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AN INVESTIGATION OF THE RELATIONSHIP BETWEEN
TAKE OFF GROSS WEIGHT AND MISSION
REQUIREMENTS FOR GEOMETRICALLY
OPTIMIZED AIRCRAFT

THESIS

AFIT/GAE/AE/77J-1 Milford K. Greenway, Jr.
Captain USAF

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by
(10) Milford K. Greenway, Jr. B.S.
Captain USAF
Graduate Aeronautical Engineering
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PREFACE

This study was conducted to determine the analytic relationship between mission requirements and the minimum take off gross weight of aircraft which have been optimized in terms of their design geometry for the particular mission. Having such a relationship and using current methods to estimate system cost in terms of gross weight, the Air Force program planners may apply this methodology to estimate the acquisition cost and schedule for future aircraft. The methods employed in this study include aircraft conceptual design sizing equations, statistical selection techniques, surface fit approximations and design optimization based on them. All of these methods exist in computer programs supplied by the Air Force Aero Propulsion Laboratory (AFAPL) and the Air Force Flight Dynamics Laboratory (AFFDL).

I am indebted to Mr. Glenn Blevins of the AFAPL Performance Branch (TBA) for his help with the surface fit program (SURFIT) and the optimization program (OAPEN). Captain Russell Morrison of the AFFDL Design Branch (FXB) was always willing to provide whatever help I needed in using the aircraft sizing program (CISE). In addition, he made the 45 sizing runs with CASP in the AFIT 799 study and helped analyze the output. Russ is a personal friend and I appreciated the opportunity to work with him on this study. Mr. Gordon Tamplin of AFFDL/FXB generated the 25 engine decks required by CASP in the AFIT 799 study. I thank you all, and sincerely appreciate what you've done for me.

I would like to thank Major Stephen Koob of the Aeronautics and Astronautics Department of the School of Engineering, Air Force Institute of Technology, for providing this thesis topic and for his aid during the conduct of this study.

Finally, I want to express my deepest appreciation to my wife, Gwen, for keeping the household running during my AFIT studies and for her patience, understanding and encouragement the past two years.

Captain Milford K. Greenway, Jr.

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LIST OF ABBREVIATIONS AND SYMBOLS

AFAPL	Air Force Aero-Propulsion Laboratory
AFFDL	Air Force Flight Dynamics Laboratory
AFIT	Air Force Institute of Technology
AMMAX	Maximum Mach number in CISE
AR	Aspect Ratio, independent design variable
BPR	Engine By-pass Ratio, independent design variable
CASP	Combat Aircraft Synthesis Program
CISE	Computerized Initial Sizing Estimate
CLMAX	Maximum aircraft lift coefficient
CV	Constraint violation
DISTL	Landing distance computed by CISE - feet
DISTTO	Take off distance computed by CISE - feet
DLN	Landing distance, dependent variable - feet
DTO	Take off distance, dependent variable - feet
F	F statistic
$F_{.05}$	Critical value of F for 95% confidence level
FACT	Used by SURFIT to select best regression equation
FT	Feet
GSS	Sustained normal load factor - "g's"
LBS	Pounds
LDGW	Landing weight computed by CISE - pounds
MACH	Dash Mach number
MACH No	Ratio of local velocity to local speed of sound
MCC	Multiple correlation coefficient
MSE	Mean square error

MSR	Regression mean square
NM	Nautical miles
OAPEN	Optimization computer program
OPR	Overall engine pressure ratio, independent design variable
P_k	Weighting factor for constraint violation in OAPEN
R	Multiple correlation coefficient
RNG	Dash range - nautical miles
SLTH	Aircraft thrust-to-weight ratio in CISE
SREF	Reference wing area in CISE - square feet
STERR	Standard error computed by SURFIT
STORES	Internal payload, independent mission variable - pounds
STR	Abbreviated label for STORES
SWPLE	Wing leading edge sweep angle in CISE - degrees
SURFIT	Regression analysis computer program
TAC	Acceleration time - minutes or seconds
TANK	Number of 2000 pound external fuel tanks in CISE
TOGW	Take off gross weight, dependent mission variable - pounds
TOGW	Take off gross weight computed by CISE - pounds
TOGW1	Current estimate of take off gross weight in CISE - pounds
TREQD	Required thrust in CISE - pounds
TROOT	Wing thickness-to-chord ratio in CISE
TW	Aircraft thrust-to-weight ratio, independent design variable
WLFUEL	Loiter fuel in CISE - pounds
WOS	Aircraft wing loading, independent design variable - pounds per square foot
WSTOR	Total weight of STORES in CISE - pounds
WSTORI	Weight of internal STORES in CISE - pounds

WSTORX Weight of external STORES in CISE - pounds

WTFUEL Weight of fuel in CISE - pounds

ABSTRACT

A study was performed to demonstrate the feasibility of using surface fit approximations in the mission analysis for future fighter aircraft. Dash Mach number (MACH), dash range (RNG), and internal payload (STR) were selected as mission variables and a mission space defined based on a simple latin square method. Wing loading (WOS), aspect ratio (AR) and aircraft thrust-to-weight ratio (TW) were selected as design variables and a design space defined based on a simple latin square method. The take off gross weight (TOGW), take off distance (DTO), and the landing distance (DLN) were determined by the use of a computer program which simulated the required mission for each design case. A regression analysis was performed on this data to obtain quadratic surface fit approximations for TOGW, DTO, and DLN in terms of the design variables WOS, AR, and TW. An unconstrained minimization of TOGW was performed for all missions using a conjugate gradient technique to determine the minimum TOGW within the design space and the corresponding values of DTO and DLN. Another regression analysis was performed on the results of the minimizations and the mission variables for specific missions to obtain quadratic surface fit approximations for TOGW, DTO, and DLN for optimum aircraft in terms of the mission variables MACH, RNG, and STR. It was concluded that these surface fit approximations in terms of the mission variables were sufficiently accurate for use in mission analysis and conceptual design studies.

AN INVESTIGATION OF THE RELATIONSHIP BETWEEN MINIMUM TAKE OFF GROSS WEIGHT AND MISSION REQUIREMENTS FOR GEOMETRICALLY OPTIMIZED AIRCRAFT

I. INTRODUCTION

Background

In the early stages of bringing a new fighter aircraft into the Air Force inventory, many trade studies are performed to establish the required capabilities of the aircraft and the operational concepts. The trade studies performed during this conceptual design phase provide the visibility necessary for sound design and management decisions. The effects of these trade studies are apparent when one considers that the conceptual design phase, and the preliminary design phase which follows, together encompass approximately five percent of the total manpower required to bring a flying prototype into existence. However, the decisions made during these stages typically commit 95 percent of the future program expenditures (Ref 1:3). Once the required capabilities are established, the objective is to acquire the most cost-effective system satisfying those requirements. The most cost-effective system is the one whose cost divided by its effectiveness is the minimum for the systems and operational concepts considered.

The difficulty lies in relating system cost and system effectiveness to the required capabilities of the aircraft. The relationship between system effectiveness and mission requirements does not generally exist as an analytical expression, and is currently limited to experience, judgment, and "gut feelings" on the part of the planners. System cost, however, can be related to aircraft gross weight (Ref 2:10). If the relationship between gross weight and mission requirements were known, the cost could then be related to the mission requirements. This study addressed that problem.

Statement of the Problem

The purpose of this study was to determine the relationship between the take off gross weight and the mission requirements for an aircraft optimized in terms of its design geometry to yield the minimum gross weight required to perform the mission.

Approach

The following nine step approach was used in this study:

1. A mission profile was selected for simulation.

2. Three independent mission variables were selected and the range of their values defined. This three-dimensional space was called the "Mission Space."

3. Three independent design variables were selected and their range of values defined. This three-dimensional space was called the "Design Space."

4. The simple latin square method was used to select several particular mission space points at which minimum weight designs were determined for points within the design space.

5. The simple latin square method was used to select several particular design space points at which aircraft sizing was performed.

6. An aircraft sizing program (CISE) was used to determine the take off gross weight (TOGW), take off distance (DTO), and landing distance (DLN) for each selected design point at each selected mission point.

7. For each mission point, TOGW was related to the design parameters by fitting a quadratic expression in the three design parameters to the sizing data using the regression analysis program SURFIT.

8. Using these expressions, the minimum TOGW for each mission was determined with the optimization program OAPEN.

9. Finally, SURFIT was used to obtain the desired relationship between these minimum TOGW's and their associated mission parameters.

Steps one through five are discussed in Chapter II, while steps six, seven, and eight are discussed in Chapters III, IV, and V respectively. The results are presented and discussed in Chapter VI. Conclusions and recommendations are found in Chapter VII.

A companion effort, arbitrarily designated as the AFIT 799 study, was performed in support of the Air Force Flight Dynamics Laboratory Design Branch (AFFDL/FXB) and their design analysis of future USAF fighter aircraft. The approach was very similar to that outlined in (1) through (8) above. The aircraft sizing program CASP was used to simulate the mission which included a supersonic dash at 1.95 Mach and 50,000 feet altitude, for a distance of 250 nautical miles. The AFIT 799 study is discussed in Appendix F.

II MISSION SPACE AND DESIGN SPACE SELECTION

Mission Space Selection

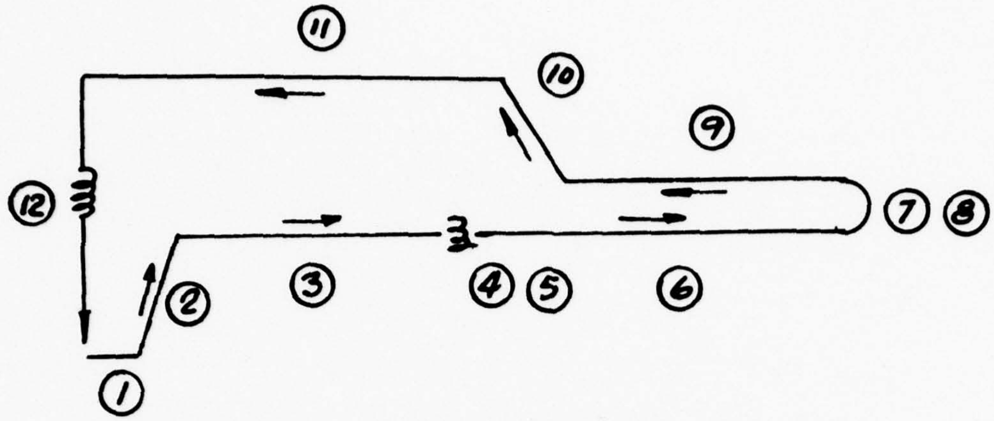
The mission profile was defined by combining several mission segments considered by the Air Force Flight Dynamics Laboratory to be representative of those required for future fighter aircraft. The complete mission profile simulated in this study is presented in Figure 1. The dash Mach number (MACH), the dash range (RNG), and the internal payload (STORES) were selected as the independent mission variables. The desired optimum aircraft were to have the minimum take off gross weights over the range of mission variables considered. The "mission space" was defined as the three dimensional space comprised of the independent mission variables and their range of values. The mission space is presented in Table I.

TABLE I

Mission Space

Variable	Range of Values
MACH	1.2 - 1.6
RNG	200 - 400 NM
STORES	5000-10000 lbs

It would have been desirable to include other mission variables, however, only three mission variables were used to limit the scope of the problem. Even so, three variables with three values each resulted in twenty-seven (3^3) possible mission points. Each of these mission points was a candidate point at which to determine optimized aircraft designs.



1. Start engines, taxi, takeoff
2. Climb at .85M to 35000 feet
3. Outbound cruise - 275 NM, .85M 35000 feet
4. Loiter - 30 minutes, .85M, 35000 feet
5. Accelerate to dash Mach number
6. Outbound dash - dash Mach number
7. Combat - 1 maximum "G" turn at dash Mach number
8. Drop stores
9. Inbound dash - dash Mach number
10. Climb to 45000 feet using afterburner
11. Inbound cruise - 325 NM, .85M
12. Descend to sea level, loiter for 20 minutes at .4M, land

Figure 1. Mission Profile

Design Space Selection

Aircraft designs are greatly influenced by the airframe variables wing loading (WOS), aspect ratio (AR), and aircraft thrust-to-weight ratio (TW) and the engine variables overall pressure ratio (OPR) and bypass ratio (BPR). For this reason, these variables were selected as the independent design variables. The objective was to find a combination of these which yields the minimum gross weight for a particular mission. A "design space" was defined as the five dimensional space comprised of the five independent design variables and their ranges of values. The ranges of values considered were recommended by the Design Branch (FXB) of the Air Force Flight Dynamics Laboratory (AFFDL) as being appropriate for future USAF fighter aircraft designs. The design space is presented in Table II.

TABLE II

Design Space

Variable	Range of Values
OPR	10-30
BPR	.2-2.2
WOS	80-160 LBS/FT^2
TW	.6-1.0
AR	1.5-3.5

The mission simulation CISE (Computerized Initial Sizing Estimate) was used in this study to reduce cost. However, the effects of OPR and BPR could not be included since CISE does not have provisions for

OPR and BPR input. If the design variables were allowed to assume five equally spaced values each, there would have been 3125(5^5) possible design points to be input to CISE for each of the 27 possible mission points -- a total of 84,375 sizing runs. The simple latin square selection method was used to reduce this number to a manageable value of 675 runs (15 mission points x 45 design points).

Simple Latin Square Method

A statistical selection technique known as the simple latin square method was used to logically identify representative subsets of the complete mission space and the complete design space. The method is based on random numbers, field algebra and the algebra of integers, and yields a sequence of values for each variable which is formed by joining together permutations of the values of that variable. Hence, each variable is stepped through all of its values every k data points, where k is the number of values each variable is allowed to assume. The values of the variables are normalized on the interval (-1, 1). For "n" independent variables, there are "n" matrices established to generate the design points or mission points (Ref.9:52-57). Table III contains the matrices for the three variables used.

TABLE III

Latin Square Matrices for Three Variables

Variable	1	2	3
M A T R I X	0 1 -1 1 -1 0 -1 0 1 -1 0 1 1 -1 0	0 1 -1 -1 0 1 1 -1 0 1 -1 0 -1 0 1	0 1 -1 0 1 -1 0 1 -1 1 1 1 -1 -1 -1

The data space is generated by locating the midpoint (0, 0, 0) and an appropriate step size for each variable. The first element of the data space is derived by multiplying the step size for each variable by element (1, 1) of the matrix for that variable and adding the result to the midpoint. The second design point is found by multiplying the step size for each variable by element (2, 1) and adding the result to the midpoint. This process is continued until the space is complete. If "n" is a prime number, there will be $n^2 + n(n - 1)$ design points generated. If "n" is not a prime number, the number of points generated is determined by the next prime number "p" greater than "n", and $p^2 + p(p - 1)$ points will be generated.

The design points generated by this method may contain duplications. The cases selected may not be well distributed over the space and would not adequately represent the space as depicted in the "bad" fit of Figure 2. A "good" fit, as shown in Figure 2 adequately represents the space. A bad representation can allow a significant buildup of cross correlations between terms with poor surface fits as a result. This situation was not encountered in this study. The three variable, latin square mission space used in this study is presented in Figure 3. The 27 possible cases are identified by line intersections. The numbers in parentheses are the order of selection and the mission case numbers.

The latin square mission space is presented in Table IV. Note that missions eight and nine are duplicates, as are missions 12 and 15. The mission space is not orthogonal because of these duplications. It is desirable to have orthogonal spaces since better surface fit approximations are generally obtained from an orthogonal space. The method described in Reference 4 assures an orthogonal space.

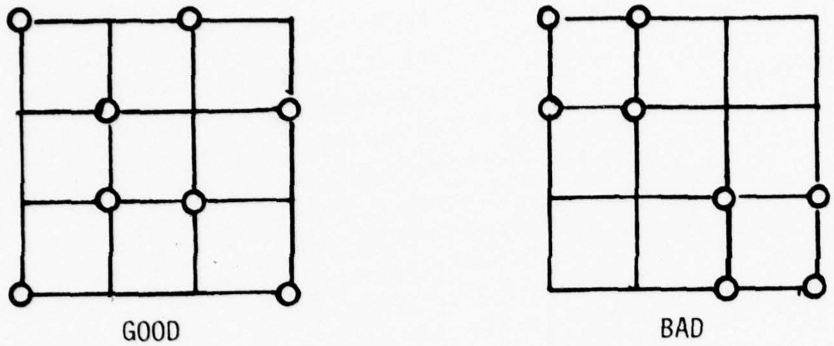


Figure 2. Two Examples of Latin Square Space (Two Dimensional Cross-Section Views)

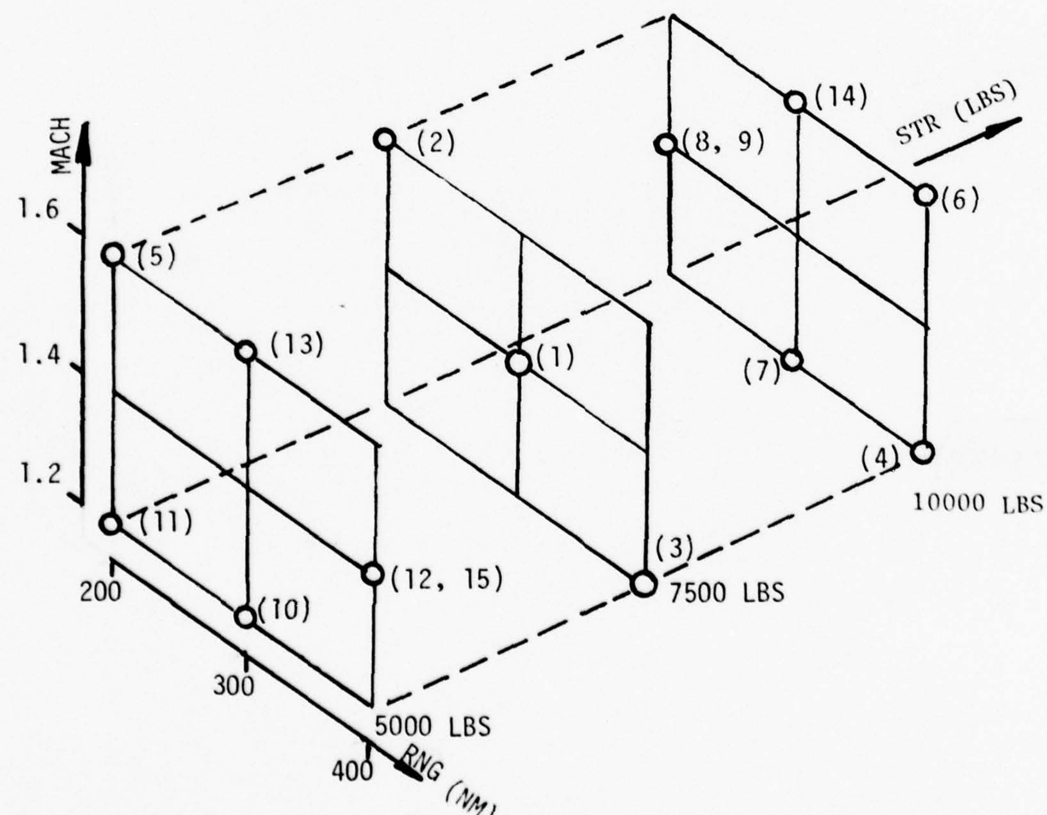


Figure 3. Latin Square Mission Space

TABLE IV

Latin Square Mission Space

Case No.	MACH No.	RANGE (NM)	STORES (LBS)
1	1.4	300	7500
2	1.6	200	7500
3	1.2	400	7500
4	1.2	400	10000
5	1.6	200	5000
6	1.6	400	10000
7	1.2	300	10000
8	1.4	200	10000
9	1.4	200	10000
10	1.2	300	5000
11	1.2	200	5000
12	1.4	400	5000
13	1.6	300	5000
14	1.6	300	10000
15	1.4	400	5000

The latin square design space is presented in Table V. Values of WOS, AR, and TW corresponding to the 45 design cases of Table V were input to the mission simulation. The design space was orthogonal.

Appendix A. contains the input requirements for the computer program LATSQR.

TABLE V

Latin Square Design Space

Case No.	WOS (LBS/FT^2)	AR	TW	OPR	BPR
1	120	2.5	.8	20	1.2
2	140	3.5	.6	15	1.2
3	160	2.0	.9	10	1.2
4	80	3.0	.7	30	1.2
5	100	1.5	1.0	25	1.2
6	160	3.0	.7	10	1.7
7	100	3.5	.6	25	2.2
8	140	1.5	1.0	15	.2
9	80	2.0	.9	30	.7
10	140	3.0	.9	25	1.7
11	160	1.5	.7	20	1.7
12	80	2.5	1.0	15	1.7
13	100	3.5	.8	10	1.7
14	120	2.0	.6	30	1.7
15	80	3.5	.8	15	1.7
16	120	1.5	.7	30	2.2
17	160	2.0	.6	20	.2
18	100	2.5	1.0	10	.7
19	160	3.5	1.0	30	2.2
20	80	2.0	.8	25	2.2
21	100	3.0	.6	20	2.2
22	120	1.5	.9	15	2.2
23	140	2.5	.7	10	2.2
24	100	1.5	.9	20	1.7
25	140	2.0	.8	10	2.2
26	80	2.5	.7	25	.2
27	120	3.0	.6	15	.7
28	80	1.5	.6	10	.2
29	100	2.5	.9	30	.2
30	120	3.5	.7	25	.2
31	140	2.0	1.0	20	.2
32	160	3.0	.8	15	.2
33	120	2.0	1.0	25	1.7
34	160	2.5	.9	15	2.2
35	100	3.0	.8	30	.2
36	140	3.5	.7	20	.7
37	100	2.0	.7	15	.7
38	120	3.0	1.0	10	.7
39	140	1.5	.8	30	.7
40	160	2.5	.6	25	.7
41	80	3.5	.9	20	.7
42	140	2.5	.6	30	1.7
43	80	3.0	1.0	20	2.2
44	120	3.5	.9	10	.2
45	160	1.5	.8	25	.7

III. AIRCRAFT SIZING

Sizing Ground Rules

The twelve segements of the mission shown in Figure 1 are representative of future USAF fighter aircraft designs. This mission and the independent design variables WOS, AR, and TW were input to an aircraft sizing program (CISE) supplied by the AFFDL Design Branch (FXB). The CISE program was used to compute the take off gross weight (TOGW), take off distance (DTO), and landing distance (DLN) to accomplish the specified mission for the input set of design variables. The aircraft was to perform the specified mission with a one-man crew, carry all stores internally, and make one 360 degree turn at the dash Mach number and altitude before expending the internal stores. Distance credit was given for all mission segments except subsonic loiter, combat, expenditure of stores, and loiter before landing.

CISE (Computerized Initial Sizing Estimate)

The CISE program was developed as a "first cut" design tool for use even before a configuration is proposed (Ref 5:2). The program performs a weight oriented aircraft sizing to predict some basic physical characteristics so that the designer has an idea of where to begin his analysis. The CISE program uses nested DO loops so that combinations of wing loading (WOS), aspect ratio (AR), wing thickness-to-chord ratio, and wing quarter chord sweep angles can be evaluated in an iterative process. The initial estimate of TOGW is given by

$$\text{TOGW1} = 2(\text{WSTOR} + 2000\ \text{TANK}) \qquad (1)$$

where WSTOR is the combined weight of internal and external stores, and TANK is the number of 2000 pound external fuel tanks. The initial geometry is estimated by the program (based on actual aircraft data) from the input variables and mission parameters.

The CISE program "flys" the input mission to determine fuel requirements based on input values for the engine thrust-to-weight ratio and engine specific fuel consumption. Major aircraft components are sized to provide adequate volume for fuel, payload, and the crew using statistical weight estimating relationships. These weights are summed to yield TOGW. When TOGW is within one percent of the estimate at the start of the iteration, the process is terminated. Another design combination is then considered and the sizing process is repeated. When TOGW is not within one percent of the estimate for that iteration, TOGW becomes the estimate for the next iteration and the sizing process is repeated. Twenty-five such iterations were allowed in this study and all design combinations converged within twenty-five iterations.

Takeoff Distance

The takeoff distance computed by CISE (DISTTO) is the takeoff roll along the runway and does not include the distance required to clear a fifty-foot obstacle. This computation is based on the following set of equations:

$$\mathrm{DISTTO} = \frac{400 + 31.4(\mathrm{TOGW1})}{(\mathrm{CLMAX})(\mathrm{SREF})(\mathrm{TREQD})} \qquad (2)$$

$$\mathrm{TOGW1} = 2(\mathrm{WSTORI} + \mathrm{WSTORX} + 2000\mathrm{TANK})$$

$$\text{or} \quad \mathrm{TOGW1} = \mathrm{TOGW\ from\ previous\ iteration} \qquad (3)$$

$$\mathrm{CLMAX} = 3.7072 - .05355\,(\mathrm{SWPLE}) + .03716(\mathrm{AR}) - 1.5355(\mathrm{TROOT}) \qquad (4)$$

$$SREF = TOGW1/WOS \quad (5)$$

$$SWPLE = 13.4 + 14.9(AMMAX) \quad (6)$$

$$TROOT = .0185 + .0637/(AMMAX) \quad (7)$$

where TREQD is the thrust; TOGW1 is the current estimate of take off gross weight in pounds; WSTORI and WSTORX are the weights in pounds of the internal and external stores load; TANK is the number of 2000 pound external fuel tanks; CLMAX is the maximum aircraft lift coefficient; SWPLE is the wing leading edge sweep angle in degrees; AR is the aspect ratio; TROOT is the wing thickness-to-chord ratio measured at the wing root; and AMMAX is the maximum Mach number for the mission. The program only computes values for CLMAX, AR, SWPLE, TROOT, and AMMAX when they are not input.

Landing Distance

The landing distance computed in CISE is the landing roll along the runway. It has the variable name DISTL in the program and is based on the following relationships:

$$DISTL = \frac{94.22\ LDGW}{(CLMAX)(SREF)} \quad (8)$$

$$LDGW = TOGW1 - WTFUEL + WLFUEL \quad (9)$$

where CLMAX, SREF, and TOGW1 are as defined in Euqation (2) through (7) above, WTFUEL is the fuel required to perform the mission, and WLFUEL is the fuel required to loiter before landing - twenty minutes at sea level altitude for this study.

CISE Operation

In order to consider the mission and only the specific design cases from Table IV, it was necessary to input the forty-five design cases one at a time. CISE was modified to output on file "TAPE12" the values for MACH, RNG, STORES, WOS, AR, TW, TOGW, DTO, and DLN. CISE was stored on a permanent file and run from a remote terminal. After all design cases had been run for the particular mission, TAPE12 was disposed to the AFIT punch for a permanent record of results. The punch cards were then input to the surface fit procedure described in Chapter IV to generate analytic expressions for TOGW, DTO, and DLN as functions of WOS, AR, and TW for each mission.

Input for CISE is described in Appendix B.

IV. SURFACE FIT APPROXIMATION

Introduction

In order to apply mathematical optimization methods to the aircraft designs generated by CISE, it was necessary to represent the dependent variables TOGW, DTO, and DLN as analytic functions of the independent design variables WOS, AR, and TW. The multidimensional representations, or "surface fit approximations" for the dependent variables were obtained through regression analysis using the computer program SURFIT (SURface FIT) supplied by the Air Force Aero Propoulsion Laboratory (AFAPL). SURFIT was developed by McDonnell-Douglas Corporation, McDonnell Aircraft Company, St. Louis, Missouri.

Quadratic Approximations

Although other options were available in SURFIT, it was decided that the dependent variables TOGW, DTO, and DLN would be represented by second order polynominals of the form:

$$\begin{aligned} TOGW = A_0 &+ A_1(WOS) + A_2(AR) + A_3(TW) + A_{11}(WOS)^2 \\ &+ A_{12}(WOS)(AR) + A_{13}(WOS)(TW) + A_{22}(AR)^2 \\ &+ A_{23}(AR)(TW) + A_{33}(TW)^2 \end{aligned} \tag{10}$$

In general summation notation for "n" independent variables, Equation (10) can be written:

$$TOGW = A_0 + \sum_{i=1}^{n} A_i X_i + \sum_{i=1}^{n} \sum_{j=1}^{n} A_{ij} X_i X_j \tag{11}$$

when the A's are the coefficients and the X's are the independent variables.

The quadratic approximation was particularly suited to this study for several reasons. First, it is simple and easy to work with and makes possible economic calculation of the partial derivatives in the optimizer. Secondly, higher order approximations are unnecessary since adequate representation can be obtained with second order surfaces (Ref 3:595). Thirdly, this second order approximation is equivalent to the assumption that the performance function can be adequately represented by the first few terms if its Taylor series expansion about some nominal design point $(WOS, AR, TW)_{nominal}$. This assumption requires that the range of values for the design variables be kept reasonably small.

Regression Analysis

The number of unknown regression coefficients (the A's in Equation (11)) in the quadratic polynominal can be expressed as $L = (n+1)(n+2)/2$, where "n" is the number of independent variables. The number of data points input to the regression analysis must be equal to or greater than the number of unknown coefficients L. This is necessary so that an over-determined system of linear equations can be solved by the method of least squares. In this method, the terms are selected so as to minimize the sum of the squares of the error,

$$SSE = \sum_{i=1}^{N} \varepsilon_L^{\,2}, \tag{12}$$

where ε_L is the difference between the actual value of the performance function and the predicted value and where N is the number of data points input to the regression analysis (Ref 6:229).

The goodness-of-fit of the regression surface is tested statistically by variance analysis. The four tests used by SURFIT to evaluate the goodness-of-fit were the standard F-statistic for regression, the multiple correlation coefficient squared (MCC^2 or R^2), the significance ratio, and the standard error.

The F-statistic is defined as the ratio of the regression mean square,

$$MSR = \frac{\sum_{\ell=1}^{N} (TOGW_\ell - \overline{TOGW})^2}{N} \tag{13}$$

to the mean square error

$$MSE = \frac{\sum_{\ell=1}^{N} (TOGW_\ell - \overline{TOGW}_\ell)^2}{L-N} \tag{14}$$

where $\overline{TOGW}$ is the mean of the actual TOGW's in the N data points, $TOGW_\ell$ is the TOGW predicted by the polynominal at the ℓ-th data point, and L is the number of coefficients in Equation (11). A good fit is assured when the calculated F value exceeds the F value found in standard tables for L and N-L degrees of freedom at the 95 percent confidence level (Ref 3:595).

The multiple correlation coefficient squared (MCC^2 or R^2) is defined as

$$MCC^2 = \frac{\sum_{\ell=1}^{N} (\overline{TOGW}_\ell - \overline{TOGW})^2}{\sum_{\ell=1}^{N} (TOGW_\ell - \overline{TOGW})^2} \tag{15}$$

where the terms are as defined for Equations (13) and (14). This quantity varies between zero and one and the closer MCC^2 is to one, the better the approximating equation follows the data.

The standard error is given by

$$STERR = \sqrt{MSE} \tag{16}$$

Smaller values of STERR indicate a better approximation of the actual data.

SURFIT Operation

The regression analysis performed by SURFIT uses the least squares method to determine the regression coefficients of Equation (11). Values of the F-statistic are computed for all variables in the problem. The variable with the largest F value is selected as the first variable to be entered in the equation. The significance ratio, MCC^2, STERR for the equation and F values for variables not in the equation are computed. The variable with the highest F value is added to the equation (forward step regression) as long as the F values from the previous step for all variables in the equation exceed the highest F value for variables not in the equation. A variable in the equation with the lowest F value is removed (backward step regression) whenever its F value from the previous step is smaller than the largest F value for variables not in the equation for the current step. In this manner, second order terms (WOS^2) and cross product terms ($WOS \times AR$) could be entered even though WOS or AR were not in the equation. This process was repeated until all variables had been entered or the desired number of steps had been reached.

The step selected as best representing the actual input data was based on the significance ratio, STERR, and MCC^2 and was the step having the largest value of FACT given by

$$FACT = \frac{(SIGNIFICANCE\ RATIO)^{\frac{1}{2}}}{(STERR)^{\frac{1}{2}}} \times MCC^2 \qquad (17)$$

The selected equation was printed and the regression coefficients punched on cards according to the input requirements for the optimizer described in Chapter V.

Results

The selected equation was used by SURFIT to compute the values of dependent variable at all N data points. These computed values were compared to the actual value at each data point and the percent error computed according to

$$\%\ ERROR = \frac{COMPUTED - ACTUAL}{ACTUAL} \times 100 \qquad (18)$$

A summary table of the computed and actual values, their difference (residual), and the percent error was printed for each problem.

The regression analysis was performed for mission case 1, using actual data and data normalized as recommended by Marler (Ref 7:14) using the transformation

$$X = \frac{X' - \frac{1}{2}(X_{max} + X_{min})}{\frac{1}{2}(X_{max} - X_{min})} \qquad (19)$$

The resulting surface fits were found to differ by no more than .02 percent in maximum error. Thus, actual data was used for all subsequent regression analysis. Very good surface fits were obtained for TOGW, DTO, and DLN for all mission cases. Most surface fits were within plus or minus two percent while the maximum error encountered was -4.57 percent. These results compared quite favorably with those obtained by Marler using normalized data in the regression analysis.

The surface fit approximations obtained for mission 13 in Equations (20) through (22) below are typical for those obtained for all missions. The TOGW, DTO, and DLN equations for all missions are presented in Appendix C.

$$\begin{aligned} TOGW = {} & 38850.416 - 28156.2033(TW) + .1780(WOS)^2 \\ & - 16.0080(WOS)(AR) + 450.7710(AR) - 1591.2582(AR)(TW) \\ & + 26021.8945(TW)^2 \end{aligned} \tag{20}$$

$$\begin{aligned} DTO = {} & 3239.8422 + 48.9005(WOS) - 7296.6377(TW) \\ & - .4827(WOS)(AR) - 30.1409(WOS)(TW) \\ & + 4549.4329(TW)^2 \end{aligned} \tag{21}$$

$$\begin{aligned} DLN = {} & -954.8010 + 36.4208(WOS) + 2556.2243(TW) \\ & -.0238(WOS)^2 + 1.1496(WOS)(AR) - 39.7089(AR)^2 \\ & + 118.2842(AR)(TW) - 1649.1797(TW)^2 \end{aligned} \tag{22}$$

Three dimensional plots of TOGW versus TW and AR were generated from the surface fit approximations in order to provide a check on the predicted minimum TOGW output from the optimizer for the unconstrained minimization. The plot presented in Figure 4 is for mission 13 at TW = .6 and was generated from Equation (20). While not suitable for determining

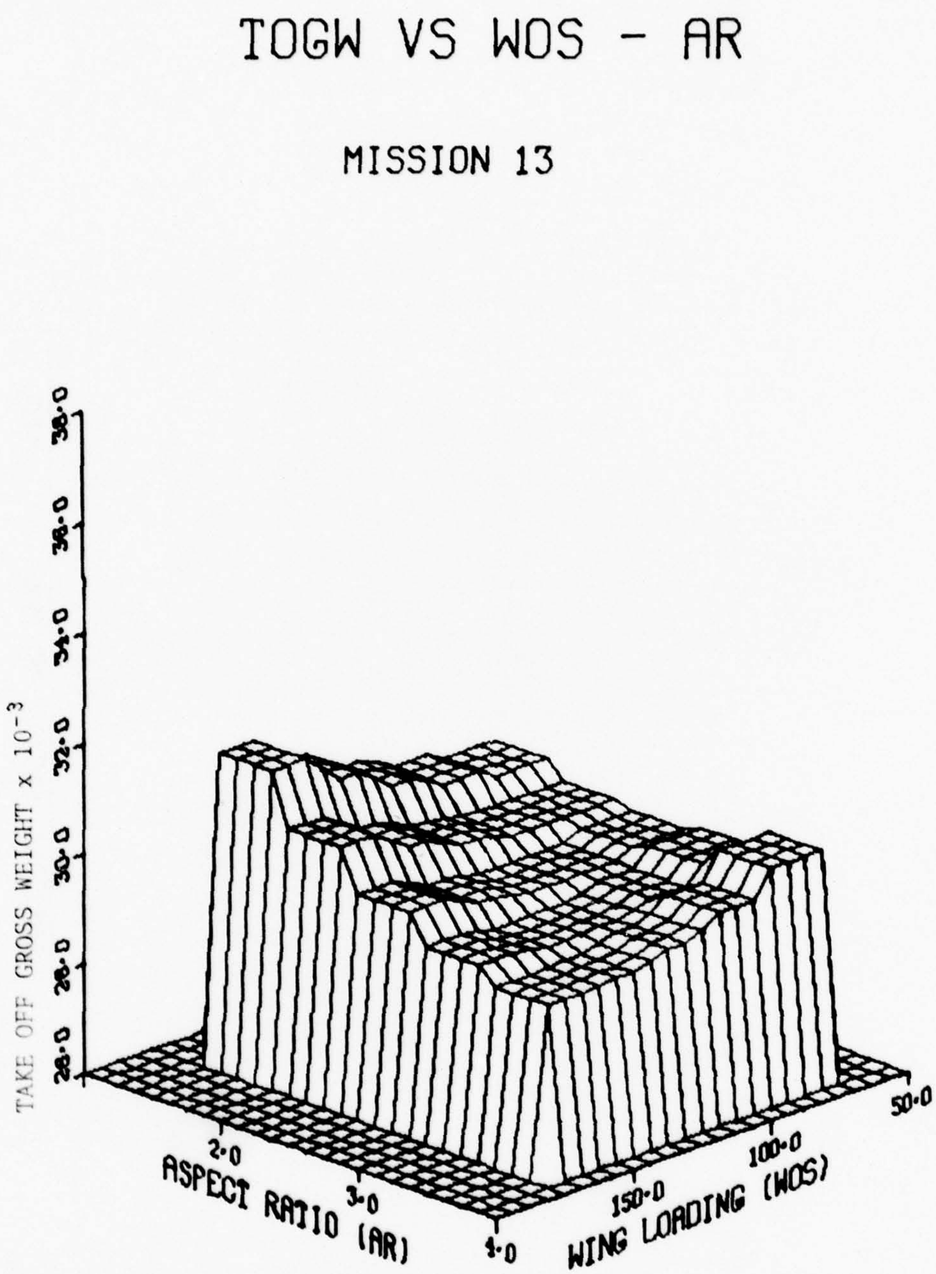


Figure 4. 3-D Plot of TOGW vs WOS and AR for Mission 13

numerical values of TOGW, these plots were sufficient to verify the existence of an apparent minimum TOGW in a particular region of the surface.

Input requirements for SURFIT are described in Appendix D.

V. OPTIMIZATION

Introduction

The optimization problems considered in this study required the minimization of a performance function such as TOGW subject to the inequality constraint that another performance function such as DTO be equal to or less than some specified value. An additional "box constraint" imposed was that the independent variables not be outside the design space. An object deck of the computer program OAPEN (Optimization Analysis by PENalty function) was supplied by the Air Force Aero Propulsion Laboratory (AFAPL) and was used to accomplish the various optimizations in this study. OAPEN was developed by The Boeing Aerospace Company, Seattle, Washington under contract F33615-73-C-2084 to AFAPL.

Problem Definition

The two optimizations performed for each mission were to: (1) minimize TOGW with no constraints on DTO and DLN other than they must be positive, and (2) minimize TOGW subject to the constraints that DTO must be equal to or less than 3500 feet and DLN must be equal to or less than 4500 feet. The independent variables WOS, AR, and TW were "box constrained" to not be outside the range of values noted in Table II for the design space.

OAPEN

OAPEN is designed to find an optimum design parameter vector using surface fit functions to approximate the true functions of the design parameters in an optimal design problem. In this study, the general optimization problem to be solved can be written as

$$\text{Minimize} \quad f_1(\underline{X})$$

$$\text{Subject to} \quad f_j(\underline{X}) \leq c_j, \; j = 2,m \qquad (23)$$

where $\underline{X}$ is the vector of independent variables, the f's are the performance functions approximated by surface fits, and the c's are the values of the upper limits for the constraint functions. OAPEN solves this problem by the penalty function method in which the inequalities of Equation (23) are used to establish a penalized cost function of the form

$$F(\underline{X}) = f_1(\underline{X}) + P_K \sum_{j=2}^{m} (CV_j)^2 \qquad (24)$$

where $f_1(\underline{X})$ is as defined for Equation (23), P_K is a weight factor which modulates the severity of violating the constraints, and CV represents the violation of the constraints inequalities. P_K corresponds to the allowable tolerance on violation of the constraints. A default value of $P_K = 50$ exists in the program and corresponds to a two percent tolerance. A value of $P_K = 100$ (one percent tolerance) was used in this study, although P_K can be input as any value. CV in Equation (24) has the form (DTO - 3500) when DTO is constrained to be less than or equal to 3500 feet. CV is equal to zero if the constraint is satisfied and takes on the value (DTO - 3500) when the constraint is violated (exceeded).

For the constrained minimization performed in this study, Equation (24) can be written

$$F(\underline{X}) = TOGW + 100(DTO - 3500)^2 + 100(DLN - 4500)^2 \qquad (25)$$

OAPEN uses the Fletcher-Reeves (Ref. 8:11-12) conjugate gradient search method to find the minimum $F(\underline{X})$ given in Equation (25). The gradient of $F(\underline{X})$ is computed from the TOGW, DTO, and DLN surface fit approximations which are input to the program. The algorithm requires an initial value from which to begin the gradient search. OAPEN has options to perform this minimization using coded (scaled) or uncoded (unscaled) variables. In this study, uncoded variables were input along with their respective minimum values and range of values. OAPEN made the transformation

$$X_s = \frac{X - \frac{1}{2}(X_{max} + X_{min})}{\frac{1}{2}(X_{max} - X_{min})} \tag{26}$$

where X_s is the scaled variable ($-1 \le X_s \le 1$), X is the actual value, X_{max} is the maximum value, and X_{min} is the minimum value. This transformation was inverted prior to output of the optimal value of the performance function, values of the constraint functions, and the vector of values of the independent variables, corresponding to the optimum.

Optimization Procedure

The optimizations performed were based on surface fit approximations for TOGW, DTO, and DLN as quadratic functions of WOS, AR, and TW such as those given in Equations (20) through (22). The coefficients of the various terms were input to OAPEN as they appear in Equations (20) through (22) with the exception of the pure quadratic terms, which were input as twice their value in the surface fit approximating equation. This was due to the way coefficients are stored in memory (Ref 8:49-51). For example, $(TW)^2$ has the coefficient 26021.8945 in Equation (20), but was input to OAPEN as 52043.9890. The mean values of WOS, AR, and TW (120, 2.5, .8) were input as the starting point for the gradient search algorithm. The minimum values and the range of values for all variables were input for use in the coding transformation. Appendix E contains the input for a typical run.

Results

The results of constrained and unconstrained optimizations are presented in Tables VI and VII respectively. The effects of the constraints ($DTO \leq 3500$ feet, $DLN \leq 4500$ feet) can be identified by comparing values from Table VI to the corresponding values in Table VII. In general, these particular constraints were satisfied at a cost of 300 - 500 pounds additional TOGW. Wing loadings (WOS) and aspect ratios (AR) were reduced while thrust-to-weight ratios (TW) remained the same with the exceptions of mission 6 and mission 13 where TW increased. Figure 4 indicates the existence of an apparent minimum TOGW for mission 13 in the general region predicted by OAPEN. The minimum is clearly confirmed by Figure 5 through Figure 7.

In order to satisfy the constraint, it was necessary to reduce the values of DTO and DLN. The change in DTO and DLN in terms of changes in WOS, AR, and TW, can be written in the form

$$\Delta DTO = \frac{\partial DTO}{\partial WOS}\bigg|_{UM} (\Delta WOS) + \frac{\partial DTO}{\partial AR}\bigg|_{UM} (\Delta AR) + \frac{\partial DTO}{\partial TW}\bigg|_{UM} (\Delta TW) \qquad (27)$$

$$\Delta DLN = \frac{\partial DLN}{\partial WOS}\bigg|_{UM} (\Delta WOS) + \frac{\partial DLN}{\partial AR}\bigg|_{UM} (\Delta AR) \quad \frac{\partial DLN}{\partial TW}\bigg|_{UM} (\Delta TW) \qquad (28)$$

where the subscript UM indicates evaluation at the unconstrained minimum TOGW. Considering mission 13 (Equations (20) - (22)), the various partial derivatives in Equations (27) and (28) are given by

TABLE VI

Unconstrained Minimum TOGW

MISSION	TOGW	WOS	AR	TW	DTO	DLN
1	27320	141.79	3.5	.6	4293	5318
2	29871	120.70	3.15	.6	4036	4787
3	25669	137.21	3.35	.6	3904	4917
4	30074	144.77	3.5	.6	4086	5260
5	26127	111.58	3.5	.6	3750	4179
6	42182	160.00	3.5	.69	4595	5816
7	28999	144.28	3.5	.6	4073	5352
8	29982	145.10	3.5	.6	4382	5728
9	29982	145.10	3.5	.6	4382	5728
10	20371	134.66	3.49	.6	3834	4836
11	19736	130.43	3.5	.6	3729	4816
12	25437	129.73	3.24	.6	3983	4493
13	29035	157.42	3.5	.648	4779	5567
14	36289	149.38	3.5	.6	4851	5813
15	25437	129.73	3.24	.6	3983	4493

TABLE VII
Constrained Minimum TOGW
(DTO $\leq$ 3500 feet, DLN $\leq$ 4500 feet)

MISSION	TOGW	WOS	AR	TW	DTO	DLN
1	27554	111.55	2.98	.6	3506	4237
2	29991	102.27	2.94	.6	3506	4109
3	25758	120.58	3.06	.6	3503	4353
4	30238	120.55	3.01	.6	3504	4422
5	26127	103.01	3.5	.6	3500	3866
6	43335	122.41	3.5	.711	3506	4503
7	29154	120.22	3.07	.6	3493	4503
8	30298	111.52	2.95	.6	3506	4459
9	30298	111.52	2.95	.6	3506	4459
10	20395	120.90	3.27	.6	3502	4364
11	19749	121.06	3.37	.6	3501	4490
12	25523	111.53	3.00	.6	3505	3892
13	29335	116.36	3.29	.679	3507	4210
14	37360	102.15	2.74	.6	3512	4052
15	25523	111.53	3.00	.6	3505	3892

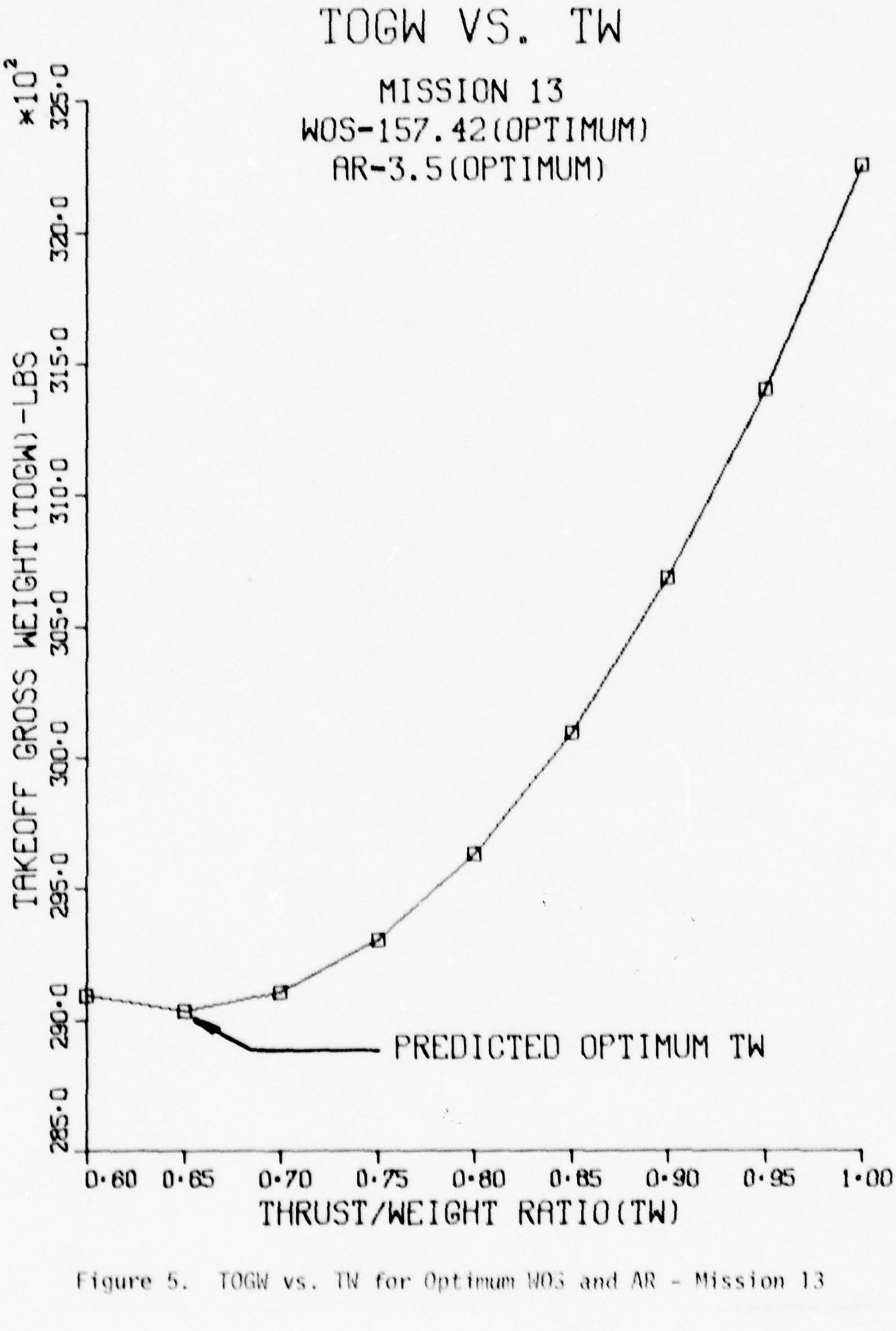


Figure 5. TOGW vs. TW for Optimum WOS and AR - Mission 13

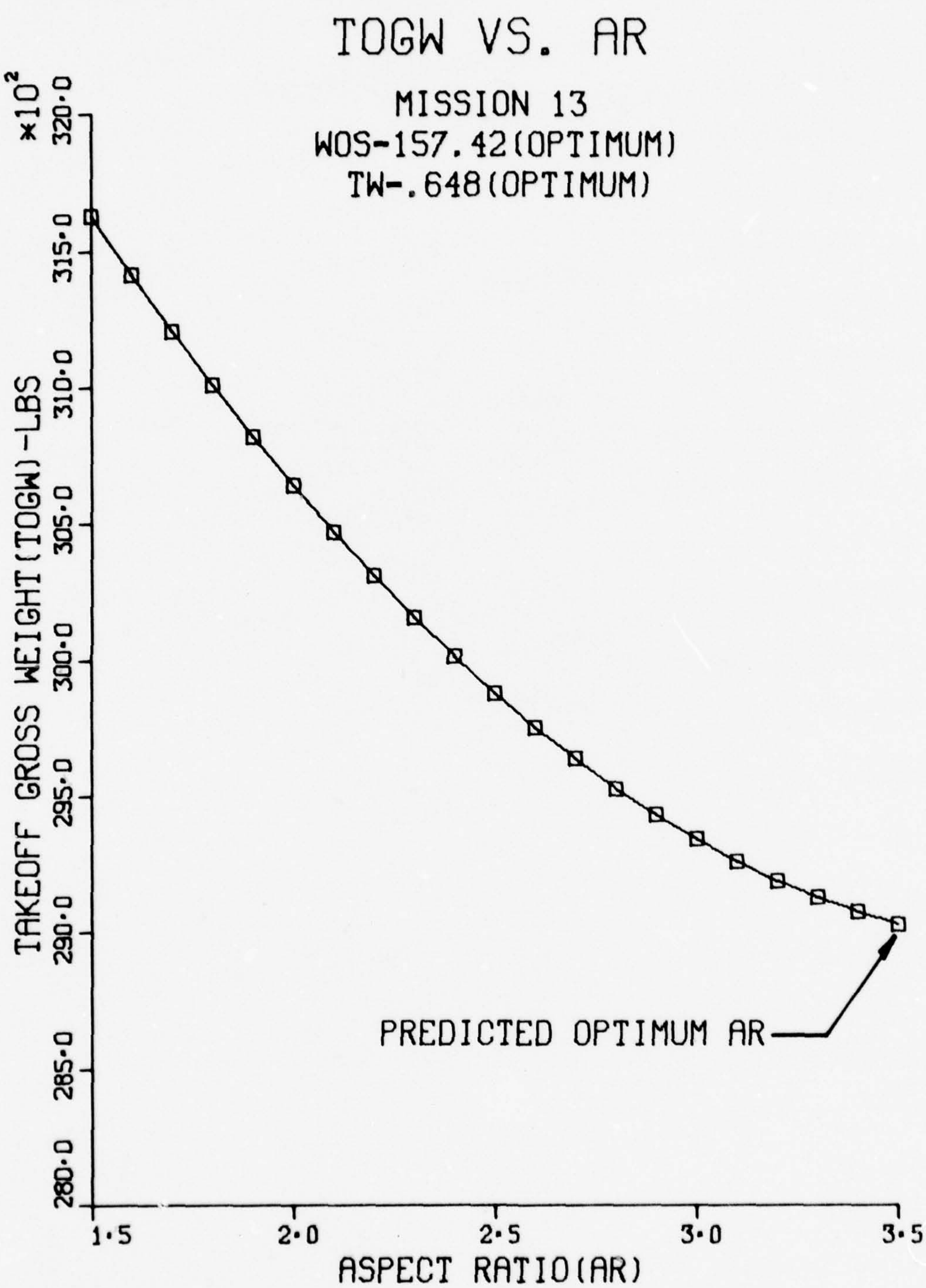


Figure 6. TOGW vs AR for Optimum WOS and TW - Mission 13.

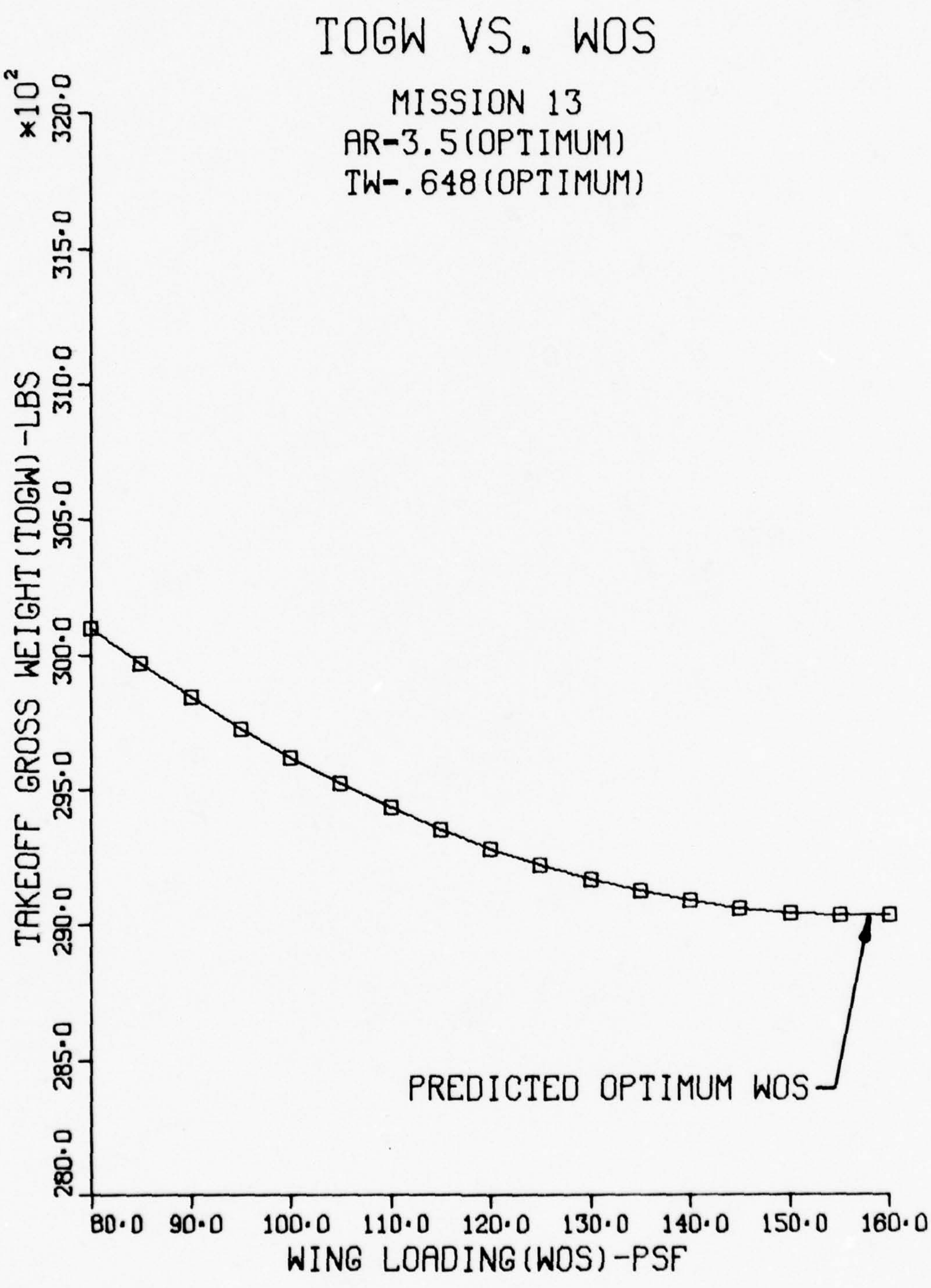


Figure 7. TOGW vs WOS for Optimum AR and TW - Mission 13

$$\frac{\partial DTO}{\partial WOS} = 48.9005 - .4827(AR) - 30.1409(TW) \tag{29}$$

$$\frac{\partial DTO}{\partial AR} = -.4827(WOS) \tag{30}$$

$$\frac{\partial DTO}{\partial TW} = 7296.6377 - 30.1409(WOS) + 9098.8658(TW) \tag{31}$$

$$\frac{\partial DLN}{\partial WOS} = 36.4208 - .0476(WOS) + 1.1496(AR) \tag{32}$$

$$\frac{\partial DLN}{\partial AR} = 1.1496(WOS) - 79.4178(AR) + 118.2846(TW) \tag{33}$$

$$\frac{\partial DLN}{\partial TW} = 2556.2243 + 118.2846(AR) - 3298.3594(TW) \tag{34}$$

Evaluating Equations (29) through (34) at the unconstrained minimum and substituting into (27) and (28), we obtain

$$\Delta DTO = 27.6796\ (\Delta WOS) - 75.9866\ (\Delta AR) + 1152.0142\ (\Delta TW) \tag{35}$$

$$\Delta DLN = 32.9512\ (\Delta WOS) - 20.3438\ (\Delta AR) + 832.88\ (\Delta TW) \tag{36}$$

The maximum reduction in DTO and DLN requires ΔWOS to be negative, ΔAR to be positive,and ΔTW to be negative. If the relative magnitudes of WOS, AR, and TW in Equations (35) and (36) are considered, the ΔWOS terms will dominate. A decrease in WOS for nearly constant TOGW requires an increase in wing area. Since the aspect ratio (AR) is the wing span squared divided by the wing area, increasing the wing area reduces the aspect ratio even if small increases in wing span are allowed. Satisfaction of the constraints in this manner is consistent with Equations (2) and (8) which were used by CISE to compute take off and landing distances. It is clear from Equations (2) and (8) that increasing the wing area (SREF) decreases both take off and landing distance.

Mission 13 was also used to examine the effects of $TOGW_{min}$, WOS, AR, and TW when increasingly severe constraints on DTO and DLN were applied in the optimization. The results are presented in Table VIII below.

TABLE VIII

Constrained Minimum TOGW - Mission 13

TOGW	WOS	AR	TW	DTO	DLN	UPPER LIMIT DTO	UPPER LIMIT DLN
LBS	LBS/FT^2			FT	FT	FT	FT
29035	157.42	3.5	.648	4779	5567	NONE	NONE
29335	116.36	3.29	.679	3507	4210	3500	4500
29552	94.89	2.88	.665	3008	3468	3000	4000
29812	80.00	2.68	.690	2517	2965	2500	3500
31449	80.00	3.29	.882	2001	2994	2000	3000

It was evident that WOS was indeed the dominant variable since successive reductions in DTO and DLN were accompanied by successive reductions in WOS. Changes in AR and TW do not conform to the trend noted for WOS and were dependent on the design configuration at which the partial derivatives of Equations (29) through (34) were evaluated.

VI. INVESTIGATION RESULTS

TOGW, DTO, and DLN in Terms of MACH, RNG, and STR

The optimum aircraft designs for the fifteen missions of Table II were represented in Table VI. Surface fit approximations were developed which relate TOGW, DTO, and DLN for these optimum aircraft to the three independent mission variables MACH, RNG, and STR. The methods of Chapter IV and the program SURFIT were used for the regression analysis resulting in the following expressions.

$$\begin{aligned} TOGW = {} & 97109.316 - 118597.9044(MACH) - 144.1725(RNG) \\ & + 2.6280(STR) + 42465.2574(MACH)^2 + 86.9971(MACH)(RNG) \\ & - .6542(MACH)(STR) + .0735(RNG)^2 \end{aligned} \tag{37}$$

$$\begin{aligned} DTO = {} & 1159.6500 + 10.6167(RNG) + .0770(STR) \\ & + 4.3653(MACH)(RNG) - .0266(RNG)^2 \end{aligned} \tag{38}$$

$$\begin{aligned} DLN = {} & 3756.6445 + .1771(STR) - 1246.7666(MACH)^2 \\ & + 13.2589(MACH)(RNG) - .0311(RNG)^2 \end{aligned} \tag{39}$$

Analysis of Investigation Results

The statistical analysis for each equation is presented in Table IX. In order for a 95 percent confidence level to exist for Equations (37) through (39), the F value for TOGW, DTO, and DLN should be greater than 4.74. This critical value was taken from standard $F_{.05}$ tables for ten degrees of freedom (ten regression coefficients) in the numerator and five degrees of freedom (fifteen data points minus ten regression coefficients) in the denominator (Ref 6:401). The F values in Table IX fail to meet this criteria. However, comparison of the values of TOGW, DTO, and DLN computed by SURFIT from Equations (27) through (39) to corresponding input values from Table VI results in maximum errors of -2.63 percent for TOGW, -7.19 percent for DTO, and -9.82 percent for DLN.

TABLE IX

Statistical Analysis of Selected Equations

	F-Value	Significance Ratio	Multiple Correlation	Standard Error	Maximum % Error
TOGW	2.4850	284.7412	.99825	465.69(LBS)	-2.63
DTO	2.7336	9.9297	.89380	189.12(FT)	-7.19
DLN	.0446	11.4594	.90604	267.89(FT)	-9.82

Application of Investigation Results

Contour plots of constant TOGW versus MACH and RNG for optimized aircraft at three store loadings were generated by solving Equation (37) for MACH, computing its value corresponding to combinations of TOGW, RNG, and STR and plotting all points (RNG, MACH) for a particular TOGW. In a similar manner, contour plots for DTO and DLN could be generated from Equations (38) and (39). The TOGW contour plots for 5000, 7500, and 10000 pound store loadings are presented in Figure 8 through Figure 10. Each contour shows the tradeoff between MACH and RNG for a constant TOGW for optimized aircraft. The actual design in terms of WOS, AR, and TW will change along the contour since the optimum design changes with the mission.

To help visualize the relationships given by Equations (37) through (39), three dimensional plots of TOGW, DTO, and DLN for optimized aircraft

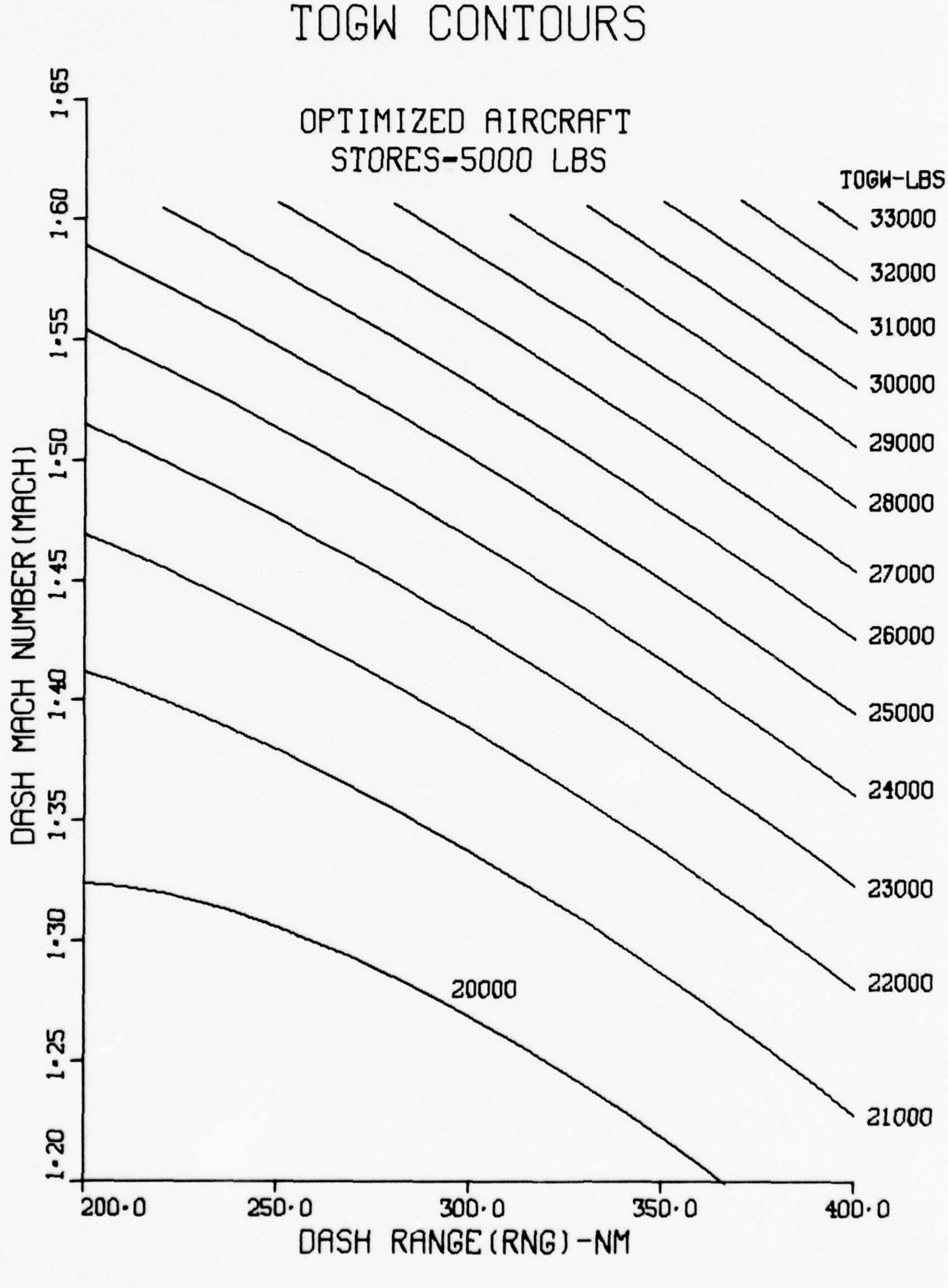


Figure 8. Contours of Minimum TOGW vs MACH and RNG (STORES = 5000 LBS)

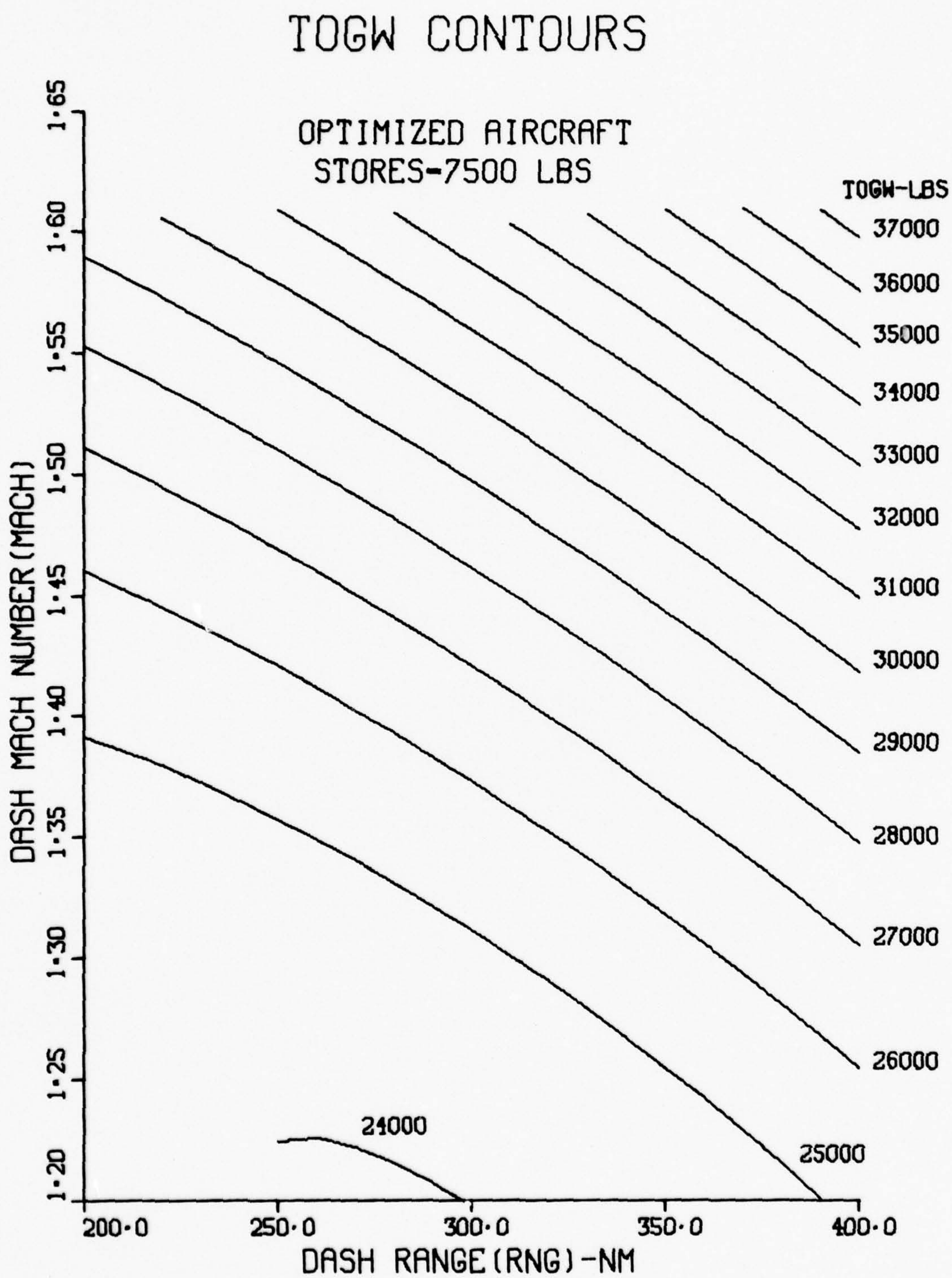


Figure 9. Contours of Minimum TOGW vs MACH and RNG (STORES = 7500 LBS)

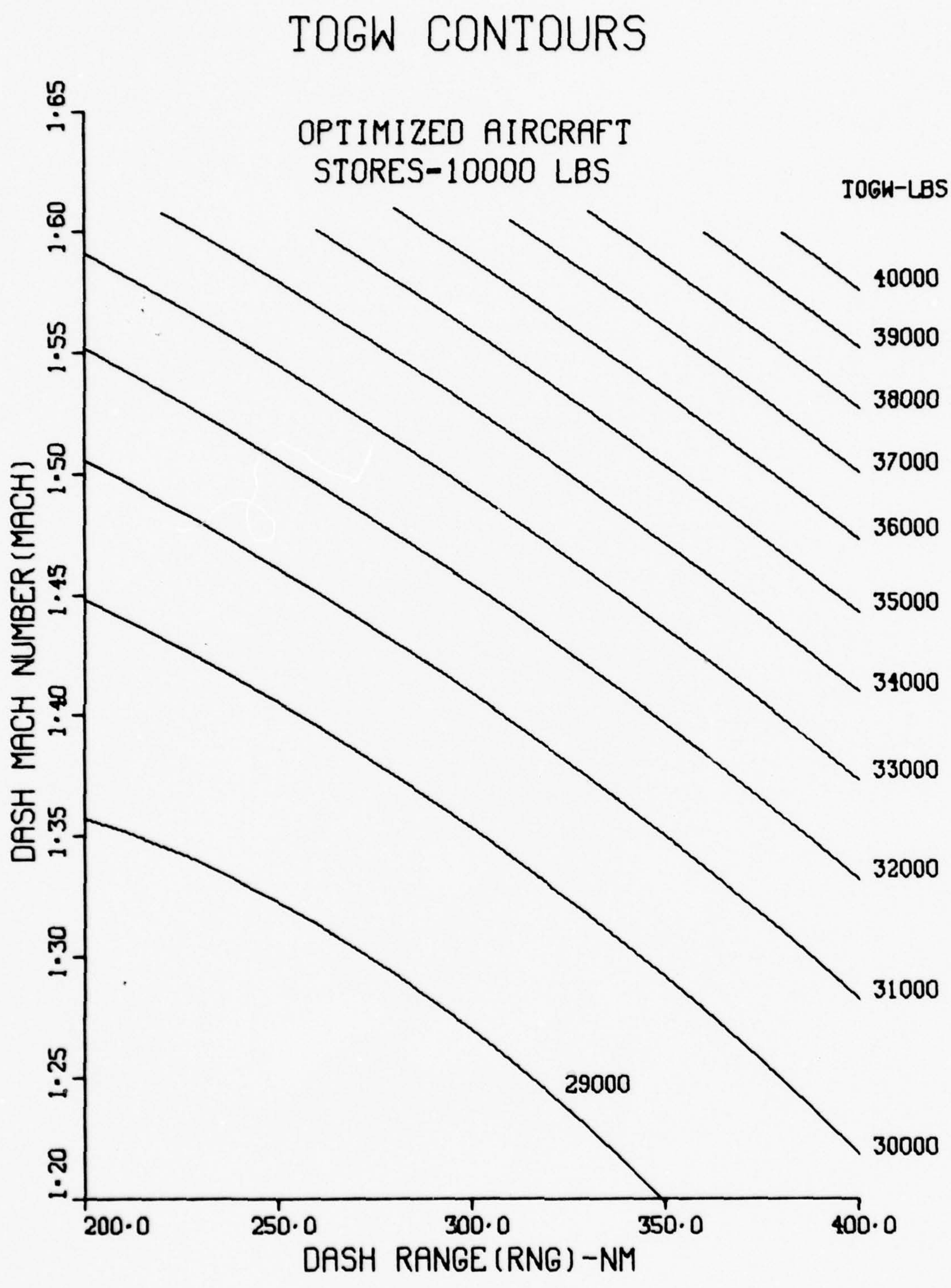


Figure 10. Contours of Minimum TOGW vs. MACH and RNG (STORES = 10000 LBS)

with 5000 pounds of stores were generated using these equations for various values of MACH and RNG. Presented in Figure 11 through Figure 13, these plots dramatically depict trends over the entire mission space. The TOGW plot (Figure 11) is particularly effective as a means of locating an apparent minimum or regions deserving more detailed analysis. For example, it can be seen from Figure 11 that an apparent minimum exists for MACH = 1.2 in the vicinity of RNG = 275NM and not at RNG = 200NM, the minimum range in the mission space. This result contradicts the input data from Table VI where the minimum TOGW did occur for MACH = 1.2 at RNG = 200NM (Mission 11). If Equation (37) were taken as exact, then it can be shown that the minimum TOGW of 19,775 pounds occurs for RNG = 270.58NM. For MACH = 1.2 and RNG = 200NM, Equation (37) predicts TOGW = 20,140 pounds. The difference of 365 pounds is, however, attributed to a buildup of error in the surface fits described in Chapter IV and the final surface fit leading to Equation (37). The many discontinuities in the surfaces of Figure 11 through Figure 13 and the viewpoint from which these must be viewed make it impossible to determine specific values of TOGW, DTO, or DLN from these plots.

The two dimensional plots of Equations (37) through (39) presented in Figure 14 through Figure 16 for STR = 5,000 pounds, allow more precise estimation of values than their three dimensional counterparts in Figure 11 through Figure 13. The existence of a minimum TOGW in the vicinity of RNG = 275NM is quite clear in Figure 14. Figure 14 through Figure 16 are suitable for reading approximate values of TOGW, DTO, and DLN at specific values of MACH and RNG.

Equations (37) through (39) can be used to evaluate TOGW, DTO, and DLN when a specific combination of MACH, RNG, and STR is of interest by

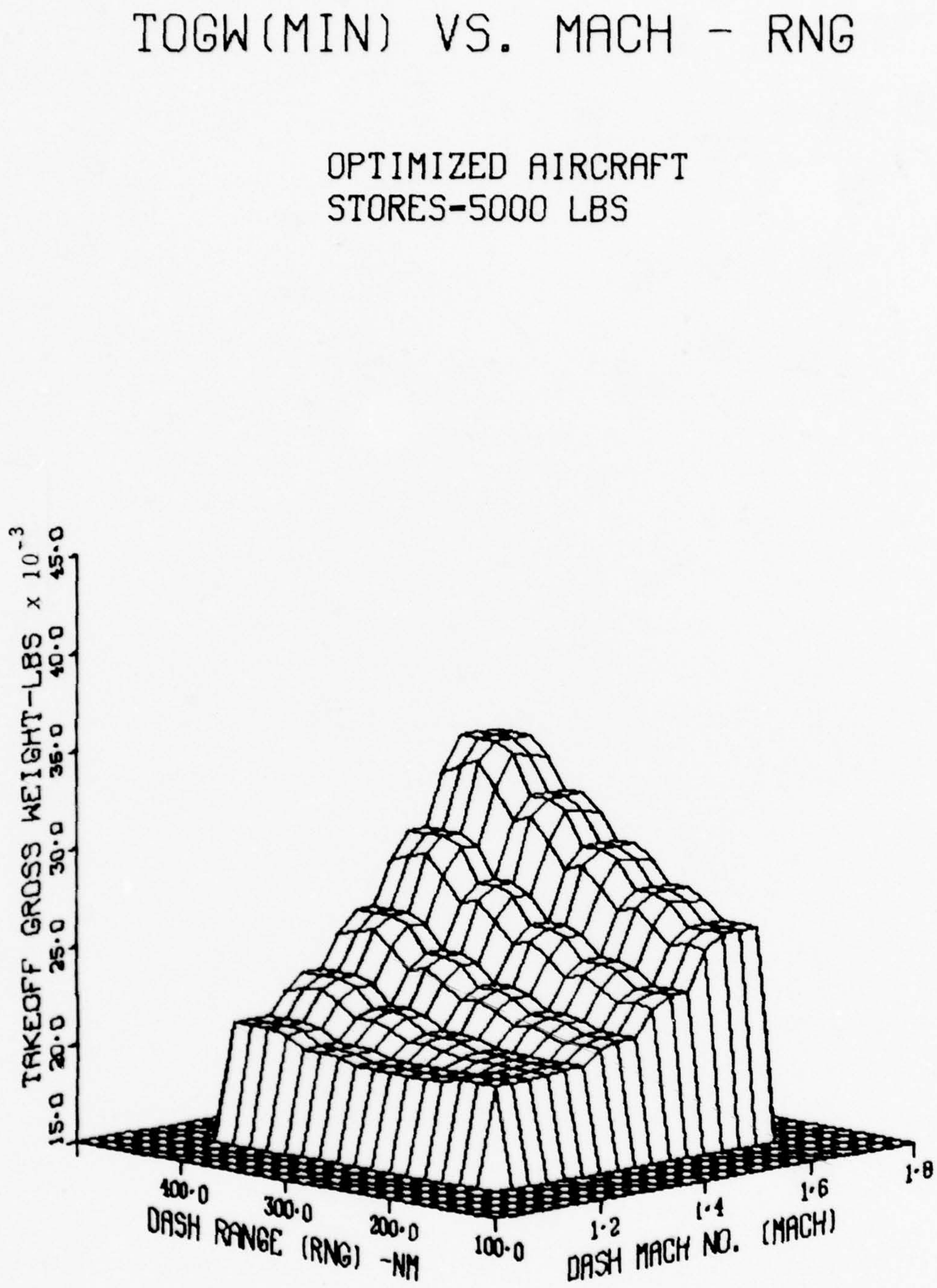


Figure 11. 3-D plot of Minimum TOGW vs MACH and RNG (STORES = 5000 LBS)

DTO VS. MACH-RNG

OPTIMIZED AIRCRAFT
STORES-5000 LBS

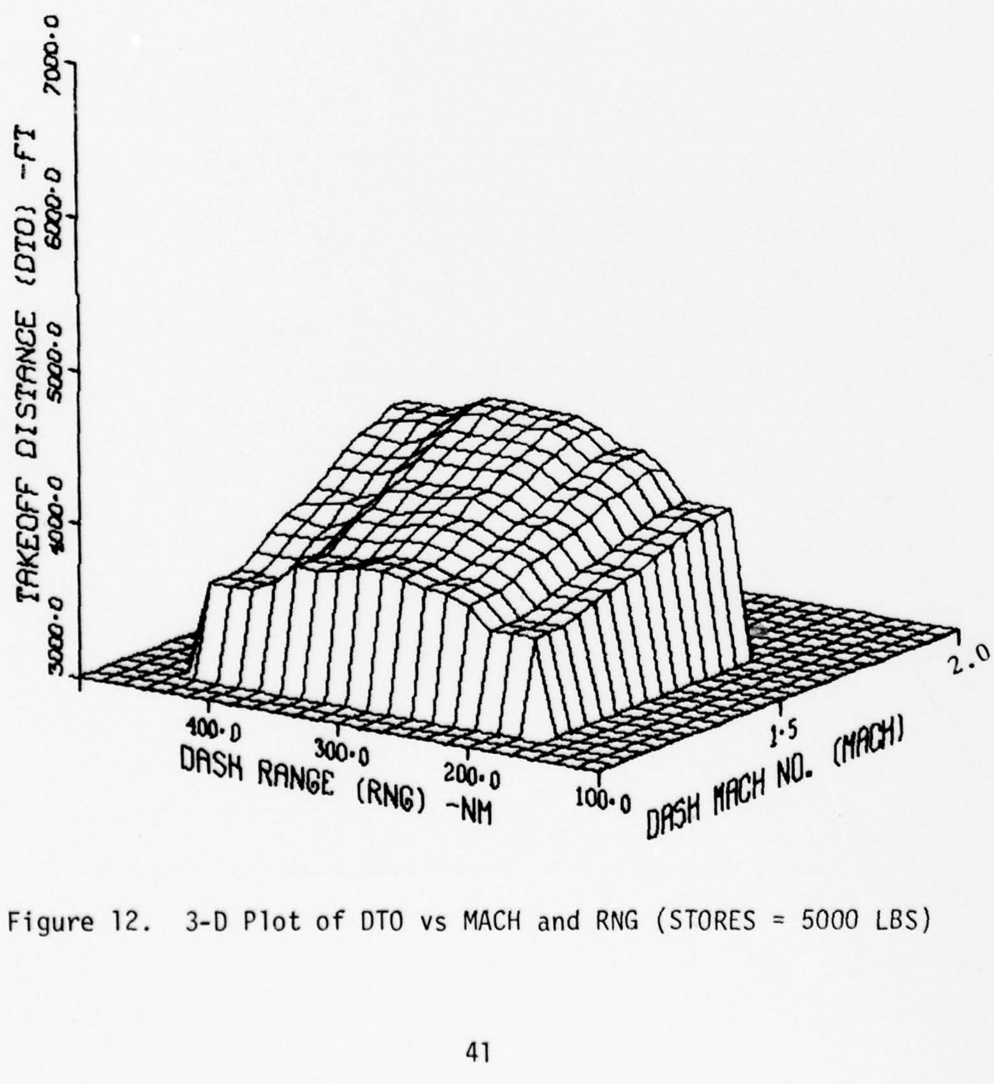


Figure 12. 3-D Plot of DTO vs MACH and RNG (STORES = 5000 LBS)

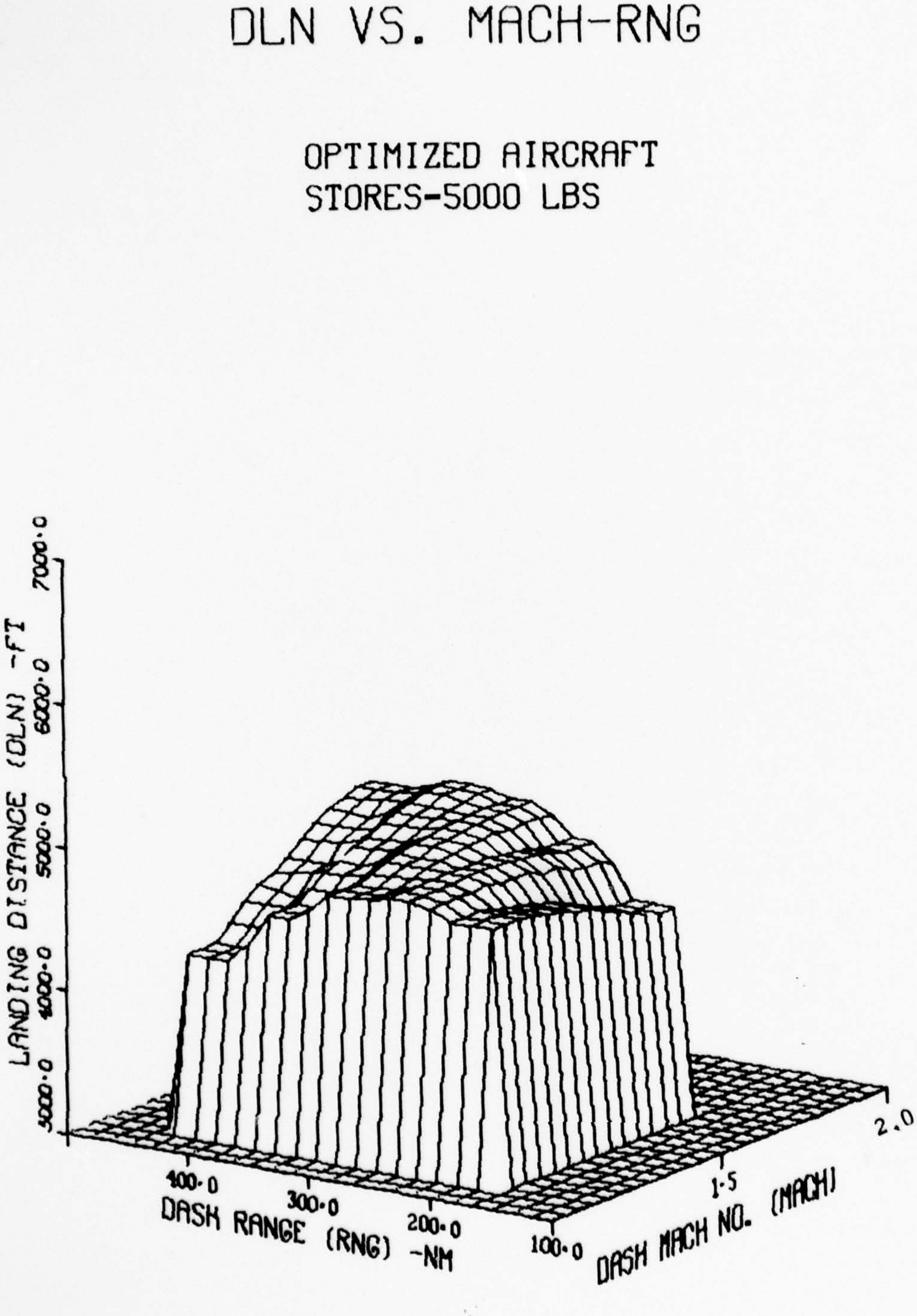


Figure 13. 3-D Plot of DLN vs MACH and RNG (STORES = 5000 LBS)

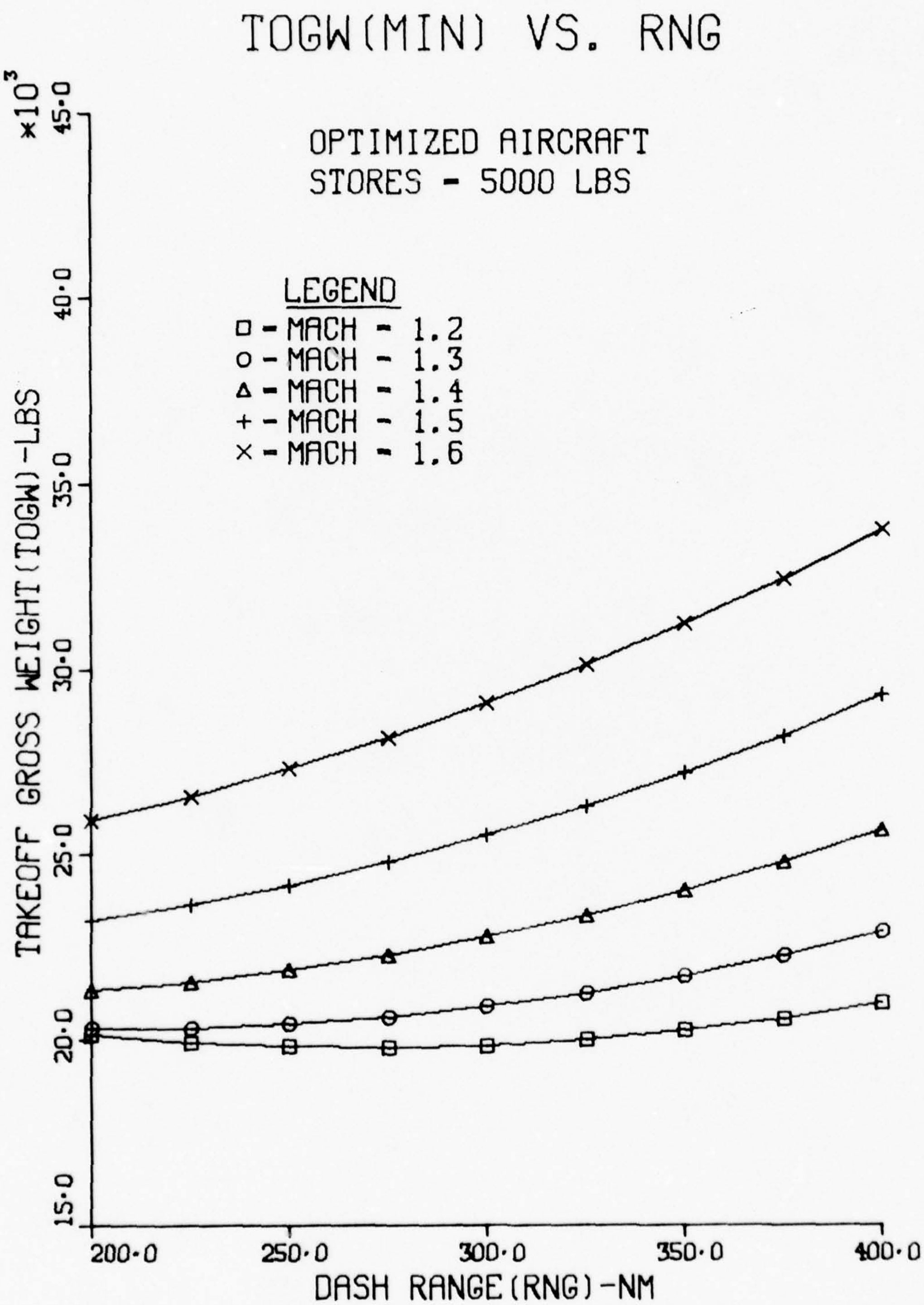


Figure 14. Minimum TOGW vs RNG (STORES = 5000 LBS)

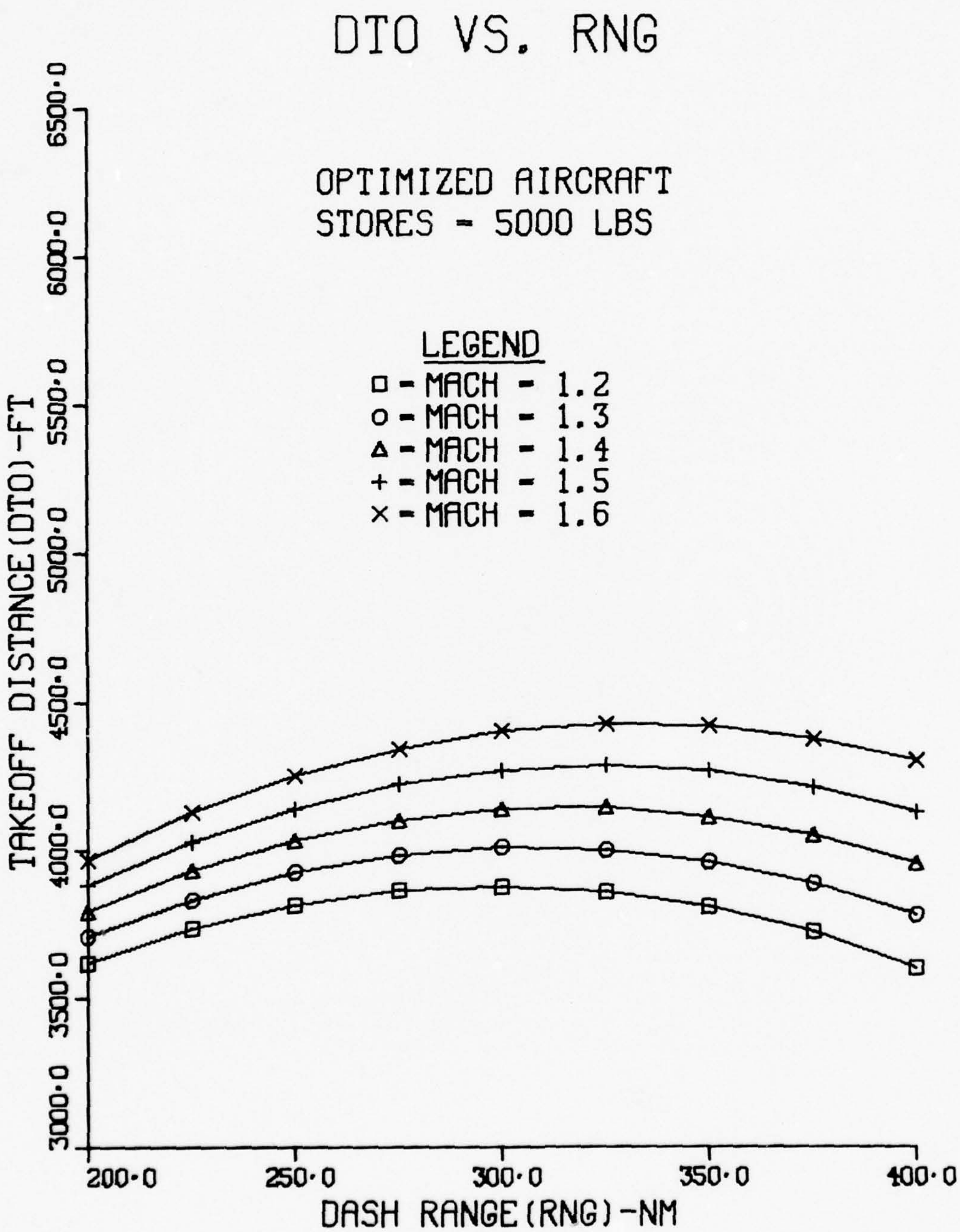


Figure 15. DTO vs RNG (STORES = 5000 LBS)

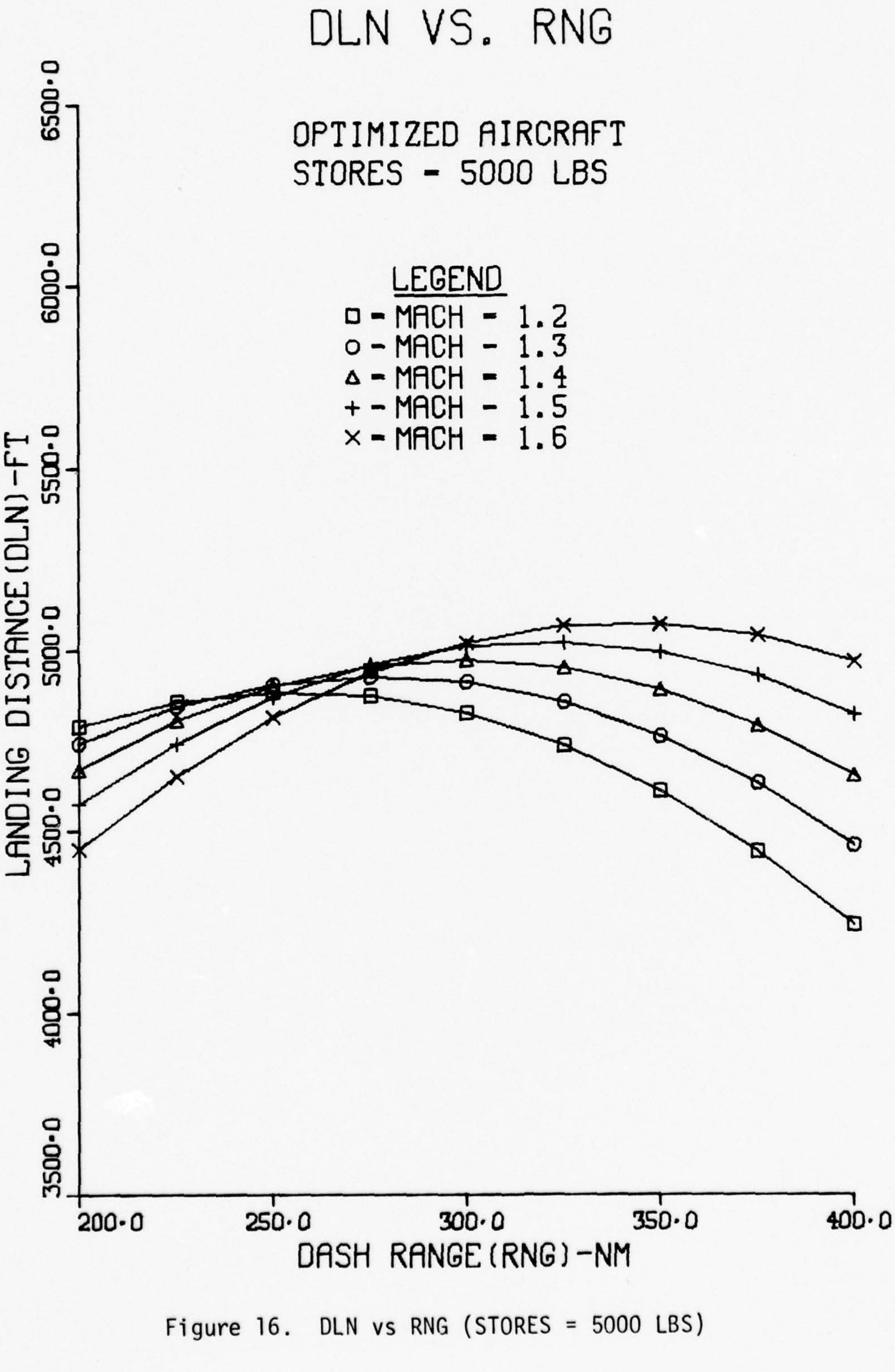


Figure 16. DLN vs RNG (STORES = 5000 LBS)

direct substitution into the appropriate equation. The effects of changes from a baseline set of requirements can also be evaluated. For example, the change in TOGW due to small changes in MACH, RNG, and STR can be written,

$$\Delta TOGW = \frac{\partial TOGW}{\partial MACH}\bigg|_B (\Delta MACH) + \frac{\partial TOGW}{\partial RNG}\bigg|_B (\Delta RNG) + \frac{\partial TOGW}{\partial STR}\bigg|_B (\Delta STR) \qquad (40)$$

Where $\Delta TOGW$ is the change in TOGW, $\Delta MACH$ is the change in MACH, ΔRNG is the change in RNG, ΔSTR is the change in STR, and $\big|_B$ indicates evaluation of the partial derivatives at the baseline set of requriements.

VII. CONCLUSIONS AND RECOMMENDATIONS

Conclusions

1. Surface fit approximations for TOGW, DTO, and DLN in terms of the mission requirements are sufficiently accurate to be used effectively in trade studies to refine performance requirements for future aircraft.

2. Surface fit approximations for TOGW in terms of the mission requirements can be used to establish initial cost and schedule estimates very early in the planning cycle and conceptual design stage for future aircraft.

3. Care must be taken when defining the independent mission variables and their ranges of values to assure that the minimum TOGW lies within the mission space, while not making the range so large that quadratic approximations are no longer valid. It may be desirable to refine the mission space and/or the design space after an initial exercise of the methodology.

4. The simple latin square method can be used to dramatically reduce the number of design cases requiring analysis, thus saving significant manpower and computer resources.

Recommendations

1. Surface fit approximations for TOGW, DTO, and DLN in terms of the mission variables MACH, RNG, and STR should be incorporated into the procedures for trade studies performed early in the planning cycle and conceptual design phase in order to provide improved estimates of performance requirements, acquisition cost, and schedules for future aircraft.

2. Further studies should be conducted to determine the relationship between system effectiveness, E, and the mission variables MACH, RNG, and STR, i.e., E = E(MACH, RNG, STR). Thus, using the results of this study, it would be possible to find the most cost effective system for a particular mission by minimizing the ratio, cost ÷ effectiveness.

3. Further studies should be performed in conjunction with AFFDL/FXB to determine the effect of including dash altitude in the mission space. These studies should make use of a mission simulation which has provisions for input of engine design variables such as by-pass ratio and overall pressure ratio.

4. Design optimization methods based on surface fit approximations should be incorporated into AFFDL procedures.

5. Future studies should make use of the orthogonal latin square method or the D-optimal method of selection in order to reduce the correlation between cases to be simulated.

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Appendix A

LATSQR Computer Program Input/Output

Appendix A

LATSQR Computer Program Input/Output

Input

Card No.	Col No.	Description
1	12-13	Number of independent design variables (Format I2)
2-N	1-6	Alphanumeric label for the variable (Format A6)
	11-20	Lower limit for the variable (Format E10.4)
	21-30	Upper limit for the variable (Format E10.4)

"N" is the number of independent design variables plus one which allows the range of each variable to be input.

Input is assigned to Tape 5.

Output

The format of the output is (I8, 10F12.4/14X, 7F12.4) which yields the data point number and the values of the design variables for that data point.

Output is assigned to Tape 6.

Appendix B

CISE Computer Program Input/Output

Appendix B

CISE Computer Program Input/Output

All input is in the standard FORTRAN Namelist format with the first character in each record appearing in the second column. The title of the design under study appears on the first data record and is in Hollerith format. The input is divided into five groups with the following names:

DESIGN, MISSION, WEIGHTS, GEOM, PROP

The input sequence and the items that can be input by each Namelist are:

$DESIGN

LF = Load Factor

VMAX = Maximum Equivalent Airspeed

AMMAX = Maximum Mach No.

ALTX = Altitude for AMMAX

PS = Energy Level Required at Flight Design Gross Wt.

GPS = G Level for PS

ALTPS = Altitude for PS

AMNPS = Mach No. for PS

NCREW = No. of Crew Members

NTANK = No. of 300 Gal External Tanks

NSTORX = No. of External Stores

NPYL = No. of Pylons to Carry External Stores and Tanks

NSTORI = No. of Internal Stores

CLMAX = Maximum Lift Coefficient for Take off and Landing

NCDX = C_{d_o} Calculation Cue; When = 0, CDOSF = C_{f_e}; When = 1, C_{d_o} is calculated by Program and CDOSF is the Modification Factor

CDOSF = Equivalent Skin Friction Coefficient or C_{d_o} Modification Factor (depending on NCDX value input)

CDSTX1 = Subsonic Store Drag Modification Factor

CDSTX2 = Supersonic Store Drag Factor

ALTTOL = Altitude for Take off and Landing

DTEMP = Take off and landing (°F) from Standard Day at ALTTOL

IPROP = 1 for Turbofan (P&W 401)

= 2 for Turbojet (GE J79)

=3 for Reciprocating (Lycoming LGO-540)

AB = 1 for afterburner

AB ≠ 1 for no afterburner

TOWE = Engine Thrust to Weight Ratio

FDGWF = Ratio of Total Fuel on Board to Define Flight Design Gross Weight (FDGW) where, in the Program FDGW = TOGW - (1.0 - FDGWF) * WFUEL (Initialized at .60)

LDGWFS = Same as FDGWF, except for Structural Design Landing Gross Weight (LDGW) where, in the Program LDGW = TPGW - (1.0 - LDGWFS) * WFUEL - WSTOR (Initialized at .90)

LDGWF = Same as LDGWFS, except for Landing Distance Calculations, Using Design Landing Distance Gross Weight (LDGWLD) where, in the the Program LDGWLD = TOGW - (1.0 - LDGWF) * WFUEL - WSTOR (Initialized at .70)

IPPRINT = 1 for Error Checkout Messages to be printed

= 0 for Error Checkout Messages not to be printed

TOTHF = Thrust Modification Factor for Nonstandard Day (Altitude and Temperature Adjustment) (Initialized at 1.0)

CDF = Total C_D Modification Factor, May be Used to Adjust L/D by Modifying C_D

CDSF = Factor to Adjust Supersonic Drag Contribution to C_{D_O}

$MISSION

N = Total Number of Mission Legs

R(I) = 0 for Warmup Fuel Allowance

= -1 to Drop Stores

= -2 to Turn at Fixed Gee

= -3 to Accelerate

= -4 for Energy Altitude Combat Fuel Allowance

= -5 for Loiter Performance

= -6 for Loiter at Fixed Altitude and Mach No.

= -7 to Turn at Maximum Possible Gee

> 0 for Climb Performance

= 1.E6 to Climb on Intermediate (Military Power)

= 1.1E6 to Climb with Afterburner with Distance Credit

GEE(I) = G Level for Turns (no 1g turns), When RANGE(I) = -7

= Time (min) on Afterburner Power, When RANGE(I) = 1.1E6

= No. of External Stores to be Dropped, When RANGE(I) = -1

NTURNS(I) = No. of Turns, When RANGE(I) = -7

= Mach, When RANGE(I) = -3

= Energy Altitude for Combat Fuel Allowance (ft), When RANGE(I) = -4

TIME(I) = Loiter Time (min), When RANGE(I) = -6, or -5

= No. of Internal Stores to be Dropped, When RANGE(I) = -1

ITANK(I) = No. of External Fuel Tanks to be Dropped, When RANGE(I) = -1

AMACH(I) = Leg Mach No., Except When RANGE(I) = -1

= Weight of Cargo to be Dropped, When RANGE(I) = -1

ALT(I) = Leg Altitude

RG(I) = Distance Covered in a Particular Segment, When RANGE(I) = 1.1E6

$WEIGHTS

WAVUN = Weight of Avionics Equipment

WMA = Weight of AMMO, Guns, etc. That Does Not Require Installation Weight in Addition

WSTORX = Weight of External Stores

WSTORI = Weight of Internal Stores

WINGF = Wing Weight Modification Factor

TAILF = Tail Weight Modification Factor

BODYF = Body Weight Modification Factor

GEARF = Gear Weight Modification Factor

$GEOM

NWOS = No. of Wing Loadings to be Cycled, Maximum of 5

WOS(I) = Wing Loadings, Maximum of 5 LBS/FT^2

NAR = No. of Aspect Ratios to be Cycled, Maximum of 5

AR(I) = Aspect Ratios, Maximum of 5

NSWP = No. of Quarter Chord Sweep Angles to be Cycled, Maximum of 5

SWP(I) = Sweep Angles (Quarter Chord) in Degrees, Maximum of 5

NTROOT = No. of Root Thickness Ratios to be Cycled, Maximum of 5

TROOT(I) = Root Thickness Ratios, Maximum of 5

TAPER = Wing Taper Ratio

SFWET = Fueslage Wetted Area

SHT = Horizontal Tail Volume Coefficient

LFUS = Fuselage Length

CWRT = Root Chord of the Wing in Inches

MAC = Wing Mean Geometric Chord in Feet

SWWET = Wing Wetted Area

$PROP

IPROP = 1 for Turbofan (P&W 401)

= 2 for Turbojet (GE J79)

= 3 for Reciprocating (Lycoming LGO-540)

AB = 1 for afterburner

AB ≠ 1 for no afterburner

SLTH = Thrust to Weight Ratio of the Vehicle

TOWE = Thrust to Weight Ratio of the Engine

SFCF = Specific Fuel Consumption Modification Factor

To end the input and begin the mission simulation, an 'E' is placed in column 2.

The input used in this study was:

```
MACH NO. 1.4  RANGE  400 STORES   5000
$DESIGN
IPRINT=0,LF=9.75,
AMMAX=1.4,VMAX=432.,
INITER=25,
STORIN=2.,
$END OF DESIGN
$WEIGHTS
```

```
WAVUN=1350.,WMA=600.,
WSTORI=  5000.,
GEARF=.97,WINGF=.83,BODYF=.83,TAILF=.83,
$END OF WEIGHTS
$GEOM
NWOS=1,WOSIN=120.,
NAR=1,ARIN=2.5,
$END OF GEOM
$PROP
IPROP=1,AB=1.,TOWE=11.0,SFCF=1.00,
SLTH=.8,
$END OF PROP
$MISSION
N=12,NTURNS(7)=1.0,DELM=.4,
TIME(1)=.75,TIME(4)=30.,TIME(8)=2.,TIME(12)=20
GMIN=1.2,
GEE(7)=6.5,
ALT(1)=0.,35000.,35000.,35000.,35000.,
        35000.,35000.,35000.,35000.,35000.,
        45000.,0.,
AMACH(1)=0.,.85,.85,.85,.85,
          1.4,1.4,1.4,1.4,1.4,
          .85,.4,
RANGE(1)=0.,.1E7,275.,-6.,-3.,
       225.,-7.,-1.,175.,1.1E6
          325.,-5.,
$END OF MISSION
```

```
E
$GEOM
WOSIN=140.,ARIN=3.5,
$END OF GEOM
$PROP                                DESIGN POINT 2
SLTH=.6,
$END OF PROP
E
o
o    DESIGN POINTS 3-44
o
$GEOM
WOSIN=160.,ARIN=1.5,
$END OF GEOM
$PROP                                DESIGN POINT 45
SLTH=.8,
$END OF PROP
E
```

Output

The values of the design variables and the corresponding performance values were output to Tape 2 and each value was of the format F10.2.

It was also possible to have a mission summary printed out which included an analysis of each leg in the mission along with a weight summary. The component weights are also output but because of the many approximations utilized to derive these weights, only the weight empty and TOGW values can be considered statistically valid (Ref 5:7). This summary data is available on Tape 6.

Appendix C

Surface Fit Approximations for

TOGW, DTO, and DLN in Terms of WOS, AR, and TW

Appendix C

TABLE X

TOGW Surface Fit Approximations

Mission	1	2	3	4	5
MACH	1.4	1.6	1.2	1.2	1.6
RNG(NM)	300	200	400	400	200
STORES(LBS)	7500	7500	7500	10000	10000
INTERCEPT	26007.566	37981.991	28723.487	32499.802	26285.989
WOS	-75.7133	-67.8492	-66.3245	-87.7478	
AR	1247.0493		1283.5189	2171.4881	
TW	4567.6560	-16763.4100	-9810.0152	-9744.5739	
WOS^2	.3433	.4173	.3035	.3807	
WOS×AR	-10.7585	-10.4468	-9.2106	-10.7483	
WOS×TW	26.6643		23.2511	25.2367	
AR^2	253.5894	408.4523	236.1505	198.5429	
AR×TW	-2558.9111	-2184.4073	-2673.6695	-3412.4439	-1160.5214
TW^2	9383.1142	22513.8374	19424.0978	23703.6018	6326.9925
% ERROR	.77	-4.21	+1.24	+1.27	-4.57

Mission	6	7	8	9	10
MACH	1.6	1.2	1.4	1.4	1.2
RNG(NM)	400	300	200	200	300
STORES(LBS)	10000	10000	10000	10000	5000
INTERCEPT	60287.329	30120.772	26030.222	26030.222	20235.390
WOS		-77.1921	-80.5090	-80.5090	-30.2597
AR	9228.7108	1727.2149	1564.7464	1564.7464	
TW	-86451.623	-5118.7707	10700.1694	10700.1694	
WOS^2	.3232	.3486	.3577	.3577	.2081
WOS×AR	-34.5719	-10.6813	-11.3031	-11.3031	-9.8071
WOS×TW		23.2955	27.1012	27.1012	14.1431
AR^2		222.7969	236.0904	236.0904	287.8370
AR×TW	-7842.9014	-2994.7320	-2780.7956	-2780.7956	-1151.5043
TW^2	82486.2967	18670.4220	7037.5085	7037.5085	7801.7026
% ERROR	3.51	1.07	1.02	1.02	1.39

NOTE: Blanks in Tables X - XII indicate that the variable did not appear in the equation selected by SURFIT for the mission considered.

TABLE X (Cont'd)

TOGW Surface Fit Approximations

Mission	11	12	13	14	15
MACH	1.2	1.4	1.6	1.6	1.4
RNG(NM)	200	400	300	300	400
STORES(LBS)	5000	5000	5000	10000	5000
INTERCEPT	17738.551	35637.224	38850.416	39018.706	35637.224
WOS	-24.7632	-61.7904		-157.3430	-61.7904
AR				2710.7175	
TW	4376.1917	-22576.9728	-28156.2033		-22576.9728
WOS^2	.1945	.3395	.1780	.5788	.3395
WOS×AR	-9.1612	-11.1916	-16.0080	-13.9018	-11.1916
WOS×TW	10.1508	16.6520		55.1242	16.6520
AR^2	258.1150	391.9026	450.7710	287.7950	391.9026
AR×TW	-1048.2631	-1815.8917	-1591.2582	-4659.1598	-1815.8917
TW^2	4777.9436	23534.0776	26021.8945	19326.4624	23534.0776
% ERROR	1.28	1.96	-4.09	2.21	1.96

TABLE XI

DTO Surface Fit Approximations

Mission	1	2	3	4	5
MACH	1.4	1.6	1.2	1.2	1.6
RNG(NM)	300	700	400	400	200
STORES(LBS)	7500	7500	7500	10000	5000
INTERCEPT	3013.7965	3239.8422	2824.5412	2824.5412	3239.8422
WOS	44.8535	48.9005	41.4857	41.4857	48.9005
AR					
TW	-6715.5369	-7296.6377	-6228.9847	-6228.9847	-7296.6377
WOS^2					
WOS×AR	-.4063	-.4827	-.3474	-.3474	-.4827
WOS×TW	-27.7031	-30.1409	-25.6668	-25.6668	-30.1409
AR^2					
AR×TW					
TW^2	4187.0144	4549.4329	3883.5409	3883.5409	4549.4329
% ERROR	+1.76	+1.79	+1.73	1.73	1.79

Mission	6	7	8	9	10
MACH	1.6	1.2	1.4	1.4	1.2
RNG(NM)	400	300	200	200	300
STORES(LBS)	10000	10000	10000	10000	5000
INTERCEPT	3239.8422	2824.5412	3013.7965	3013.7965	2824.5412
WOS	48.9005	41.4857	44.8535	44.8535	41.4857
AR					
TW	-7296.6377	-6228.9847	-6715.5369	-6715.5369	-6228.9847
WOS^2					
WOS×AR	-.4827	-.3474	-.4063	-.4063	-.3474
WOS×TW	-30.1409	-25.6668	-27.7031	-27.7031	-25.6668
AR^2					
AR×TW					
TW^2	4549.4329	3883.5408	4187.0144	4187.0144	3883.5408
% ERROR	1.79	1.73	1.76	1.76	1.73

TABLE XI (Cont'd)

DTO Surface Fit Approximations

Mission	11	12	13	14	15
MACH	1.2	1.4	1.6	1.6	1.4
RNG(NM)	200	400	300	300	400
STORES(LBS)	5000	5000	5000	10000	5000
INTERCEPT	2824.5412	3013.7965	3239.8422	3239.8422	3013.7965
WOS	41.4857	44.8535	48.9005	48.9005	44.8535
AR					
TW	-6228.9847	-6715.5369	-7296.6377	-7296.6377	-6715.5369
WOS^2					
WOS×AR	-.3474	-.4063	-.4827	-.4827	-.4063
WOS×TW	-25.6668	-27.7031	-30.1409	-30.1409	-27.7031
AR^2					
AR×TW					
TW^2	3883.5409	4187.0144	4549.4329	4549.4329	4187.0144
% ERROR	1.73	1.76	1.79	1.79	1.76

TABLE XII

DLN Surface Fit Approximations

Mission	1	2	3	4	5
MACH RNG(NM) STORES(LBS)	1.4 300 7500	1.6 200 7500	1.2 400 7500	1.2 400 10000	1.6 200 5000
INTERCEPT	-65.9673	93.0035	-429.5366	-353.9872	-449.6767
WOS	43.1109	41.7754	41.9190	43.6554	31.9541
AR				-45.7567	
TW			974.7361	837.7123	2127.0361
WOS^2	-.0220	-.0301	-.0214	-.0200	
WOS×AR	.9131	.7855	.8157	.7308	1.2957
WOS×TW	-6.6417		-7.2321	-8.8234	
AR^2	-36.6957	-41.6313	-36.9886	-29.9526	-24.0529
AR×TW	131.2679	184.1080	148.6128	168.9536	
TW^2		-396.9336	-696.1927	-615.5980	-1179.0946
% ERROR	.60	1.86	.70	-.54	2.54

Mission	6	7	8	9	10
MACH RNG(NM) STORES(LBS)	1.6 400 10000	1.2 300 10000	1.4 200 10000	1.4 200 10000	1.2 300 5000
INTERCEPT	-544.5098	-321.5099	-75.5938	-75.5938	31.2968
WOS	30.6154	43.8369	45.9105	45.9105	39.4081
AR	-326.0750				
TW	3848.2647	663.6104			
WOS^2		-.0201	-.0215	-.0215	-.0225
WOS×AR	1.3310	.7820	.8777	.8777	1.2703
WOS×TW		-8.2100	-7.7821	-7.7821	-5.2938
AR^2		-36.8052	-37.4956	-37.4958	-35.5349
AR×TW	241.9731	149.0058	135.3914	135.3914	81.0997
TW^2	2902.5906	-493.6867			
% ERROR	2.15	-.46	-.45	-.45	1.13

TABLE XII (Cont'd)

DLN Surface Fit Approximations

Mission	11	12	13	14	15
MACH	1.2	1.4	1.6	1.6	1.4
RNG(NM)	200	400	300	300	400
STORES(LBS)	5000	5000	5000	10000	5000
INTERCEPT	-68.1200	-836.9182	-954.8010	-122.4515	-836.9182
WOS	38.9359	37.7589	36.4208	45.9740	37.7589
AR	155.1002				
TW		2138.5329	2556.2243		2138.5329
WOS^2	-.0211	-.0257	-.0238	-.0212	-.0257
WOS×AR	1.1748	1.1526	1.1496	.7351	1.1526
WOS×TW	-3.7638	-2.8546		-8.1732	-2.8546
AR^2	-50.6007	-38.1813	-39.7089	-39.5253	-38.1813
AR×TW		112.2287	118.2842		112.2287
TW^2		-1384.1546	-1649.1797	177.5628	-1384.1546
% ERROR	-1.08	-.87	1.94	.71	-.87

Appendix D

SURFIT Computer Program Input/Output

Appendix D

SURFIT Computer Program Input/Output

Input

All numeric data requires a decimal point with the exception of card number three.

Card No.	Col. No.	Description
1	1-6	The word PROGRM must appear (Required card)
	12-17	A six character identification word in alpha-numeric format
	22-31	Number of input variables per data point including dependent variables
	32-41	Number of variables added by synthesis
	42-51	Number of variable synthesis cards
	52-61	Number of labeled variables
	62-71	Number of data points
2	1-6	The word PRGOPT must appear (Required card)
	12-21	Number of Format cards if the default Format of (11X,6F10.0) is not used
	22-25	TRUE if input data is on magnetic tape otherwise leave blank
	32-35	TRUE rewinds auxiliary input data tape otherwise leave blank
	52-55	TRUE prints covariance and correlation matrices otherwise leave blank

Card No.	Col. No.	Description
	62-65	TRUE calculates the equation based on a curve through the origin (zero intercept) otherwise leave blank
3	1-3	If variable synthesis data is on cards then the integer 0 must appear in column 3; if the data is assigned to Tape 8 then a 1 must appear in column 3 (Required card)
as needed	1-6	The word VARSYN must appear; these are the variable synthesis cards which form the second order terms in the equations; in general these cards are optional but were required in this study because of the form of surface fit approximation.
	8-10	Synthesis operation code which can take on the following values:

1.0	VAR(I) = Constant
2.0	VAR(I) = VAR(J)
3.0	VAR(I) = $[VAR(J)]^{1/2}$
4.0	VAR(I) = EXP [VAR(J)]
5.0	VAR(I) = SIN[VAR(J)]
6.0	VAR(I) = COS[VAR(J)]
7.0	VAR(I) = TAN[VAR(J)]
8.0	VAR(I) = Natural Log [VAR(J)]
9.0	VAR(I) = ARCSIN[VAR(J)]
10.	VAR(I) = ARCCOS[VAR(J)]
11.	VAR(I) = VAR(J) + VAR(K)
12.	VAR(I) = VAR(J) - VAR(K)
13.	VAR(I) = VAR(J) * VAR(K)
14.	VAR(I) = VAR(J)/VAR(K)
15.	VAR(I) = VAR(J)**VAR(K) i.e. VAR(J) raised to the power VAR(K)
16.	VAR(I) = ARCTAN[VAR(J)/VAR(K)]
17.	VAR(I) = $[VAR(J)**2 + VAR(K)**2]^{1/2}$
18.	VAR(I) = MAX[VAR(J), VAR(K), Constant]
19.	VAR(I) = MIN[VAR(J), VAR(K), Constant]

Card No.	Col. No.	Description
	12-21	Assigns a value to I in the above operations

Card No.	Col. No.	Description
	22-31	Assigns a value of J in the above operations
	32-41	Assigns a value of K in the above operations
	42-61	Assigns a value to the Constant in the above operations
as needed	1-6	The word LABELS must appear; is used to assign alphanumeric titles to each of the variables, both intput and synthesized; is an optional item in the program
	12-15	Index number for the first labeled variable
	16-21	A six character label for the first labeled variable
	22-25	Index number for the second labeled variable
	26-31	A six character label for the second labeled variable
	32-35	Index number for the third labeled variable
	36-41	A six character label for the third labeled variable
	.....	
	62-65	Index number for the sixth labeled variable
	66-71	A six character label for the sixth labeled variable
as needed	1-6	The word FORMAT must appear if the input data points are in a Format other than the default value of (11X, 6F10.0)
	12-71	Valid Format specification for the input data points; must begin with a left parenthesis and end with a right parenthesis

(Data points are input at this point)

Card No.	Col. No.	Description
as needed	1-6	The word PROBLM must appear; initiate the analysis for the designated dependent variable (Required card)
	12-21	The index number of the variable designated as the dependent variable
	22-31	Number of input or synthesized variables deleted from the regression analysis
	32-41	Limit the number of steps for calculation
	42-45	TRUE deletes the detailed printout of steps otherwise leave blank
	52-55	TRUE deletes the summary printout otherwise leave blank
	62-65	TRUE deletes the residual printout otherwise leave blank
as needed	1-6	The word DELETE must appear if this optional routine is used; is used in conjunction with the PROBLM card columns 22-31
	12-21	The index number of the first deleted variable
	22-31	The index number of the second deleted variable
	.....	
	62-71	The index number of the sixth deleted variable

(Additional PROBLM cards can be input at this time to restart the regression analysis using a new dependent variable or deleting different variables from the analysis)

Last	1-6	The word FINISH must appear to cause proper termination of the program (Required card)

The only variable synthesis operation code used in this study was code 13., VAR(I) = VAR(J)*VAR(K). This was used to form the pure quadratic and cross product terms.

The input for the regression analysis based on the design variables was made up of the three independent design variables [VAR(1) = WOS, VAR(2) = AR, VAR(3) = TW] and the three performance functions (VAR(4) = TOGW, VAR(5) = DTO, VAR(6) = DLN). Regression analysis was done for all three performance functions. Typical input is found on page 73 of this appendix.

The input for the regression analysis based on the mission variables was made up of the independent mission variables [VAR(1) = MACH, VAR(2) = RNG, VAR(3) = STR] and the three performance functions [VAR(4) = TOGW, VAR(5) = DTO, VAR(6) = DLN]. Regression analysis was performed on all three performance functions.

Output

The output from the regression analysis will depend on the options selected in the input. A complete listing of the means and standard deviations for the input parameters is possible and a printout containing the covariance and correlation matrices may also be obtained. A detailed printout of the variables entered or deleted at each step of the regression analysis along with regression statistics will be received unless otherwise specified. A point by point comparison of the actual data with the calculated data will be made and yields information indicating the percent error at each point (residual information). The coefficients for the selected equation are printed and also appear as punched cards. The coefficients are available on Tape 7 with the first record having a Format of (16X, 4E16.8) and the following records have a Format of (5E16.8).

```
CARD NO.

  1     PROGRM     MSNS13   6.       6.       6.        12.       45.
  2     PRGOPT     1.
  3       0
  4     VARSYN 13. 7.       1.       1.    (SETS VAR(7) = WOS²)
  5     VARSYN 13. 8.       1.       2.    (SETS VAR(8) = WOS×AR)
  6     VARSYN 13. 9.       1.       3.
  7     VARSYN 13. 10.      2.       2.
  8     VARSYN 13. 11.      2.       3.
  9     VARSYN 13. 12.      3.       3.    (SETS VAR(12) - TW²)
 10     LABELS     1.00WOS  2.00AR   3.00TW    4.00TOGW  5.00DTO   6.00DLN
 11     LABELS     7.00WOS**28.00WOS*AR9.00WOS*TW10.0AR**2 11.0AR*TW  12.0TW**2
 12     FORMAT     (24X,F8.2,F6.2,F6.2,F10.2,F9.2,F9.2)
 13       1.60   300.00  5000.00  140.00  3.50   .60  29438.91  4578.26   4901.11
  .
  .       TOTAL OF 45 DATA POINTS
  .
  .
 57       1.60   300.00  5000.00   80.00  3.00  1.00  33102.04  1847.89   3004.87
 58     PROBLM     4.       2.       25.        TRUE  (SETS TOGW AS DEPENDENT VARIABLE)
 59     DELETE     5.       6.    (DELETES DTO AND DLN FROM REGRESSION ANALYSIS)
 60     PROBLM     5.       2.       25.        TRUE  (SETS DTO AS DEPENDENT VARIABLE)
 61     DELETE     4.       6.    (DELETES TOGW AND DLN FROM REGRESSION ANALYSIS)
 62     PROBLM     6.       2.       25.        TRUE  (SETS DLN AS DEPENDENT VARIABLE
 63     DELETE     4.       5.    (DELETES TOGW AND DTO FROM REGRESSION ANALYSIS)
 64     FINISH
```

NOTE: SURFIT contains material which is proprietary to McDonnell-Douglas Corporation, McDonnell Aircraft Company, St. Louis, Missouri. Government agencies desiring SURFIT in source deck form must submit written requests to The Air Force Aero Propulsion Laboratory, Attn: Mr. Joe Frederick (AFAPL/TBA), Wright-Patterson AFB, OH 45433.

Appendix E

OAPEN Input

Appendix E

OAPEN INPUT

NOTE: A complete description of OAPEN, its capabilities, and input requirements for all options is found in Reference 8.

```
SET FUN FUNCT 2 LENGTH 10 N 3 LABEL
MISSION 1 4/300/7500 TOGWMIN DTO LE 3500 DLN LE 4500   (TITLE OF  COMMON   PROBLEM)
VARIABLES
WOS AR TW
TOGW
+.260075E+05 -.757133E+02 + .124705E+04 + .456766E+04 + .686680E+00 - .107585E+02
+.266643E+02 +.507179E+03 - .255891E+04 + .187662E+05
DTO
+.301380E+04 +.448534E+02 0.            - .671554E+04 0.            - .406270E+00
-.277031E+02 0            0.            + .837403E+04
DLN
-.659673E+02 +.431109E+02 0.            0.            - .440784E-01 + .913070E+00
-.664169E+01 -.733915E+02 + .131277E+03 0.
999
SET CODING ON 3 TRAN 6
80,80 1.5,2 .6,.4
27422.19,8912.4 1732.07,3197.42 2978.93,3001.56
999
```

This data stored on permanent file and must be attached as local file "TAPE4"

```
SET CONSTRAINTS
TOGW MIN            (MINIMIZE TOGW)
TOGW ADD 100000     (ASSURES TOGW ALWAYS POSITIVE)
DTO LE 3500         (CONSTRAINT: DTO ≤ 3500 FT)
DLN LE 4500         (CONSTRAINT: DLN ≤ 4500 FT)
999                 (END OF "SET CONSTRAINT" PROCEDURE)
CALL FR X                            (STARTS CONJUGATE GRADIENT SEARCH AT "X"
120 2.5 .8                           ("X" - MEAN VALUES OF WOS, AR, AND TW)
PENALTY 2 BOOST 100 EPSCON 1E-2      (2 CONSTRAINTS, Pk = 100, 1% TOLERANCE)
BOX                                  (CONSTRAINS INDEPENDENT VARIABLES TO BE IN DESIGN SPACE)
80,160 1.5,3.5 .6,1                  (MIN,MAX - WOS, AR, TW)
SET X SAVE        (END OF COMMON     PROBLEM SAVES SOLUTION VECTOR TO START NEXT PROBLEM IF DESIRED)


SET FUN FUNCT 2 LENGTH 10 N 3        (FUNCT 2→ UNCODED INPUT, LENGTH 10→10 REGRESSION COEFFICIENTS
VARIABLES                                    3→ 3 INDEPENDENT VARIABLES)
WOS AR TW                            (INDEPENDENT VARIABLES)
TOGW
  .287234E+05 - .663245E+02   .128352E+04 - .981080E+04   .606918E+00 - .921061E+01
  .232511E+02   .472301E+03 - .267367E+04   .388482E+05
DTO                                                                                    Dependent
  .282343E+04   .414857E+02 0.            - .622898E+04 0.            - .347445E+00    Variables and
 -.256668E+02 0.            0.              .776708E+04                                Their Regression
DLN                                                                                    Equations
 -.429537E+03   .419190E+02 0.              .974736E+03 - .427398E-01   .815713E+00
 -.723210E+01 - .739773E+02   .148613E+03 - .139239E+04
999
SET CODING ON 3 TRAN 6   (INITIATES CODING TRANSFORMATION, "3" CAN BE ANY NUMBER, "6" IS TOTAL NO. OF
80,80 1.5,2 .6,.4          (MIN, RANGE OF INDEPENDENT VARIABLES WOS, AR, TW)                VARIABLES)
25702,9747 1647,2928 2725,2972  (MIN, RANGE FOR DEPENDENT VARIABLES TOGW, DTO, DLN)
999
```

```
SET CONSTRAINTS
TOGW MIN
TOGW ADD L00000
DTO GE 0            (DTO IS UNCONSTRAINED)
DLN GE 0            (DLN IS UNCONSTRAINED)
999
CALL FR X
120 3.0 .6
PENALTY 2 BOOST 100 EPSCON 1E-2 TITLE
MSNS3   1.2/400/7500 UNCONSTRAINED MINIMUM TOGW   (TITLE FOR SECOND PROBLEM)
BOX
80,160 1.5,3.5 .6,1.
SET XSAVE           (END OF PROBLEM, SAVES SOLUTION TO START NEXT PROBLEM IF DESIRED)


SET CONSTRAINTS     (STARTS NEW PROBLEM)
TOGW MIN
TOGW ADD 100000
DTO LE 3500         (CONSTRAINT:  DTO ≤ 3500 FT)
DLN LE 4500         (CONSTRAINT:  DLN ≤ 4500 FT)
999
CALL FR  X=XSAVE  (STARTS GRADIENT SEARCH FROM SOLUTION TO PREVIOUS PROBLEM)
PENALTY 2 BOOST 100 EPSCON 1E-2 TITLE
MSNS3   1.2/400/7500   CONSTRAINED MINIMUM TOGW  DTO LE 3500 & DLN LE 4500  (TITLE PROBLEM 3)
BOX
80,160 1.5,3.5 .6,1
```

Appendix F

AFIT 799 Study

Appendix F

AFIT 799 Study

Introduction

A study was conducted in conjunction with the Air Force Flight Dynamics Laboratory Design Branch (AFFDL/FXB) to demonstrate the use of the latin square selection technique and surface fit approximations as the basis for optimization in the design analysis of future USAF fighter aircraft. The methods discussed in Chapters II through V were used in this study.

Purpose and Approach

The purpose of the AFIT 799 Study was to consider a variety of constraints and find the minimum take off gross weight within the design space. This was accomplished by (1) defining a mission profile; (2) defining a mission space; (3) defining a five dimensional design space; (4) simulating the missions to determine take off gross weight (TOGW), take off distance (DTO), landing distance (DLN), sustained G's in combat (GSS), and the time-to-accelerate (TAC) from the subsonic cruise Mach number to the supersonic dash Mach member; (5) performing a regression analysis on the mission simulation results to obtain quadratic surface fit approximations for TOGW, DTO, DLN, GSS, and TAC in terms of the design variables; and finally, (6) performing minimizations to find values for the minimum TOGW and the corresponding independent design variables, within the design space.

Mission Profile

The mission profile presented in Figure 17 was defined by AFFDL/FXB based on typical requirements for future fighter aircraft. The mission profile was made up of twelve segments. Distance credit was given for all segments and fuel was used on all segments. The aircraft was to have a one-man crew and carry 5500 pounds of STORES internally.

Mission Space

The dash Mach number (MACH) and dash altitude (ALT) were selected by AFFDL/FXB as the two independent mission variables. MACH was allowed to vary from 1.6 to 2.3 while ALT ranged from 20,000 feet to 60,000 feet. The specific mission cases are presented in Table XIII. The analysis that follows considers only mission case 1, where MACH = 1.95 and ALT = 50,000 feet.

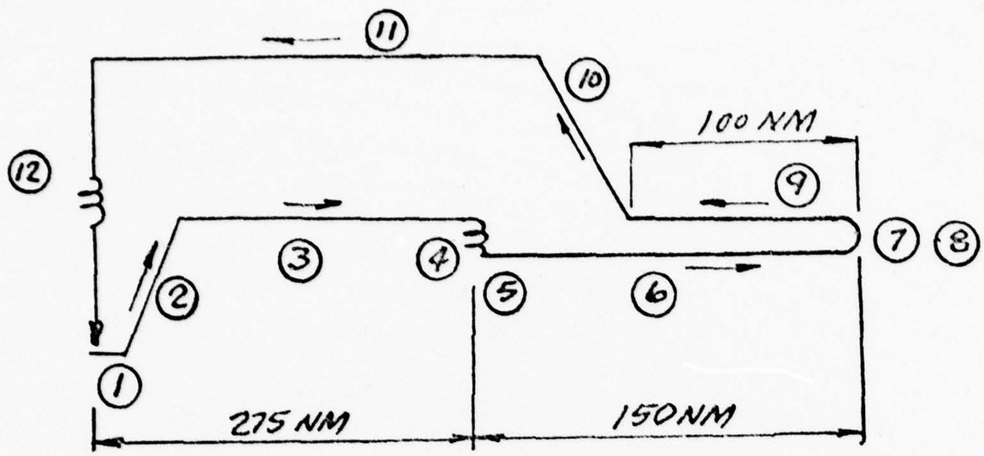
TABLE XIII

Mission Cases - AFIT 799 Study

Case No.	MACH No.	Altitude
1	1.95	50,000 ft
2	2.3	60,000 ft
3	1.6	60,000 ft
4	1.6	20,000 ft
5	2.3	36,089 ft

Design Space

The five independent design variables used in this study included two engine variables and three airframe variables. The engine variables



1. Start engines, taxi, takeoff: 15 minutes idle power, maximum power takeoff (1.2 V_{stall})

2. Climb: Accelerate and climb at intermediate power to optimum subsonic cruise altitude

3. Outbound cruise: $M > .8$, optimum altitude

4. Loiter: 30 minutes at cruise Mach number and altitude

5. Energy exchange to dash Mach number and altitude in minimum time

6. Outbound dash: at dash Mach number and altitude

7. Turn: One maximum "G" 360° turn at dash Mach number and altitude

8. Drop "stores payload"

9. Inbound dash: Dash Mach number and altitude

10. Climb: Energy exchange to optimum subsonic cruise altitude and Mach number ($M > .8$)

11. Inbound cruise: $M > .8$ at optimum subsonic cruise altitude

12. Loiter and Land: Loiter 20 minutes at sea level at optimum endurance Mach number

GENERAL RULES: (1) Fuel used and distance gained on all mission segments

(2) 5% fuel flow conservatism applied throughout mission

Figure 17. Mission Profile - AFIT 799 Study

were overall pressure ratio (OPR) and by-pass ratio (BPR), while the air-frame variables were wing loading (WOS), aircraft thrust-to-weight ratio (TW), and aspect ratio (AR). The range for each of these variables is given in Table XIV, which defines the design space.

TABLE XIV

Design Space - AFIT 799 Study

Variable	Range of Values
OPR	10 - 30
BPR	.2 - 2.2
WOS	80 - 120 LBS/FT^2
AR	1.5 - 3.5
TW	.6 - 1.0

The simple latin square selection method was used to obtain the latin square design cases listed in Table XV.

Mission Simulation

The computer program CASP (Combat Aircraft Synthesis Program) was used by AFFDL/FXB to sumulate mission case 1 from Table XIII for the mission profile presented in Figure 18 and to determine TOGW, DTO, DLN, TAC, and GSS for the design configurations from Table XV. CASP is generally more sophisticated than CISE (discussed in Chapter III), particularly in two important areas. First, CASP requires input tables for installed engine thrust and fuel flow rate for each power setting at various Mach numbers and altitudes throughout the anticipated flight envelope. Engine physical characteristics such as length, diameter, and weight of the installed engine must also be input. CISE requires only that engine thrust-to-weight ratio and a fuel flow factor be input.

TABLE XV

Latin Square Design Space - AFIT 799 Study

Case No.	OPR	BPR	WOS	TW	AR
1	20	1.2	100	.8	2.5
2	25	2.2	80	.7	2.5
3	30	.7	110	.6	2.5
4	10	1.7	90	1.0	2.5
5	15	.2	120	.9	2.5
6	30	1.7	90	.6	3.0
7	15	2.2	80	.9	3.5
8	25	.2	120	.7	1.5
9	10	.7	110	1.0	2.0
10	25	1.7	110	.9	3.0
11	30	.2	90	.8	3.0
12	10	1.2	120	.7	3.0
13	15	2.2	100	.6	3.0
14	20	.7	80	1.0	3.0
15	10	2.2	100	.7	3.0
16	20	.2	90	1.0	3.5
17	30	.7	80	.8	1.5
18	15	1.2	120	.6	2.0
19	30	2.2	120	1.0	3.5
20	10	.7	100	.9	3.5
21	15	1.7	80	.8	3.5
22	20	.2	110	.7	3.5
23	25	1.2	90	.6	3.5
24	15	.2	110	.8	3.0
25	25	.7	100	.6	3.5
26	10	1.2	90	.9	1.5
27	20	1.7	80	.7	2.0
28	10	.2	80	.6	1.5
29	15	1.2	110	1.0	1.5
30	20	2.2	90	.9	1.5
31	25	.7	120	.8	1.5
32	30	1.7	100	.7	1.5
33	20	.7	120	.9	3.0
34	30	1.2	110	.7	3.5
35	15	1.7	100	1.0	1.5
36	25	2.2	90	.8	2.0
37	15	.7	90	.7	2.0
38	20	1.7	120	.6	2.0
39	25	.2	100	1.0	2.0
40	30	1.2	80	.9	2.0
41	10	2.2	110	.8	2.0
42	25	1.2	80	1.0	3.0
43	10	1.7	120	.8	3.5
44	20	2.2	110	.6	1.5
45	30	.2	100	.9	2.0

AD-A055 882 AIR FORCE INST OF TECH WRIGHT-PATTERSON AFB OHIO SCH--ETC F/G 1/3
AN INVESTIGATION OF THE RELATIONSHIP BETWEEN TAKE OFF GROSS WEI--ETC(U)
MAY 77 M K GREENWAY

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Engine size, weight, and fuel flow variation with thrust output are computed internally. Twenty-five engine decks were required to represent the combinations of OPR and BPR in Table XV. Secondly, CASP integrates backward from a lift-off condition to determine the take off roll along the runway and integrates forward from a touchdown condition to determine the landing roll. CISE computes these by use of Equations (2) through (9) in Chapter III. Both programs scale the physical size of the aircraft according to fuel load required and component volume requirements while computing the aerodynamic characteristics at each flight condition.

TOGW, DTO, DLN, TAC, and GSS in Terms of the Design Variables

The output from the mission simulation is presented in Table XVI. This data, together with the corresponding values for the five design variables from Table XV, were input to the regression analysis program SURFIT discussed in Chapter IV to obtain the following quadratic expressions for TOGW, DTO, DLN, GSS, and TAC in terms of OPR, BPR, WOS, TW, and AR.

$$\begin{aligned} TOGW = {} & 45849.081 + 53.3127(OPR)^2 - 3938.1491(OPR)(TW) \\ & + 86838.3926(TW)^2 - 900.9884(AR) \end{aligned} \tag{41}$$

$$\begin{aligned} DTO = {} & 9781.7277 + 77.6748(WOS) - 14341.0841(TW) - 3086.5461(AR) \\ & - 41.3483(WOS)(TW) + 7.4961(WOS)(AR) + 6227.6061(TW)^2 \\ & + 1605.3901(TW)(AR) + 333.0961(AR)^2 \end{aligned} \tag{42}$$

$$\begin{aligned} DLN = {} & 2848.4882 + 71.6588(WOS) - 1881.9125(AR) - 36.3198(WOS)(TW) \\ & -5.4750(WOS)(AR) + 570.6408(TW)(AR) + 245.5962(AR)^2 \end{aligned} \tag{43}$$

TABLE XVI

Aircraft Sizing Results - AFIT 799 Study

Design Case	TOGW (LBS)	DTO (FT)	DLN (FT)	TAC (MIN)	GSS (G's)
1	48510	2462	3732	.88	2.06
2	47826	2365	3301	1.06	2.33
3	40764	3853	4463	1.36	1.77
4	99643	1704	3102	.65	2.42
5	82183	2506	3890	.77	1.91
6	41886	2739	3485	1.34	2.31
7	64699	1364	2665	.75	3.21
8	51721	5089	5711	1.16	1.26
9	94043	2381	3774	.67	1.81
10	51581	2026	3555	.73	2.28
11	46023	1935	3009	.95	2.55
12	52660	2977	4133	1.04	2.01
13	47111	3022	3763	1.26	2.18
14	54998	1335	2744	.70	2.96
15	57170	2514	3581	1.00	2.33
16	65246	1347	2479	.71	3.03
17	49690	2968	4014	.95	1.70
18	46309	4991	5348	1.32	1.42
19	58310	1752	3411	.62	2.44
20	66122	1675	2904	.78	2.74
21	54765	1562	2767	.91	3.06
22	46263	2456	3428	1.12	2.34
23	41395	2448	3251	1.39	2.56
24	63444	2329	3575	.91	2.23
25	40591	2701	3524	1.39	2.37
26	86629	2847	4091	.76	1.70
27	48733	2805	3669	1.08	1.99
28	63327	4366	4373	1.46	1.57
29	73741	2971	4507	.66	1.49
30	65740	2840	4123	.73	1.69
31	50962	4285	5475	.92	1.32
32	48224	4312	5054	1.06	1.42
33	49428	2158	3788	.76	2.13
34	42258	2457	3636	1.05	2.34
35	81957	2731	4187	.65	1.61
36	52815	2633	3811	.85	1.91
37	49946	3124	4014	1.11	1.83
38	45353	4992	5349	1.29	1.42
39	69335	2182	3564	.68	1.92
40	51581	2040	3330	.77	2.13
41	75713	3169	4365	.83	1.70
42	54013	7337	2748	.68	2.96
43	62577	2273	3673	.83	2.33
44	48285	5828	5846	1.32	1.26
45	53797	2498	3713	.80	1.83

$$TAC = 4.9253 - .1225(BPR) - .008399(WOS) - 6.9671(TW) + .00001336(OPR)^2 + .002236(BPR)^2 + .08645(BPR)(TW) + .00003341(WOS)^2 + 00003342(WOS)(TW) - .008496(WOS)(AR) + 3.0129(TW)^2 + .0159(AR)^2 \quad (44)$$

$$GSS = .6559232 + .8677(AR) - .00588(WOS)(AR) + .3618(TW)(AR) \quad (45)$$

Notice that WOS and BPR terms do not appear in Equation (41) for TOGW, and that OPR and BPR terms do not appear in Equations (42), (43), or (45) for DTO, DLN, or GSS.

The multiple correlation and maximum error for Equations (41) through (45) are presented in Table XVII. Although the maximum error in TOGW was 20.26 percent, there were only seven of 45 data points at which the error was greater than 10 percent, with most errors less than seven percent. For DTO, the maximum error was 15.08 percent, although there were only four points with errors greater than four percent. DLN had a maximum error of 13.08 percent, but there were only four cases where the error exceeded five percent. GSS had a maximum error of 12.09 percent and there were only two other cases where the error exceeded four percent. Considering these errors, Equations (41) through (45) track the data reasonably well. The errors are attributed to correlation between design cases, the distribution of selected design cases within the design space, and the range of dependent variables (TOGW varied between 40591 and 99643 pounds).

Minimization Results

Based on Equations (41) through (45), several minimizations with a variety of constraints were performed using OAPEN, which is discussed in Chapter V. The results are presented in Table XVIII. The results

TABLE XVII

Multiple Correlation and Maximum Error for Regression Equations
AFIT 799 Study

Variable	Multiple Correlation	Maximum % Error
TOGW	.94306	20.26
DTO	.99626	-15.08
DLN	.98791	-13.08
TAC	.99888	-3.00
GSS	.99508	12.09

TABLE XVIII

Minimization Results - AFIT 799 Study

Variable	Minimization Case				
	1	2	3	4	5
TOGW (LBS)	39224	39678	39678	39918	41514
DTO (FT)	2729	3002	3002	2442	1682
DLN (FT)	3537	3990	3990	3399	2797
TAC (SEC)	81	70	70	70	61
GSS(G's)	2.40	2.08	2.08	2.50	2.99
OPR	22.41	23.55	23.53	24.41	27.66
BPR	1.2	2.2	2.2	2.2	2.2
WOS(LBS/FT^2)	100	116.94	116.94	97.77	80
TW	.60	.63	.63	.65	.74
AR	3.5	3.5	3.5	3.5	3.5
Constraints					
DTO	None	≤3000	≤3000	≤3000	≤3000
DLN	None	None	≤4000	≤3500	≤3000
TAC	None	≤70	≤70	≤70	≤70
GSS	None	None	≥2.0	≥2.5	≥3.0

indicate that there is only 2290 pounds (5.8%) difference in TOGW between Case 1 (39224 lbs) where there were no constraints, and Case 5 (41514 lbs), where the most severe constraints were applied. The optimum design configurations were similar for all constrained cases in that there was very little change in OPR, BPR, TW, and AR. Note that BPR, TW, and AR were either on or very near the boundary of the design space. Wing loading (WOS) was very sensitive to the constraints on landing distance (DLN) and acceleration time (TAC). For later ease of discussion, the design configuration resulting from a particular minimization case of Table XVIII will be referred to by the minimization case number. The results of minimization Case 1 are referred to as "Aircraft 1," and so on for the five cases.

The variation of TOGW with OPR, AR, and TW for the unconstrained minimum case is clearly indicated by the three dimensional plots presented in Figures 18 through 20. These plots also indicate that the minimum probably lies outside the design space of Table XIV and that higher aspect ratios (AR) and lower thrust-to-weight ratios (TW) should be considered for the unconstrained case. Also, higher by-pass ratios (BPR) should be considered, particularly if the constraints in Cases 2 through 5 become overriding requirements. Note that as TW requirements increase, as in Case 5, the optimum OPR also increases and may eventually exceed the design space limit of 30. Three dimensional plots for DTO, DLN, TAC, and GSS, similar to those presented for TOGW could have been generated from Equations (42) through (45) if desired in the design analysis. Figures 21 and 22 present two-dimensional plots of TOGW vs OPR and TOGW vs AR respectively for the unconstrained case. These plots are suitable for determining approximate values of TOGW for specific values of OPR, TW,

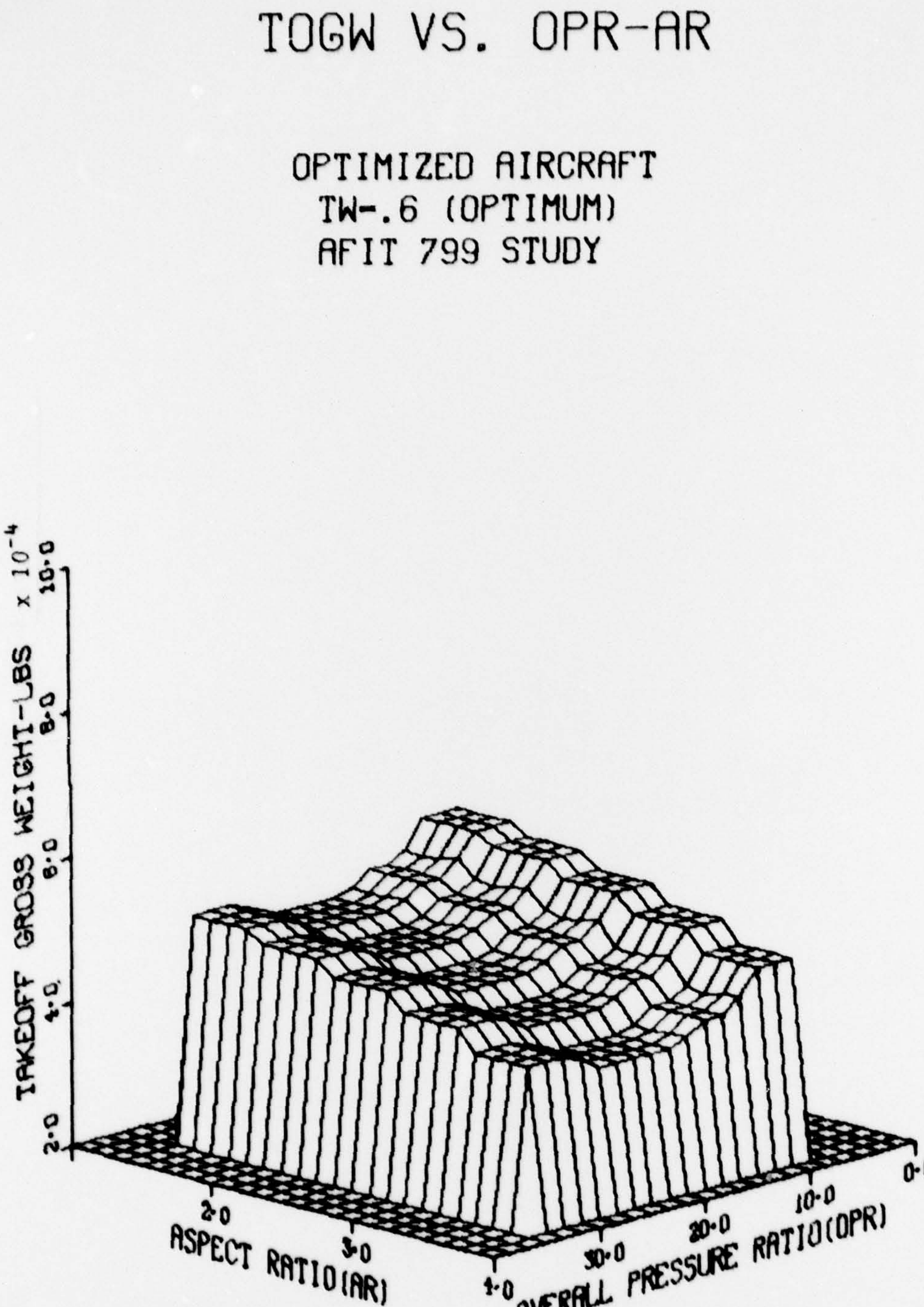

Figure 18. 3-D Plot of TOGW vs. OPR and AR - AFIT 799 Study

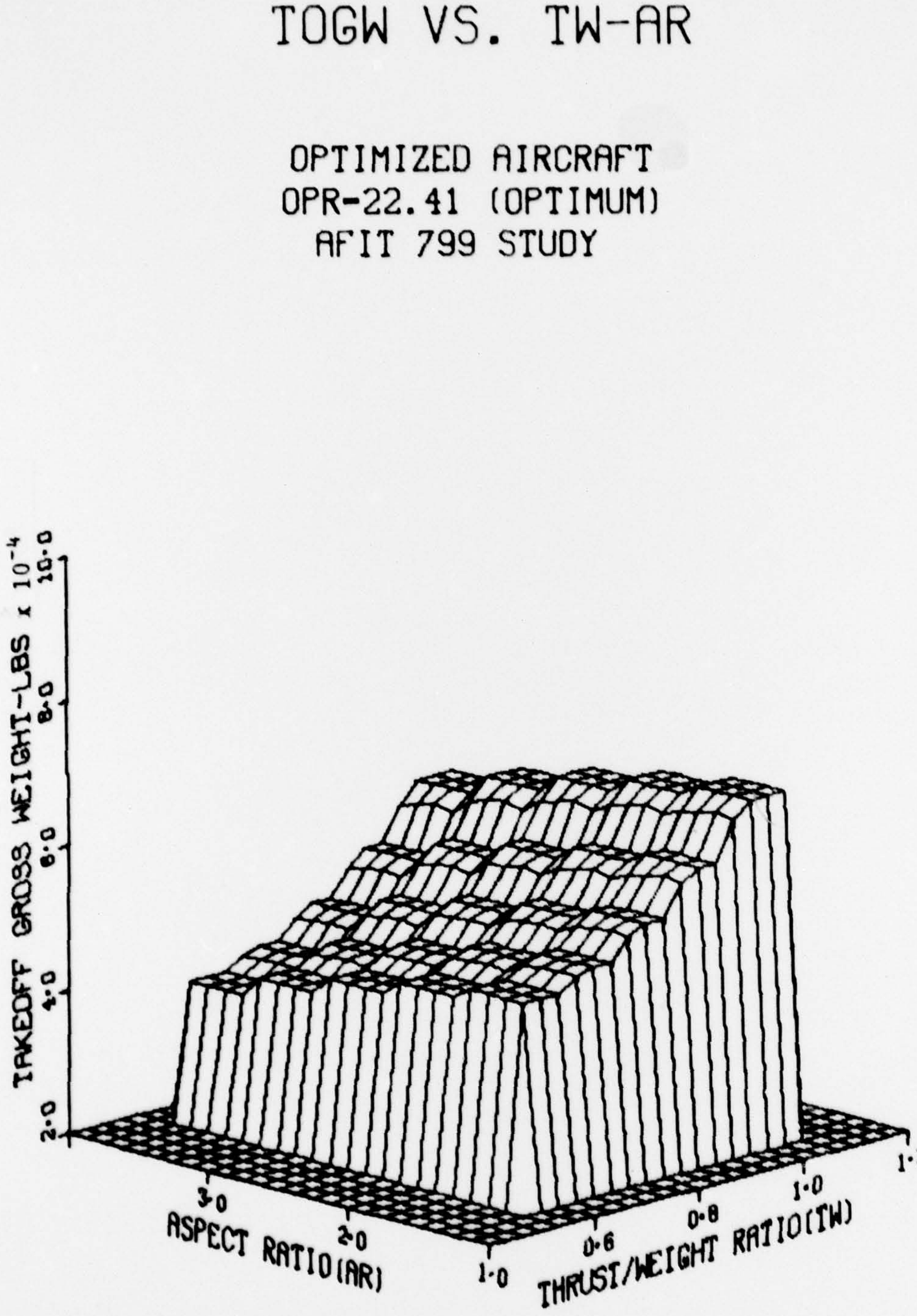

Figure 19. 3-D Plot of TOGW vs. TW and AR - AFIT 799 Study

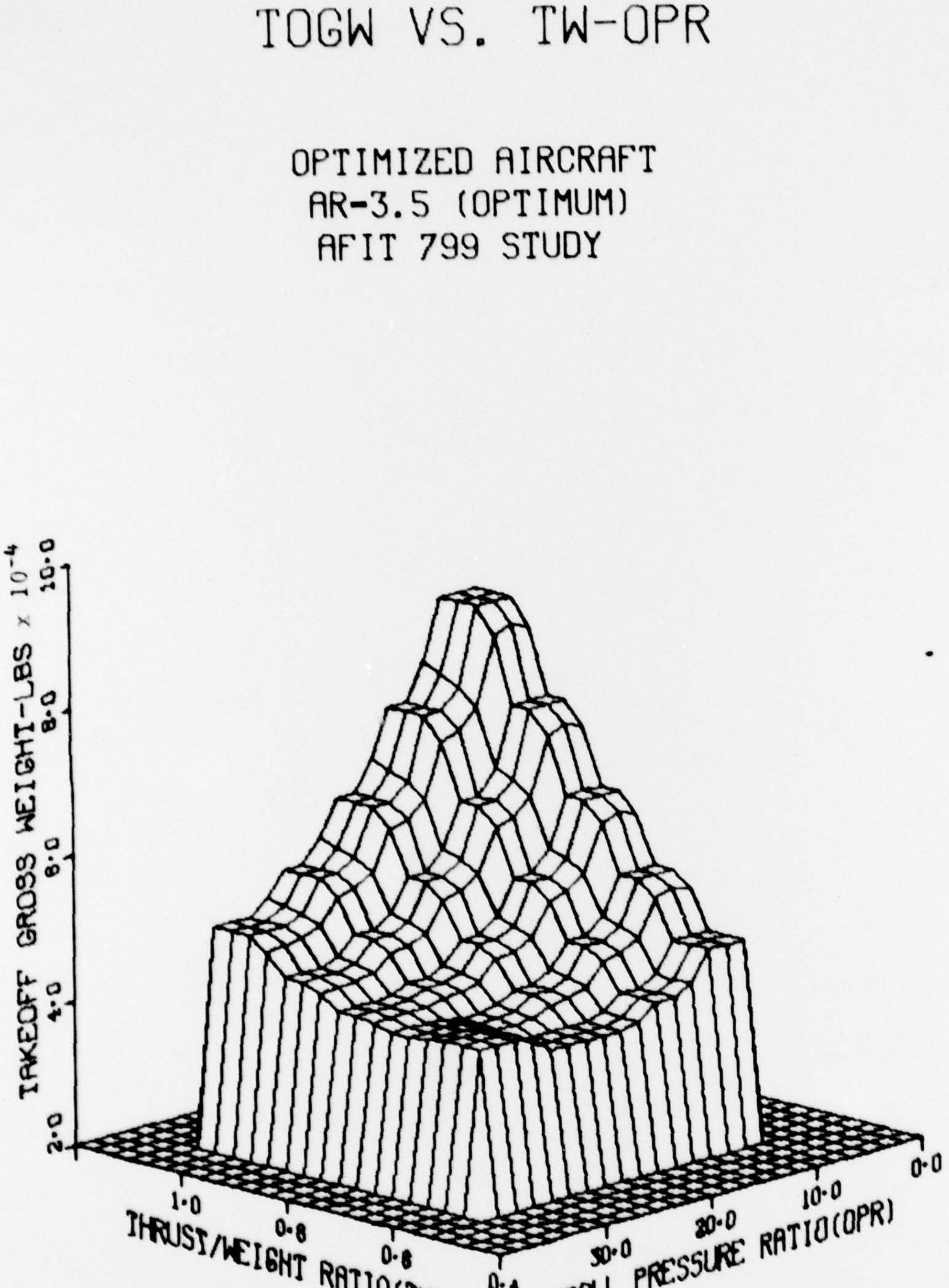

Figure 20. 3-D Plot of TOGW vs. TW and OPR - AFIT 799 Study

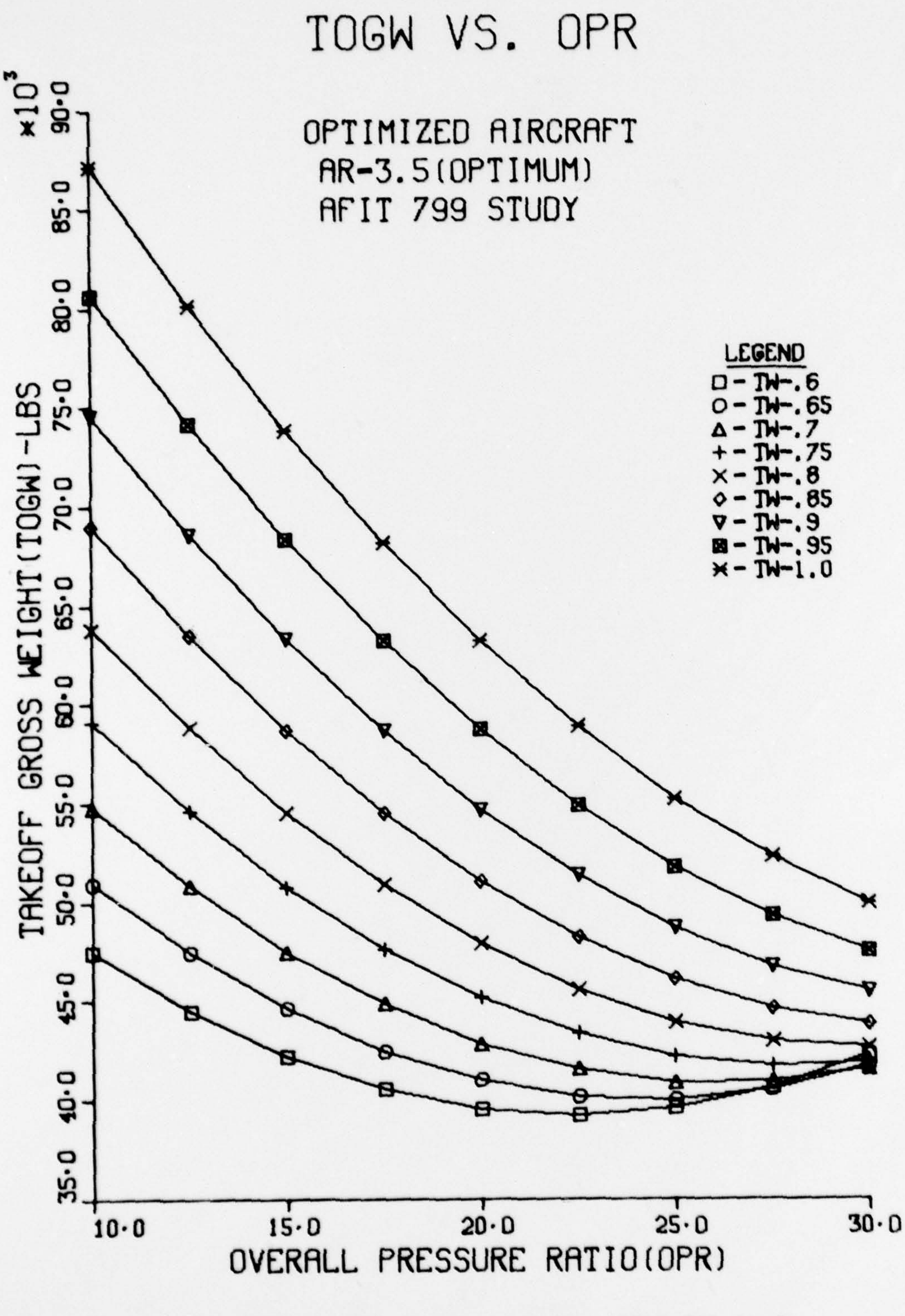

Figure 21. TOGW vs OPR for Optimum AR - AFIT 799 Study

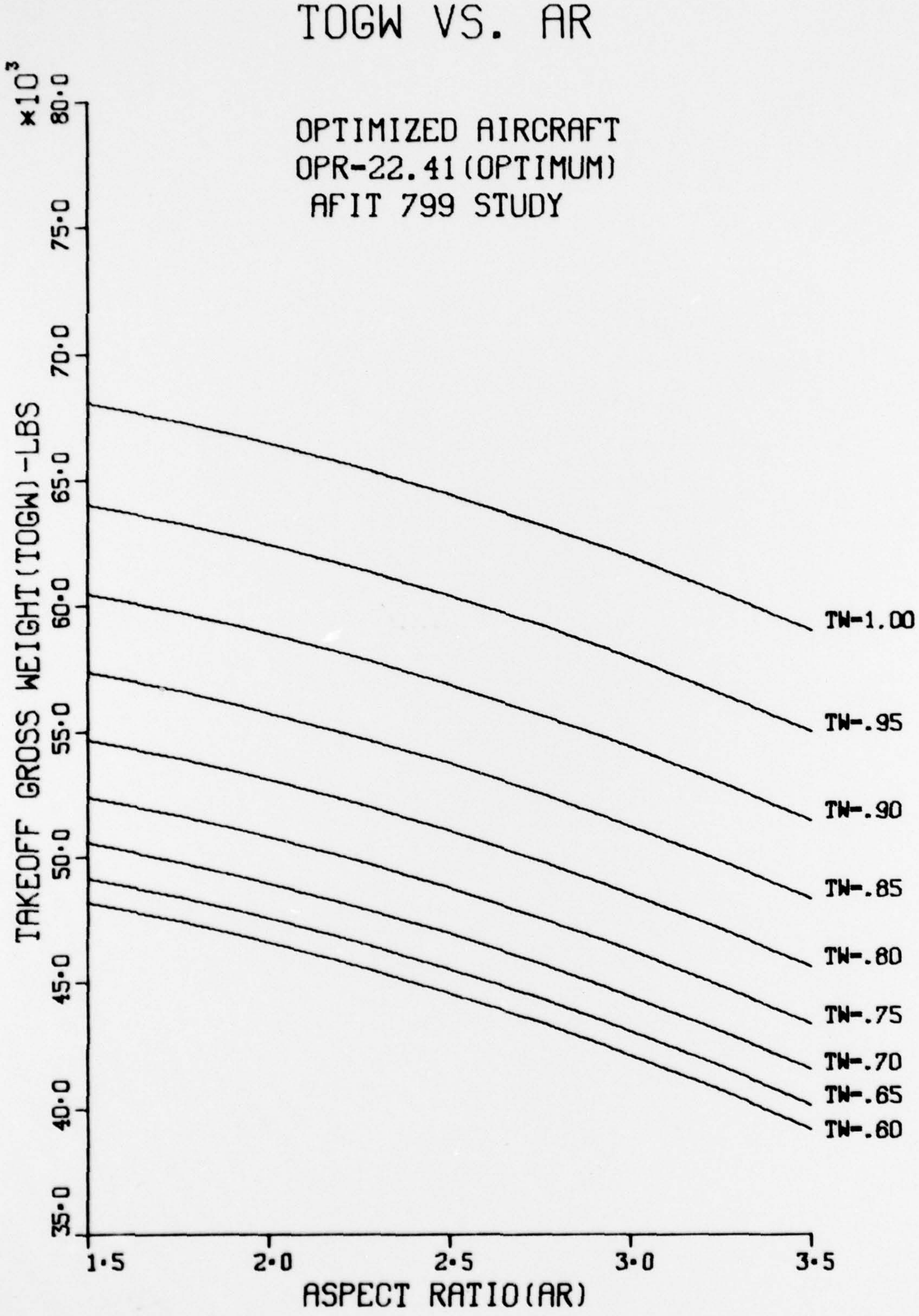

Figure 22. TOGW vs AR for Optimum OPR - AFIT 799 Study

and AR, and clearly indicate that the unconstrained minimum TOGW occurs in the vicinity of OPR = 22.5, for AR = 3.5 and TW = .6.

Conclusions

The following conclusions were drawn from study results. They are based on the limits of the design space (Table XV) and consider only mission case 1 for a dash Mach number of 1.95 and a dash altitude of 50000 feet:

1. Aircraft 1 will adequately perform the desired mission unless acceleration times (TAC) less than 81 seconds or sustained load factors (GSS) greater than 2.4 are required.
2. If an acceleration time of 70 seconds or less is a requirement, then Aircraft 4 is suitable for the mission. This configuration provides a reduced acceleration time (TAC), increased sustained load factor capability (GSS), and reduced take off and landing distances (DTO and DLN) over that of Aircraft 1 with only 694 pounds additional gross weight.
3. Aircraft 5 offers the operational flexibility of requiring less than 2800 feet for either the take off or landing roll. Compared to Aircraft 4, it also offers a reduction in acceleration time and an increase in sustained load factor capability for a gross weight increase of about 1600 pounds.
4. Aircraft 2 and 3 offer no significant operational advantage when compared to Aircraft 1, 4, and 5.

Recommendations

The following recommendations are offered regarding future design analysis studies:

1. The surface fit approximation used for TOGW should include BPR and WOS, even thought such an equation was not selected by SURFIT as best representing the data. Use of such an approximation and repeating the analysis for Mission 1 would permit additional design visibility, in that the effects of BPR and WOS on TOGW could be examined very early in the design analysis. If the effects are indeed small, Equation (41) can be used for the remainder of the design analysis.

2. The design space should be expanded to include aspect ratios up to 4.5 and thrust-to-weight ratios as low as .5. This expansion is recommended since the minimum gross weight aircraft capable of performing this mission does not lie within the design space defined by Table XV. Based strictly on Table XVIII higher by-pass ratios should also be considered. However, this should be done only if the constrained otpimum BPR from (1) above remains at 2.2.

3. The remaining missions, 2 through 5 of Table XIII, should be analyzed to find the optimum configuration for each mission.

a. If the optimum designs for missions 2 through 5 are not "close" to that for mission 1 for similar constraints, it may be necessary to designate a specific mission as the primary mission, design an optimum aircraft for it, and accept the performance penalties for the remaining missions; or, redefine the mission space to allow compatibility between missions in terms of reasonable performance for more than one mission by a single aircraft.

b. In the fortunate event that the optimum designs from Mission 2 through 5 are very close to that selected for Mission 1, the design analysis should consider a configuration which is a near optimum solution for all (or most) missions, rather than emphasize a particular mission.

VITA

Milford K. Greenway, Jr. was born 15 May 1944 in Astoria, Oregon. He graduated from Rancho High School in Las Vegas, Nevada in 1962, attended Wichita State University from which he received the Bachelor of Science Degree in Aeronautical Engineering and an ROTC commission in the USAF in June 1968. He was employed as an Associate Flight Test Engineer at The Boeing Company, Wichita Division, Wichita, Kansas, until he entered active duty in July 1968. He served as a Flight Controls Engineer and a System Engineer within the Drone/RPV SPO at Headquarters Aeronautical Systems Division, Wright-Patterson Air Force Base, Ohio from July 1968 to November 1972. He served as a Staff Development Engineer within the Deputy for Development Plans, Headquarters Space and Missile Systems Organization, Los Angeles Air Force Station, California from November 1972 to May 1975. He entered the Air Force Institute of Technology in June 1975.

Permanent Address: P. O. Box 435
La Crosse, KS 67548

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A study was performed to demonstrate the feasibility of using surface fit approximations in the mission analysis for future fighter aircraft. Dash Mach number (MACH), dash range (RNG), and internal payload (STR) were selected as mission variables and a mission space defined based on a simple latin square method. Wing loading (WOS), aspect ratio (AR) and aircraft thrust-to-weight ratio (TW) were selected as design variables and a design space defined based on a simple latin square method. The take off gross weight (TOGW), take off distance (DTO), and the landing distance (DLN) were determined by the use of a

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SECURITY CLASSIFICATION OF THIS PAGE (When Data Entered) computer program which simulated the required mission for each design case. A regression analysis was performed on this data to obtain quadratic surface fit approximations for TOGW, DTO, and DLN in terms of the design variables WOS, AR, and TW. An unconstrained minimization of TOGW was performed for all missions using a conjugate gradient technique to determine the minimum TOGW within the design space and the corresponding values of DTO and DLN. Another regression analysis was performed on the results of the minimizations and the mission variable for specific missions to obtain quadratic surface fit approximations for TOGW, DTO, and DLN for optimum aircraft in terms of the mission variables MACH, RNG, and STR. It was concluded that these surface fit approximations in terms of the mission variables were sufficiently accurate for use in mission analysis and conceptual design studies.