .0060  
 u - .2747                      C - 1.2485 1/hr  
 TSFC - 1.1619 1/hr                      PI - .9971  
 Beta 7 - .9672                      Beta 8 - .9644

MISSION LEG # 8 NAME: C&A4 TYPE: C - CLIMB AND ACCELERATION

1 - Initial Altitude (ft) - - - - 23000.  
 2 - Temperature (R) - - - - - 436.80  
     Speed of Sound (A0 - ft/sec) - 1024.5  
 3 - Initial Velocity (ft/sec) - - - 901.5  
 4 - Initial Mach Number - - - - - .8800  
 5 - Final Altitude (ft) - - - - - 30000.  
 6 - Final Velocity (ft/sec) - - - - 895.4  
 7 - Final Mach Number - - - - - .9000  
 8 - Average Mach Number - - - - - .8900  
 10 - CDR - - - - - .0000  
 18 - Engine AB (1-ON/0-OFF) - - - - 0  
 19 - Maximum TT4 (R) - - - - - 3200.

----- RESULTS -----  
 Avg Mach - .8900                      Avg Vel - 898.7 ft/sec  
 Time - 27.4 sec                      Distance - 4.05 n mi  
 Delta ze - 6828 ft  
 CL - .1511                      CD - .01897  
 CD/CL - .1255                      Thrust - 9481.1b  
 TT4 - 2941.R                      Limit - %RPM LP Spool  
 Area 0\* - 2.65 ft2                      Area 9 - 2.04 ft2  
 IMS Noz - .0833                      CD Noz - .0172  
 Phi I - .0210                      Phi N - .0058  
 u - .3115                      C - 1.2576 1/hr  
 TSFC - 1.1375 1/hr                      PI - .9965  
 Beta 8 - .9644                      Beta 9 - .9611

MISSION LEG # 9 NAME: SUBCRS TYPE: E - CONSTANT ALTITUDE/SPEED CRUISE

1 - Altitude (ft) - - - - - 30000.  
 2 - Temperature (R) - - - - - 411.90  
     Speed of Sound (A0 - ft/sec) - 994.9  
 3 - Velocity (ft/sec) - - - - - 895.4  
 4 - Mach Number - - - - - .0000  
 10 - CDR - - - - - .0000  
 15 - Distance (Nautical Miles) - - 150.0  
 16 - Distance includes all prior  
     mission legs beginning with leg 9  
 18 - Engine AB (1-ON/0-OFF) - - - - 0  
 19 - Maximum TT4 (R) - - - - - 3200.

----- RESULTS -----

Distance - 150.0 n mi  
 CL - .1723 CD - .02060  
 Thrust - 2804.1b TSFC - 1.4824 1/hr  
 TT4 - 2214.R Limit - Thrust  
 Area 0\* - 1.77 ft2 Area 9 - 1.56 ft2  
 IMS Noz - .1427 CD Noz - .0170  
 Phi I - .2186 Phi N - .0134  
 C - 1.6635 1/hr PI - .9511  
 Beta 9 - .9611 Beta 10 - .9141

MISSION LEG #10 NAME: PATROL TYPE: H - LOITER

1 - Altitude (ft) - - - - - 30000.  
 2 - Temperature (R) - - - - - 411.90  
     Speed of Sound (A0 - ft/sec) - 994.9  
 10 - CDR - - - - - .0000  
 16 - Time (sec) - - - - - 1200.0  
 18 - Engine AB (1-ON/0-OFF) - - - - 0  
 19 - Maximum TT4 (R) - - - - - 3200.

----- RESULTS -----

Mach - .7361 Vel - 732.3 ft/sec  
 CL - .2449 CD - .02400  
 Thrust - 2185.1b TSFC - 1.3625 1/hr  
 TT4 - 2016.R Limit - Thrust  
 Area 0\* - 1.65 ft2 Area 9 - 1.40 ft2  
 IMS Noz - .1677 CD Noz - .0006  
 Phi I - .1764 Phi N - .0003  
 C - 1.5289 1/hr PI - .9565  
 Beta 10 - .9141 Beta 11 - .8743

MISSION LEG #11 NAME: PENACC TYPE: B - HORIZONTAL ACCELERATION

1 - Altitude (ft) - - - - - 30000.  
 2 - Temperature (R) - - - - - 411.90  
     Speed of Sound (A0 - ft/sec) - 994.9  
 3 - Initial Velocity (ft/sec) - - 895.4  
 4 - Initial Mach Number - - - - - .9000  
 6 - Final Velocity (ft/sec) - - - 1492.3  
 7 - Final Mach Number - - - - - 1.5000  
 10 - CDR - - - - - .0000  
 18 - Engine AB (1-ON/0-OFF) - - - - 1  
 19 - Maximum TT4 (R) - - - - - 3200.  
 20 - Maximum TT7 (R) - - - - - 3600.

----- RESULTS -----  
 Avg Mach = 1.2000                      Avg Vel = 1193.8 ft/sec  
 Time = 29.4 sec                      Distance = 5.76 n mi  
 CL = .0882                      CD = .02422  
 CD/CL = .2748                      Thrust = 19344.1b  
 TT4 = 3106.R                      Limit = 3RPM LP Spool  
 TT7 = 3600.R  
 Area 0 = 2.62 ft2                      Area 9 = 3.82 ft2  
 IMS Noz = .0007                      CD Noz = .1160  
 Phi I = .0115                      Phi N = .0294  
 u = .3030                      C = 2.1302 1/hr  
 TSFC = 1.8983 1/hr                      PI = .9861  
 Beta 11 = .8743                      Beta 12 = .8621

MISSION LEG #12 NAME: PEN TYPE: E - CONSTANT ALTITUDE/SPEED CRUISE

1 - Altitude (ft) - - - - - 30000.  
 2 - Temperature (R) - - - - - 411.90  
     Speed of Sound (A0 - ft/sec) - 994.9  
 3 - Velocity (ft/sec) - - - - - 1492.3  
 4 - Mach Number - - - - - 1.5000  
 10 - CDR - - - - - .0000  
 15 - Distance (Nautical Miles) - - 100.0  
 16 - Distance includes all prior  
     mission legs beginning with leg 12  
 18 - Engine AB (1-ON/0-OFF) - - - - 0  
 19 - Maximum TT4 (R) - - - - - 3200.

----- RESULTS -----  
 Distance = 100.0 n mi  
 CL = .0556                      CD = .02868  
 Thrust = 10846.1b                      TSFC = 1.3505 1/hr  
 TT4 = 3138.R                      Limit = Thrust  
 Area 0 = 2.48 ft2                      Area 9 = 2.69 ft2  
 IMS Noz = .0332                      CD Noz = .0055  
 Phi I = .0726                      Phi N = .0012  
 C = 1.5154 1/hr                      PI = .9242  
 Beta 12 = .8621                      Beta 13 = .7968

## MISSION LEG #13 NAME: TURN1 TYPE: F - CONSTANT ALTITUDE/SPEED TURN

1 - Altitude (ft) - - - - - 30000.  
 2 - Temperature (R) - - - - - 411.90  
     Speed of Sound (A0 - ft/sec) - 994.9  
 3 - Velocity (ft/sec) - - - - - 1591.8  
 4 - Mach Number - - - - - 1.6000  
 8 - Number of G's - - - - - 5.0  
 9 - Number of Turns - - - - - 1.0  
 10 - CDR - - - - - .0000  
 18 - Engine AB (1-ON/0-OFF) - - - - 1  
 19 - Maximum TT4 (R) - - - - - 3200.  
 20 - Maximum TT7 (R) - - - - - 3600.

----- RESULTS -----  
 CL = .2260 CD = .04298  
 Thrust = 18491.1b TSFC = 1.7183 1/hr  
 TT4 = 3200.R Limit = Thrust  
 TT7 = 2750.R  
 Area 0 = 2.54 ft2 Area 9 = 3.75 ft2  
 IMS Noz = .0012 CD Noz = .0002  
 Phi I = .0517 Phi N = .0000  
 C = 1.9283 1/hr PI = .9716  
 Beta 13 = .7968 Beta 14 = .7741

## MISSION LEG #14 NAME: TURN2 TYPE: F - CONSTANT ALTITUDE/SPEED TURN

1 - Altitude (ft) - - - - - 30000.  
 2 - Temperature (R) - - - - - 411.90  
     Speed of Sound (A0 - ft/sec) - 994.9  
 3 - Velocity (ft/sec) - - - - - 895.4  
 4 - Mach Number - - - - - .9000  
 8 - Number of G's - - - - - 5.0  
 9 - Number of Turns - - - - - 2.0  
 10 - CDR - - - - - .0000  
 18 - Engine AB (1-ON/0-OFF) - - - - 1  
 19 - Maximum TT4 (R) - - - - - 3200.  
 20 - Maximum TT7 (R) - - - - - 3600.

----- RESULTS -----  
 CL = .6939 CD = .11096  
 Thrust = 15103.1b TSFC = 1.8187 1/hr  
 TT4 = 2889.R Limit = %RPM LP Spool  
 TT7 = 3464.R  
 Area 0\* = 2.68 ft2 Area 9 = 3.27 ft2  
 IMS Noz = .0096 CD Noz = .0170  
 Phi I = .0111 Phi N = .0032  
 C = 2.0409 1/hr PI = .9716  
 Beta 14 = .7741 Beta 15 = .7521

## MISSION LEG #15 NAME: ACC TYPE: B - HORIZONTAL ACCELERATION

1 - Altitude (ft) - - - - - 30000.  
 2 - Temperature (R) - - - - - 411.90  
     Speed of Sound (A0 - ft/sec) - 994.9  
 3 - Initial Velocity (ft/sec) - - 795.9  
 4 - Initial Mach Number - - - - - .8000  
 6 - Final Velocity (ft/sec) - - - 1591.8  
 7 - Final Mach Number - - - - - 1.6000  
 10 - CDR - - - - - .0000  
 18 - Engine AB (1=ON/0=OFF) - - - - 1  
 19 - Maximum TT4 (R) - - - - - 3200.  
 20 - Maximum TT7 (R) - - - - - 3600.

----- RESULTS -----  
 Avg Mach = 1.2000      Avg Vel = 1193.8 ft/sec  
 Time = 33.4 sec      Distance = 6.56 n mi  
 CL = .0758      CD = .02382  
 CD/CL = .3141      Thrust = 19344.1b  
 TT4 = 3106.R      Limit = 3RPM LP Spool  
 TT7 = 3600.R  
 Area 0 = 2.62 ft2      Area 9 = 3.82 ft2  
 IMS Noz = .0007      CD Noz = .1160  
 Phi I = .0115      Phi N = .0294  
 u = .2979      C = 2.1302 1/hr  
 TSFC = 1.8983 1/hr      PI = .9816  
 Beta 15 = .7521      Beta 16 = .7383

## MISSION LEG #16 NAME: DELEXP TYPE: L - DELIVER EXPENDABLES

21 - Payload Expended (lb) - - - - 1309.

----- RESULTS -----  
 Beta 16 = .7383      Beta 17 = .6846

## MISSION LEG #17 NAME: ESC TYPE: E - CONSTANT ALTITUDE/SPEED CRUISE

1 - Altitude (ft) - - - - - 30000.  
 2 - Temperature (R) - - - - - 411.90  
     Speed of Sound (A0 - ft/sec) - 994.9  
 3 - Velocity (ft/sec) - - - - - 1492.3  
 4 - Mach Number - - - - - 1.5000  
 10 - CDR - - - - - .0000  
 15 - Distance (Nautical Miles) - - 25.0  
 16 - Distance includes all prior  
     mission legs beginning with leg 17  
 18 - Engine AB (1=ON/0=OFF) - - - - 0  
 19 - Maximum TT4 (R) - - - - - 3200.

----- RESULTS -----  
 Distance = 25.0 n mi  
 CL = .0442      CD = .02837  
 Thrust = 10727.1b      TSFC = 1.3531 1/hr  
 TT4 = 3128.R      Limit = Thrust  
 Area 0 = 2.47 ft2      Area 9 = 2.68 ft2  
 IMS Noz = .0338      CD Noz = .0056  
 Phi I = .0743      Phi N = .0013  
 C = 1.5184 1/hr      PI = .9757  
 Beta 17 = .6846      Beta 18 = .6680

## MISSION LEG #18 NAME: CLIMB TYPE: A - CONSTANT SPEED CLIMB

1 - Initial Altitude (ft) - - - - 30000.  
 2 - Temperature (R) - - - - - 411.90  
     Speed of Sound (A0 - ft/sec) - 994.9  
 3 - Velocity (ft/sec) - - - - - 1492.3  
 4 - Mach Number - - - - - 1.5000  
 5 - Final Altitude (ft) - - - - - 38000.  
 10 - CDR - - - - - .0000  
 18 - Engine AB (1=ON/0=OFF) - - - - 1  
 19 - Maximum TT4 (R) - - - - - 3200.  
 20 - Maximum TT7 (R) - - - - - 3600.

----- RESULTS -----  
 Avg Mach = 1.5267      Avg Vel = 1492.3 ft/sec  
 Time = 7.3 sec      Distance = 1.78 n mi  
 Delta ze = 8000 ft  
 CL = .0501      CD = .02849  
 CD/CL = .5693      Thrust = 21327.1b  
 TT4 = 3200.R      Limit = None  
 TT7 = 3600.R  
 Area 0 = 2.69 ft2      Area 9 = 4.50 ft2  
 IMS Noz = .0033      CD Noz = .0006  
 Phi I = .0258      Phi N = .0000  
 u = .4351      C = 2.1397 1/hr  
 TSFC = 1.8734 1/hr      PI = .9951  
 Beta 18 = .6680      Beta 19 = .6647

## MISSION LEG #19 NAME: CLIMB TYPE: A - CONSTANT SPEED CLIMB

1 - Initial Altitude (ft) - - - - 38000.  
 2 - Temperature (R) - - - - - 390.00  
     Speed of Sound (A0 - ft/sec) - 968.1  
 3 - Velocity (ft/sec) - - - - - 1452.1  
 4 - Mach Number - - - - - 1.5000  
 5 - Final Altitude (ft) - - - - - 45000.  
 10 - CDR - - - - - .0000  
 18 - Engine AB (1=ON/0=OFF) - - - - 1  
 19 - Maximum TT4 (R) - - - - - 3200.  
 20 - Maximum TT7 (R) - - - - - 3600.

----- RESULTS -----  
 Avg Mach = 1.5000      Avg Vel = 1452.1 ft/sec  
 Time = 8.6 sec      Distance = 2.05 n mi  
 Delta ze = 7000 ft  
 CL = .0738      CD = .02933  
 CD/CL = .3974      Thrust = 15550.1b  
 TT4 = 3200.R      Limit = None  
 TT7 = 3600.R  
 Area 0 = 2.77 ft2      Area 9 = 4.56 ft2  
 IMS Noz = .0041      CD Noz = .0007  
 Phi I = .0202      Phi N = .0000  
 u = .4145      C = 2.1243 1/hr  
 TSFC = 1.8420 1/hr      PI = .9958  
 Beta 19 = .6647      Beta 20 = .6619

MISSION LEG #20 NAME: SUBCRS TYPE: E - CONSTANT ALTITUDE/SPEED CRUISE

1 - Altitude (ft) - - - - - 45000.  
 2 - Temperature (R) - - - - - 390.00  
     Speed of Sound (A0 - ft/sec) - 968.1  
 3 - Velocity (ft/sec) - - - - - 871.2  
 4 - Mach Number - - - - - .9000  
 10 - CDR - - - - - .0000  
 15 - Distance (Nautical Miles) - - 100.0  
 16 - Distance includes all prior  
     mission legs beginning with leg 20  
 18 - Engine AB (1=ON/0=OFF) - - - - 0  
 19 - Maximum TT4 (R) - - - - - 3200.

----- RESULTS -----

Distance = 100.0 n mi  
 CL = .2415 CD = .02633  
 Thrust = 1761.1b TSFC = 1.3580 1/hr  
 TT4 = 2249.R Limit = Thrust  
 Area O\* = 1.88 ft2 Area 9 = 1.63 ft2  
 IMS Noz = .1321 CD Noz = .0170  
 Phi I = .1620 Phi N = .0113  
 C = 1.5661 1/hr PI = .9717  
 Beta 20 = .6619 Beta 21 = .6432

MISSION LEG #21 NAME: IOITER TYPE: H - LOITER

1 - Altitude (ft) - - - - - 10000.  
 2 - Temperature (R) - - - - - 483.00  
     Speed of Sound (A0 - ft/sec) - 1077.3  
 10 - CDR - - - - - .0000  
 16 - Time (sec) - - - - - 1200.0  
 18 - Engine AB (1=ON/0=OFF) - - - - 0  
 19 - Maximum TT4 (R) - - - - - 3200.

----- RESULTS -----

Mach = .4061 Vel = 437.5 ft/sec  
 CL = .2449 CD = .02400  
 Thrust = 1538.1b TSFC = 1.6059 1/hr  
 TT4 = 1637.R Limit = Thrust  
 Area O\* = 1.16 ft2 Area 9 = 1.27 ft2  
 IMS Noz = .1915 CD Noz = .0007  
 Phi I = .1370 Phi N = .0003  
 C = 1.6642 1/hr PI = .9489  
 Beta 21 = .6432 Beta 22 = .6103

MISSION ANALYSIS CALCULATIONS  
MISSION DATA FILE: MISSION5.DAT  
MODELS: AIRCRAFT # 5 THRUST # 7 TSFC # 7  
ENGINE DATA FILE: AAFSP100.DAT  
NUMBER OF ENGINES 2  
MAX PRESSURE AT STATION 3 350.0 psia  
MAX TEMPERATURE AT STATION 3 1760.0 R  
MAX % REF RPM - LP SPOOL 110.0 %  
MAX % REF RPM - HP SPOOL 110.0 %  
Area 1 = 3.29 Area 10 = 4.03 N Length = 4.09  
CURRENT SELECTION:  
WING LOADING (W/S) 64.00 psf  
THRUST LOADING (T/W) 1.20  
WEIGHT FRACTION (BETA) 1.0000  
AIRCRAFT GROSS TAKEOFF WEIGHT 24400.1b

| LEG | NAME   | PI       | BETA I   | BETA F  | WEIGHT CHANGE | DRAG      |
|-----|--------|----------|----------|---------|---------------|-----------|
| 1   | WARMUP | .988474  | 1.000000 | .988474 | 281.2 lb      | 0. lb     |
| 2   | TOACC  | .995504  | .988474  | .984029 | 108.4 lb      | 8124. lb  |
| 3   | TOROT  | .998249  | .984029  | .982307 | 42.0 lb       | 0. lb     |
| 4   | ACC    | .993326  | .982307  | .975751 | 160.0 lb      | 2350. lb  |
| 5   | C&A1   | .994617  | .975751  | .970499 | 128.2 lb      | 3696. lb  |
| 6   | C&A2   | .996617  | .970499  | .967216 | 80.1 lb       | 3699. lb  |
| 7   | C&A3   | .997122  | .967216  | .964432 | 67.9 lb       | 3287. lb  |
| 8   | C&A4   | .996520  | .964432  | .961075 | 81.9 lb       | 2953. lb  |
| 9   | SUBCRS | .951078  | .961075  | .914058 | 1147.2 lb     | 2804. lb  |
| 10  | PATROL | .956477  | .914058  | .874275 | 970.7 lb      | 2185. lb  |
| 11  | PENACC | .986062  | .874275  | .862090 | 297.3 lb      | 5861. lb  |
| 12  | PEN    | .924222  | .862090  | .796763 | 1594.0 lb     | 10846. lb |
| 13  | TURN1  | .971604  | .796763  | .774137 | 552.1 lb      | 18491. lb |
| 14  | TURN2  | .971577  | .774137  | .752134 | 536.9 lb      | 15103. lb |
| 15  | ACC    | .981592  | .752134  | .738289 | 337.8 lb      | 5764. lb  |
| 16  | DELEXP | 1.000000 | .738289  | .684641 | 1309.0 lb     | 0. lb     |
| 17  | ESC    | .975717  | .684641  | .668016 | 405.7 lb      | 10727. lb |
| 18  | CLIMB  | .995074  | .668016  | .664725 | 80.3 lb       | 9279. lb  |
| 19  | CLIMB  | .995796  | .664725  | .661931 | 68.2 lb       | 6445. lb  |
| 20  | SUBCRS | .971706  | .661931  | .643202 | 457.0 lb      | 1761. lb  |
| 21  | LOITER | .948903  | .643202  | .610336 | 801.9 lb      | 1538. lb  |

SUMMARY OF MISSION WEIGHTS  
AIRCRAFT TAKEOFF WEIGHT 24400. lb  
WEIGHT OF FUEL USED 8199. lb  
WEIGHT OF PAYLOAD EXPENDED 1309. lb  
AIRCRAFT LANDING WEIGHT 14892. lb

### Appendix E: AAF Engine ONX Design Data

This appendix contains the design data used for creating the solution surfaces and trend analyses. The combinations of  $\pi_c$  and  $\alpha$  which fit the requirement that  $M_5$  and  $M_5'$  lie between 0.4 and 0.6 were taken from this data.

## TURBOFAN ENGINE WITH MIXED EXHAUST

```

***** INPUT DATA *****
MACH NO   = 1.600      ALPHA   = .400
ALT (FT)  = 35000.     PI C'   = 3.700
TO (R)    = 394.10     PI D (MAX) = .97
PO (PSIA) = 3.4680     PI B    = .97
DENSITY   = .00073824  PI N    = .98
(SLUG/CUFT)
CP C = .238 BTU/LBM-R  BURNER   = .98
CP T = .295 BTU/LBM-R  MECH HI PR = .98
GAMMA C = 1.400        MECH LO PR = .99
GAMMA T = 1.300        LP COMPR (FAN) = .89 (EC')
TT4 MAX = 3200. (R)    HP COMPR   = .90 (ECH)
H - FUEL (BTU/LBM) = 18000. HP TURBINE = .89 (ETH)
CTO LOW   = .0160      LP TURBINE = .91 (ETL)
CTO HIGH  = .0000      PWR MECH EFF L = .98
COOLING AIR #1 = 5.00 % PWR MECH EFF H = .98
COOLING AIR #2 = 5.00 % BLEED AIR  = 1.00 %
PO/P9 = 1.00
*** DRY AFTERBURNER ***
*** MIXER ***
***** RESULTS *****
TAU R = 1.512
PI R = 4.250
PI D = .933
A0 = 973.1 FT/SEC
VO = 1556.9 FT/SEC
TAU L = 10.064

+
PI C F/MDOT  S    M5  M5P TAU TL  M6  PT9/P9  V9/VO  T EFF  P EFF
  LBF      1/H
  LBM/S

10.00  64.42  1.3789 .400 .638 .8698 .448 11.496  2.29  47.65  61.33
11.00  64.24  1.3634 .400 .599 .8684 .445 11.816  2.29  48.16  61.38
12.00  64.00  1.3502 .400 .565 .8670 .442 12.087  2.28  48.58  61.44
13.00  63.73  1.3386 .400 .535 .8657 .439 12.317  2.28  48.94  61.53
14.00  63.42  1.3285 .400 .509 .8644 .436 12.510  2.27  49.24  61.62
15.00  63.10  1.3195 .400 .486 .8632 .433 12.673  2.27  49.49  61.73
16.00  62.75  1.3115 .400 .467 .8620 .430 12.808  2.26  49.70  61.85
17.00  62.40  1.3044 .400 .450 .8609 .427 12.918  2.25  49.88  61.97
18.00  62.03  1.2979 .400 .436 .8597 .425 13.008  2.25  50.02  62.09
19.00  61.65  1.2921 .400 .425 .8586 .422 13.079  2.24  50.15  62.23
20.00  61.27  1.2868 .400 .417 .8575 .421 13.134  2.23  50.25  62.36
21.00  60.88  1.2820 .400 .410 .8564 .419 13.174  2.23  50.33  62.50
22.00  60.50  1.2777 .400 .406 .8554 .418 13.200  2.22  50.39  62.64
23.00  60.10  1.2737 .400 .404 .8544 .417 13.215  2.21  50.44  62.78
24.00  59.71  1.2700 .400 .403 .8533 .417 13.219  2.20  50.47  62.93
25.00  59.32  1.2667 .400 .404 .8523 .417 13.213  2.20  50.49  63.07
26.00  58.92  1.2637 .400 .407 .8514 .417 13.199  2.19  50.49  63.22
27.00  58.52  1.2609 .400 .411 .8504 .418 13.176  2.18  50.49  63.37
28.00  58.13  1.2584 .400 .416 .8494 .419 13.147  2.17  50.48  63.52
29.00  57.73  1.2561 .400 .422 .8485 .420 13.110  2.16  50.45  63.67
30.00  57.34  1.2540 .400 .429 .8475 .421 13.067  2.16  50.42  63.82

```

## TURBOFAN ENGINE WITH MIXED EXHAUST

\*\*\*\*\*

## INPUT DATA

\*\*\*\*\*

MACH NO - 1.600  
 ALT (FT) - 35000.  
 TO (R) - 394.10  
 PO (PSIA) - 3.4680  
 DENSITY - .00073824  
 (SLUG/CUFT)

ALPHA - .450  
 PI C' - 3.700  
 PI D (MAX) - .97  
 PI B - .97  
 PI N - .98

## EFFICIENCY

CP C - .238 BTU/LBM-R  
 CP T - .295 BTU/LBM-R  
 GAMMA C - 1.400  
 GAMMA T - 1.300  
 TT4 MAX - 3200. (R)  
 H - FUEL (BTU/LBM) - 18000.  
 CTO LOW - .0160  
 CTO HIGH - .0000  
 COOLING AIR #1 - 5.00 %  
 COOLING AIR #2 - 5.00 %  
 PO/P9 - 1.00

BURNER - .98  
 MECH HI PR - .98  
 MECH LO PR - .99  
 LP COMPR (FAN) - .89 (EC')  
 HP COMPR - .90 (ECH)  
 HP TURBINE - .89 (ETH)  
 LP TURBINE - .91 (ETL)  
 PWR MECH EFF L - .98  
 PWR MECH EFF H - .98  
 BLEED AIR - 1.00 %

\*\*\* DRY AFTERBURNER \*\*\*

PI AB - .96

\*\*\* MIXER \*\*\*

PI MIXER MAX - .97

\*\*\*\*\*

## RESULTS

\*\*\*\*\*

TAU R - 1.512  
 PI R - 4.250  
 PI D - .933

A0 - 973.1 FT/SEC  
 V0 - 1556.9 FT/SEC  
 TAU L - 10.064

| PI C  | F/MDOT | S   | M5 | M5P | TAUTL | M6 | PT9/P9 | V9/V0 | T EFF | P EFF |
|-------|--------|-----|----|-----|-------|----|--------|-------|-------|-------|
| LBF   |        | 1/H |    |     |       |    |        |       |       |       |
| LBM/S |        |     |    |     |       |    |        |       |       |       |

|       |       |        |      |      |       |      |        |      |       |       |
|-------|-------|--------|------|------|-------|------|--------|------|-------|-------|
| 10.00 | 62.77 | 1.3663 | .400 | .668 | .8651 | .455 | 11.268 | 2.26 | 47.64 | 61.93 |
| 11.00 | 62.60 | 1.3509 | .400 | .631 | .8637 | .452 | 11.576 | 2.26 | 48.15 | 61.97 |
| 12.00 | 62.37 | 1.3378 | .400 | .599 | .8623 | .450 | 11.837 | 2.25 | 48.57 | 62.04 |
| 13.00 | 62.10 | 1.3263 | .400 | .571 | .8609 | .447 | 12.057 | 2.25 | 48.93 | 62.12 |
| 14.00 | 61.80 | 1.3163 | .400 | .547 | .8596 | .444 | 12.243 | 2.24 | 49.23 | 62.22 |
| 15.00 | 61.48 | 1.3075 | .400 | .526 | .8583 | .441 | 12.398 | 2.24 | 49.48 | 62.33 |
| 16.00 | 61.15 | 1.2996 | .400 | .509 | .8571 | .439 | 12.526 | 2.23 | 49.69 | 62.44 |
| 17.00 | 60.80 | 1.2925 | .400 | .494 | .8559 | .436 | 12.632 | 2.22 | 49.87 | 62.56 |
| 18.00 | 60.44 | 1.2862 | .400 | .482 | .8547 | .434 | 12.717 | 2.22 | 50.01 | 62.69 |
| 19.00 | 60.07 | 1.2805 | .400 | .472 | .8536 | .433 | 12.784 | 2.21 | 50.14 | 62.82 |
| 20.00 | 59.69 | 1.2753 | .400 | .464 | .8524 | .431 | 12.835 | 2.20 | 50.23 | 62.96 |
| 21.00 | 59.32 | 1.2706 | .400 | .459 | .8513 | .430 | 12.871 | 2.19 | 50.31 | 63.10 |
| 22.00 | 58.93 | 1.2663 | .400 | .456 | .8502 | .429 | 12.895 | 2.19 | 50.38 | 63.24 |
| 23.00 | 58.55 | 1.2624 | .400 | .454 | .8492 | .429 | 12.907 | 2.18 | 50.42 | 63.38 |
| 24.00 | 58.16 | 1.2588 | .400 | .454 | .8481 | .429 | 12.909 | 2.17 | 50.45 | 63.52 |
| 25.00 | 57.78 | 1.2556 | .400 | .455 | .8471 | .429 | 12.901 | 2.17 | 50.47 | 63.67 |
| 26.00 | 57.39 | 1.2527 | .400 | .458 | .8460 | .429 | 12.885 | 2.16 | 50.47 | 63.82 |
| 27.00 | 57.00 | 1.2500 | .400 | .462 | .8450 | .429 | 12.861 | 2.15 | 50.47 | 63.97 |
| 28.00 | 56.61 | 1.2476 | .400 | .467 | .8440 | .430 | 12.830 | 2.14 | 50.45 | 64.12 |
| 29.00 | 56.22 | 1.2454 | .400 | .473 | .8430 | .431 | 12.793 | 2.14 | 50.42 | 64.27 |
| 30.00 | 55.83 | 1.2434 | .400 | .480 | .8421 | .432 | 12.749 | 2.13 | 50.39 | 64.42 |

## TURBOFAN ENGINE WITH MIXED EXHAUST

\*\*\*\*\*

## INPUT DATA

\*\*\*\*\*

MACH NO = 1.600  
 ALT (FT) = 35000.  
 TO (R) = 394.30  
 PO (PSIA) = 3.4680  
 DENSITY = .00073824  
 (SLUG/CUFT)  
 CP C = .238 BTU/LBM-R  
 CP T = .295 BTU/LBM-R  
 GAMMA C = 1.400  
 GAMMA T = 1.300  
 TT4 MAX = 3200. (R)  
 H - FUEL (BTU/LBM) = 18000.  
 CTO LOW = .0160  
 CTO HIGH = .0000  
 COOLING AIR #1 = 5.00 %  
 COOLING AIR #2 = 5.00 %  
 PO/P9 = 1.00

\*\*\* DRY AFTERBURNER \*\*\*

\*\*\* MIXER \*\*\*

ALPHA = .500  
 PI C' = 3.700  
 PI D (MAX) = .97  
 PI B = .97  
 PI N = .98  
 EFFICIENCY  
 BURNER = .98  
 MECH HI PR = .98  
 MECH LO PR = .99  
 LP COMPR (FAN) = .89 (EC')  
 HP COMPR = .90 (ECH)  
 HP TURBINE = .89 (ETH)  
 LP TURBINE = .91 (ETL)  
 PWR MECH EFF L = .98  
 PWR MECH EFF H = .98  
 BLEED AIR = 1.00 %

PI AB = .96

PI MIXER MAX = .97

\*\*\*\*\*

## RESULTS

\*\*\*\*\*

TAU R = 1.512  
 PI R = 4.250  
 PI D = .933

A0 = 973.1 FT/SEC  
 V0 = 1556.9 FT/SEC  
 TAU L = 10.064

| PI C F/MDOT<br>LBF | S<br>1/H | M5     | M5P  | TAUTL | M6    | PT9/P9 | V9/V0  | T EFF | P EFF |
|--------------------|----------|--------|------|-------|-------|--------|--------|-------|-------|
| 10.00              | 61.21    | 1.3546 | .400 | .697  | .8605 | .462   | 11.048 | 2.23  | 47.62 |
| 11.00              | 61.03    | 1.3393 | .400 | .662  | .8590 | .459   | 11.346 | 2.23  | 48.13 |
| 12.00              | 60.81    | 1.3263 | .400 | .632  | .8575 | .457   | 11.597 | 2.22  | 48.55 |
| 13.00              | 60.55    | 1.3150 | .400 | .606  | .8561 | .454   | 11.808 | 2.22  | 48.91 |
| 14.00              | 60.26    | 1.3051 | .400 | .583  | .8548 | .452   | 11.986 | 2.21  | 49.21 |
| 15.00              | 59.94    | 1.2963 | .400 | .564  | .8534 | .449   | 12.134 | 2.21  | 49.46 |
| 16.00              | 59.62    | 1.2885 | .400 | .548  | .8522 | .447   | 12.257 | 2.20  | 49.67 |
| 17.00              | 59.27    | 1.2816 | .400 | .534  | .8509 | .445   | 12.357 | 2.19  | 49.84 |
| 18.00              | 58.92    | 1.2753 | .400 | .523  | .8497 | .444   | 12.438 | 2.19  | 49.99 |
| 19.00              | 58.56    | 1.2697 | .400 | .515  | .8485 | .442   | 12.500 | 2.18  | 50.11 |
| 20.00              | 58.19    | 1.2646 | .400 | .508  | .8473 | .441   | 12.548 | 2.17  | 50.21 |
| 21.00              | 57.82    | 1.2600 | .400 | .504  | .8462 | .440   | 12.581 | 2.17  | 50.29 |
| 22.00              | 57.45    | 1.2558 | .400 | .501  | .8451 | .439   | 12.602 | 2.16  | 50.35 |
| 23.00              | 57.07    | 1.2520 | .400 | .500  | .8440 | .439   | 12.612 | 2.15  | 50.39 |
| 24.00              | 56.69    | 1.2485 | .400 | .500  | .8429 | .439   | 12.612 | 2.14  | 50.42 |
| 25.00              | 56.31    | 1.2454 | .400 | .502  | .8418 | .439   | 12.602 | 2.14  | 50.44 |
| 26.00              | 55.93    | 1.2425 | .400 | .505  | .8407 | .439   | 12.585 | 2.13  | 50.44 |
| 27.00              | 55.55    | 1.2399 | .400 | .508  | .8397 | .440   | 12.559 | 2.12  | 50.43 |
| 28.00              | 55.16    | 1.2376 | .400 | .513  | .8387 | .440   | 12.527 | 2.11  | 50.41 |
| 29.00              | 54.78    | 1.2355 | .400 | .519  | .8376 | .441   | 12.489 | 2.11  | 50.38 |
| 30.00              | 54.40    | 1.2336 | .400 | .526  | .8366 | .442   | 12.444 | 2.10  | 50.35 |

LBM/S

## TURBOFAN ENGINE WITH MIXED EXHAUST

## \*\*\*\*\* INPUT DATA \*\*\*\*\*

|                             |                            |
|-----------------------------|----------------------------|
| MACH NO - 1.600             | ALPHA - .550               |
| ALT (FT) - 35000.           | PI C' - 3.700              |
| TO (R) - 394.10             | PI D (MAX) - .97           |
| PO (PSIA) - 3.4680          | PI B - .97                 |
| DENSITY -.00073824          | PI N - .98                 |
| (SLUG/CUFT)                 |                            |
| CP C - .238 BTU/LBM-R       | EFFICIENCY                 |
| CP T - .295 BTU/LBM-R       | BURNER - .98               |
| GAMMA C - 1.400             | MECH HI PR - .98           |
| GAMMA T - 1.300             | MECH LO PR - .99           |
| TT4 MAX - 3200. (R)         | LP COMPR (FAN) - .89 (EC') |
| H - FUEL (BTU/LBM) - 18000. | HP COMPR - .90 (ECH)       |
| CTO LOW - .0160             | HP TURBINE - .89 (ETH)     |
| CTO HIGH - .0000            | LP TURBINE - .91 (ETL)     |
| COOLING AIR #1 - 5.00 %     | PWR MECH EFF L - .98       |
| COOLING AIR #2 - 5.00 %     | PWR MECH EFF H - .98       |
| PO/P9 - 1.00                | BLEED AIR - 1.00 %         |
| *** DRY AFTERBURNER ***     |                            |
| *** MIXER ***               | PI AB - .96                |
|                             | PI MIXER MAX - .97         |

## \*\*\*\*\* RESULTS \*\*\*\*\*

|               |                    |
|---------------|--------------------|
| TAU R - 1.512 | A0 - 973.1 FT/SEC  |
| PI R - 4.250  | V0 - 1556.9 FT/SEC |
| PI D - .933   | TAU L - 10.064     |

| PI C F/MDOT | S   | M5 | M5P | TAUTL | M6 | PT9/P9 | V9/V0 | T EFF | P EFF |
|-------------|-----|----|-----|-------|----|--------|-------|-------|-------|
| LBF         | 1/H |    |     |       |    |        |       |       |       |
| LBM/S       |     |    |     |       |    |        |       |       |       |

|       |       |        |      |      |       |      |        |      |       |       |
|-------|-------|--------|------|------|-------|------|--------|------|-------|-------|
| 10.00 | 59.71 | 1.3437 | .400 | .726 | .8558 | .468 | 10.837 | 2.20 | 47.59 | 63.07 |
| 11.00 | 59.54 | 1.3286 | .400 | .692 | .8543 | .466 | 11.124 | 2.20 | 48.10 | 63.12 |
| 12.00 | 59.32 | 1.3156 | .400 | .664 | .8528 | .464 | 11.365 | 2.19 | 48.52 | 63.18 |
| 13.00 | 59.07 | 1.3044 | .400 | .639 | .8513 | .461 | 11.569 | 2.19 | 48.88 | 63.27 |
| 14.00 | 58.78 | 1.2946 | .400 | .618 | .8499 | .459 | 11.739 | 2.18 | 49.17 | 63.36 |
| 15.00 | 58.48 | 1.2859 | .400 | .600 | .8486 | .457 | 11.881 | 2.18 | 49.43 | 63.47 |
| 16.00 | 58.16 | 1.2783 | .400 | .585 | .8472 | .455 | 11.998 | 2.17 | 49.64 | 63.59 |
| 17.00 | 57.82 | 1.2714 | .400 | .573 | .8459 | .454 | 12.093 | 2.16 | 49.81 | 63.71 |
| 18.00 | 57.47 | 1.2652 | .400 | .563 | .8447 | .452 | 12.169 | 2.16 | 49.96 | 63.84 |
| 19.00 | 57.12 | 1.2597 | .400 | .555 | .8435 | .451 | 12.229 | 2.15 | 50.08 | 63.97 |
| 20.00 | 56.76 | 1.2547 | .400 | .549 | .8423 | .450 | 12.272 | 2.14 | 50.17 | 64.10 |
| 21.00 | 56.39 | 1.2501 | .400 | .545 | .8411 | .449 | 12.303 | 2.14 | 50.25 | 64.24 |
| 22.00 | 56.03 | 1.2461 | .400 | .543 | .8399 | .449 | 12.321 | 2.13 | 50.31 | 64.38 |
| 23.00 | 55.66 | 1.2423 | .400 | .542 | .8388 | .448 | 12.329 | 2.12 | 50.35 | 64.53 |
| 24.00 | 55.28 | 1.2390 | .400 | .543 | .8376 | .448 | 12.327 | 2.12 | 50.38 | 64.67 |
| 25.00 | 54.91 | 1.2359 | .400 | .545 | .8365 | .448 | 12.315 | 2.11 | 50.39 | 64.82 |
| 26.00 | 54.53 | 1.2332 | .400 | .548 | .8354 | .449 | 12.296 | 2.10 | 50.39 | 64.97 |
| 27.00 | 54.16 | 1.2307 | .400 | .552 | .8343 | .449 | 12.270 | 2.09 | 50.38 | 65.12 |
| 28.00 | 53.78 | 1.2285 | .400 | .557 | .8333 | .449 | 12.237 | 2.09 | 50.36 | 65.27 |
| 29.00 | 53.40 | 1.2265 | .400 | .562 | .8322 | .450 | 12.197 | 2.08 | 50.33 | 65.42 |
| 30.00 | 53.03 | 1.2247 | .400 | .569 | .8312 | .451 | 12.152 | 2.07 | 50.29 | 65.58 |

## TURBOFAN ENGINE WITH MIXED EXHAUST

```

***** INPUT DATA *****
MACH NO - 1.600      ALPHA - .600
ALT (FT) - 35000.    PI C' - 3.700
TO (R) - 394.10      PI D (MAX) - .97
PO (PSIA) - 3.4680    PI B - .97
DENSITY - .00073824   PI N - .98
(SLUG/CUFT)
CP C - .238 BTU/LBM-R  BURNER - .98
CP T - .295 BTU/LBM-R  MECH HI PR - .98
GAMMA C - 1.400        MECH LO PR - .99
GAMMA T - 1.300        LP COMPR (FAN) - .89 (EC')
TT4 MAX - 3200. (R)    HP COMPR - .90 (ECH)
H - FUEL (BTU/LBM) - 18000. HP TURBINE - .89 (ETH)
CTO LOW - .0160        LP TURBINE - .91 (ETL)
CTO HIGH - .0000       PWR MECH EFF L - .98
COOLING AIR #1 - 5.00 % PWR MECH EFF H - .98
COOLING AIR #2 - 5.00 % BLEED AIR - 1.00 %
PO/P9 - 1.00
*** DRY AFTERBURNER ***
*** MIXER ***
***** RESULTS *****
TAU R - 1.512      AO - 973.1 FT/SEC
PI R - 4.250       VO - 1556.9 FT/SEC
PI D - .933        TAU L - 10.064

+
PI C F/MDOT      S      M5      M5P TAU TL  M6      PT9/P9  V9/V0  T EFF  P EFF
LBF      1/H
LBM/S

10.00  58.28  1.3336 .400 .754 .8512 .474  10.633  2.17  47.55  63.62
11.00  58.12  1.3186 .400 .722 .8496 .472  10.910  2.17  48.05  63.67
12.00  57.91  1.3058 .400 .694 .8480 .470  11.143  2.16  48.48  63.73
13.00  57.66  1.2946 .400 .671 .8465 .468  11.338  2.16  48.83  63.82
14.00  57.38  1.2849 .400 .651 .8451 .466  11.502  2.16  49.13  63.91
15.00  57.08  1.2763 .400 .634 .8437 .464  11.638  2.15  49.38  64.02
16.00  56.76  1.2687 .400 .620 .8423 .463  11.749  2.14  49.59  64.14
17.00  56.43  1.2620 .400 .609 .8410 .461  11.840  2.14  49.77  64.26
18.00  56.09  1.2559 .400 .600 .8397 .460  11.912  2.13  49.91  64.39
19.00  55.74  1.2504 .400 .593 .8384 .459  11.967  2.12  50.03  64.52
20.00  55.39  1.2455 .400 .588 .8372 .458  12.008  2.12  50.13  64.65
21.00  55.03  1.2411 .400 .584 .8359 .458  12.035  2.11  50.20  64.79
22.00  54.67  1.2371 .400 .583 .8347 .457  12.051  2.10  50.26  64.93
23.00  54.30  1.2335 .400 .582 .8336 .457  12.057  2.10  50.30  65.08
24.00  53.94  1.2302 .400 .583 .8324 .457  12.052  2.09  50.32  65.22
25.00  53.57  1.2272 .400 .585 .8312 .457  12.040  2.08  50.33  65.37
26.00  53.20  1.2246 .400 .588 .8301 .457  12.019  2.07  50.33  65.52
27.00  52.83  1.2222 .400 .592 .8290 .458  11.991  2.07  50.32  65.67
28.00  52.46  1.2200 .400 .597 .8279 .458  11.957  2.06  50.30  65.82
29.00  52.09  1.2181 .400 .603 .8268 .459  11.917  2.05  50.26  65.98
30.00  51.72  1.2165 .400 .609 .8257 .459  11.872  2.05  50.22  66.13

```

## TURBOFAN ENGINE WITH MIXED EXHAUST

```

***** INPUT DATA *****
MACH NO   = 1.600      ALPHA      = .650
ALT (FT)  = 35000.     PI C'     = 3.700
TO (R)    = 394.10     PI D (MAX) = .97
PO (PSIA) = 3.4680     PI B      = .97
DENSITY   = .00073824  PI N      = .98
(SLUG/CUFT)
CP C      = .238 BTU/LBM-R    BURNER     = .98
CP T      = .295 BTU/LBM-R    MECH HI PR = .98
GAMMA C   = 1.400           MECH LO PR = .99
GAMMA T   = 1.300           LP COMPR (FAN) = .89 (EC')
TT4 MAX   = 3200. (R)       HP COMPR   = .90 (ECH)
H - FUEL (BTU/LBM) = 18000. HP TURBINE = .89 (ETH)
CTO LOW   = .0160          LP TURBINE = .91 (ETL)
CTO HIGH  = .0000          PWR MECH EFF L = .98
COOLING AIR #1 = 5.00 %    PWR MECH EFF H = .98
COOLING AIR #2 = 5.00 %    BLEED AIR   = 1.00 %
PO/P9     = 1.00
*** DRY AFTERBURNER ***    PI AB      = .96
*** MIXER ***              PI MIXER MAX = .97
***** RESULTS *****
TAU R     = 1.512
PI R      = 4.250
PI D      = .933
A0 = 973.1 FT/SEC
VO = 1556.9 FT/SEC
TAU L = 10.004

+
PI C F/MDOT   S   M5   M5P TAU TL  M6   PT9/P9  V9/VO  T EFF  P EFF
LBF          1/H
LBM/S

10.00  56.91  1.3243 .400 .781 .8465 .480 10.436 2.14 47.49 64.16
11.00  56.75  1.3094 .400 .750 .8449 .478 10.703 2.14 48.00 64.21
12.00  56.55  1.2966 .400 .724 .8433 .477 10.928 2.14 48.43 64.27
13.00  56.30  1.2856 .400 .702 .8417 .475 11.116 2.13 48.78 64.35
14.00  56.03  1.2759 .400 .683 .8402 .473 11.273 2.13 49.08 64.45
15.00  55.74  1.2675 .400 .667 .8388 .472 11.403 2.12 49.33 64.56
16.00  55.42  1.2599 .400 .654 .8374 .470 11.509 2.12 49.54 64.67
17.00  55.10  1.2532 .400 .644 .8360 .469 11.595 2.11 49.71 64.80
18.00  54.77  1.2473 .400 .635 .8347 .468 11.663 2.10 49.86 64.92
19.00  54.43  1.2419 .400 .629 .8334 .467 11.715 2.10 49.97 65.05
20.00  54.08  1.2371 .400 .625 .8321 .466 11.753 2.09 50.07 65.19
21.00  53.73  1.2327 .400 .622 .8308 .466 11.778 2.08 50.14 65.33
22.00  53.37  1.2288 .400 .620 .8296 .465 11.791 2.08 50.20 65.47
23.00  53.01  1.2253 .400 .620 .8284 .465 11.794 2.07 50.23 65.62
24.00  52.65  1.2221 .400 .621 .8272 .465 11.788 2.06 50.26 65.76
25.00  52.29  1.2192 .400 .624 .8260 .465 11.774 2.06 50.27 65.91
26.00  51.92  1.2167 .400 .627 .8248 .465 11.752 2.05 50.26 66.06
27.00  51.56  1.2144 .400 .631 .8237 .466 11.723 2.04 50.25 66.21
28.00  51.19  1.2123 .400 .636 .8225 .466 11.688 2.04 50.22 66.36
29.00  50.83  1.2105 .400 .642 .8214 .466 11.648 2.03 50.18 66.52
30.00  50.46  1.2089 .400 .648 .8203 .467 11.602 2.02 50.14 66.67

```

## Appendix F: SAS Modeling Results for the Two-Variable Design Example

This appendix contains the SAS results used for determining the best design choices for the two-variable analysis example.

```

TITLE 'MODELING MISSION FUEL CONSUMPTION AND THRUST AT SEA LEVEL';
OPTIONS LINESIZE=78;
DATA ENGINES;
  INPUT FUEL THRUST MACH ALT PIC ALPHA PICP MDOT;
  PICSQ=PIC**2;
  MACHSQ=MACH**2;
  ALTSQ=ALT**2;
  ALPHASQ=ALPHA**2;
  PICPSQ=PICP**2;
  MDOTSQ=MDOT**2;
  B=PIC*ALPHA;
  D=PIC**2*ALPHA**2;
CARDS;
8579 14539 1.6 35 15 .4 3.7 100
8410 14400 1.6 35 16 .5 3.7 100
8314 14465 1.6 35 18 .45 3.7 100
8268 14375 1.6 35 18 .55 3.7 100
8243 14394 1.6 35 20 .5 3.7 100
8159 14166 1.6 35 20 .6 3.7 100
8143 13079 1.6 35 22 .55 3.7 100
. . 1.6 35 22 .65 3.7 100
. . 1.6 35 22 .45 3.7 100
. . 1.6 35 21 .6 3.7 100
. . 1.6 35 21 .55 3.7 100
. . 1.6 35 21 .4 3.7 100
. . 1.6 35 20 .65 3.7 100
. . 1.6 35 20 .55 3.7 100
. . 1.6 35 20 .45 3.7 100
. . 1.6 35 19 .6 3.7 100
. . 1.6 35 19 .45 3.7 100
. . 1.6 35 17.5 .5 3.7 100
. . 1.6 35 17 .6 3.7 100
. . 1.6 35 17 .4 3.7 100
. . 1.6 35 16 .6 3.7 100
. . 1.6 35 16 .45 3.7 100
. . 1.6 35 15 .6 3.7 100
;
PROC PRINT;
PROC REG SIMPLE;
  MODEL THRUST=PIC ALPHA D/CLI NOINT;
  MODEL THRUST=PIC ALPHA PICSQ B/CLI NOINT;
  MODEL THRUST=PIC ALPHA ALPHASQ PICSQ/CLI NOINT;
  MODEL FUEL=PIC ALPHA PICSQ B/CLI;
  MODEL FUEL=PIC ALPHA ALPHASQ PICSQ/CLI;
  MODEL FUEL=PIC ALPHA PICSQ B D/CLI;

```

## MODELING MISSION FUEL CONSUMPTION AND THRUST AT SEA LEVEL

1

13:09 Friday, October 16, 1992

| OBS | FUEL | THRUST | MACH | ALT | PIC  | ALPHA | PICP | MDOT | PICSQ  |
|-----|------|--------|------|-----|------|-------|------|------|--------|
| 1   | 8579 | 14539  | 1.6  | 35  | 15.0 | 0.40  | 3.7  | 100  | 225.00 |
| 2   | 8410 | 14400  | 1.6  | 35  | 16.0 | 0.50  | 3.7  | 100  | 256.00 |
| 3   | 8314 | 14465  | 1.6  | 35  | 18.0 | 0.45  | 3.7  | 100  | 324.00 |
| 4   | 8268 | 14375  | 1.6  | 35  | 18.0 | 0.55  | 3.7  | 100  | 324.00 |
| 5   | 8243 | 14394  | 1.6  | 35  | 20.0 | 0.50  | 3.7  | 100  | 400.00 |
| 6   | 8159 | 14166  | 1.6  | 35  | 20.0 | 0.60  | 3.7  | 100  | 400.00 |
| 7   | 8143 | 13079  | 1.6  | 35  | 22.0 | 0.55  | 3.7  | 100  | 484.00 |
| 8   | .    | .      | 1.6  | 35  | 22.0 | 0.65  | 3.7  | 100  | 484.00 |
| 9   | .    | .      | 1.6  | 35  | 22.0 | 0.45  | 3.7  | 100  | 484.00 |
| 10  | .    | .      | 1.6  | 35  | 21.0 | 0.60  | 3.7  | 100  | 441.00 |
| 11  | .    | .      | 1.6  | 35  | 21.0 | 0.55  | 3.7  | 100  | 441.00 |
| 12  | .    | .      | 1.6  | 35  | 21.0 | 0.40  | 3.7  | 100  | 441.00 |
| 13  | .    | .      | 1.6  | 35  | 20.0 | 0.65  | 3.7  | 100  | 400.00 |
| 14  | .    | .      | 1.6  | 35  | 20.0 | 0.55  | 3.7  | 100  | 400.00 |
| 15  | .    | .      | 1.6  | 35  | 20.0 | 0.45  | 3.7  | 100  | 400.00 |
| 16  | .    | .      | 1.6  | 35  | 19.0 | 0.60  | 3.7  | 100  | 361.00 |
| 17  | .    | .      | 1.6  | 35  | 19.0 | 0.45  | 3.7  | 100  | 361.00 |
| 18  | .    | .      | 1.6  | 35  | 17.5 | 0.50  | 3.7  | 100  | 306.25 |
| 19  | .    | .      | 1.6  | 35  | 17.0 | 0.60  | 3.7  | 100  | 289.00 |
| 20  | .    | .      | 1.6  | 35  | 17.0 | 0.40  | 3.7  | 100  | 289.00 |
| 21  | .    | .      | 1.6  | 35  | 16.0 | 0.60  | 3.7  | 100  | 256.00 |
| 22  | .    | .      | 1.6  | 35  | 16.0 | 0.45  | 3.7  | 100  | 256.00 |
| 23  | .    | .      | 1.6  | 35  | 15.0 | 0.60  | 3.7  | 100  | 225.00 |

| OBS | MACHSQ | ALTSQ | ALPHASQ | PICPSQ | MDOTSQ | B     | D       |
|-----|--------|-------|---------|--------|--------|-------|---------|
| 1   | 2.56   | 1225  | 0.1600  | 13.69  | 10000  | 6.00  | 36.000  |
| 2   | 2.56   | 1225  | 0.2500  | 13.69  | 10000  | 8.00  | 64.000  |
| 3   | 2.56   | 1225  | 0.2025  | 13.69  | 10000  | 8.10  | 65.610  |
| 4   | 2.56   | 1225  | 0.3025  | 13.69  | 10000  | 9.90  | 98.010  |
| 5   | 2.56   | 1225  | 0.2500  | 13.69  | 10000  | 10.00 | 100.000 |
| 6   | 2.56   | 1225  | 0.3600  | 13.69  | 10000  | 12.00 | 144.000 |
| 7   | 2.56   | 1225  | 0.3025  | 13.69  | 10000  | 12.10 | 146.410 |
| 8   | 2.56   | 1225  | 0.4225  | 13.69  | 10000  | 14.30 | 204.490 |
| 9   | 2.56   | 1225  | 0.2025  | 13.69  | 10000  | 9.90  | 98.010  |
| 10  | 2.56   | 1225  | 0.3600  | 13.69  | 10000  | 12.60 | 158.760 |
| 11  | 2.56   | 1225  | 0.3025  | 13.69  | 10000  | 11.55 | 133.403 |
| 12  | 2.56   | 1225  | 0.1600  | 13.69  | 10000  | 8.40  | 70.560  |
| 13  | 2.56   | 1225  | 0.4225  | 13.69  | 10000  | 13.00 | 169.000 |
| 14  | 2.56   | 1225  | 0.3025  | 13.69  | 10000  | 11.00 | 121.000 |
| 15  | 2.56   | 1225  | 0.2025  | 13.69  | 10000  | 9.00  | 81.000  |
| 16  | 2.56   | 1225  | 0.3600  | 13.69  | 10000  | 11.40 | 129.960 |
| 17  | 2.56   | 1225  | 0.2025  | 13.69  | 10000  | 8.55  | 73.103  |
| 18  | 2.56   | 1225  | 0.2500  | 13.69  | 10000  | 8.75  | 76.563  |
| 19  | 2.56   | 1225  | 0.3600  | 13.69  | 10000  | 10.20 | 104.040 |
| 20  | 2.56   | 1225  | 0.1600  | 13.69  | 10000  | 6.80  | 46.240  |
| 21  | 2.56   | 1225  | 0.3600  | 13.69  | 10000  | 9.60  | 92.160  |
| 22  | 2.56   | 1225  | 0.2025  | 13.69  | 10000  | 7.20  | 51.840  |
| 23  | 2.56   | 1225  | 0.3600  | 13.69  | 10000  | 9.00  | 81.000  |

Descriptive Statistics

| Variables | Sum    | Mean         | Uncorrected SS |
|-----------|--------|--------------|----------------|
| INTERCEP  | 7      | 1            | 7              |
| PIC       | 129    | 18.428571429 | 2413           |
| ALPHA     | 3.55   | 0.5071428571 | 1.8275         |
| D         | 654.03 | 93.432857143 | 71474.5203     |
| THRUST    | 99418  | 14202.571429 | 1413542404     |
| PICSQ     | 2413   | 344.71428571 | 880369         |
| B         | 66.1   | 9.4428571429 | 654.03         |
| ALPHASQ   | 1.8275 | 0.2610714286 | 0.50421875     |
| FUEL      | 58116  | 8302.2857143 | 482634540      |

| Variables | Variance     | Std Deviation |
|-----------|--------------|---------------|
| INTERCEP  | 0            | 0             |
| PIC       | 5.9523809524 | 2.4397501824  |
| ALPHA     | 0.0045238095 | 0.0672592709  |
| D         | 1727.7714571 | 41.566470347  |
| THRUST    | 258526.28571 | 508.45480204  |
| PICSQ     | 8095.5714286 | 89.975393462  |
| B         | 4.9761904762 | 2.2307376529  |
| ALPHASQ   | 0.0045184524 | 0.0672194345  |
| FUEL      | 23150.571429 | 152.15311837  |

Model: MODEL1

NOTE: No intercept in model. R-square is redefined.

Dependent Variable: THRUST

# Analysis of Variance

| Source   | DF | Sum of Squares | Mean Square  | F Value  | Prob>F |
|----------|----|----------------|--------------|----------|--------|
| Model    | 3  | 1412616465.6   | 470872155.22 | 2034.140 | 0.0001 |
| Error    | 4  | 925938.35499   | 231484.58875 |          |        |
| U Total  | 7  | 1413542404     |              |          |        |
| Root MSE |    | 481.12845      | R-square     | 0.9993   |        |
| Dep Mean |    | 14202.57143    | Adj R-sq     | 0.9989   |        |
| C.V.     |    | 3.38762        |              |          |        |

# Parameter Estimates

| Variable | DF | Parameter Estimate | Standard Error | T for H0:<br>Parameter=0 | Prob >  T |
|----------|----|--------------------|----------------|--------------------------|-----------|
| PIC      | 1  | 498.701031         | 104.07926820   | 4.792                    | 0.0087    |
| ALPHA    | 1  | 22357              | 3746.6443856   | 5.967                    | 0.0040    |
| D        | 1  | -67.769722         | 6.50490755     | -10.418                  | 0.0005    |

## MODELING MISSION FUEL CONSUMPTION AND THRUST AT SEA LEVEL

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| Obs | Dep Var<br>THRUST | Predict<br>Value | Std Err<br>Predict | Lower95%<br>Predict | Upper95%<br>Predict | Residual |
|-----|-------------------|------------------|--------------------|---------------------|---------------------|----------|
| 1   | 14539.0           | 13983.4          | 310.175            | 12394.1             | 15572.8             | 555.6    |
| 2   | 14400.0           | 14820.2          | 319.913            | 13216.1             | 16424.4             | -420.2   |
| 3   | 14465.0           | 14590.7          | 288.515            | 13033.1             | 16148.3             | -125.7   |
| 4   | 14375.0           | 14630.6          | 275.186            | 13091.7             | 16169.5             | -255.6   |
| 5   | 14394.0           | 14375.3          | 264.498            | 12851.0             | 15899.7             | 18.6928  |
| 6   | 14166.0           | 13629.1          | 358.870            | 11962.6             | 15295.6             | 536.9    |
| 7   | 13079.0           | 13345.3          | 371.734            | 11657.3             | 15033.4             | -266.3   |
| 8   | .                 | 11644.9          | 623.529            | 9458.3              | 13831.6             | .        |
| 9   | .                 | 14389.7          | 607.029            | 12239.2             | 16540.3             | .        |
| 10  | .                 | 13127.5          | 380.117            | 11425.1             | 14829.9             | .        |
| 11  | .                 | 13728.2          | 280.929            | 12181.3             | 15275.0             | .        |
| 12  | .                 | 14633.5          | 701.960            | 12270.7             | 16996.3             | .        |
| 13  | .                 | 13052.7          | 562.952            | 10996.6             | 15108.7             | .        |
| 14  | .                 | 14070.0          | 222.927            | 12597.7             | 15542.2             | .        |
| 15  | .                 | 14545.1          | 425.333            | 12762.2             | 16328.1             | .        |
| 16  | .                 | 14081.9          | 383.379            | 12373.8             | 15789.9             | .        |
| 17  | .                 | 14581.6          | 347.979            | 12933.0             | 16230.2             | .        |
| 18  | .                 | 14716.9          | 216.269            | 13252.4             | 16181.5             | .        |
| 19  | .                 | 14841.1          | 526.454            | 12861.0             | 16821.2             | .        |
| 20  | .                 | 14286.9          | 382.705            | 12580.0             | 15993.7             | .        |
| 21  | .                 | 15147.5          | 620.903            | 12966.6             | 17328.3             | .        |
| 22  | .                 | 14526.5          | 267.731            | 12997.8             | 16055.2             | .        |
| 23  | .                 | 15405.1          | 721.492            | 12997.4             | 17812.8             | .        |

Sum of Residuals 43.36123

Sum of Squared Residuals 925938.3550

Predicted Resid SS (Press) 3556090.1815

Model: MODEL2

NOTE: No intercept in model. R-square is redefined.

Dependent Variable: THRUST

# Analysis of Variance

| Source   | DF          | Sum of Squares | Mean Square  | F Value  | Prob>F |
|----------|-------------|----------------|--------------|----------|--------|
| Model    | 4           | 1413417256.6   | 353354314.14 | 8470.513 | 0.0001 |
| Error    | 3           | 125147.43104   | 41715.81035  |          |        |
| U Total  | 7           | 1413542404     |              |          |        |
| Root MSE | 204.24449   | R-square       | 0.9999       |          |        |
| Dep Mean | 14202.57143 | Adj R-sq       | 0.9998       |          |        |
| C.V.     | 1.43808     |                |              |          |        |

# Parameter Estimates

| Variable | DF | Parameter Estimate | Standard Error | T for H0:<br>Parameter=0 | Prob >  T |
|----------|----|--------------------|----------------|--------------------------|-----------|
| PIC      | 1  | 2221.176536        | 451.28504867   | 4.922                    | 0.0161    |
| ALPHA    | 1  | -17745             | 16601.933980   | -1.069                   | 0.3635    |
| PICSQ    | 1  | -75.604434         | 23.93552439    | -3.159                   | 0.0509    |
| B        | 1  | 882.244408         | 888.27395877   | 0.993                    | 0.3938    |

## MODELING MISSION FUEL CONSUMPTION AND THRUST AT SEA LEVEL

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| Obs | Dep Var<br>THRUST | Predict<br>Value | Std Err<br>Predict | Lower95%<br>Predict | Upper95%<br>Predict | Residual |
|-----|-------------------|------------------|--------------------|---------------------|---------------------|----------|
| 1   | 14539.0           | 14501.9          | 152.187            | 13691.3             | 15312.5             | 37.0716  |
| 2   | 14400.0           | 14369.3          | 183.465            | 13495.6             | 15243.0             | 30.6909  |
| 3   | 14465.0           | 14646.1          | 133.104            | 13870.2             | 15421.9             | -181.1   |
| 4   | 14375.0           | 14459.6          | 116.944            | 13710.5             | 15208.6             | -84.5515 |
| 5   | 14394.0           | 14131.5          | 112.686            | 13389.1             | 14873.8             | 262.5    |
| 6   | 14166.0           | 14121.4          | 185.689            | 13242.9             | 14999.9             | 44.5927  |
| 7   | 13079.0           | 13188.5          | 177.404            | 12327.5             | 14049.5             | -109.5   |
| 8   | .                 | 13354.9          | 307.202            | 12180.8             | 14528.9             | .        |
| 9   | .                 | 13022.1          | 461.415            | 11416.2             | 14628.0             | .        |
| 10  | .                 | 13772.1          | 186.891            | 12891.1             | 14653.2             | .        |
| 11  | .                 | 13733.1          | 119.486            | 12980.0             | 14486.1             | .        |
| 12  | .                 | 13615.8          | 425.354            | 12114.2             | 15117.5             | .        |
| 13  | .                 | 14116.4          | 282.636            | 13006.6             | 15226.1             | .        |
| 14  | .                 | 14126.4          | 109.933            | 13388.3             | 14864.6             | .        |
| 15  | .                 | 14136.5          | 190.575            | 13247.5             | 15025.5             | .        |
| 16  | .                 | 14319.5          | 174.783            | 13463.9             | 15175.0             | .        |
| 17  | .                 | 14466.9          | 146.357            | 13667.2             | 15266.5             | .        |
| 18  | .                 | 14563.6          | 88.706             | 13855.0             | 15272.3             | .        |
| 19  | .                 | 14261.9          | 281.128            | 13156.0             | 15367.8             | .        |
| 20  | .                 | 14811.4          | 206.379            | 13887.3             | 15735.5             | .        |
| 21  | .                 | 14006.4          | 446.341            | 12444.2             | 15568.5             | .        |
| 22  | .                 | 14550.8          | 114.846            | 13805.1             | 15296.5             | .        |
| 23  | .                 | 13599.6          | 671.916            | 11364.6             | 15834.5             | .        |

Sum of Residuals -0.20635

Sum of Squared Residuals 125147.4310

Predicted Resid SS (Press) 554407.0485

Model: MODEL3

NOTE: No intercept in model. R-square is redefined.

Dependent Variable: THRUST

# Analysis of Variance

| Source   | DF          | Sum of Squares | Mean Square | F Value  | Prob>F |
|----------|-------------|----------------|-------------|----------|--------|
| Model    | 4           | 1413414284     | 353353571   | 8273.967 | 0.0001 |
| Error    | 3           | 128120.00466   | 42706.66822 |          |        |
| U Total  | 7           | 1413542404     |             |          |        |
| Root MSE | 206.65592   | R-square       | 0.9999      |          |        |
| Dep Mean | 14202.57143 | Adj R-sq       | 0.9998      |          |        |
| C.V.     | 1.45506     |                |             |          |        |

# Parameter Estimates

| Variable | DF | Parameter Estimate | Standard Error | T for H0:<br>Parameter=0 | Prob >  T |
|----------|----|--------------------|----------------|--------------------------|-----------|
| PIC      | 1  | 2266.201050        | 520.67499340   | 4.352                    | 0.0224    |
| ALPHA    | 1  | -19381             | 19154.638118   | -1.012                   | 0.3861    |
| ALPHASQ  | 1  | 17425              | 18429.262131   | 0.946                    | 0.4142    |
| PICSQ    | 1  | -64.634572         | 13.61000100    | -4.749                   | 0.0177    |

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| Obs | Dep Var<br>THRUST | Predict<br>Value | Std Err<br>Predict | Lower95%<br>Predict | Upper95%<br>Predict | Residual |
|-----|-------------------|------------------|--------------------|---------------------|---------------------|----------|
| 1   | 14539.0           | 14485.8          | 150.796            | 13671.6             | 15299.9             | 53.2393  |
| 2   | 14400.0           | 14378.4          | 182.394            | 13501.2             | 15255.6             | 21.5818  |
| 3   | 14465.0           | 14657.0          | 140.714            | 13861.4             | 15452.7             | -192.0   |
| 4   | 14375.0           | 14461.4          | 118.362            | 13703.5             | 15219.3             | -86.4206 |
| 5   | 14394.0           | 14135.8          | 113.857            | 13384.9             | 14886.7             | 258.2    |
| 6   | 14166.0           | 14114.5          | 186.141            | 13229.3             | 14999.6             | 51.5289  |
| 7   | 13079.0           | 13184.7          | 182.751            | 12306.7             | 14062.7             | -105.7   |
| 8   | .                 | 13337.6          | 303.866            | 12168.1             | 14507.1             | .        |
| 9   | .                 | 13380.3          | 262.675            | 12316.7             | 14444.0             | .        |
| 10  | .                 | 13730.7          | 166.686            | 12885.7             | 14575.6             | .        |
| 11  | .                 | 13697.8          | 122.609            | 12933.1             | 14462.5             | .        |
| 12  | .                 | 14121.9          | 363.302            | 12791.7             | 15452.1             | .        |
| 13  | .                 | 14234.5          | 384.411            | 12845.5             | 15623.4             | .        |
| 14  | .                 | 14081.6          | 96.167             | 13356.2             | 14807.0             | .        |
| 15  | .                 | 14277.2          | 195.278            | 13372.4             | 15182.1             | .        |
| 16  | .                 | 14369.0          | 205.531            | 13441.4             | 15296.6             | .        |
| 17  | .                 | 14531.8          | 170.192            | 13679.8             | 15383.8             | .        |
| 18  | .                 | 14529.8          | 94.339             | 13806.9             | 15252.8             | .        |
| 19  | .                 | 14490.3          | 236.633            | 13490.5             | 15490.1             | .        |
| 20  | .                 | 14881.6          | 260.424            | 13823.5             | 15939.6             | .        |
| 21  | .                 | 14357.0          | 267.308            | 13281.8             | 15432.3             | .        |
| 22  | .                 | 14159.8          | 125.044            | 13751.1             | 15288.5             | .        |
| 23  | .                 | 14094.5          | 325.949            | 12866.3             | 15322.8             | .        |

Sum of Residuals 0.34916  
Sum of Squared Residuals 128120.0047  
Predicted Resid SS (Press) 614342.9747

Model: MODEL4  
Dependent Variable: FUEL

# Analysis of Variance

| Source   | DF         | Sum of Squares | Mean Square | F Value | Prob>F |
|----------|------------|----------------|-------------|---------|--------|
| Model    | 4          | 137787.25036   | 34446.81259 | 61.723  | 0.0160 |
| Error    | 2          | 1116.17822     | 558.08911   |         |        |
| C Total  | 6          | 138903.42857   |             |         |        |
| Root MSE | 23.62391   | R-square       | 0.9920      |         |        |
| Dep Mean | 8302.28571 | Adj R-sq       | 0.9759      |         |        |
| C.V.     | 0.28455    |                |             |         |        |

# Parameter Estimates

| Variable | DF | Parameter Estimate | Standard Error | T for H0:<br>Parameter=0 | Prob >  T |
|----------|----|--------------------|----------------|--------------------------|-----------|
| INTERCEP | 1  | 11472              | 705.32403309   | 16.265                   | 0.0038    |
| PIC      | 1  | -235.758661        | 77.15070873    | -3.056                   | 0.0925    |
| ALPHA    | 1  | -1749.844789       | 2073.4895355   | -0.844                   | 0.4876    |
| PICSQ    | 1  | 4.389897           | 2.90845631     | 1.509                    | 0.2703    |
| B        | 1  | 58.108370          | 112.43356293   | 0.517                    | 0.6568    |

## MODELING MISSION FUEL CONSUMPTION AND THRUST AT SEA LEVEL

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| Obs | Dep Var<br>FUEL | Predict<br>Value | Std Err<br>Predict | Lower95%<br>Predict | Upper95%<br>Predict | Residual |
|-----|-----------------|------------------|--------------------|---------------------|---------------------|----------|
| 1   | 8579.0          | 8572.5           | 22.987             | 8430.7              | 8714.3              | 6.5078   |
| 2   | 8410.0          | 8414.1           | 21.260             | 8277.3              | 8550.8              | -4.0527  |
| 3   | 8314.0          | 8334.4           | 18.705             | 8204.7              | 8464.0              | -20.3514 |
| 4   | 8268.0          | 8264.0           | 15.074             | 8143.4              | 8384.5              | 4.0380   |
| 5   | 8243.0          | 8219.4           | 15.756             | 8097.2              | 8341.6              | 23.6200  |
| 6   | 8159.0          | 8160.6           | 21.894             | 8022.0              | 8299.2              | -1.6123  |
| 7   | 8143.0          | 8151.1           | 22.480             | 8010.8              | 8291.5              | -8.1494  |
| 8   | .               | 8104.0           | 47.431             | 7876.0              | 8332.0              | .        |
| 9   | .               | 8198.3           | 54.943             | 7941.0              | 8455.6              | .        |
| 10  | .               | 8139.7           | 24.431             | 7993.5              | 8285.9              | .        |
| 11  | .               | 8166.2           | 14.053             | 8047.9              | 8284.5              | .        |
| 12  | .               | 8245.6           | 54.721             | 7989.2              | 8502.1              | .        |
| 13  | .               | 8131.2           | 34.430             | 7951.6              | 8310.9              | .        |
| 14  | .               | 8190.0           | 12.922             | 8074.1              | 8305.9              | .        |
| 15  | .               | 8248.8           | 26.893             | 8094.7              | 8402.8              | .        |
| 16  | .               | 8190.3           | 20.246             | 8056.4              | 8324.2              | .        |
| 17  | .               | 8287.2           | 21.908             | 8148.5              | 8425.8              | .        |
| 18  | .               | 8324.6           | 12.692             | 8209.2              | 8440.0              | .        |
| 19  | .               | 8276.0           | 33.151             | 8100.9              | 8451.2              | .        |
| 20  | .               | 8428.4           | 24.444             | 8282.1              | 8574.7              | .        |
| 21  | .               | 8332.0           | 52.028             | 8086.2              | 8577.9              | .        |
| 22  | .               | 8455.1           | 13.346             | 8338.3              | 8571.8              | .        |
| 23  | .               | 8396.8           | 77.858             | 8046.8              | 8746.9              | .        |

Sum of Residuals 9.5E-13  
Sum of Squared Residuals 1116.1782  
Predicted Resid SS (Press) 27807.6847

Model: MODEL5  
Dependent Variable: FUEL

Analysis of Variance

| Source   | DF         | Sum of Squares | Mean Square | F Value | Prob>F |
|----------|------------|----------------|-------------|---------|--------|
| Model    | 4          | 137757.89584   | 34439.47396 | 60.128  | 0.0164 |
| Error    | 2          | 1145.53273     | 572.76636   |         |        |
| C Total  | 6          | 138903.42857   |             |         |        |
| Root MSE | 23.93254   | R-square       | 0.9918      |         |        |
| Dep Mean | 8302.28571 | Adj R-sq       | 0.9753      |         |        |
| C.V.     | 0.28826    |                |             |         |        |

Parameter Estimates

| Variable | DF | Parameter Estimate | Standard Error | T for H0:<br>Parameter=0 | Prob >  T |
|----------|----|--------------------|----------------|--------------------------|-----------|
| INTERCEP | 1  | 11496              | 753.57667504   | 15.256                   | 0.0043    |
| PIC      | 1  | -236.101345        | 78.82521667    | -2.995                   | 0.0957    |
| ALPHA    | 1  | -1833.003889       | 2522.8309458   | -0.727                   | 0.5430    |
| ALPHASQ  | 1  | 1126.117952        | 2463.1919266   | 0.457                    | 0.6924    |
| PICSQ    | 1  | 5.200016           | 2.08497870     | 2.494                    | 0.1301    |

## MODELING MISSION FUEL CONSUMPTION AND THRUST AT SEA LEVEL

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| Obs | Dep Var<br>FUEL | Predict<br>Value | Std Err<br>Predict | Lower95%<br>Predict | Upper95%<br>Predict | Residual |
|-----|-----------------|------------------|--------------------|---------------------|---------------------|----------|
| 1   | 8579.0          | 8571.8           | 23.176             | 8428.5              | 8715.2              | 7.1653   |
| 2   | 8410.0          | 8415.0           | 21.296             | 8277.1              | 8552.8              | -4.9841  |
| 3   | 8314.0          | 8334.5           | 18.999             | 8203.1              | 8466.0              | -20.5421 |
| 4   | 8268.0          | 8263.9           | 15.373             | 8141.5              | 8386.2              | 4.1465   |
| 5   | 8243.0          | 8219.4           | 16.104             | 8095.3              | 8343.5              | 23.6189  |
| 6   | 8159.0          | 8160.0           | 22.339             | 8019.1              | 8300.8              | -0.9537  |
| 7   | 8143.0          | 8151.5           | 22.750             | 8009.4              | 8293.5              | -8.4507  |
| 8   | .               | 8103.3           | 50.162             | 7864.1              | 8342.4              | .        |
| 9   | .               | 8222.1           | 30.920             | 8053.9              | 8390.4              | .        |
| 10  | .               | 8137.1           | 22.243             | 7996.5              | 8277.6              | .        |
| 11  | .               | 8164.0           | 14.205             | 8044.2              | 8283.7              | .        |
| 12  | .               | 8278.4           | 42.423             | 8068.9              | 8488.0              | .        |
| 13  | .               | 8138.7           | 49.942             | 7900.4              | 8377.0              | .        |
| 14  | .               | 8186.9           | 12.114             | 8071.4              | 8302.3              | .        |
| 15  | .               | 8257.5           | 23.850             | 8112.2              | 8402.9              | .        |
| 16  | .               | 8193.3           | 24.044             | 8047.3              | 8339.2              | .        |
| 17  | .               | 8290.8           | 22.118             | 8150.6              | 8431.1              | .        |
| 18  | .               | 8322.1           | 15.001             | 8200.6              | 8443.7              | .        |
| 19  | .               | 8291.1           | 28.203             | 8131.9              | 8450.2              | .        |
| 20  | .               | 8432.4           | 30.178             | 8266.7              | 8598.2              | .        |
| 21  | .               | 8355.6           | 33.346             | 8179.0              | 8532.2              | .        |
| 22  | .               | 8453.1           | 14.518             | 8332.7              | 8573.6              | .        |
| 23  | .               | 8430.5           | 43.125             | 8218.2              | 8642.7              | .        |

Sum of Residuals 0

Sum of Squared Residuals 1145.5327

Predicted Resid SS (Press) 26573.8607

Model: MODEL6  
Dependent Variable: FUEL

Analysis of Variance

| Source   | DF         | Sum of Squares | Mean Square | F Value | Prob>F |
|----------|------------|----------------|-------------|---------|--------|
| Model    | 5          | 138594.90499   | 27718.98100 | 89.844  | 0.0799 |
| Error    | 1          | 308.52359      | 308.52359   |         |        |
| C Total  | 6          | 138903.42857   |             |         |        |
| Root MSE | 17.56484   | R-square       | 0.9978      |         |        |
| Dep Mean | 8302.28571 | Adj R-sq       | 0.9867      |         |        |
| C.V.     | 0.21157    |                |             |         |        |

Parameter Estimates

| Variable | DF | Parameter Estimate | Standard Error | T for H0:<br>Parameter=0 | Prob >  T |
|----------|----|--------------------|----------------|--------------------------|-----------|
| INTERCEP | 1  | 17739              | 3908.4586594   | 4.539                    | 0.1381    |
| PIC      | 1  | -758.240366        | 327.98085619   | -2.312                   | 0.2599    |
| ALPHA    | 1  | -17795             | 10036.114849   | -1.773                   | 0.3269    |
| PICSQ    | 1  | 6.451742           | 2.51004741     | 2.570                    | 0.2362    |
| B        | 1  | 1487.021376        | 887.10306668   | 1.676                    | 0.3424    |
| D        | 1  | -28.945486         | 17.89007601    | -1.618                   | 0.3524    |

## MODELING MISSION FUEL CONSUMPTION AND THRUST AT SEA LEVEL

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13:09 Friday, October 16, 1992

| Obs | Dep Var<br>FUEL | Predict<br>Value | Std Err<br>Predict | Lower95%<br>Predict | Upper95%<br>Predict | Residual |
|-----|-----------------|------------------|--------------------|---------------------|---------------------|----------|
| 1   | 8579.0          | 8579.0           | 17.565             | 8263.4              | 8894.7              | -0.0477  |
| 2   | 8410.0          | 8404.9           | 16.797             | 8096.1              | 8713.7              | 5.1377   |
| 3   | 8314.0          | 8319.0           | 16.850             | 8009.7              | 8628.2              | -4.9590  |
| 4   | 8268.0          | 8278.2           | 14.267             | 7990.7              | 8565.8              | -10.2456 |
| 5   | 8243.0          | 8233.0           | 14.410             | 7944.3              | 8521.6              | 10.0431  |
| 6   | 8159.0          | 8153.9           | 16.802             | 7845.0              | 8462.7              | 5.1198   |
| 7   | 8143.0          | 8148.0           | 16.824             | 7839.0              | 8457.1              | -5.0483  |
| 8   | .               | 7958.8           | 96.411             | 6713.7              | 9204.0              | .        |
| 9   | .               | 8057.1           | 96.366             | 6812.5              | 9301.7              | .        |
| 10  | .               | 8125.1           | 20.273             | 7784.3              | 8466.0              | .        |
| 11  | .               | 8187.5           | 16.821             | 7878.5              | 8496.5              | .        |
| 12  | .               | 7991.7           | 162.139            | 5919.5              | 10063.9             | .        |
| 13  | .               | 8027.5           | 69.029             | 7122.5              | 8932.5              | .        |
| 14  | .               | 8222.4           | 22.193             | 7862.7              | 8582.0              | .        |
| 15  | .               | 8185.7           | 43.829             | 7585.7              | 8785.6              | .        |
| 16  | .               | 8174.7           | 17.882             | 7856.2              | 8493.2              | .        |
| 17  | .               | 8251.7           | 27.301             | 7839.2              | 8664.2              | .        |
| 18  | .               | 8343.3           | 14.946             | 8050.3              | 8636.4              | .        |
| 19  | .               | 8192.5           | 57.211             | 7432.1              | 8952.9              | .        |
| 20  | .               | 8368.7           | 41.143             | 7800.3              | 8937.1              | .        |
| 21  | .               | 8189.5           | 96.233             | 6946.5              | 9432.4              | .        |
| 22  | .               | 8457.0           | 9.994              | 8200.2              | 8713.8              | .        |
| 23  | .               | 8178.5           | 146.828            | 6299.6              | 10057.4             | .        |

Sum of Residuals 9.98E-13

Sum of Squared Residuals 308.5236

Predicted Resid SS (Press) 41932612.664

### **Appendix G: SAS Modeling Results for the Six-Variable Design Example**

**This appendix contains the SAS results used for determining the best design choices for the six-variable analysis example .**

```

TITLE 'MODELING MISSION FUEL CONSUMPTION AND THRUST AT SEA LEVEL';
OPTIONS LINESIZE=78;
DATA ENGINES;
  INPUT FUEL THRUST MACH ALT PIC ALPHA PICP MDOT;
  PICSQ=PIC**2;
  MACHSQ=MACH**2;
  ALTSQ=ALT**2;
  ALPHASQ=ALPHA**2;
  PICPSQ=PICP**2;
  MDOTSQ=MDOT**2;
  B=PIC*ALPHA;
  C=PICP*ALPHA;
  D=PIC**2*ALPHA**2;
CARDS;
8203 14972 1.5 30 20 .5 3.6 115
7784 15029 1.7 35 18 .7 3.6 120
8268 12904 1.5 25 21 .5 3.3 130
8579 14539 1.6 35 15 .4 3.7 100
8118 17004 1.4 30 18 .55 3.5 120
7895 17710 1.6 38 22 .5 3.7 120
8130 14161 1.4 25 22 .6 3.6 130
8393 12820 1.7 30 18 .5 3.4 120
7997 18288 1.4 35 17 .7 3.7 110
8071 12855 1.6 35 22 .65 3.7 100
8292 14509 1.6 35 20 .45 3.7 100
8190 14308 1.6 35 19 .6 3.7 100
8048 16469 1.5 35 19 .6 3.7 105
7911 17653 1.5 40 20 .6 3.7 90
;
PROC PRINT;
PROC REG SIMPLE;
  MODEL FUEL=MACH ALT PIC ALPHA ALPHASQ PICSQ MDOTSQ/NOINT CLI;
  MODEL FUEL=MACH ALT PIC ALPHA ALPHASQ PICSQ PICPSQ/NOINT CLI;
  MODEL FUEL=MACH ALT PIC D ALPHASQ PICSQ MDOTSQ/NOINT CLI;
  MODEL THRUST=MACH ALT PIC ALPHA ALPHASQ PICSQ MDOTSQ/CLI;
  MODEL THRUST=MACH ALT PIC D ALPHASQ PICSQ MDOTSQ/CLI;

```

## MODELING MISSION FUEL CONSUMPTION AND THRUST AT SEA LEVEL

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12:19 Wednesday, October 14, 1992

| OBS | FUEL | THRUST | MACH | ALT | PIC | ALPHA | PICP | MDOT | PICSQ | MACHSQ |
|-----|------|--------|------|-----|-----|-------|------|------|-------|--------|
| 1   | 8203 | 14972  | 1.5  | 30  | 20  | 0.50  | 3.6  | 115  | 400   | 2.25   |
| 2   | 7784 | 15029  | 1.7  | 35  | 18  | 0.70  | 3.6  | 120  | 324   | 2.89   |
| 3   | 8268 | 12904  | 1.5  | 25  | 21  | 0.50  | 3.3  | 130  | 441   | 2.25   |
| 4   | 8579 | 14539  | 1.6  | 35  | 15  | 0.40  | 3.7  | 100  | 225   | 2.56   |
| 5   | 8118 | 17004  | 1.4  | 30  | 18  | 0.55  | 3.5  | 120  | 324   | 1.96   |
| 6   | 7895 | 17710  | 1.6  | 38  | 22  | 0.50  | 3.7  | 120  | 484   | 2.56   |
| 7   | 8130 | 14161  | 1.4  | 25  | 22  | 0.60  | 3.6  | 130  | 484   | 1.96   |
| 8   | 8393 | 12820  | 1.7  | 30  | 18  | 0.50  | 3.4  | 120  | 324   | 2.89   |
| 9   | 7997 | 18288  | 1.4  | 35  | 17  | 0.70  | 3.7  | 110  | 289   | 1.96   |
| 10  | 8071 | 12855  | 1.6  | 35  | 22  | 0.65  | 3.7  | 100  | 484   | 2.56   |
| 11  | 8292 | 14509  | 1.6  | 35  | 20  | 0.45  | 3.7  | 100  | 400   | 2.56   |
| 12  | 8190 | 14308  | 1.6  | 35  | 19  | 0.60  | 3.7  | 100  | 361   | 2.56   |
| 13  | 8048 | 16469  | 1.5  | 35  | 19  | 0.60  | 3.7  | 105  | 361   | 2.25   |
| 14  | 7911 | 17653  | 1.5  | 40  | 20  | 0.60  | 3.7  | 90   | 400   | 2.25   |

| OBS | ALTSQ | ALPHASQ | PICPSQ | MDOTSQ | B    | C     | D      |
|-----|-------|---------|--------|--------|------|-------|--------|
| 1   | 900   | 0.2500  | 12.96  | 13225  | 10.0 | 1.800 | 100.00 |
| 2   | 1225  | 0.4900  | 12.96  | 14400  | 12.6 | 2.520 | 158.76 |
| 3   | 625   | 0.2500  | 10.89  | 16900  | 10.5 | 1.650 | 110.25 |
| 4   | 1225  | 0.1600  | 13.69  | 10000  | 6.0  | 1.480 | 36.00  |
| 5   | 900   | 0.3025  | 12.25  | 14400  | 9.9  | 1.925 | 98.01  |
| 6   | 1444  | 0.2500  | 13.69  | 14400  | 11.0 | 1.850 | 121.00 |
| 7   | 625   | 0.3600  | 12.96  | 16900  | 13.2 | 2.160 | 174.24 |
| 8   | 900   | 0.2500  | 11.56  | 14400  | 9.0  | 1.700 | 81.00  |
| 9   | 1225  | 0.4900  | 13.69  | 12100  | 11.9 | 2.590 | 141.61 |
| 10  | 1225  | 0.4225  | 13.69  | 10000  | 14.3 | 2.405 | 204.49 |
| 11  | 1225  | 0.2025  | 13.69  | 10000  | 9.0  | 1.665 | 81.00  |
| 12  | 1225  | 0.3600  | 13.69  | 10000  | 11.4 | 2.220 | 129.96 |
| 13  | 1225  | 0.3600  | 13.69  | 11025  | 11.4 | 2.220 | 129.96 |
| 14  | 1600  | 0.3600  | 13.69  | 8100   | 12.0 | 2.220 | 144.00 |

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## Descriptive Statistics

| Variables | Sum     | Mean         | Uncorrected SS |
|-----------|---------|--------------|----------------|
| INTERCEP  | 14      | 1            | 14             |
| MACH      | 21.6    | 1.5428571429 | 33.46          |
| ALT       | 463     | 33.071428571 | 15569          |
| PIC       | 271     | 19.357142857 | 5301           |
| ALPHA     | 7.85    | 0.5607142857 | 4.5075         |
| ALPHASQ   | 4.5075  | 0.3219642857 | 1.58521875     |
| PICSQ     | 5301    | 378.64285714 | 2086965        |
| MDOTSQ    | 175850  | 12560.714286 | 2309131250     |
| FUEL      | 113879  | 8134.2142857 | 926891867      |
| PICPSQ    | 183.1   | 13.078571429 | 2405.5018      |
| D         | 1710.28 | 122.16285714 | 232769.0932    |
| THRUST    | 213221  | 15230.071429 | 3293382083     |

| Variables | Variance     | Std Deviation |
|-----------|--------------|---------------|
| INTERCEP  | 0            | 0             |
| MACH      | 0.0103296703 | 0.1016349858  |
| ALT       | 19.763736264 | 4.4456423904  |
| PIC       | 4.2472527473 | 2.0608863984  |
| ALPHA     | 0.0081456044 | 0.0902530021  |
| ALPHASQ   | 0.0103049794 | 0.1015134444  |
| PICSQ     | 6136.8626374 | 78.338130163  |
| MDOTSQ    | 7717664.8352 | 2778.068544   |
| FUEL      | 44282.950549 | 210.43514571  |
| PICPSQ    | 0.8319516484 | 0.9121138352  |
| D         | 1833.5693758 | 42.820198223  |
| THRUST    | 3539309.456  | 1881.3052533  |

Model: MODEL1

NOTE: No intercept in model. R-square is redefined.

Dependent Variable: FUEL

# Analysis of Variance

| Source   | DF         | Sum of Squares | Mean Square  | F Value  | Prob>F |
|----------|------------|----------------|--------------|----------|--------|
| Model    | 7          | 926489467.26   | 132355638.18 | 2302.411 | 0.0001 |
| Error    | 7          | 402399.73569   | 57485.67653  |          |        |
| U Total  | 14         | 926891867      |              |          |        |
| Root MSE | 239.76171  | R-square       | 0.9996       |          |        |
| Dep Mean | 8134.21429 | Adj R-sq       | 0.9991       |          |        |
| C.V.     | 2.94757    |                |              |          |        |

# Parameter Estimates

| Variable | DF | Parameter Estimate | Standard Error | T for H0:<br>Parameter=0 | Prob >  T |
|----------|----|--------------------|----------------|--------------------------|-----------|
| MACH     | 1  | 572.833042         | 779.50133272   | 0.735                    | 0.4863    |
| ALT      | 1  | -27.906763         | 26.05537616    | -1.071                   | 0.3197    |
| PIC      | 1  | 961.144625         | 518.38092227   | 1.854                    | 0.1061    |
| ALPHA    | 1  | 750.043663         | 16155.568176   | 0.046                    | 0.9643    |
| ALPHASQ  | 1  | -2126.812070       | 14114.001294   | -0.151                   | 0.8845    |
| PICSQ    | 1  | -25.960271         | 12.86106263    | -2.019                   | 0.0833    |
| MDOTSQ   | 1  | -0.027051          | 0.03917372     | -0.691                   | 0.5121    |

MODELING MISSION FUEL CONSUMPTION AND THRUST AT SEA LEVEL 4  
12:19 Wednesday, October 14, 1992

| Obs | Dep Var<br>FUEL | Predict<br>Value | Std Err<br>Predict | Lower95%<br>Predict | Upper95%<br>Predict | Residual |
|-----|-----------------|------------------|--------------------|---------------------|---------------------|----------|
| 1   | 8203.0          | 8346.4           | 110.395            | 7722.2              | 8970.6              | -143.4   |
| 2   | 7784.0          | 7979.9           | 204.937            | 7234.1              | 8725.8              | -195.9   |
| 3   | 8268.0          | 8283.3           | 151.217            | 7613.0              | 8953.6              | -15.2955 |
| 4   | 8579.0          | 8205.1           | 173.681            | 7505.0              | 8905.2              | 373.9    |
| 5   | 8118.0          | 8233.9           | 158.449            | 7554.3              | 8913.4              | -115.9   |
| 6   | 7895.0          | 7890.3           | 231.530            | 7102.1              | 8678.4              | 4.7287   |
| 7   | 8130.0          | 7911.9           | 160.967            | 7229.0              | 8594.8              | 218.1    |
| 8   | 8393.0          | 8479.9           | 173.092            | 7780.6              | 9179.1              | -86.8736 |
| 9   | 7997.0          | 7817.7           | 191.434            | 7092.2              | 8543.2              | 179.3    |
| 10  | 8071.0          | 7838.6           | 178.216            | 7132.2              | 8545.1              | 232.4    |
| 11  | 8292.0          | 8414.9           | 196.550            | 7681.8              | 9148.0              | -122.9   |
| 12  | 8190.0          | 8243.8           | 137.232            | 7590.5              | 8897.0              | -53.7504 |
| 13  | 8048.0          | 8158.7           | 103.796            | 7540.9              | 8776.5              | -110.7   |
| 14  | 7911.0          | 8047.0           | 154.766            | 7372.2              | 8721.8              | -136.0   |

Sum of Residuals 27.51616  
Sum of Squared Residuals 402399.7357  
Predicted Resid SS (Press) 2153167.3292

Model: MODEL2

NOTE: No intercept in model. R-square is redefined.

Dependent Variable: FUEL

# Analysis of Variance

| Source   | DF         | Sum of Squares | Mean Square  | F Value  | Prob>F |
|----------|------------|----------------|--------------|----------|--------|
| Model    | 7          | 926652389.08   | 132378912.73 | 3869.469 | 0.0001 |
| Error    | 7          | 239477.91551   | 34211.13079  |          |        |
| U Total  | 14         | 926891867      |              |          |        |
| Root MSE | 184.96251  | R-square       | 0.9997       |          |        |
| Dep Mean | 8134.21429 | Adj R-sq       | 0.9995       |          |        |
| C.V.     | 2.27388    |                |              |          |        |

# Parameter Estimates

| Variable | DF | Parameter Estimate | Standard Error | T for H0: Parameter=0 | Prob >  T |
|----------|----|--------------------|----------------|-----------------------|-----------|
| MACH     | 1  | 899.931461         | 616.91201063   | 1.459                 | 0.1880    |
| ALT      | 1  | -51.084435         | 20.28806379    | -2.518                | 0.0399    |
| PIC      | 1  | 555.164873         | 420.17671073   | 1.321                 | 0.2280    |
| ALPHA    | 1  | 5563.412736        | 12620.004285   | 0.441                 | 0.6726    |
| ALPHASQ  | 1  | -6437.671430       | 11024.625782   | -0.584                | 0.5776    |
| PICSQ    | 1  | -15.985206         | 10.42460535    | -1.533                | 0.1690    |
| PICPSQ   | 1  | 205.962298         | 87.32001637    | 2.359                 | 0.0504    |

MODELING MISSION FUEL CONSUMPTION AND THRUST AT SEA LEVEL 6  
12:19 Wednesday, October 14, 1992

| Obs | Dep Var<br>FUEL | Predict<br>Value | Std Err<br>Predict | Lower95%<br>Predict | Upper95%<br>Predict | Residual |
|-----|-----------------|------------------|--------------------|---------------------|---------------------|----------|
| 1   | 8203.0          | 8368.1           | 83.940             | 7887.8              | 8848.4              | -165.1   |
| 2   | 7784.0          | 7964.9           | 151.988            | 7398.8              | 8531.0              | -180.9   |
| 3   | 8268.0          | 8097.0           | 142.695            | 7544.6              | 8649.4              | 171.0    |
| 4   | 8579.0          | 8397.7           | 156.027            | 7825.5              | 8969.9              | 181.3    |
| 5   | 8118.0          | 8176.7           | 123.484            | 7650.8              | 8702.5              | -58.6516 |
| 6   | 7895.0          | 7967.4           | 128.265            | 7435.1              | 8499.6              | -72.3818 |
| 7   | 8130.0          | 8149.3           | 155.807            | 7577.5              | 8721.2              | -19.3381 |
| 8   | 8393.0          | 8364.3           | 142.099            | 7812.8              | 8915.9              | 28.6758  |
| 9   | 7997.0          | 7849.6           | 144.761            | 7294.2              | 8405.0              | 147.4    |
| 10  | 8071.0          | 7844.6           | 120.983            | 7322.0              | 8367.3              | 226.4    |
| 11  | 8292.0          | 8380.7           | 142.487            | 7828.6              | 8932.8              | -88.6814 |
| 12  | 8190.0          | 8269.5           | 92.302             | 7780.7              | 8758.3              | -79.5182 |
| 13  | 8048.0          | 8179.5           | 79.451             | 7703.5              | 8655.5              | -131.5   |
| 14  | 7911.0          | 7855.8           | 133.155            | 7316.9              | 8394.8              | 55.1552  |

Sum of Residuals 13.78584  
Sum of Squared Residuals 239477.9155  
Predicted Resid SS (Press) 1366258.7671

Model: MODEL3

NOTE: No intercept in model. R-square is redefined.

Dependent Variable: FUEL

# Analysis of Variance

| Source   | DF | Sum of Squares | Mean Square  | F Value  | Prob>F |
|----------|----|----------------|--------------|----------|--------|
| Model    | 7  | 926638920.98   | 132376988.71 | 3663.386 | 0.0001 |
| Error    | 7  | 252946.02116   | 36135.14588  |          |        |
| U Total  | 14 | 926891867      |              |          |        |
| Root MSE |    | 190.09247      | R-square     | 0.9997   |        |
| Dep Mean |    | 8134.21429     | Adj R-sq     | 0.9995   |        |
| C.V.     |    | 2.33695        |              |          |        |

# Parameter Estimates

| Variable | DF | Parameter Estimate | Standard Error | T for H0:<br>Parameter=0 | Prob >  T |
|----------|----|--------------------|----------------|--------------------------|-----------|
| MACH     | 1  | 102.961951         | 619.62076319   | 0.166                    | 0.8727    |
| ALT      | 1  | -6.991986          | 23.05783755    | -0.303                   | 0.7705    |
| PIC      | 1  | 1136.829226        | 139.72124993   | 8.136                    | 0.0001    |
| D        | 1  | 17.375389          | 8.54016273     | 2.035                    | 0.0814    |
| ALPHASQ  | 1  | -7577.532815       | 3053.4525697   | -2.482                   | 0.0421    |
| PICSQ    | 1  | -36.018544         | 5.71338691     | -6.304                   | 0.0004    |
| MDOTSQ   | 1  | 0.012339           | 0.03660211     | 0.337                    | 0.7459    |

MODELING MISSION FUEL CONSUMPTION AND THRUST AT SEA LEVEL 8  
12:19 Wednesday, October 14, 1992

| Obs | Dep Var<br>FUEL | Predict<br>Value | Std Err<br>Predict | Lower95%<br>Predict | Upper95%<br>Predict | Residual |
|-----|-----------------|------------------|--------------------|---------------------|---------------------|----------|
| 1   | 8203.0          | 8280.2           | 87.571             | 7785.3              | 8775.1              | -77.1841 |
| 2   | 7784.0          | 7946.4           | 155.877            | 7365.1              | 8527.7              | -162.4   |
| 3   | 8268.0          | 8198.7           | 121.958            | 7664.6              | 8732.7              | 69.3450  |
| 4   | 8579.0          | 8404.8           | 169.062            | 7803.2              | 9006.3              | 174.2    |
| 5   | 8118.0          | 8315.7           | 121.384            | 7782.4              | 8849.1              | -197.7   |
| 6   | 7895.0          | 7862.0           | 182.749            | 7238.5              | 8485.6              | 32.9738  |
| 7   | 8130.0          | 8054.7           | 145.136            | 7489.2              | 8620.3              | 75.2868  |
| 8   | 8393.0          | 8448.9           | 121.506            | 7915.4              | 8982.4              | -55.8928 |
| 9   | 7997.0          | 7713.0           | 149.209            | 7141.6              | 8284.4              | 284.0    |
| 10  | 8071.0          | 7972.3           | 155.606            | 7391.4              | 8553.2              | 98.7408  |
| 11  | 8292.0          | 8245.5           | 135.375            | 7693.7              | 8797.4              | 46.4712  |
| 12  | 8190.0          | 8170.7           | 95.351             | 7667.8              | 8673.5              | 19.3396  |
| 13  | 8048.0          | 8173.0           | 71.895             | 7692.4              | 8653.6              | -125.0   |
| 14  | 7911.0          | 8078.0           | 120.420            | 7545.9              | 8610.1              | -167.0   |

Sum of Residuals 15.09726  
Sum of Squared Residuals 252946.0212  
Predicted Resid SS (Press) 2051958.1201

Model: MODEL4  
Dependent Variable: THRUST

Analysis of Variance

| Source   | DF          | Sum of Squares | Mean Square  | F Value | Prob>F |
|----------|-------------|----------------|--------------|---------|--------|
| Model    | 7           | 45698053.07    | 6528293.2957 | 125.155 | 0.0001 |
| Error    | 6           | 312969.85843   | 52161.64307  |         |        |
| C Total  | 13          | 46011022.929   |              |         |        |
| Root MSE | 228.38924   | R-square       | 0.9932       |         |        |
| Dep Mean | 15230.07143 | Adj R-sq       | 0.9853       |         |        |
| C.V.     | 1.49959     |                |              |         |        |

Parameter Estimates

| Variable | DF | Parameter Estimate | Standard Error | T for H0: Parameter=0 | Prob >  T |
|----------|----|--------------------|----------------|-----------------------|-----------|
| INTERCEP | 1  | -9830.408896       | 5100.1114533   | -1.927                | 0.1022    |
| MACH     | 1  | -15210             | 744.27074445   | -20.435               | 0.0001    |
| ALT      | 1  | 609.068150         | 25.69605142    | 23.703                | 0.0001    |
| PIC      | 1  | 2443.924487        | 707.69540040   | 3.453                 | 0.0136    |
| ALPHA    | 1  | 5084.647466        | 15390.789693   | 0.330                 | 0.7524    |
| ALPHASQ  | 1  | -7317.429166       | 13444.542503   | -0.544                | 0.6059    |
| PICSQ    | 1  | -69.709396         | 18.05144696    | -3.862                | 0.0083    |
| MDOTSQ   | 1  | 0.555410           | 0.03864811     | 14.371                | 0.0001    |

MODELING MISSION FUEL CONSUMPTION AND THRUST AT SEA LEVEL 10  
12:19 Wednesday, October 14, 1992

| Obs | Dep Var<br>THRUST | Predict<br>Value | Std Err<br>Predict | Lower95%<br>Predict | Upper95%<br>Predict | Residual |
|-----|-------------------|------------------|--------------------|---------------------|---------------------|----------|
| 1   | 14972.0           | 14680.3          | 112.045            | 14057.9             | 15302.8             | 291.7    |
| 2   | 15029.0           | 15007.2          | 200.605            | 14263.4             | 15751.0             | 21.8133  |
| 3   | 12904.0           | 13262.0          | 144.160            | 12601.1             | 13922.8             | -358.0   |
| 4   | 14539.0           | 14543.1          | 222.735            | 13762.5             | 15323.8             | -4.1493  |
| 5   | 17004.0           | 17134.0          | 153.632            | 16460.5             | 17807.5             | -130.0   |
| 6   | 17710.0           | 17716.8          | 220.735            | 16939.6             | 18494.0             | -6.7924  |
| 7   | 14161.0           | 13932.9          | 174.476            | 13229.6             | 14636.1             | 228.1    |
| 8   | 12820.0           | 12701.1          | 173.610            | 11999.1             | 13403.1             | 118.9    |
| 9   | 18288.0           | 18288.5          | 185.713            | 17568.2             | 19008.8             | -0.5075  |
| 10  | 12855.0           | 12946.2          | 190.436            | 12218.6             | 13673.9             | -91.2238 |
| 11  | 14509.0           | 14506.9          | 195.151            | 13771.8             | 15241.9             | 2.1309   |
| 12  | 14308.0           | 14391.8          | 135.044            | 13742.6             | 15041.0             | -83.8131 |
| 13  | 16469.0           | 16482.1          | 106.327            | 15865.6             | 17098.5             | -13.0618 |
| 14  | 17653.0           | 17628.1          | 151.042            | 16958.1             | 18298.1             | 24.9142  |

Sum of Residuals 0  
Sum of Squared Residuals 312969.8584  
Predicted Resid SS (Press) 1072911.2265

Model: MODEL5  
Dependent Variable: THRUST

Analysis of Variance

| Source   | DF | Sum of Squares | Mean Square  | F Value | Prob>F |
|----------|----|----------------|--------------|---------|--------|
| Model    | 7  | 45711111.217   | 6530158.7452 | 130.642 | 0.0001 |
| Error    | 6  | 299911.71188   | 49985.28531  |         |        |
| C Total  | 13 | 46011022.929   |              |         |        |
| Root MSE |    | 223.57389      | R-square     | 0.9935  |        |
| Dep Mean |    | 15230.07143    | Adj R-sq     | 0.9859  |        |
| C.V.     |    | 1.46798        |              |         |        |

Parameter Estimates

| Variable | DF | Parameter Estimate | Standard Error | T for H0:<br>Parameter=0 | Prob >  T |
|----------|----|--------------------|----------------|--------------------------|-----------|
| INTERCEP | 1  | -12995             | 7157.0914986   | -1.816                   | 0.1193    |
| MACH     | 1  | -15495             | 754.32761738   | -20.541                  | 0.0001    |
| ALT      | 1  | 623.381481         | 34.81374883    | 17.906                   | 0.0001    |
| PIC      | 1  | 2988.163977        | 809.58964055   | 3.691                    | 0.0102    |
| D        | 1  | 8.820048           | 14.40046890    | 0.612                    | 0.5627    |
| ALPHASQ  | 1  | -6092.486721       | 5286.9474790   | -1.152                   | 0.2930    |
| PICSQ    | 1  | -86.484675         | 24.93667524    | -3.468                   | 0.0133    |
| MDOTSQ   | 1  | 0.581526           | 0.05711261     | 10.182                   | 0.0001    |

## MODELING MISSION FUEL CONSUMPTION AND THRUST AT SEA LEVEL

12

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| Obs | Dep Var<br>THRUST | Predict<br>Value | Std Err<br>Predict | Lower95%<br>Predict | Upper95%<br>Predict | Residual |
|-----|-------------------|------------------|--------------------|---------------------|---------------------|----------|
| 1   | 14972.0           | 14682.6          | 103.811            | 14079.5             | 15285.8             | 289.4    |
| 2   | 15029.0           | 15036.4          | 188.093            | 14321.5             | 15751.3             | -7.4090  |
| 3   | 12904.0           | 13235.5          | 150.125            | 12576.6             | 13894.5             | -331.5   |
| 4   | 14539.0           | 14552.5          | 218.583            | 13787.4             | 15317.5             | -13.4559 |
| 5   | 17004.0           | 17174.5          | 169.807            | 16487.6             | 17861.5             | -170.5   |
| 6   | 17710.0           | 17700.3          | 214.955            | 16941.4             | 18459.2             | 9.6868   |
| 7   | 14161.0           | 13948.6          | 173.524            | 13256.1             | 14641.1             | 212.4    |
| 8   | 12820.0           | 12695.9          | 155.654            | 12029.3             | 13362.4             | 124.1    |
| 9   | 18288.0           | 18234.9          | 209.848            | 17484.6             | 18985.2             | 53.0655  |
| 10  | 12855.0           | 12956.9          | 187.583            | 12242.8             | 13671.0             | -101.9   |
| 11  | 14509.0           | 14496.4          | 162.045            | 13820.8             | 15172.1             | 12.5708  |
| 12  | 14308.0           | 14353.4          | 112.417            | 13741.1             | 14965.8             | -45.4304 |
| 13  | 16469.0           | 16499.0          | 107.112            | 15892.4             | 17105.6             | -29.9949 |
| 14  | 17653.0           | 17654.0          | 156.329            | 16986.5             | 18321.6             | -1.0332  |

Sum of Residuals 3.11E-11

Sum of Squared Residuals 299911.7119

Predicted Resid SS (Press) 1439588.8208

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### Vita

Captain Alan Lach was born on March 21, 1956 in Southbridge, Massachusetts. He graduated from Bay Path Regional Vocational Technical School in Charlton, Massachusetts in 1974 and enlisted in the U. S. Air Force. After achieving the rank of Technical Sergeant in 1982, he was accepted into the Airman's Education and Commissioning Program. He graduated cum laude from the University of Utah with a Bachelor of Science in Mechanical Engineering in March 1985. His first commissioned assignment was as Officer in Charge of the Peacekeeper Mechanical Engineering for the 90th Strategic Missile Wing, Francis E. Warren AFB, Wyoming. He was responsible for the operational integration of the Peacekeeper missile system in Minuteman silos. He created and led a special inspection team and was responsible for inspecting and accepting all Peacekeeper missile sites for the U. S. Air Force. In July 1988 he was reassigned as Chief of Mechanical Engineering for Detachment 1, Ballistic Missile Office, Site Activation Task Force at Francis E. Warren AFB. In this capacity he was responsible for follow-on test and evaluation and operational integration of the Peacekeeper missile system as well as deployment planning for the Peacekeeper Rail Garrison program. He entered the School of Engineering, Air Force Institute of Technology, in May 1991.