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AFFDL-TR-73-154

ANALYTICAL AND EXPERIMENTAL INVESTIGATION OF OPTIMUM FIGHTER AIRCRAFT MANEUVERS

RICHARD C. NASH

TECHNICAL REPORT AFFDL–TR–73–154

JULY 197

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AFFDL-TR-73-154

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(FXG), Wright-Patterson AFB, Ohio 45433

FOREWORD

This report was prepared by personnel of the High Speed Aero Performance Branch, Flight Mechanics Division of the Air Force Flight Dynamics Laboratory (AFFDL/FXG), Wright Patterson Air Force Base, Ohio. The research was accomplished under Project 1366, "Aeroperformance and Aeroheating Technology," and Task 136602, "Performance Analysis of Military Flight Vehicle."

The research reported in this study was conducted during the period October 1967 through November 1972. Acknowledgement is made of the help received from B. R. Benson for overall guidance and D. T. Johnson for the optimized flight profiles calculated using the Energy Maneuverability Optimization Program.

This report was submitted by the author 28 September 1973.

This technical report has been reviewed and is approved.

Philip P Antonatos
PHILIP P. ANTONATOS
Chief, Flight Mechanics Division
Air Force Flight Dynamics Laboratory

ABSTRACT

This report presents the results of a four-phase research program consisting of (1) application of the energy-maneuverability and variational steepest-descent optimization techniques to a series of maneuvers typical of a multipurpose tactical fighter aircraft, (2) flight testing of the analytically predicted optimal flight paths to obtain measured flight data, (3) correlation of these data with analytical results and (4) comparison of analytical optimum paths with nonoptimum flight paths. The results of this study indicate that for most of the maneuvers analyzed, the pilot was able to fly the optimum flight profiles with reasonable accuracy. Also, definite gains in performance can be realized through the application of optimization techniques.

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SYMBOLS

a	Acceleration
A/B	Afterburner
C_L	Lift Force Coefficient
C_D	Drag Force Coefficient
D	Drag Force
E	Total Energy
E_s	Specific Energy
g	Gravitational Acceleration
H	Altitude
M	Mach Number
N	Throttle Setting
N_z	Normal Load Factor
P_s	Specific Excess Power
T_a	Thrust Available
T_{am}	Ambient Temperature
V	Velocity
W	Weight
w_f	Fuel Weight
α	Angle of Attack
σ	Heading Angle

Dot over symbol denotes differentiation with respect to time.

SECTION I

INTRODUCTION

BACKGROUND

During the past decade, numerous techniques have been developed to conduct studies of optimization of flight paths for highly maneuverable fighter aircraft. A considerable number of reports and papers have been published on the application of optimization techniques to a wide variety of aircraft performance problems (References 1 through 8). Despite this, there is very little information available regarding the flyability and accuracy of the results obtained from applying optimization techniques to actual flight.

PURPOSE

The overall purpose of this study was to perform an analytical and experimental investigation of two optimization techniques to determine their utility for generating optimum flight maneuvers. Specific objectives were:

1. Apply the energy - maneuverability and variational steepest-descent optimization techniques to a series of maneuvers typical of a multipurpose tactical fighter aircraft.

2. Flight test the analytical predicted optimal flight paths to obtain quantitative performance data.

3. Correlate the analytical and experimental data to determine the utility of the techniques.

4. Compare the optimum and nonoptimum maneuver results to evaluate the increased effectiveness or performance gains due to optimization.

APPROACH SELECTED

For this study the Air Force Flight Dynamics Laboratory's (AFFDL) Three-Degree-of-Freedom Trajectory Optimization Computer Program (TOP) (Reference 9) and the Energy-Maneuverability (EM) Computer Program developed by Air Proving Ground Center (Reference 10) were used. For brevity, the two programs will be referred to as TOP and EM in the remainder of the report. The reasons for selecting these two techniques are (1) both are receiving widespread use at the present time and (2) techniques differ drastically in that the aircraft's dynamic equations of motion are integrated by the TOP providing an integrated solution while the EM provides an approximate solution due to the physical assumptions introduced in the formulation of the method.

The following is a brief discussion of both techniques and how they are used to obtain optimal solutions for various performance problems. For a more detailed discussion of the techniques the reader is referred to References 9, 10, 11 and 12.

STEEPEST DESCENT

This technique is a generalized method of trajectory optimization which retains the vehicle's dynamic equations of motion. The technique commences with an arbitrary nonoptimal trajectory which is perturbed in an iterative procedure until the desired terminal and in-flight constraints are satisfied and the payoff being optimized is either minimized or maximized. These solutions are obtained by means of a large scale digital computer. The TOP program is quite versatile in that it has the ability to solve practically any flight performance problem; however, this versatility requires increased computer time to solve a given problem.

ENERGY MANEUVERABILITY

This method determines the vehicle's maneuverability as a function of its total energy (potential and kinetic). The following equations are used in determining how to change energy states optimally.

$$E_s = \frac{E}{W} = H + \frac{V^2}{2g} \quad \text{Specific Energy}$$

$$P_s = \dot{E}_s = \frac{V}{W}(T_a - D) \quad \text{Specific Excess Power}$$

where T_a is the thrust available, D is the aircraft drag in steady-state level flight at the particular velocity and altitude under consideration, and W is the weight. For the minimum time to climb problem, it can be shown that the quickest way to increase specific energy is to follow a path that connects the points of tangency between the lines of constant E_s and P_s. Figure 1 illustrates the concept. If the problem's initial and terminal conditions do not lie on the path, the tangency condition acquired by a constant energy maneuver. Similarly, but not shown, the minimum fuel path to change energy states can be shown to be the path obtained by connecting the points of tangency between the E_s and $P_s/\dot{W}_f$ contours. The advantages of this technique are simplicity and rapid application. Graphical solutions are easily understood by operational pilots since they show the vehicle's specific energy and specific excess power at any point within the steady-state operating envelope. Its main difficulty is that the technique lacks generality in solving an optimal control problem.

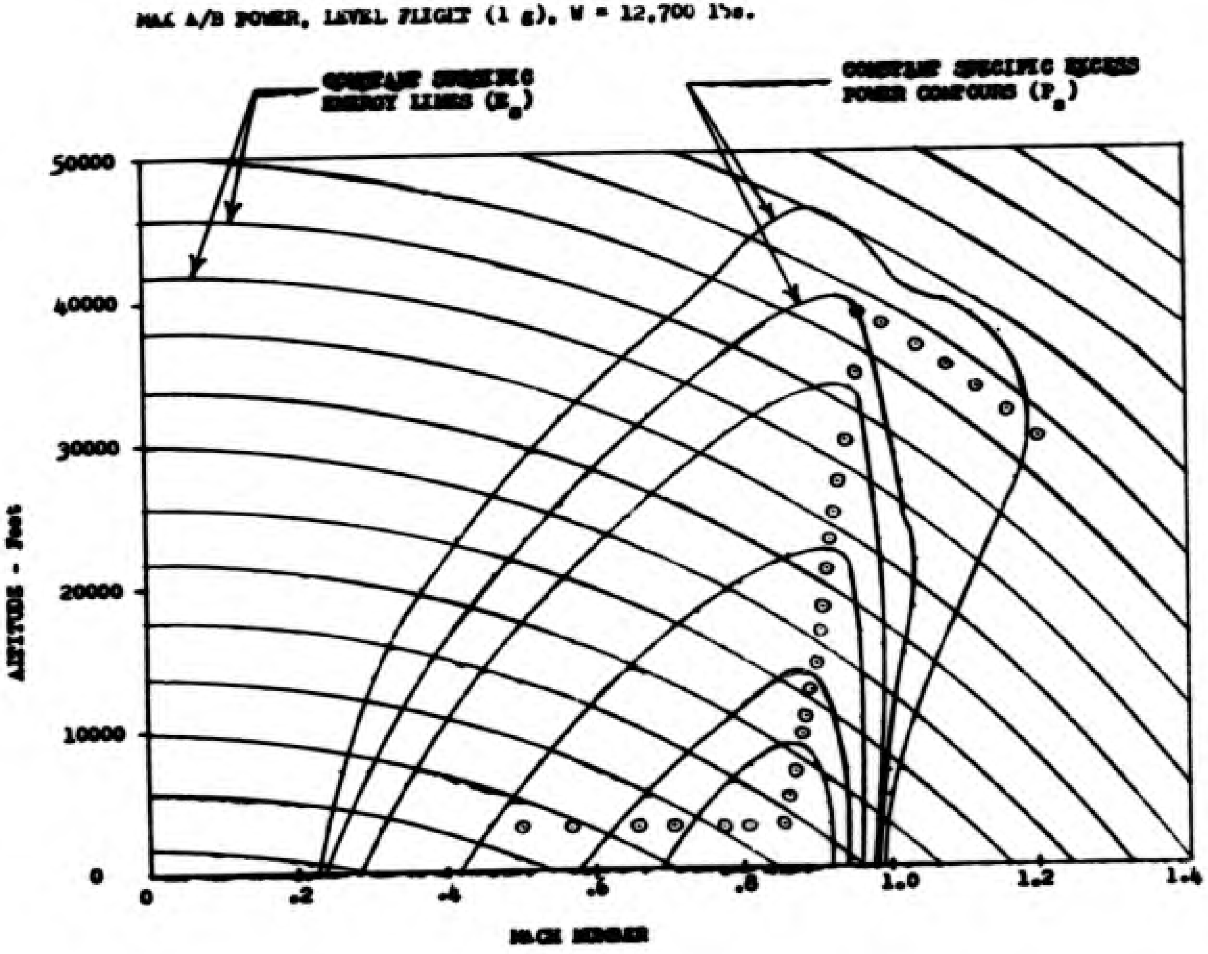

Figure 1. F-5A Minimum Time Path as Predicted by Energy Maneuverability Method

SECTION II

MANEUVERS SELECTED FOR ANALYSIS

Phase I of the study consisted of formulating and obtaining optimal flight profiles for a series of maneuvers typical of a multipurpose tactical fighter aircraft (F-5A). The maneuver selected for analysis consisted of minimum time to climb (fixed throttle and max A/B power) with and without a heading change, minimum time to descend with a heading change and minimum fuel to climb (variable throttle). The specific details of each maneuver are listed in Table I. Also shown are the initial and final flight conditions, the performance parameter optimized, and the computer program utilized to generate the optimum flight profile for each maneuver.

At the onset of the study it was realized that a meaningful comparison of the analytical and experimental results could only be made if the data used in the computer simulations closely approximated the test vehicle performance and the atmosphere existing at time of flight. Therefore, the airframe and engine data used in the trajectory optimization programs were supplied by the Northrop Corporation for the aircraft configuration flown and consisted of the following:

Aerodynamic Data

C_L and $C_D = f\ (M,\alpha)$

Reference Area

Engine Data

T_{Net} and $\dot{\omega}_f = f\ (M,H,N)$ for standard and nonstandard atmospheres

TABLE I

MANEUVERS SELECTED FOR ANALYSIS

Maneuver Number	Initial Conditions			Final Conditions			Parameter Optimized	Computer Program Utilized
	Weight (lbs.)	Mach Number	Altitude (ft.)	Mach Number	Altitude (ft.)	Heading Change (deg.)		
1	12,700	0.5	3,000	1.2	30,000	0	Time	TOP
2	12,700	0.5	3,000	1.2	30,000	0	Time	EM
3	12,700	0.5	3,000	1.2	30,000	180	Time	TOP
4	11,700	0.7	35,000	1.2	30,000	0	Time	TOP
5	11,700	0.7	25,000	0.7	40,000	0	Time	TOP
6	11,700	0.7	25,000	0.7	40,000	180	Time	TOP
7	11,700	1.2	30,000	0.6	10,000	180	Time	TOP
8	12,700	0.5	3,000	1.2	30,000	0	Fuel	TOP
9	12,700	0.5	3,000	1.2	30,000	0	Fuel	EM

Weight Summary

Operating Limits

- Buffet
- Structural
- Engine

Since aircraft thrust characteristics are a function of temperature, flying in a nonstandard atmosphere will affect aircraft performance. An investigation into temperature conditions at Edwards Air Force Base (EAFB) for the month of September over a ten year period revealed that higher than standard temperatures prevailed. The average EAFB temperature profile closely approximated a constant 10°C hotter than a standard day except for altitudes above the tropopause. Therefore, for each maneuver an optimum flight profile was calculated using a standard day and a standard day plus 10°C atmosphere in order that the influence of temperature on the particular day of flight could be included in the flight plans. Table II lists the analytical predicted results for both standard and nonstandard atmospheres. The flight profiles and analytical results generated for each maneuver will be discussed later in the report.

TABLE II

ANALYTICAL PREDICTED RESULTS FOR STANDARD AND NONSTANDARD DAY ATMOSPHERES

Maneuver Number	Parameter Optimized	
	Time, Seconds	Fuel, Pounds
1	203 (239)	--
2	194 (215)	--
3	206 (247)	--
4	85 (101)	--
5	87 (92)	--
6	97 (102)	--
7	50	--
8	--	658 (718)
9	--	584 (627)

(   ) Nonstandard day results

SECTION III

FLIGHT TEST PROGRAM

The flight test program was conducted at Edwards Air Force Base, California. To satisfy the overall objective of the study, a twelve flight program consisting of one data substantiation flight and eleven flights to obtain experimental data for comparison with analytical data were flown.

AIRCRAFT DESCRIPTION AND PARTICIPATING PILOTS

The F-5A employed for the test program is a single-seat fighter aircraft capable of carrying stores at wing and fuselage pylon stations. The aircraft is powered by two General Electric J-85-13 afterburning engines. The aircraft configurations was clean except for the installation of AIM-9B launcher rails on the wing tips. A three-view drawing of the production aircraft is shown in Figure 2. The two pilots that participated in the test program were Northrop test pilots. The first pilot was given the assignment of flying all of the optimum maneuvers. The second pilot was not informed about the test program until the first pilot had completed his assignment. The reason for this was to observe and obtain data on how a pilot, not familiar with computer predicted optimum maneuvers, would perform a maneuver if just given the initial and final conditions and the parameter to be optimized.

TEST INSTRUMENTATION

Flight test instrumentation was installed and maintained by the Northrop Corporation, Aircraft Division during the test program.

The data acquisition system installed in the test aircraft consisted of a photo-recorder, PCM magnetic tape data recording system and a flight test airspeed boom. A complete listing of the parameters recorded during each flight is contained in Table III.

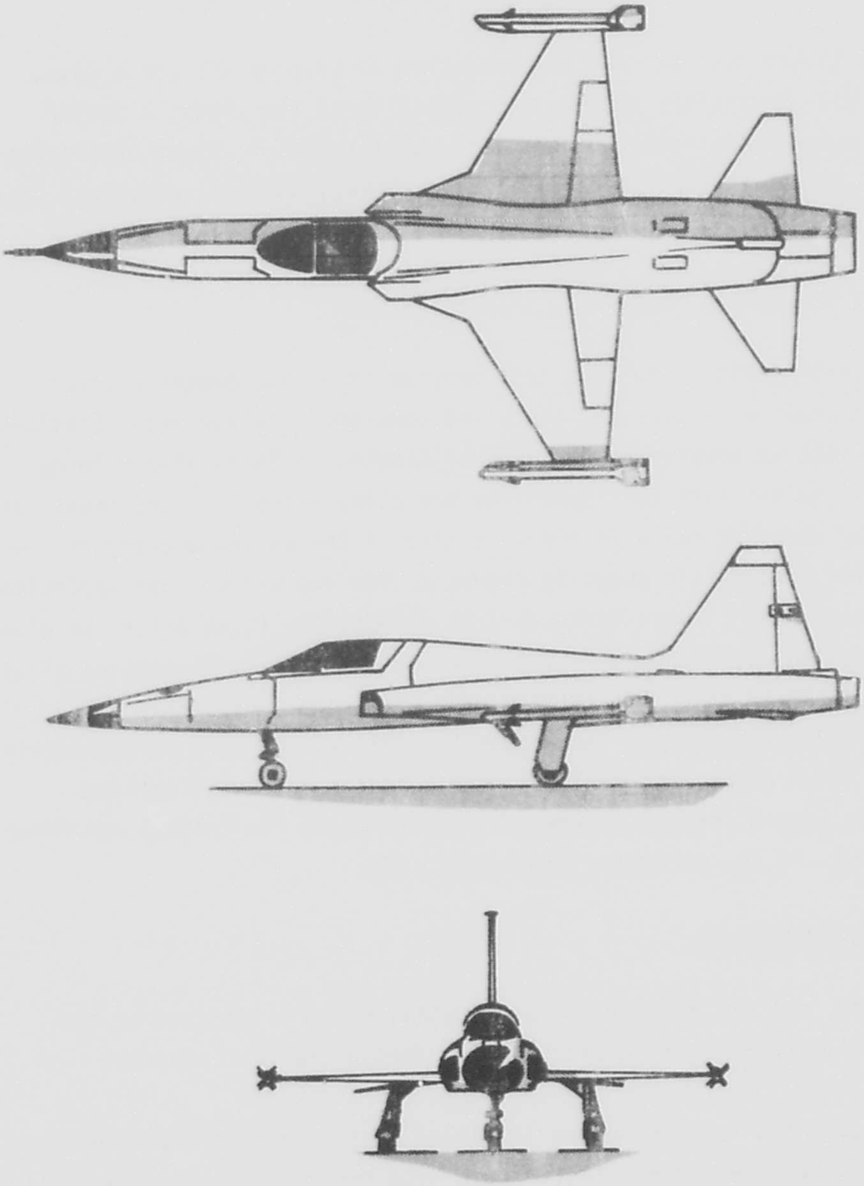

Figure 2. Three View Drawing of F-5A Aircraft

TABLE III

IN-FLIGHT RECORDED PARAMETERS

PHOTO PANEL	RANGE
1. Altitude	0 - 60,000 feet
2. Airspeed	0 - 600 knots
3. Mach number	.5 - 1.5
4. Fuel remaining, Left & Right	-
5. Engine RPM, Left & Right	60 - 104%
6. Engine EFT, Left & Right	-
7. OAT (Rosemount Probe)	-60 ± 120°C
8. Time	-
9. Pilot Event Mark	-
10. Acceleration (n_z)	-4 + 8g's

PCM MAGNETIC TAPE	
1. Pitch angle	± 90°
2. Roll angle	0 to 360°
3. Pitch rate	± 40° /sec.
4. Roll rate	± 250° /sec.
5. Yaw rate	± 40° /sec.
6. Angle of attack	± 20°
7. Angle of sideslip	± 20°
8. Normal load factor, c.g.	-4 - +8g's
9. Normal load factor, cockpit	±5g's
10. Lateral load factor, c.g.	±1g
11. Lateral load factor, cockpit	±2g's
12. Longitudinal load factor, c.g.	±2g's
13. Engine fuel flow, Left & Right	0 - 12 gpm
14. Afterburner fuel flow, Left & Right	0 - 12 gpm
15. Fuel temperature, main and A/B, Left & Right	50 to 200°F
16. Throttle angle, Left & Right	-
17. Event marker	-

Atmospheric conditions were measured on the day of each flight using data telemetered to the Air Force Flight Test Center (AFFTC) Rawinsonde Balloon Station from a weather balloon launched within two to four hours prior to each flight. Recorded parameters were absolute temperature, air density, wind direction and velocity, and atmospheric pressure. Although the altitude-temperature profiles change during the day this data did indicate what atmospheric conditions could be expected for each flight.

Ground radar data were obtained for each flight using the AFFTC Space Positioning facilities. The following parameters were recorded:

1. XYZ space position
2. Airspeed
3. Aircraft heading
4. Time and event mark

To obtain an accurate time correlation between on-board and radar data the aircraft was instrumented whereby the pilot turned on the instrumentation at the start of the maneuver and a mark was made on the radar data.

The on-board and space positioning data obtained from all of the flights were reduced by the Northrop Corporation. The reduced data consisted of the time histories for all of the parameters listed in Table III for each maneuver. These flight test data were supplied to the Air Force Flight Dynamics Laboratory (AFFDL) for correlation with the analytical results.

FLIGHT PROCEDURE

Before each scheduled flight a meeting was held with the test pilot to discuss the types of maneuvers to be flown. During this meeting the pilot would determine the parameters and the method of presentation he preferred to use in attempting to fly the prescribed maneuvers.

From this meeting an engineering flight test card, Figure 3, was given to the pilot for each flight. Voice communication with the pilot was maintained throughout each flight. The pilot would read out values of altitude and Mach number at the end of each segment of the flight profile and in this manner his progress could be monitored on the ground. At the conclusion of each flight, a debriefing session was conducted to determine how the pilot felt he had flown the maneuvers and to discuss any difficulties encountered during the flight.

ENGINEERING FLIGHT TEST CARD

Model F-5A No 372 Date______ Flight No 671

Pilot Thomas OBS —

T.O. Wt 13,344 CG 14.01% Mac. Time T.O.____ L'nd____

Test Optimized Traj., Page____ of____

Special Note Test Freq. MHz

1450-1590#/Side				
SEG.	FLT. COND.	ROLL	PITCH	Nz
Init.	2900; 0.49 M	21°		1.0
①	Level Accel.			
	2900; 0.68M	33°		2.75
②	Const. Climb			
	5600; 0.69M	26°		
③	Accel. Climb	↑		
	9000; 0.86M			
④	Decel. Climb			
	17,600; 0.84M			
⑤	Accel. Climb			
	22,600; 0.90M	↓		
⑥	Decel. Climb	26°		1.0
	31,600; 0.87M			
⑦	Accel. Climb	0°		
	33,100; 0.90M	↑		
⑧	Decel. Climb			0.5
	37,500; 0.87M	↓		
⑨	Accel. Dive	0°		0
	28,500; 1.20M			

Figure 3. Engineering Flight Test Card

SECTION IV

DISCUSSION OF RESULTS

DATA DIFFERENCES

As mentioned previously, the atmospheric and F-5A performance data were supplied by AFFTC and the Northrop Corporation respectively. An analysis of the data obtained from the atmospheric (radiosonde weather balloon) facilities and the performance data substantiation flight, conducted prior to the scheduled first flight of the test program, showed that differences existed between the data used in the computer simulations and the actual measured data. The following is a discussion of these data differences and what effect they had upon the missions flown.

TEMPERATURE PROFILES

Shown in Figure 4 are the temperature profiles for a standard day, a constant 10°C hotter than standard day (profile used in the computer simulations) and the average that existed at EAFB during the test program. The actual average temperature varied from 3°C hotter at sea level to 6.5°C colder at 36,000 feet when compared with the temperatures used in the computer simulation. Since the engine characteristics are a function of temperature the computer predicted performance would show an increase over the actual performance at the lower altitudes and a decrease at the higher altitudes. For all of the minimum time flight profiles the aircraft was flying above 20,000 feet 60 to 100 percent of the total flight time. Therefore, the net effect of the temperature difference was the actual aircraft could accelerate and/or change altitude quicker than the aircraft being simulated.

Maneuver Number 1 was selected to show the sensitivity of the temperature profile on the optimal computer generated flight profile since this maneuver started at a low altitude and terminated at a much higher altitude. Shown in Figure 5 are the two optimal flight profiles. One was obtained using a standard day temperature profile while the other was generated using a constant 10°C hotter than standard profile.

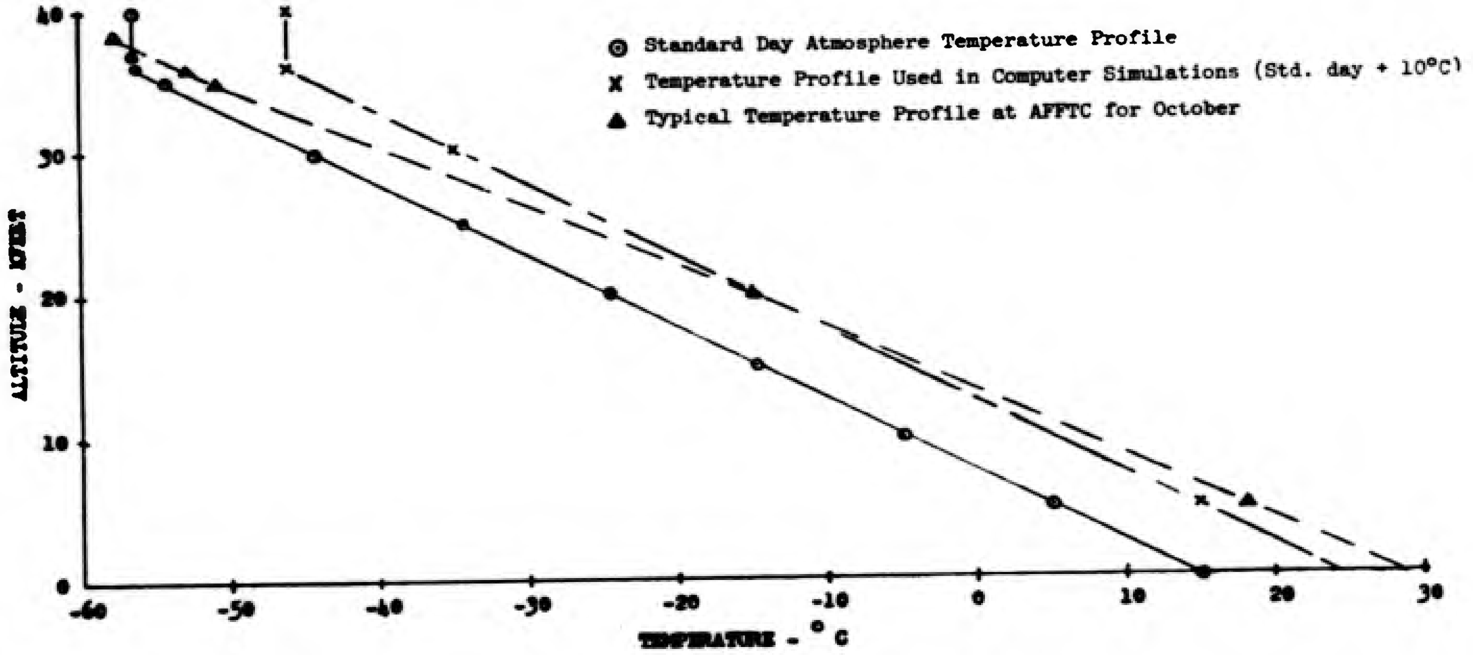

Figure 4. Temperature Profiles for Standard and Nonstandard Atmospheres

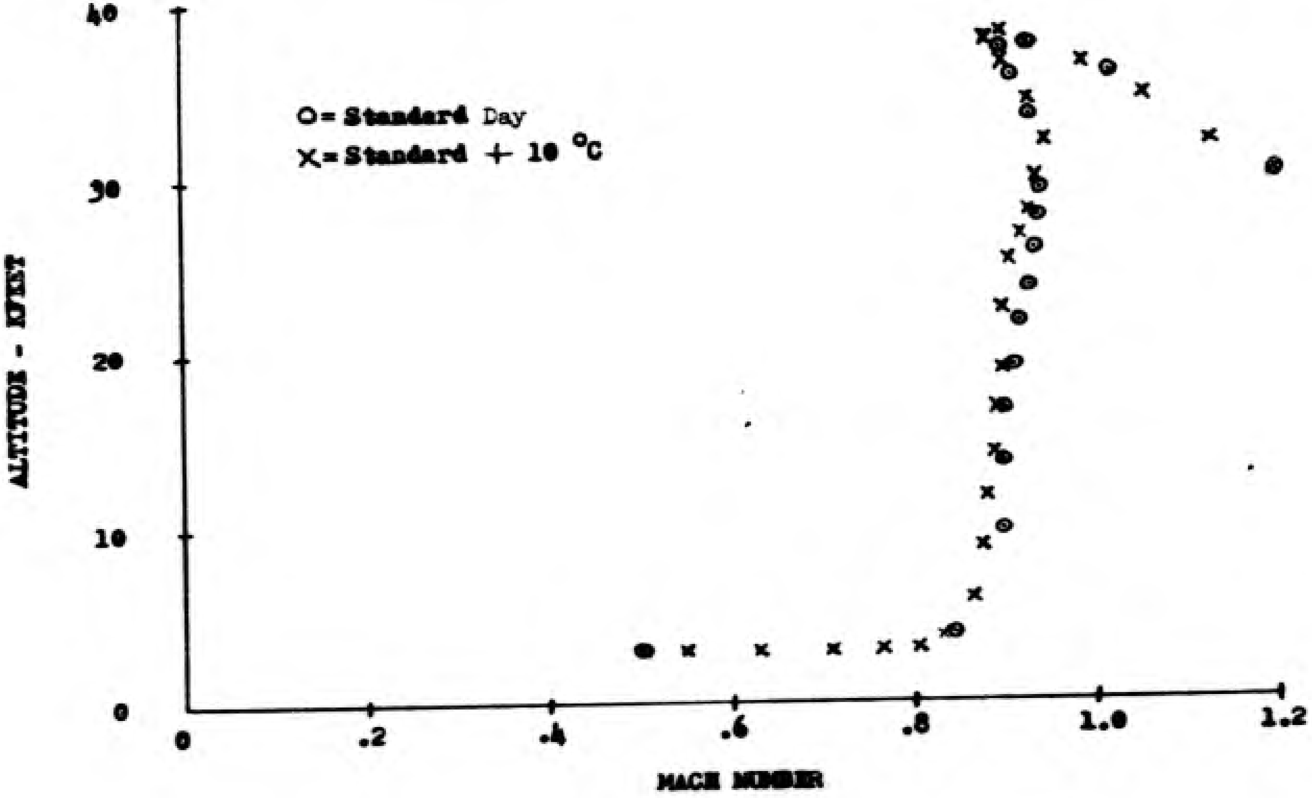

Figure 5. Optimum Flight Profile Variation with Increased Atmospheric Temperature

The increased temperature had very little effect upon the shape of the flight profile, however it had a pronounced effect upon the total time to fly the maneuver. The total time difference between the two optimal flight profiles was 36 seconds.

AIRCRAFT PERFORMANCE

Before flying the optimum flight paths, it was necessary to assure that the engines were delivering specified values of thrust. This was accomplished by performing a level acceleration flight at 15,000 feet and comparing the results with performance data acquired from earlier performance test programs.

It was not necessary to explicitly measure thrust output, per se, (which would have required additional engine instrumentation) but merely to measure the acceleration, as the F-5A drag had been previously determined from Category I and II flight tests.

Results of the level acceleration flight indicated that at the higher Mach numbers, in the region of best climb speed, the engines were delivering five to six percent more thrust than demonstrated in the USAF Category II test program.

Figure 6 presents a comparison of flight test and expected longitudinal acceleration for the test day ambient temperature condition. The flight test acceleration exceeded the expected value by eight to nine percent at the higher speeds, which implies the five to six percent thrust increase discussed previously. No attempt was made to demonstrate maximum speed, as power was retarded after attaining 0.97 Mach number. The data points were computed from the relation

$$\frac{a}{g} = \frac{\dot{H}}{1.689V} + \frac{\dot{V}}{19.05} \quad \text{(G's)}$$

$T_{am} = -2\ ^{\circ}C$

Wt = 11,400 lbs

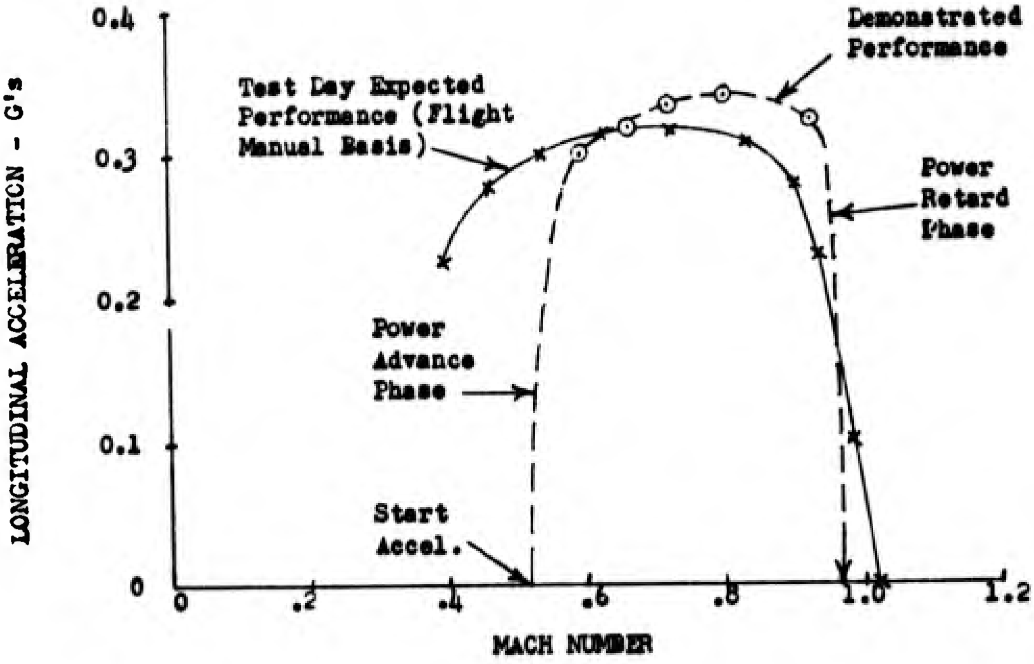

Figure 6. Comparison of Demonstrated Longitudinal Acceleration with Expected Performance at 15,000 feet

a = acceleration in (fps^2)

$\dot{H}$ = measured rate of climb (fps)

V = true airspeed (knots)

$\dot{V}$ = rate of change of speed (KTAS/sec)

The data used in computing the acceleration are shown in Figure 7. If the flight had been truly level, the energy expended in the climb would have been utilized as improved $\dot{V}$.

It was determined from the acceleration check flight that at the high subsonic Mach numbers, characteristic of climb speed, engine thrust output was within marginal acceptable limits to conduct the flight evaluation of optimum maneuvers.

Since the test aircraft performance exceeded the predicted performance it was necessary to determine how the deviations in aircraft performance varied with changing altitude and Mach number before a correlation of the actual and predicted results could be performed. Shown in Figure 8 are the F-5A subsonic rate-of-climb versus Mach number curves for the conditions indicated. The solid curves were obtained from the F-5A Category II Performance Test reports (References 13, 14, and 15) while the dashed curves were constructed from the engineering data used in the computer simulation. These deviations in climb performance, at approximately the best climb speed, vary from 4.4 percent at 5,000 feet to 15.4 percent at 36,000 feet. To determine the total deviation in the subsonic climb performance between the predicted and what was actually obtained by the test aircraft, the results from the data substantiation flight had to be included. These measured results obtained from the level acceleration flight to M=0.97 at 15,000 feet showed that at the higher Mach numbers the engines were delivering approximately six percent more thrust than demonstrated in the USAF Category II test program. Since only one data substantiation flight was flown, it was assumed that the six percent increase in thrust was constant for all altitudes. The circles shown on Figure 8 are the recomputed rate-of-climb values, at

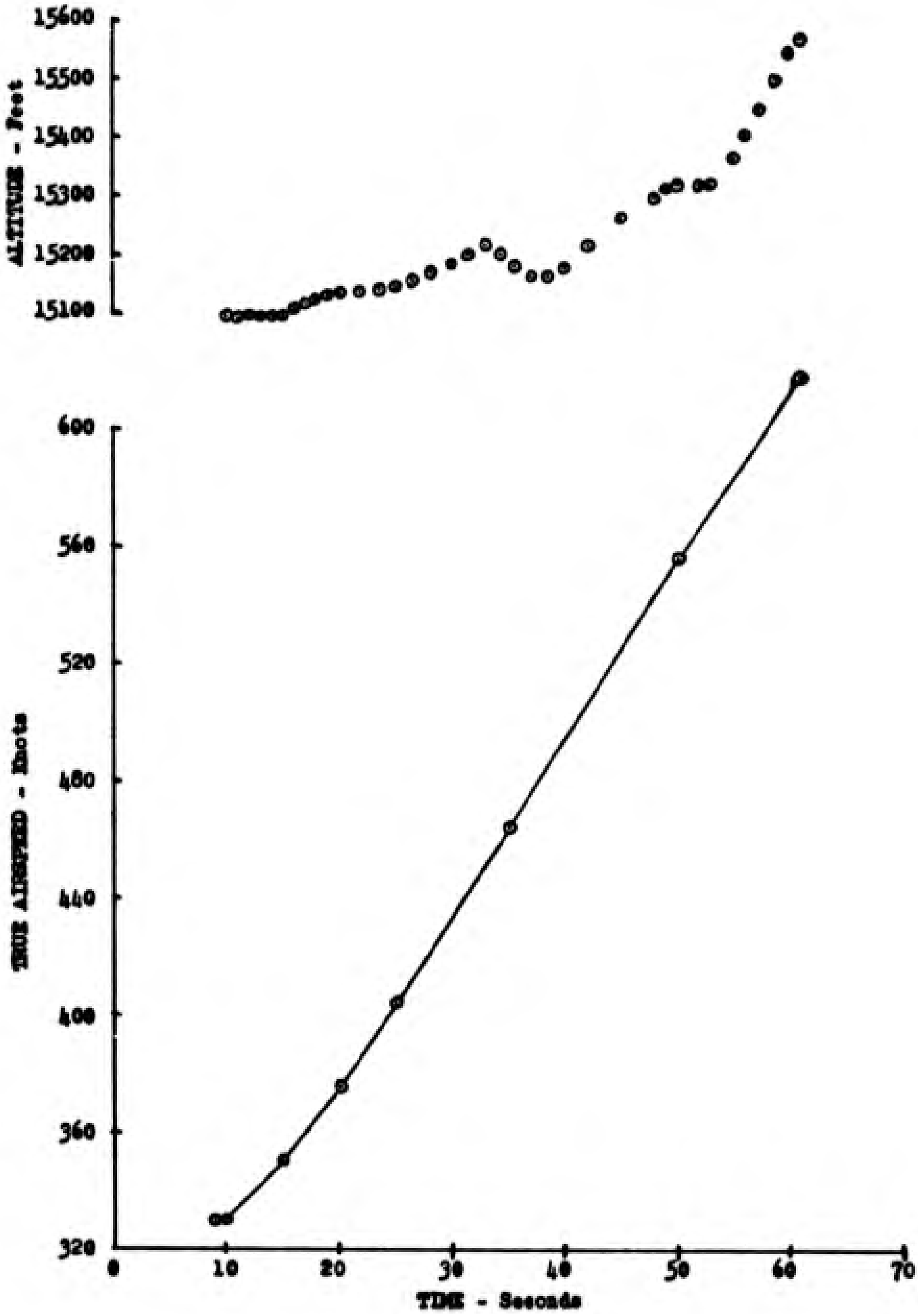

Figure 7. Demonstration Flight Results

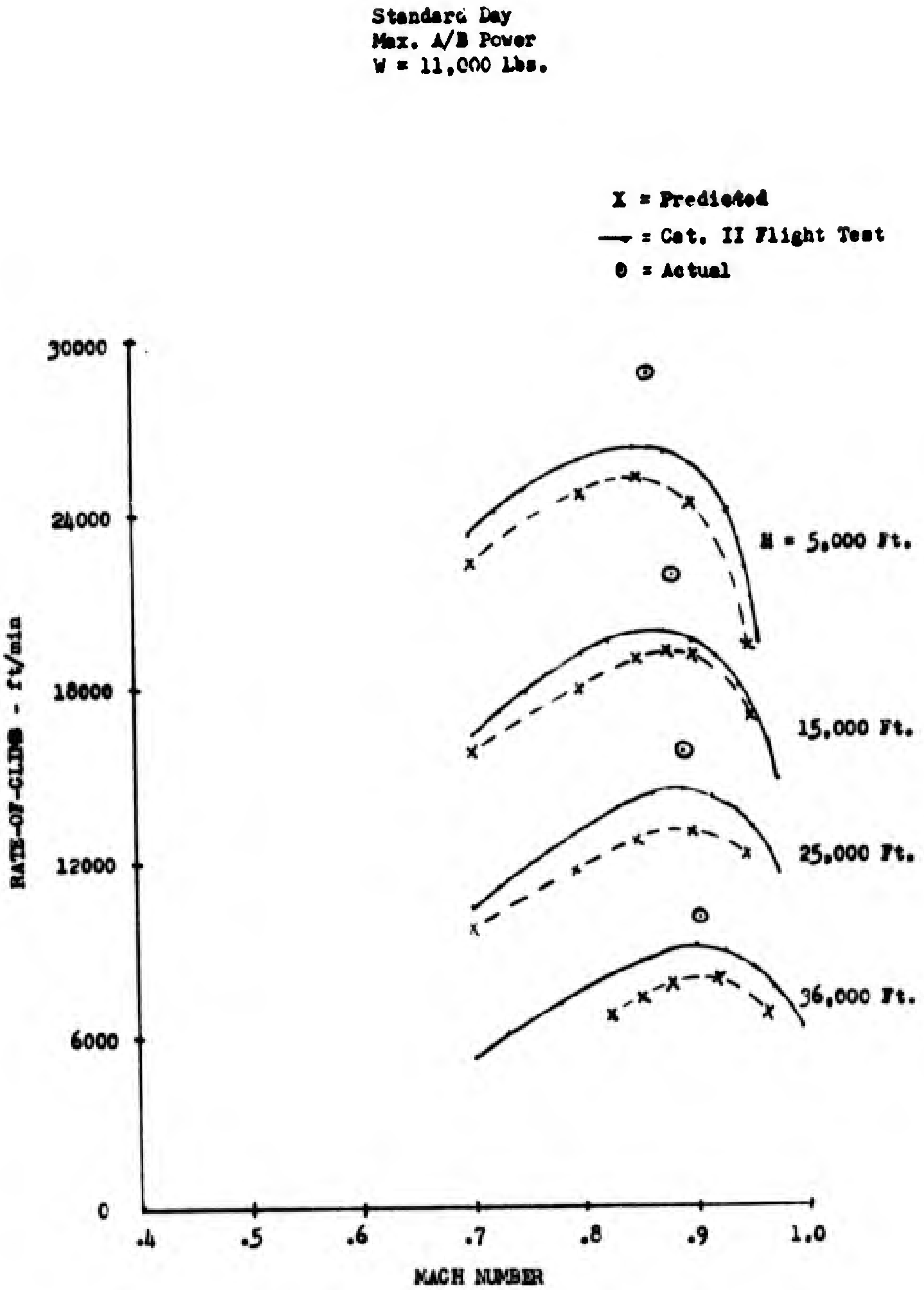

Figure 8. Comparison of Predicted and Actual Rate-of-Climb Capability

approximately the best climb Mach number, using the corrected thrust data. The total differences in climb performance between the predicted and actual are the differences between the dashed curves and the circles. These differences range from 15 percent at 5,000 feet to 26 percent at 36,000 feet. Using maneuver Number 1 as an example, the total effect upon the subsonic climb performance resulting from the data differences in temperature-altitude profiles and engine characteristics was that the actual test aircraft reduced the predicted time to climb from 5,000 feet to 39,000 feet by approximately 38 seconds.

PILOT'S ABILITY

One important facet of the study was to determine the pilot's ability to fly the computer predicted optimum flight profile for each mission. Before each scheduled flight, the pilot was briefed on the type of mission to be flown. Also, the optimum mission profile and control parameter schedules were broken down into straight line segments whereby the flight conditions at the beginning and end of each segment were recorded on the pilot's engineering flight test card (see Figure 3). Comparison of the actual and predicted minimum time to climb flight profiles indicated that the pilot was able to fly the predicted level acceleration to the best climb Mach number and subsonic climb segments for all of the intercept missions with reasonable accuracy. However, the mission requiring an initial push-over and acceleration segment followed by a pull-up proved to be a difficult task for the pilot to perform. The pilot, in attempting to meet the Mach-altitude flight conditions at the end of this segment, would constantly overshoot the Mach number if he pulled out at the desired altitude or undershoot the altitude if he pulled out at the desired Mach number.

Another segment that caused problems was the last segment of the supersonic intercept mission profiles. This segment was a push-over and acceleration to the terminal conditions of 30,000 feet and 1.2 Mach number. The pilot in attempting to fly the predicted optimum path could never attain the required altitude loss upon reaching the terminal supersonic Mach number. These problems were due to the data differences that existed between the simulated and actual test aircraft, resulting in flight conditions being predicted which were not compatible with the test aircraft performance.

CORRELATION OF ANALYTICAL AND EXPERIMENTAL RESULTS

The predicted and actual flight profiles for each mission are shown in Figures 9 through 19. Table IV contains a complete listing of the initial conditions, final conditions, analytical results, and experimental results for each mission. An analysis of the test results showed that for all of the minimum time to climb maneuvers investigated (except for Maneuver Number 7 which was flown at idle power) the test aircraft flew each maneuver in less time than was predicted. This time difference between the analytical and experimental varied from 7 percent for Maneuver 6 to 20 percent for Maneuver 1.

The predicted and actual flight profiles for Maneuver Number 1 are shown in Figure 9. The predicted optimum flight profile consisted of a level acceleration to the best climb Mach number, a varying Mach number climb to approximately 39,000 feet, followed by an unloaded acceleration initiated at that altitude. The analytical results show that the terminal Mach number of 1.2 is attained when the aircraft passes through 30,000 feet. As can be seen in Figure 9 the pilot was able to maintain, within reasonable limits, the desired Mach-altitude schedule through the level acceleration and subsonic segments. However, upon reaching the push-over altitude and applying full forward stick the test aircraft could not attain the predicted altitude loss (9,000 feet) upon reaching the terminal Mach number. To indicate the test aircraft's increased performance capability resulting from the data differences discussed previously, Maneuver Number 1 was subdivided into the four segments shown in Table V. By subdividing the maneuver it was possible to obtain a direct comparison between the predicted and actual aircraft performance for the low altitude acceleration, subsonic climb, and the high altitude acceleration phases. The results show that the test aircraft, while flying approximately the optimum Mach-altitude schedule, was able to reduce the predicted total flight time by 20.8 percent. Also, the largest percent

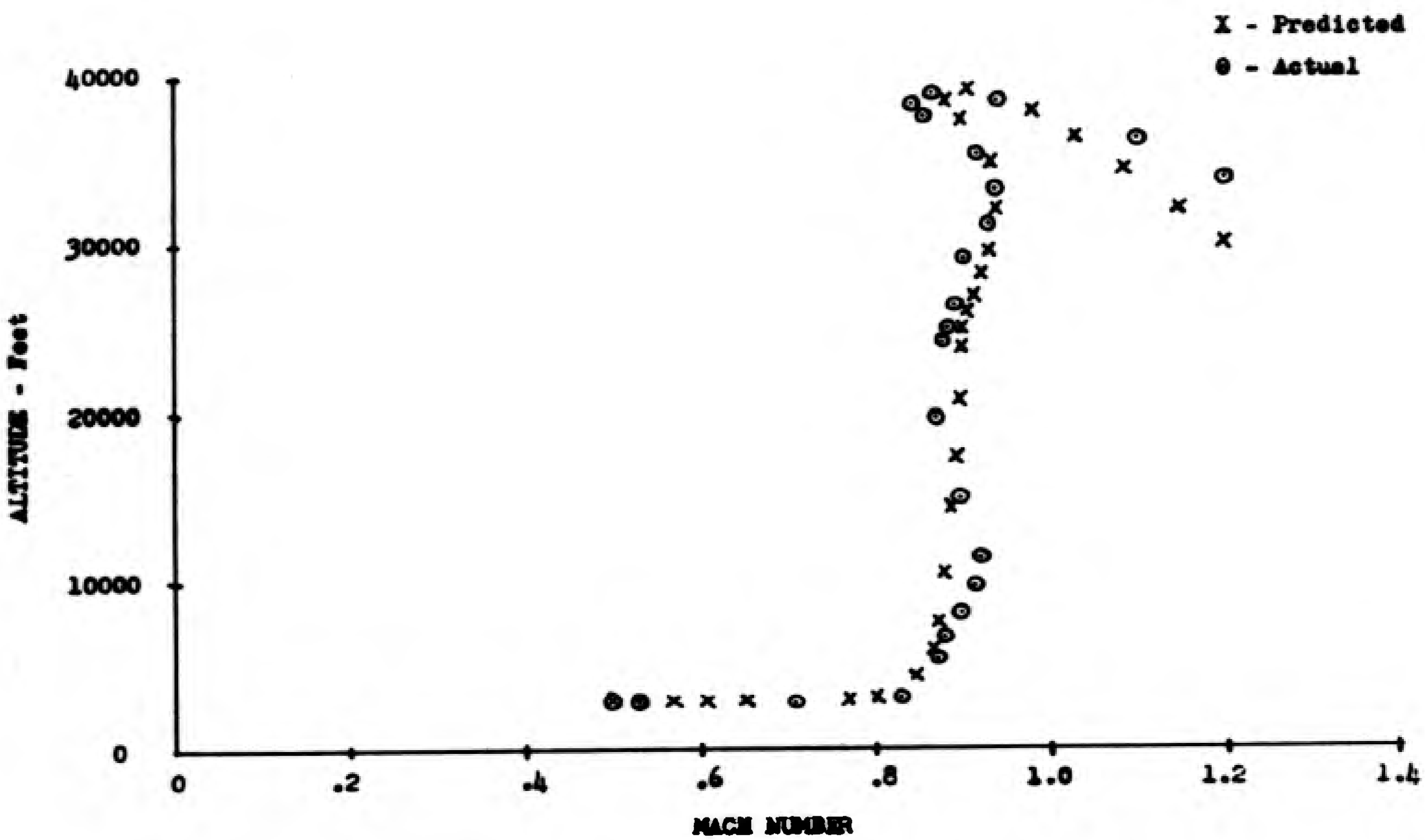

Figure 9. Predicted and Actual Flight Profiles for Maneuver Number 1 (TOP)

TABLE IV

SUMMARY OF MANEUVERS AND RESULTS

Maneuver Number	Initial Conditions			Final Conditions				Results		
	Weight (lbs.)	Mach Number	Altitude (ft.)	Mach Number	Altitude (ft.)	Heading Change (deg.)	Parameter Optimized	Analytical	Experimental	Computer Program
1	12,700	0.5	3,000	1.2	30,000	0	Time	239 Sec.	190 Sec.	TOP
1A*								185 Sec.	190 Sec.	TOP
2	12,700	0.5	3,000	1.2	30,000	0	Time	215 Sec.	216 Sec.	EM
3	12,700	0.5	3,000	1.2	30,000	180	Time	247 Sec.	200 Sec.	TOP
4	11,700	0.7	35,000	1.2	30,000	0	Time	101 Sec.	88 Sec.	TOP
5	11,700	0.7	25,000	0.7	40,000	0	Time	92 Sec.	85 Sec.	TOP
6	11,700	0.7	25,000	0.7	40,000	180	Time	102 Sec.	95 Sec.	TOP
7	11,700	1.2	30,000	0.6	10,000	180	Time	50 Sec.	76 Sec.	TOP
8	12,700	0.5	3,000	1.2	30,000	0	Fuel	718 Lbs.	644 Lbs.	TOP
9	12,700	0.5	3,000	1.2	30,000	0	Fuel	627 Lbs.	635 Lbs.	EM

* Maneuver 1 re-optimized using updated atmospheric and thrust data

TABLE V

MANEUVER NUMBER ONE SUMMARY

SEGMENT	Time (Seconds)		Percent reduction in time over predicted
	Actual	Predicted	
Level acceleration to M = 0.84	30	35	14.3
Climb from 3,000 to 20,000 feet	48	57	15.8
Climb from 20,000 to 39,000 feet	93	122	23.7
Push - over and accelerate to M = 1.2	19	25	24.0
TOTAL	190	239	20.8

reduction in time over the predicted occurred during the subsonic climb from 20,000 feet to 39,000 feet and the high altitude acceleration segments. These reductions in time resulted from the test aircraft's engines delivering more thrust at these altitudes than predicted. An analysis of the subsonic climb segments indicated that the percent reduction in time values shown in Table V compared favorably with the time differences in climb performance discussed previously under aircraft performance. Since the total flight time difference between the analytical and experimental for Maneuver 1 was quite large (49 seconds) the question of whether or not the TOP solution was truly optimum remained unanswered.

To try and answer this question Maneuver 1 was selected to be rerun using the TOP program. The computer input data was modified to account for the engines' increased thrust and the atmospheric characteristics that existed during the flight. Also, the terminal flight conditions were changed to match those actually obtained by the test aircraft, namely M=1.2 and H=33,750 feet. The optimal solution obtained, using the updated data, resulted in a flight profile quite similar to the actual profile shown in Figure 9 with a time of 185 seconds. Since the TOP program was able to reduce the experimentally measured total flight time by only 2.6 percent, it was concluded that these flight profiles generated by the TOP program do indeed indicate to the pilot how to transfer between energy levels optimally.

Due to the amount of computer time involved in obtaining optimal solutions using the TOP program, this in-depth analysis was not performed for all of the maneuvers investigated. Instead, it was assumed (from the results of analyzing the maneuver with the largest percentage difference in total flight time) that had the atmospheric temperature and engine thrust data used in performing the computer simulations matched the actual flight data within one to two percent, the resulting differences between the predicted and measured values of the parameter being optimized would have been very small.

Mission Number 2 is identical to Number 1 except the Energy Maneuverability optimization method was used to obtain the minimum time flight profile. The reasons for obtaining an EM and TOP minimum time solution for the same maneuver were to determine the accuracy of the predicted solutions and the flyability of the profiles. The EM predicted and actual flight profiles for Maneuver Number 2 are shown in Figure 10. Analysis of the flight profiles indicated that the pilot was able to remain relatively close to the EM predicted flight profile through the level acceleration and subsonic climb to 38,000 feet. During the subsonic climb the maximum deviation in Mach number was 0.03 which occurred at 24,000 feet. As was the case with Maneuver Number 1 the push-over and dive phase proved to be the most critical since the aircraft upon reaching the terminal Mach number was 6,000 feet above the desired altitude. Comparing the results from all of the maneuvers flight tested, Maneuver Number 2 had the largest deviation in terminal altitude. However, it is assumed that, had the pilot been able to adequately practice how best to perform the push-over, the time from push-over to terminal flight conditions could have been reduced.

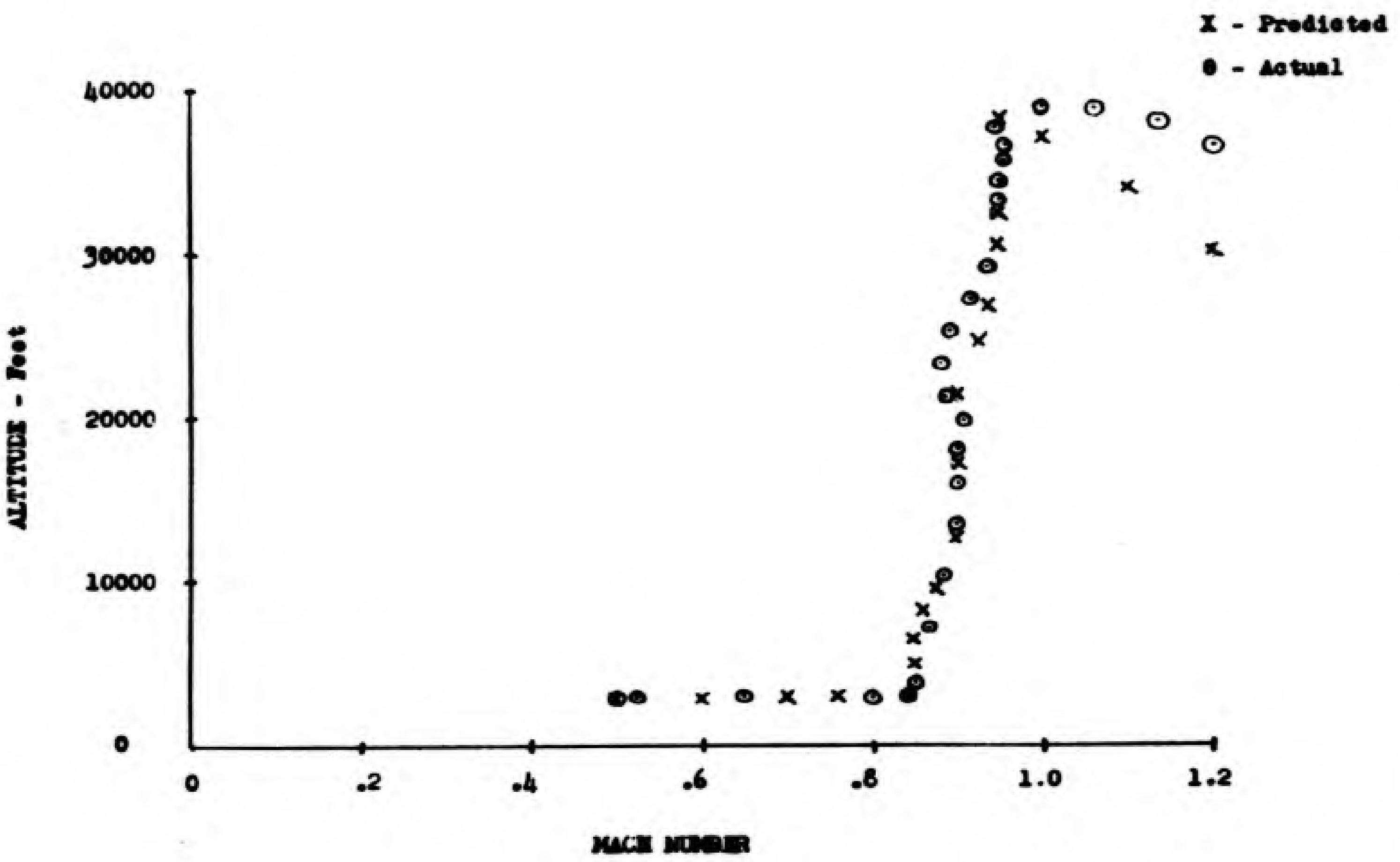

Figure 10. Predicted and Actual Flight Profiles for Maneuver Number 2 (EM)

Some interesting results were obtained from analyzing the predicted EM and actual flight profiles. First, even though inaccuracies in the atmospheric and engine data existed between the analytical model and test aircraft the actual total flight time was within one second of the predicted time. However, to determine the optimality of the EM flight profile the flight results had to be compared with the results obtained from flying the TOP flight profile since they were obtained for identical maneuvers. An analysis of these results showed that the pilot was able to fly the TOP generated flight profile in 26 seconds less time than it took him to fly the EM profile. Therefore, this 12 percent reduction in EM total flight time is an indication of the approximate optimality of the EM method in predicting the payoff function (time in this case) due to the assumptions introduced in the formulation of the method. Secondly, an analysis of the experimental results showed that the assumption of a constant load factor (1 g flight) made in obtaining the EM flight profile compared favorably from the initial flight conditions through the subsonic climb to 38,000 feet, see Figure 11.

At the present time, optimization of aircraft maneuvers out of the vertical plane is a subject receiving a great deal of attention. For this reason, Maneuver Number 3 was formulated to be flight tested to try and obtain a better understanding of how the aircraft should be banked to perform a specified heading change optimally. Maneuver Number 3 is a minimum time to intercept maneuver with the same initial and final conditions as Maneuver 1 except in performing the maneuver the pilot was required to execute a 180 degree heading change. Therefore, the actual differences in flight times between these two maneuvers would indicate the penalty associated with performing the desired change in heading. Up to this point in the test program the pilot had been monitoring only the Mach number and altitude cockpit instruments in flying maneuvers in the vertical plane. Since Maneuver Number 3 required a heading reversal, an additional parameter had to be added to the pilots engineering flight test card, namely the roll angle schedule. Figure 12 is the flight test card used by the pilot in flying this maneuver. The nine segments shown in Figure 12 are the

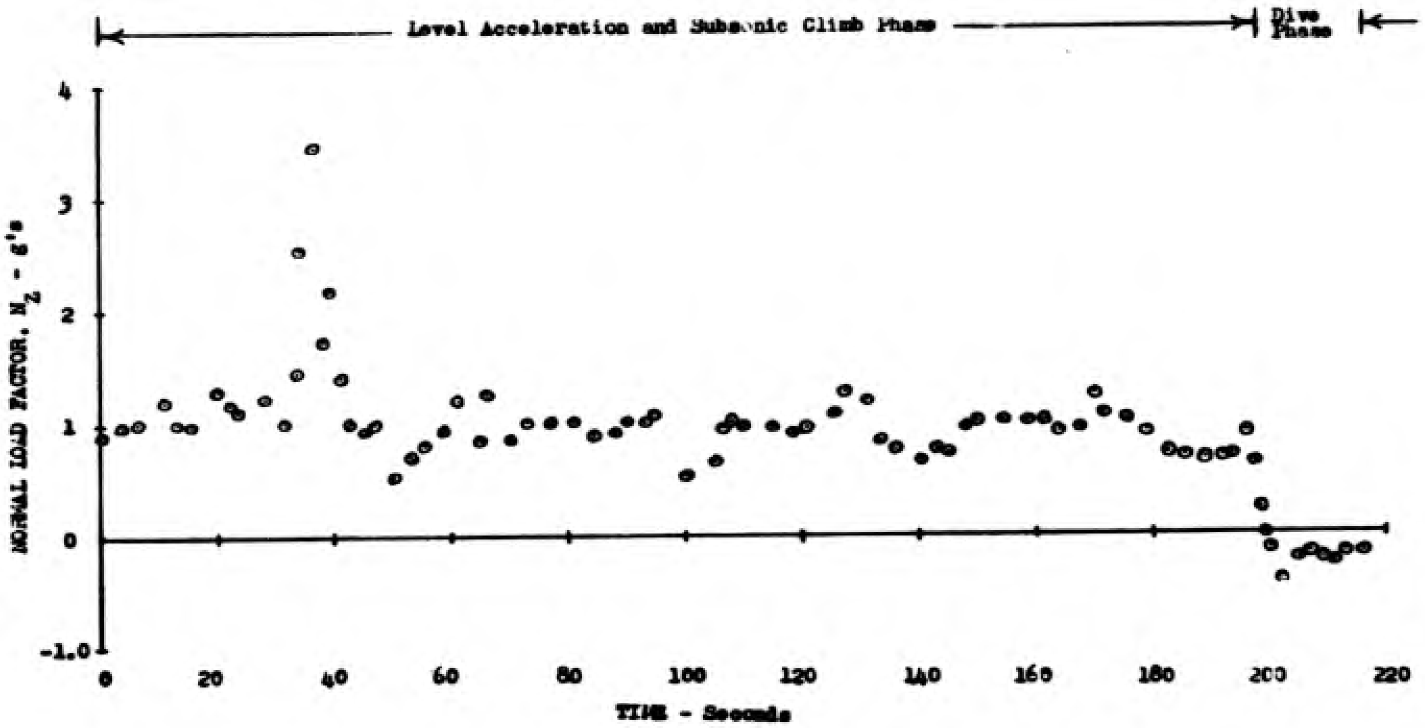

Figure 11. Actual Normal Load Factor Time History for Maneuver Number 2 (EM)

SEGMENT	FLIGHT CONDITIONS	ROLL ANGLE (degrees)	
		Predicted	Actual
Initial	2900 ft, 0.49 Mach	21	20
1	Level Accel. to 2900 ft, 0.68 Mach	33	38
2	Const. Climb to 5600 ft, 0.69 Mach	26	40
3	Accel. Climb to 9000 ft, 0.86 Mach	↓	27
4	Decel. Climb to 17600 ft, 0.84 Mach	↓	25
5	Accel. Climb to 22600 ft, 0.90 Mach	↓	25
6	Decel. Climb to 31600 ft, 0.87 Mach	26	25
7	Accel. Climb to 33100 ft, 0.90 Mach	0	0
8	Decel. Climb to 37500 ft, 0.87 Mach	↓	0
9	Accel. Dive to 28500 ft, 1.20 Mach	0	0

Figure 12. Pilot's Flight Test Card for Maneuver Number Three

result of the pilot segmenting the maneuver before the flight based upon his analysis of the predicted flight profile and corresponding data. The important item to note in Figure 12 is how the predicted optimum roll angle schedule changes with Mach number and altitude.

Since the TOP program did not predict any high roll rates the pilot was able to follow the predicted roll angle schedule within reasonable limits. However, the addition of the third parameter to be monitored resulted in a work load such that the pilot stated after completing the maneuver "the roll angle schedule could not be followed exactly while trying to monitor the altitude and Mach number". The actuall roll angle schedule shown in Figure 12 produced a total heading change which was within 5 degrees of the required 180 degrees. The pilot's ability to fly relatively close to the predicted roll angle at each check point is reflected in how well the predicted and actual flight profiles compare in Figure 13. Through the subsonic climb and turn segments the maximum deviation from the predicted Mach number schedule was only 0.04. The difference in total flight time between the predicted and actual was 47 seconds for Maneuver Number 3. It should be noted that the time difference between the analytical and experimental results for both Maneuvers Number 1 and 3 (See Table IV) are of approximately the same magnitude, namely 49 and 47 seconds respectively. This is significant in that it substantiates the conclusions made after reoptimizing Maneuver Number 1 using the updated atmospheric and engine data. Although the time penalty for performing the heading reversal differed by 2 seconds between the analytical and experimental results, it was concluded that the results were comparable.

The fourth maneuver listed in Table IV was a minimum time supersonic intercept maneuver starting from 35,000 feet and 0.7 Mach number and terminating at 30,000 feet and 1.2 Mach. The actual and predicted flight profiles are shown in Figure 14. The problems discussed previously relating to the push-over and pull-up segments are immediately obvious upon comparing the two flight profiles. The pilot, upon undershooting the altitude and overshooting the Mach number at the pull-out conditions, in trying to reacquire the optimum profile pulled up to a high pitch

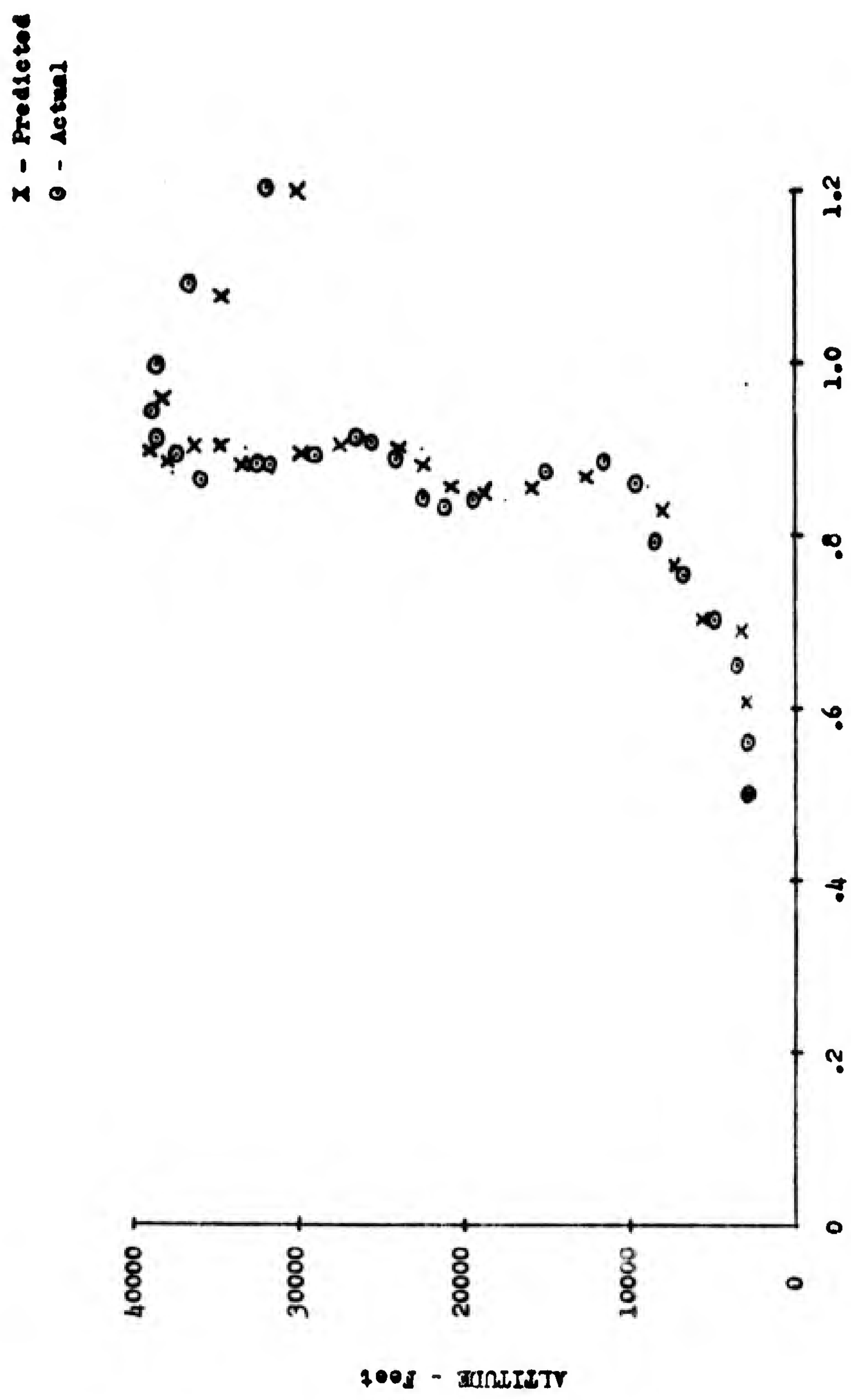

Figure 13. Predicted and Actual Flight Profiles for Maneuver Number 3

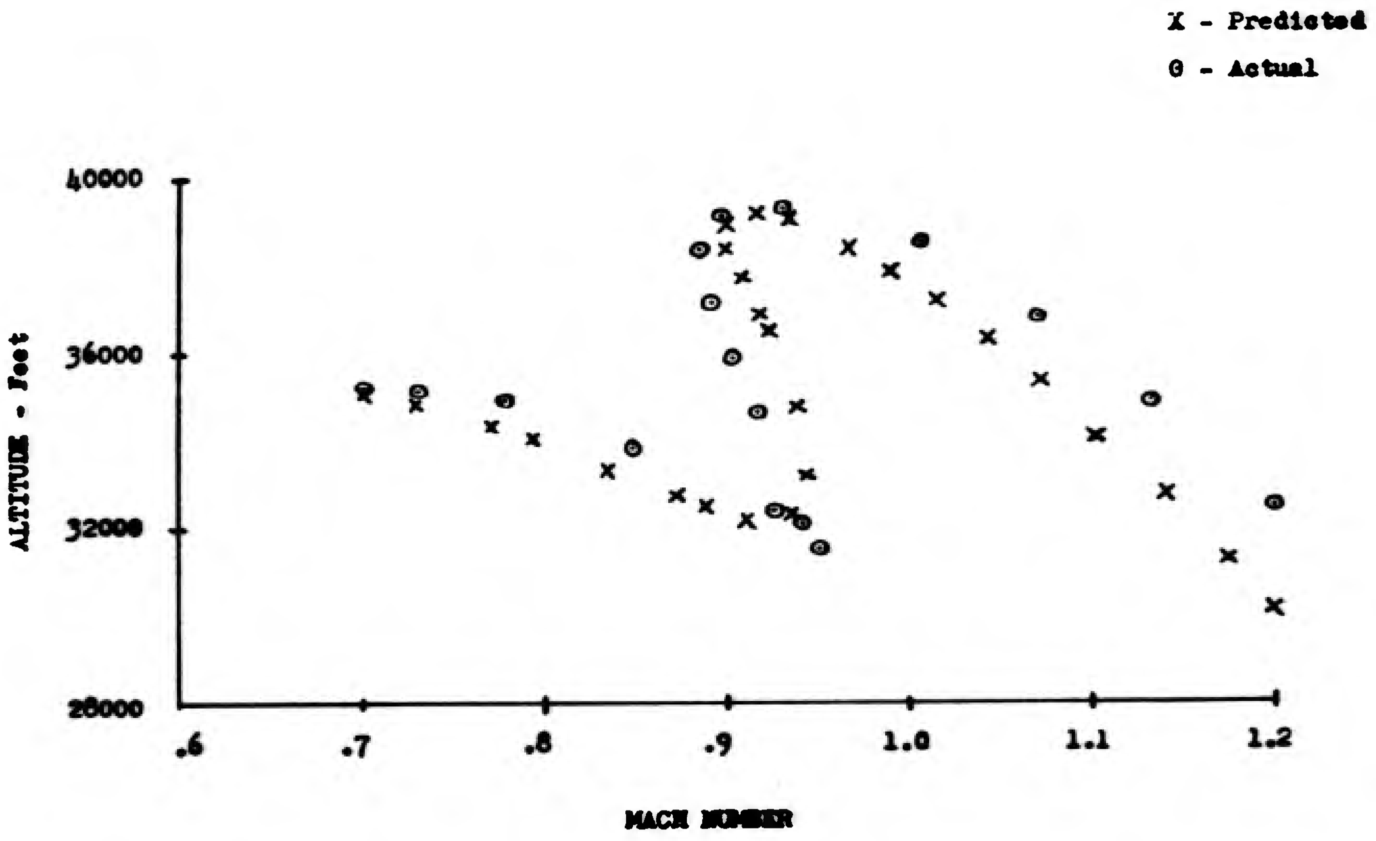

Figure 14. Predicted and Actual Flight Profiles for Maneuver Number 4

attitude resulting in an undershoot of approximately 0.03 Mach number through the subsonic climb and decelerate segment. Although the pilot experienced some difficulties in trying to fly the optimum flight profile he was still able to reduce the predicted time by approximately 13 percent.

Maneuver Number 5 was a subsonic intercept maneuver with a set of initial and final conditions of 25,000 feet at 0.7 Mach and 40,000 feet at 0.7 Mach respectively. The predicted and actual flight profiles are shown in Figure 15. From the previous maneuvers flown the pilot was beginning to acquire a feel for how and when to lead the push-over and pull-up events. This is reflected in his ability to fly relatively close to the optimum flight profile over the entire maneuver. Due to the vehicle's increase performance, the actual total flight time was 7 seconds less than the predicted time. The TOP predicted time for this mission was 92 seconds.

Mission Number 6 is identical to mission 5 except a 180 degree turn had to be performed. The mission profiles for this mission are shown in Figure 16. The pilot was able to fly close to the optimum profile up until approximately the initiation of the zoom segment. A too early initiation of the zoom resulted in an undershoot on altitude at the terminal Mach number. The pilot's increased workload associated with the heading reversal was probably the reason for performing the zoom segment too early since this difficulty was not encountered in performing Mission Number 5. The difference in total flight time between the predicted and actual was 7.5 seconds. The actual time to complete the 180 degree turn (total flight time difference between missions number six and five) was 10 seconds which agreed almost exactly with the predicted time of 10.5 seconds.

Maneuver Number 7 was the last minimum time mission and it proved to be the most difficult for the pilot to perform. This mission required the pilot to fly a descending, decelerating and turning flight profile starting from 30,000 feet at 1.2 Mach and terminating at 10,000 feet and 0.6 Mach. This mission was performed with the throttles set in

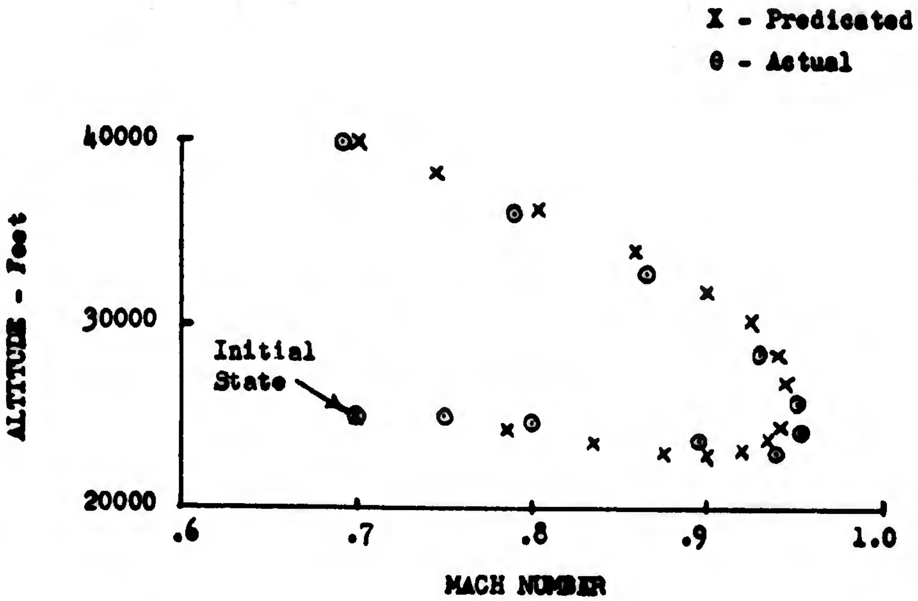

Figure 15. Predicted and Actual Flight Profiles for Maneuver Number 5

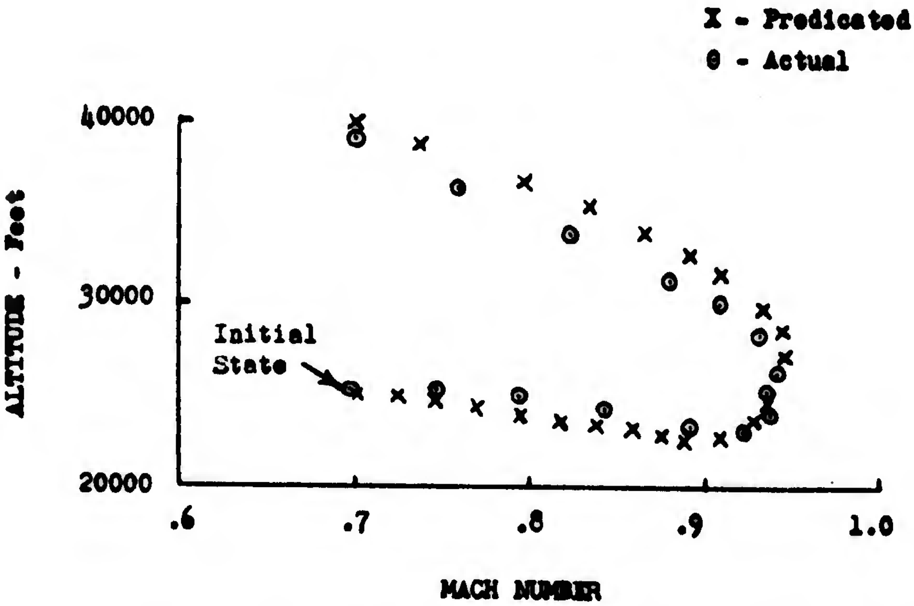

Figure 16. Predicted and Actual Flight Profiles for Maneuver Number 6

the idle position. The predicted and actual flight profiles are shown in Figure 17. The pilot's comments relating to his difficulties in trying to fly the optimum mission profile were:

a. Events were changing too rapidly.

b. The initial segment was too sensitive to the initial roll rate since once the bank angle was set it could not be monitored during the high load factor variation segments of the path because other instruments required monitoring and because of "grey out" vision problems.

c. Power reduction from maximum to idle resulted in almost an instantaneous reduction of Mach number of 0.04 before the load factor could be applied.

The actual and predicted flight times were 76 and 50 seconds respectively.

These mission results bring out an important point, namely that the analyst should exercise extreme caution when interpreting computer generated results especially if they are to be used as a source of mission design.

The last two maneuvers, eight and nine, were flown to determine the utility of the TOP and EM programs for generating minimum fuel (variable throttle) flight profiles. The EM minimum fuel flight profile was obtained using the approach outlined in Reference 7 to determine the energy levels where it is most beneficial, in terms of fuel required for increasing energy, to change the throttle setting. The initial and final flight conditions were identical to Maneuvers 1 and 2 except for the parameter being optimized, see Table IV. Therefore, the differences in fuel required between the minimum time (fixed throttle-max A/B power) and minimum fuel (variable throttle) flight profiles would indicate the actual fuel savings realized by varying the throttle setting.

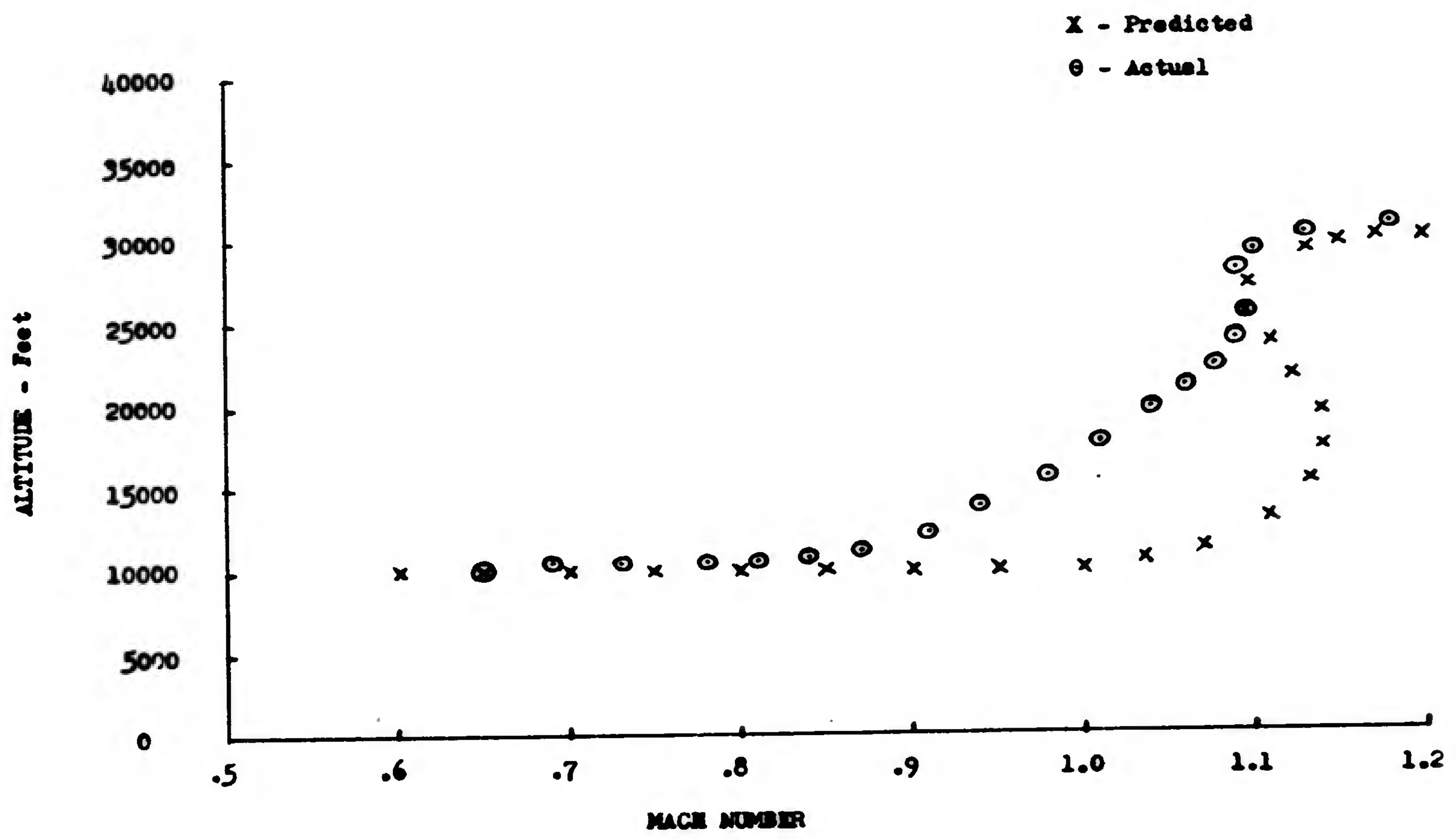

Figure 17. Predicted and Actual Flight Profiles for Maneuver Number 7

Shown in Figures 18 and 19 are the predicted and actual flight profiles for Maneuvers 8 and 9 respectively. Although the analytical results for both the TOP and EM showed a substantial reduction in fuel required over the minimum time (fixed throttle-max A/B power) case, namely 7.6 percent and 13.6 percent respectively, the experimental results failed to produce these predicted fuel savings. The poor correlation between the actual and predicted fuel results was due primarily to the data differences discussed in Section IV. These differences in engine and atmospheric data resulted in the pilot being briefed to switch power settings at flight conditions which were not compatible with the actual test aircraft performance. An analysis of the minimum fuel results showed that as the aircraft's performance increases the optimum altitude to switch from military to afterburner power also increases. Therefore, since the higher performance aircraft spends more time in the non-afterburner power range the total flight time increases while the amount of fuel used decreases. The analytical and experimental results for Maneuvers 8 and 9 are shown in Table IV.

OPTIMUM AND NONOPTIMUM FLIGHT PROFILES

The fourth objective of the study was to compare optimum and non-optimum maneuver results to determine the performance gains due to optimizing. Nonoptimum results were obtained from the last two flights which were flown by a Northrop test pilot not familiar with the optimum maneuvers flown previously in the test. His assignment was to fly two intercept missions in minimum time, at maximum power, given the initial and terminal conditions for each. He was informed that he could use any information available to him, i.e., previous experience or pilot's handbook to fly the maneuvers.

The first maneuver initial and terminal conditions were 0.5 Mach number at 3,000 feet and 1.2 Mach number at 30,000 feet respectively. During the course of the maneuver, a 180 degree heading change was to be performed. Shown in Figure 20 are the optimum and nonoptimum flight profiles that were flown while performing the first intercept mission. The nonoptimum profile consisted of a 180 degree turn at approximately

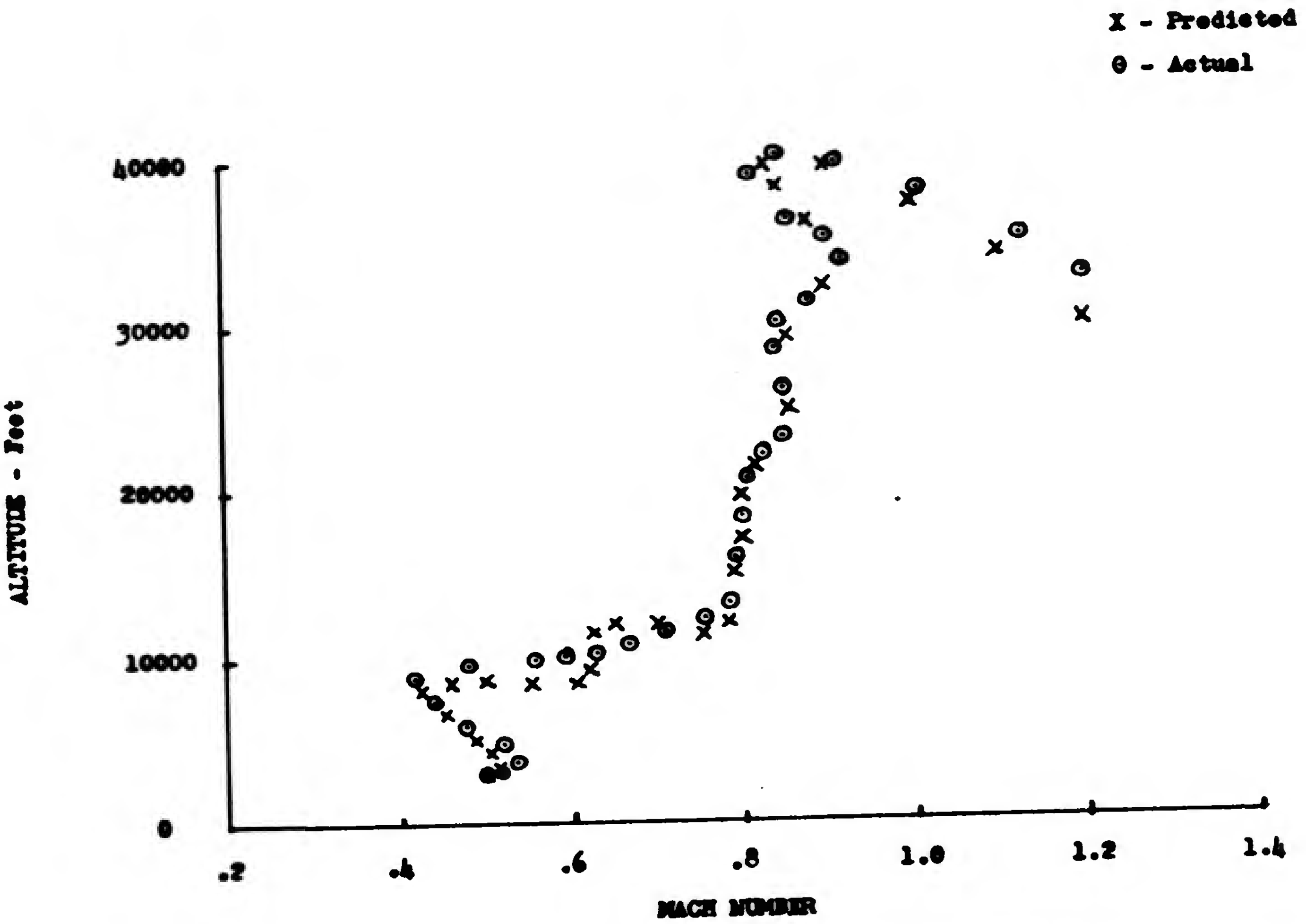

Figure 18. Predicted and Actual Flight Profiles for Maneuver Number 8

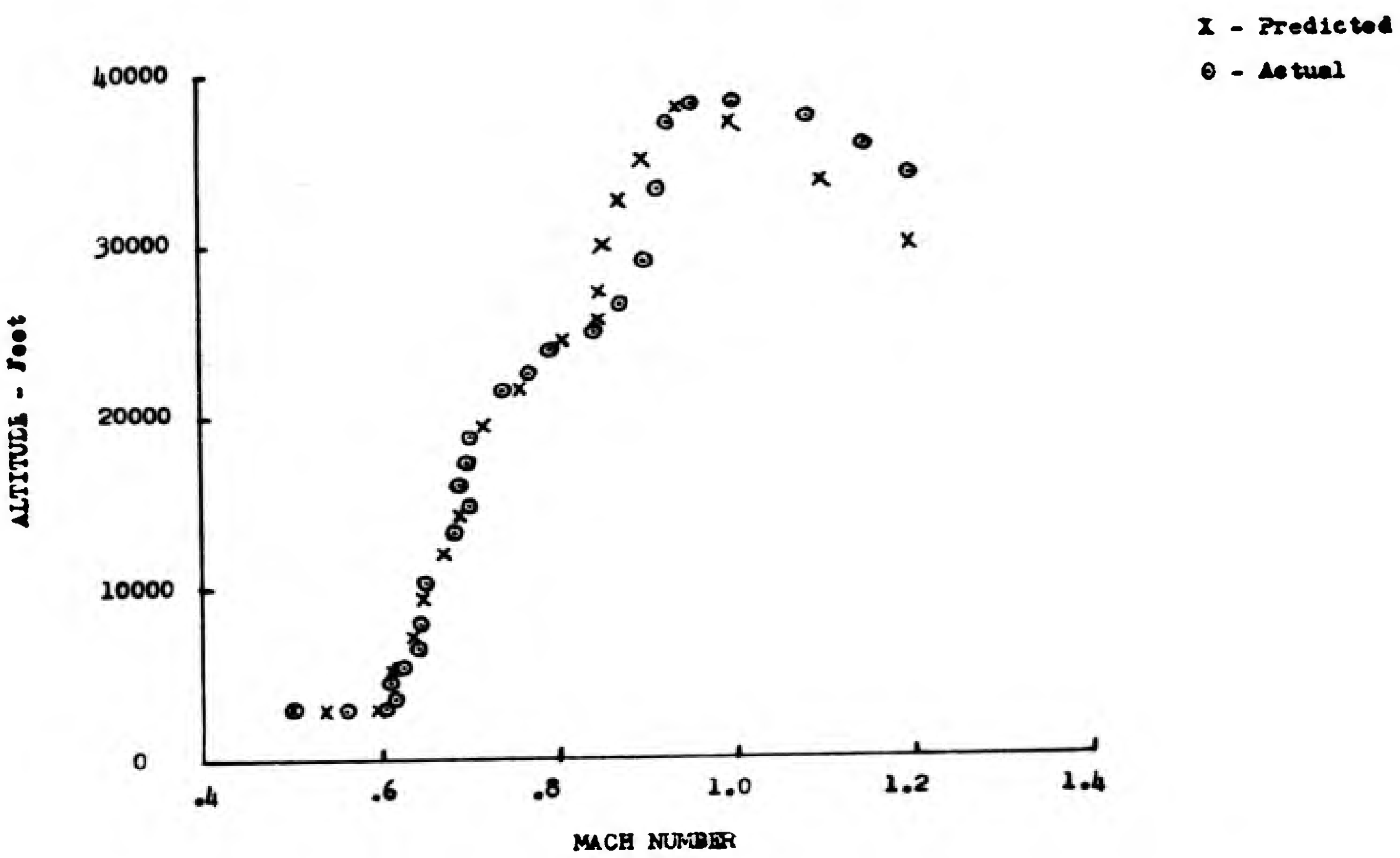

Figure 19. Predicted and Actual Flight Profiles for Maneuver Number 9

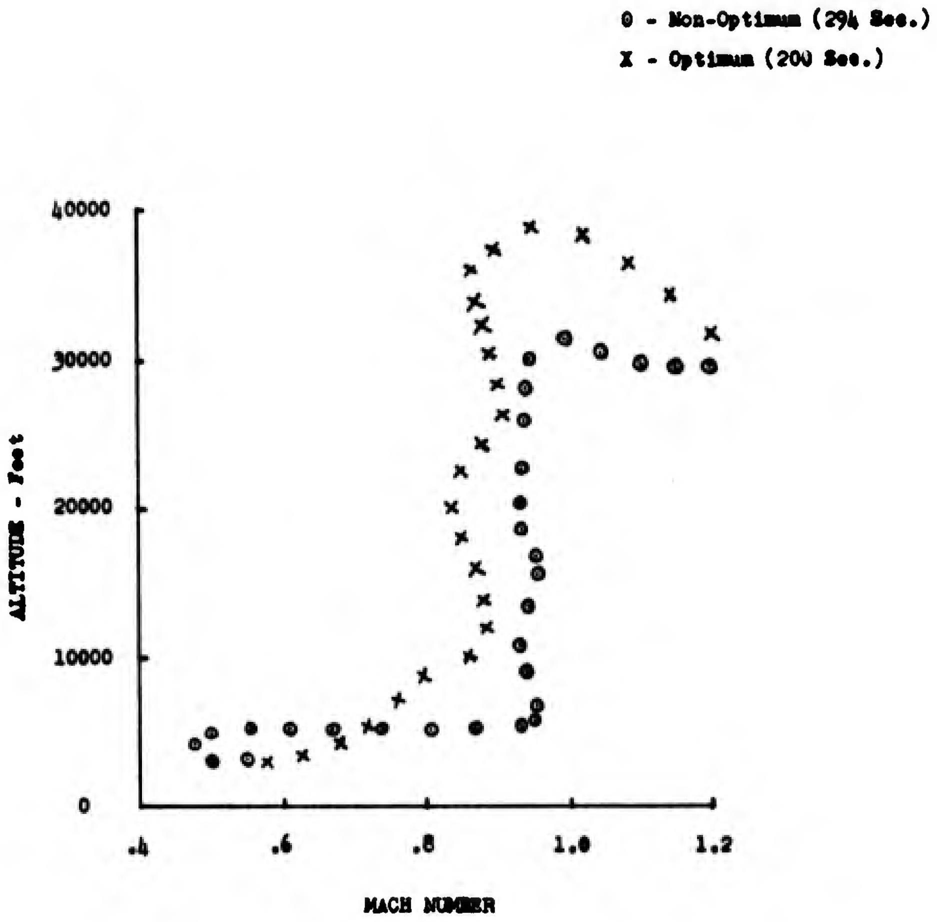

Figure 20. Optimum and Nonoptimum Flight Profiles for Maneuver Number 3

the initial altitude, level acceleration to 0.95 Mach number, climb to 30,000 feet at approximately a constant Mach number of 0.95 folllowed by a unloaded acceleration at that altitude. Performing the pushover in this manner resulted in the terminal altitude being attained while still at a Mach number of 1.08 requiring a time consuming one "g" acceleration to the terminal Mach number of 1.2. The optimum path differs considerably from the nonoptimum path in that the turn and climb are not performed at constant altitude and Mach number respectively, and the "zero-g" pushover and acceleration to the terminal supersonic Mach number are not performed at approximately the terminal altitude. The test results for this intercept mission show flying the optimum trajectory will attain the intercept conditions 94 seconds quicker and with 340 pounds more fuel remaining for combat than the aircraft flying the nonoptimum trajectory.

The initial and final conditions for the second maneuver were 0.7 Mach number at 25,000 feet and 0.7 Mach number at 40,000 feet respectively. Again, a 180 degree heading change was to be performed. The optimum and nonoptimum profiles are shown in Figure 21. The non-optimum maneuver was performed by completing the turn just prior to the initiation of the pullout at 0.85 Mach number, followed by a climb and acceleration to 0.945 Mach number and 34,000 feet respectively, where a zoom to the terminal altitude was accomplished. Timing of the zoom resulted in the terminal altitude being attained while still at 0.74 Mach number.

Again, the differences are considerable between the optimum and non-optimum flight profiles. For the optimum path a gradual turn was performed during the entire maneuver while initially doing a hard pushover and acceleration to 0.87 Mach number and 23,500 feet, followed by a pullup to the best climb Mach number of 0.935, climb to 28,000 feet where a zoom to 40,000 feet was performed. Early initiation of the zoom resulted in reaching the intercept altitude at a Mach number of 0.67 instead of 0.7. The optimum flight profile for this intercept mission produced a performance improvement of 30 percent in time over that which was obtained from flying the nonoptimum flight profile. Table VI contains

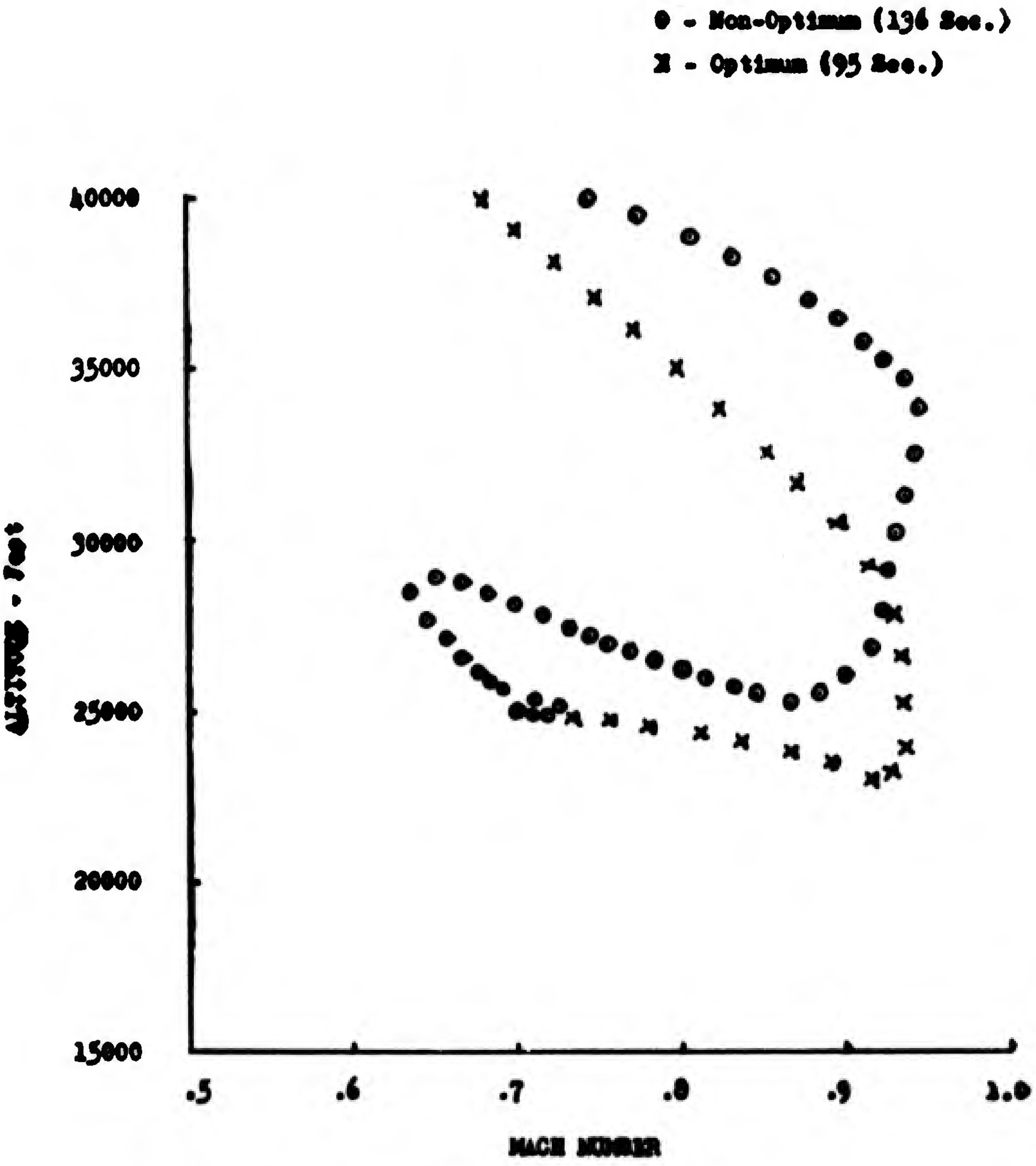

Figure 21. Optimum and Nonoptimum Flight Profiles for Maneuver Number 6

a summary of the parameters and performance improvements for both intercept missions. These results definitely confirm the adequacy of the variational steepest-descent technique for generating optimum flight profiles since they were obtained from actual flight using the same aircraft and flying in approximately like atmospheres. One would expect these performance improvements to decrease with repeated nonoptimum flights by the same pilot, however, even if a 50 percent decrease in these substantiated performance differences were possible the remaining differences (approximately 15 percent) would still be quite substantial.

TABLE VI

SUMMARY OF MISSION PARAMETERS AND PERFORMANCE IMPROVEMENTS DUE TO OPTIMIZING

Maneuver	Initial Conditions			Final Conditions				Parameter Optimized Time (Sec.)	Fuel Used (#)	Performance Improvements
	W(lbs)	H(ft)	M	W(lbs)	H(ft)	M	$\Delta\sigma$ (deg)			
Optimum	12,823	3,000	.5	12,133	32,111	1.2	180	200	690	32% time saved
Nonoptimum	12,813	3,000	.5	11,783	29,285	1.198	180	294	1030	33% fuel saved
Optimum	11,833	25,000	.7	11,593	40,000	0.675	180	95	240	30% time saved
Nonoptimum	11,663	25,000	.7	11,353	40,000	0.74	180	136	310	23% fuel saved

SECTION V

CONCLUSIONS

1. Comparisons made between the EM and TOP time solutions have shown that the EM technique tends to predict optimistic solutions. This is the result of making simplifying assumptions which reduce computer time at the expense of solution accuracy. Another difficulty with the EM technique is it lacks generality in solving optimal control problems. However, for situations when solution time is more important than accuracy the EM technique should be employed.

2. Experimental results showed that the assumption of a constant load factor (1g flight) made in predicting the EM flight profile compared favorably from the initial flight conditions through the subsonic climb to the push over altitude.

3. Results of this study indicate that optimization techniques can be used to provide operational information beneficial to fighter pilots.

4. Even though it is difficult to duplicate the optimum path exactly in flight, results show that the actual path can oscillate about the optimum path with a very small penalty in payoff.

5. More advanced cockpit instrumentation could improve the pilot's ability to duplicate optimum flight paths more exactly. An instrument displaying in three dimensions the flight profile of the aircraft relative to the optimum flight profile would be desirable.

SECTION VI

RECOMMENDATIONS

1. Current flight manuals should be updated to include optimal flight profiles. The profiles would indicate to the pilot how to fly an aircraft between different energy states optimally.

2. Investigations should be conducted to determine the usefulness of ground based simulators as tools for developing and evaluating optimization techniques.

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UNCLASSIFIED

Security Classification

DOCUMENT CONTROL DATA - R & D

(Security classification of title, body of abstract and indexing annotation must be entered when the overall report is classified)

1. ORIGINATING ACTIVITY *(Corporate author)*

Air Force Flight Dynamics Laboratory
Air Force Systems Command
Wright-Patterson Air Force Base, Ohio

2a. REPORT SECURITY CLASSIFICATION

UNCLASSIFIED

2b. GROUP

3. REPORT TITLE

ANALYTICAL AND EXPERIMENTAL INVESTIGATION OF OPTIMUM FIGHTER AIRCRAFT MANEUVERS

4. DESCRIPTIVE NOTES *(Type of report and inclusive dates)*

Final Report October 1967 through November 1972

5. AUTHOR(S) *(First name, middle initial, last name)*

Richard C. Nash

6. REPORT DATE

July 1974

7a. TOTAL NO. OF PAGES

62

7b. NO. OF REFS

15

8a. CONTRACT OR GRANT NO.

b. PROJECT NO. 1366

c. Task No 136602

d.

9a. ORIGINATOR'S REPORT NUMBER(S)

AFFDL-TR-73-154

9b. OTHER REPORT NO(S) *(Any other numbers that may be assigned this report)*

10. DISTRIBUTION STATEMENT Distribution limited to U. S. Government agencies only; test and evaluation; statement applied November, 1973. Other requests for this document must be referred to AF Flight Dynamics Laboratory, (FXG), Wright-Patterson AFB, Ohio 45433

11. SUPPLEMENTARY NOTES

12. SPONSORING MILITARY ACTIVITY

Air Force Flight Dynamics Laboratory (FXG)
Wright-Patterson Air Force Base, Ohio
45433

13. ABSTRACT

This report presents the results of a four-phase research program consisting of (1) application of the energy-maneuverability and variational steepest-descent optimization techniques to a series of maneuvers typical of a multipurpose tactical fighter aircraft, (2) flight testing of the analytically predicted optimal flight paths to obtain measured flight data, (3) correlation of these data with analytical results and (4) comparison of analytical optimum paths with nonoptimum flight paths. The results of this study indicate that for most of the maneuvers analyzed, the pilot was able to fly the optimum flight profiles with reasonable accuracy. Also, definite gains in performance can be realized through the application of optimization techniques.

DD FORM 1 NOV 65 1473

UNCLASSIFIED

Security Classification

UNCLASSIFIED
Security Classification

14. KEY WORDS	LINK A		LINK B		LINK C	
	ROLE	WT	ROLE	WT	ROLE	WT
Energy-Maneuverability						
Optimization Techniques						
Optimum and Nonoptimum Aircraft Trajectories						

UNCLASSIFIED
Security Classification

*U.S.Government Printing Office: 1974 — 657-014/149