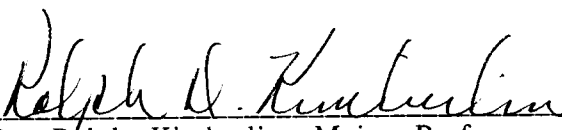


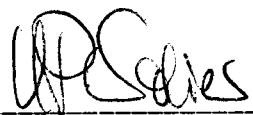
To the Graduate council:

I am submitting herewith a thesis written by Patrick Martin Leard entitled "The Evaluation of the F-111 Airplane with an Advanced Technology Engine." I have examined the final copy of this thesis for form and content and recommend that it be accepted in partial fulfillment of the requirements for the degree of Master of Science, with a major in Aviation Systems.

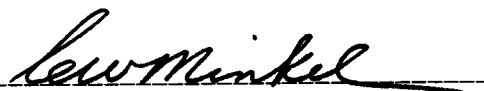

Dr. Ralph Kimberlin, Major Professor

We have read this thesis
and recommend its acceptance:





Accepted for the Council:


Associate Vice Chancellor
and Dean of the Graduate School

**THE EVALUATION OF THE F-111 AIRPLANE
WITH AN
ADVANCED TECHNOLOGY ENGINE**

A Thesis

Presented for the

Master of Science

Degree

The University of Tennessee, Knoxville

Patrick Martin Leard

December 1991

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ABSTRACT

This thesis evaluated the performance benefits from replacing the TF-30 engines with the advanced technology F-110 engines in the F-111 airplane for the all weather attack mission. The F-111 was assessed during six hours of flight test at Edwards Air Force base, California. The re-engining analysis used flight test and flight manual performance data as the TF-30 baseline. Net thrust and installed fuel flow of the TF-30 and F-110 engines were determined by cross referencing F-111 flight manual performance data with the engine performance data for the installation of both engines on the F-14 airplane. Stepwise integration was used extensively throughout the analysis to calculate specific airplane performance parameters. Where possible an appropriate TF-30 parameter was calculated and then compared to the flight manual performance data to determine calculation accuracy.

It was determined that the F-111 airplane with advanced technology General Electric F-110 engines would provide excellent performance benefits in several mission critical flight phases. These included: shortened takeoff ground roll, decreased time to climb, tighter sustained turns and quicker acceleration. The mission capability and overall airplane survivability during the low-level, all-weather attack missions would be significantly enhanced by the greater thrust capability of the F-110 engine.

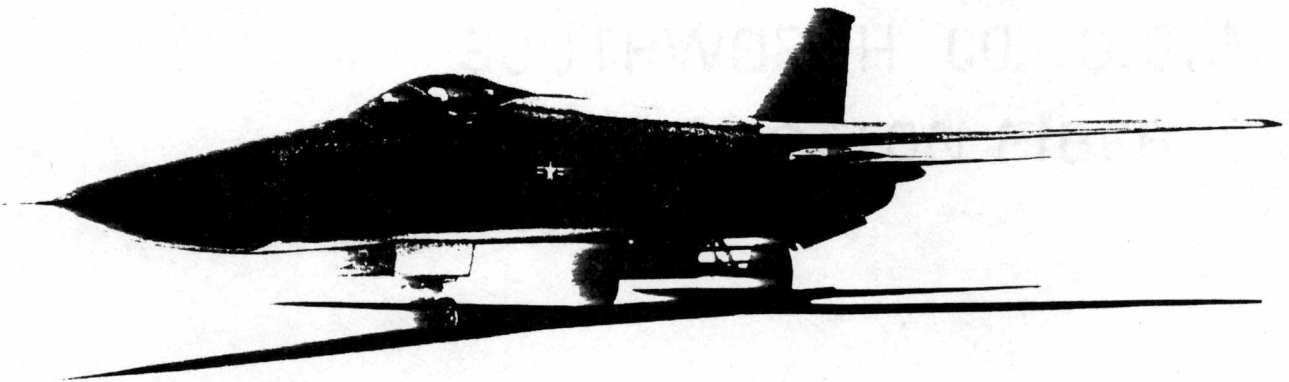


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I. INTRODUCTION

BACKGROUND

A prerequisite to certification from the United States Navy Test Pilot School was the completion of a short and intensive preliminary evaluation on an aircraft which was unfamiliar to the student test pilot. The evaluation consisted of approximately six flight-hours during which aircraft flying qualities and performance as well as overall mission capability was investigated. In November, 1989, the author evaluated the F-111A/E airplane at Edwards AFB, California, for its ability to accomplish the long range, all-weather attack mission.

During the course of the evaluation several significant deficiencies were identified which could cause the F-111 to be unable to accomplish its mission. The most significant deficiency noted was the poor sustained turn capability which made the airplane vulnerable to enemy ground and air missile attacks. Although still quite capable as a high speed, low-level bomber, the variable-geometry F-111 is saddled with its original 1960's technology Pratt & Whitney TF-30 engines. In 1988 the United States Navy replaced the TF-30 engines in their F-14 airplanes with the advanced technology General Electric F-110 turbofan engine. The increased thrust of the F-110 over the TF-30 provided significant tactical advantages for the F-14. The F-111 also could gain mission capability with the incorporation of the advanced technology F-110 engine.

PURPOSE

The purpose of this thesis is to evaluate the performance benefits obtained by replacing the TF-30 engines with the advanced technology F-110 engines in the F-111 airplane for the all-weather attack mission.

AIRPLANE DESCRIPTION

The F-111, shown in appendix C, figure C-1, is a two-place (side-by-side) high mounted, swing wing, supersonic airplane built by General Dynamics, Fort Worth Division. The aircraft was designed for all-weather supersonic operation at both high and low altitudes. Power is provided by two TF-30 axial flow, dual-compressor turbofan engines equipped with afterburners developing approximately 10,000 lb and 18,000 lb uninstalled thrust (sea level, standard day) in military and maximum thrust settings, respectively. The airplane has a quarter-conic moveable inlet spike and variable area exhaust nozzle. The variable geometry wings can be swept from 16° aft to 72.5° aft and are equipped with leading edge slats and trailing edge Fowler-type flaps (the slats were designed to extend prior to flap extension and retract after full flap retraction). The irreversible flight controls consist of a rudder mounted to the fixed vertical stabilizer and a horizontal stabilizer that was designed to move symmetrically for pitch control and asymmetrically for roll control. Triple-redundant stability augmentation was incorporated in all three axes. A multi-mode autopilot was designed to provide attitude stabilization, heading, track, Mach number and altitude hold. The crew emergency escape system consists of an ejection capsule, comprised of the cockpit and a portion of the forward

wing root section. The capsule is equipped with a single parachute, inflatable impact reducer and flotation bladders. Short and long term survival packs are also included in the cockpit/capsule. Other airplane features include retractable tricycle landing gear with steerable nose wheel, under-fuselage mounted speedbrake (the speedbrake is the forward landing gear door - selectable only when gear are up), ground and roll-control spoilers, fuselage-enclosed weapons bay and pivoting and fixed wing mounted pylons. A more complete description of the airplane is contained in the F-111 flight manual, reference 1.

ENGINE DESCRIPTION

TF-30

The military designated TF-30 engine is built by Pratt & Whitney under the company designation of JTF10A. Original engine design began in 1958. Engine parametric data is presented in table I. The TF-30 shown in figure 1, is twin-shaft, axial flow, afterburning turbofan containing inlet guide vanes, a three stage fan, a low and a high pressure compressor.

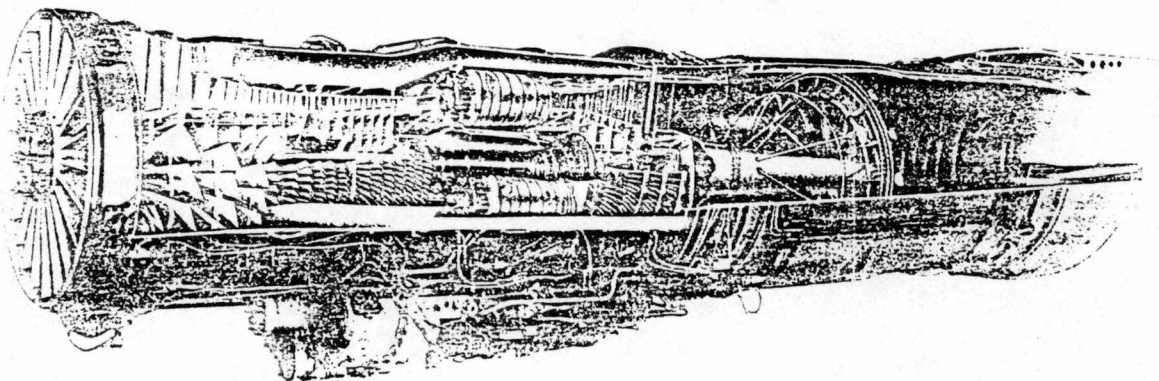


Figure 1
CUTAWAY DRAWING OF PRATT & WHITNEY TF-30 ENGINE

Combustion occurs in a can-annular section comprised of eight combustion cans, two of which contain igniters for starting. The turbine section has both a high and low pressure section. The high pressure section uses both film and internal air cooling. A five stage afterburner uses three fuel spraybars and is ignited by a hot streak originating in the number 4 burner can. The engine exit nozzle is a variable area design, actuated by engine fuel pistons (reference 2).

Table I
TF-30 AND F-110 ENGINE DATA

Parameter (1)	Engine	
	TF-30	F110
Thrust (2) (lb)		
Military/Maximum AB	10,300/17,300	13,600/22,200
Specific Fuel Consumption (2) (1/hr)		
Military/Maximum AB	0.680/2.86	0.743/2.25
Bypass Ratio	0.88	0.81
Overall Pressure Ratio	19.8	31.6
Compressor Stages (fan/low/high)	3/6/7	3/0/9
Turbine Stages (high/low)	1/3	1/2
Maximum Turbine Temperature (°C)	1130	1390
Length (in)	233.5	230.6
Weight (lb)	4205	4368

Notes: 1. Sea level, static, standard day. Source 1 except thrust and specific fuel consumption.

2. Installed; calculated from source 2 and 3.

Sources: 1. Thomas Griffin and Oscar Bryan, "Re-engining the F-14 with the F110-GE-400 Turbofan Engine", brief given June 8, 1989.

2. F-14/TF-30-P-414A Installed Performance and Operating Characteristics, Grumman A51-333-I-83-01, November 15, 1983.

3. F-14D/F-110-GE-400 Installed Performance and Operating Characteristics, Grumman A55-333-R-84-05, November, 1984.

F-110

The General Electric F-110 engine is a derivative of the F-101 engine and began trials in late 1979. It is a twin shaft, axial flow, afterburning engine. Parametric data is contained in table I, and the F-110 engine is shown in figure 2. The engine compression section consist of a three stage fan and a high pressure compressor. The combustor is an annular scroll type. The turbine section is comprised of a single stage high pressure turbine which uses air cooled blades and the low pressure turbine which provides power only to the fan. The engine uses a close coupled mixed flow linear thrust afterburner and a hydraulically controlled convergent-divergent exhaust nozzle (reference 3).

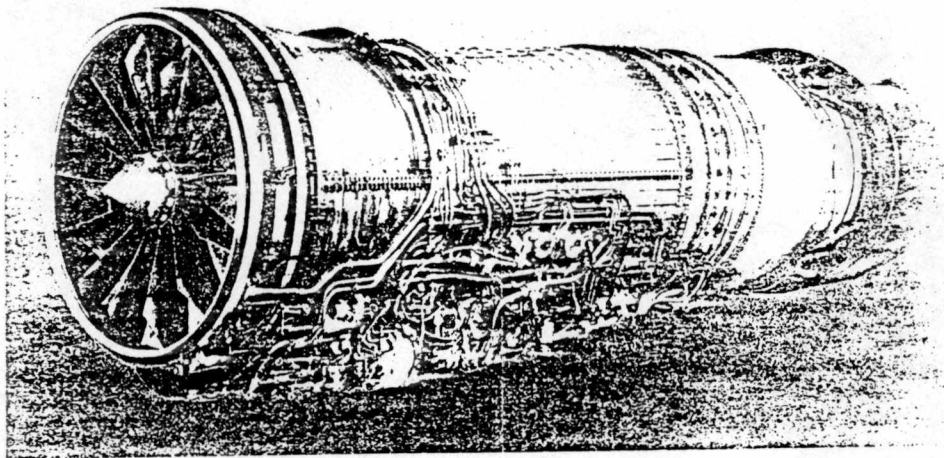


Figure 2

GENERAL ELECTRIC F-110 ENGINE

SCOPE

The F-111 preliminary flight evaluation consisted of a preflight human factors evaluation of the pilot station (left seat), a one hour simulator period and three flights totaling 6.0 hours. Human factors and system evaluation data were collected during the ground school/simulator training period at Cannon AFB, New Mexico. In-flight data were collected using F-111 Combined Test Force (F-111 CTF) airplanes at Edwards AFB (EAFB), California. The pertinent test conditions are listed in appendix B, table B-I. The tests were conducted within the limits of the flight manual, reference 1, EAFB and F-111 CTF Standard Operating Procedures (SOP) and all F-111 CTF specific limitations, including those listed in table II. The flight test envelope is shown in table III.

Table II
FLIGHT RESTRICTIONS

Type	Restriction
Minimum Altitude	500 ft AGL (subsonic only)
Maximum Mach Number	1.2 M at 5,000 ft MSL 1.4 M at 25,000 ft MSL
Maximum Angle of Attack	18° (14° plus pitch rate in °/sec.)
Maximum Load Factor	2.0 g -supersonic 4.0 g -when changing wing sweep

No external stores were used during the flight evaluation and typical takeoff weight was 80,000 lb including 30,000 lb fuel. The center of gravity ranged from 29 to 40% mean aerodynamic chord (MAC), within the manufacture's limits.

Table III
F-111 FLIGHT TEST ENVELOPE

Parameter	Limits
Airspeed	0-620 KCAS 0-1.4 M
Altitude	SFC-25000 FT MSL
Load Factor	0.5-5.5 g

Test configurations are shown in table IV. The analysis presented below covers performance differences of the F-111 with the higher thrust F-110 engines. The analysis will focus on take-off, climb, cruise, maneuvering and high-speed dash flight phases.

Table IV
F-111 FLIGHT TEST CONFIGURATION

CONFIGURATION	WING SWEEP (°)	GEAR	FLAPS/ SLATS	SPEED BRAKE	THRUST
Takeoff (TO)	16	DN	25°	NA ¹	MAX ²
Climb (CL)	54	UP	UP	Retracted	MAX
Power ## (P##) ³	# #	UP	UP	Retracted	MIL ⁴
Combat ## (CO##)	# #	UP	UP	Retracted	MAX
Cruise ## (CR##)	# #	UP	UP	Retracted	TLF ⁵

Note: 1. Not applicable. 4. Military rated thrust.
2. Maximum afterburner. 5. Thrust for level flight.
3. "##" indicates wing sweep of 26, 40, 54 or 72.5°.

II. METHOD

The F-111 flight evaluation was conducted per reference 4. Special instrumentation consisted of a hand-held force gauge and a stop watch. Ambient temperature was extrapolated from the surface reading using the standard temperature lapse rate. Data were recorded on kneeboard cards and portable voice recorder.

The F-111 equipped with the TF-30 engines was analyzed using the performance capabilities as presented in the flight manual performance data, reference 5, for an international standard atmosphere. The appropriate "drag index" from the flight manual is presented during flight phases in which external stores were assumed to be carried. The drag index is a measure of increased drag due to stores carriage which is used in the F-111 performance charts. Net thrust and installed fuel flow of the TF-30 and F-110 engines were determined by cross-referencing F-111 performance data with the engine performance data for the F-14 installation of both engines, reference 6 and 7. Specific methods used for each flight phase are presented in conjunction with the analysis.

During analysis the mission representative starting gross weight was assumed to be 89,500 pounds, which included 36,500 pounds of fuel and 3,600 pounds of laser-guided munitions. The empty weight was 49,400 pounds. The analysis and results proceed through a typical F-111 mission, comparing the TF-30 to the advanced technology F-110 engine. Specific airplane performance parameters, such as takeoff distance, were approximated by stepwise integration (i.e. adding discrete distances). This method allowed airplane performance differences, caused by the different engines, to be

calculated for the discrete step and then totaled when a summation process exit criteria was reached. Where possible, an appropriate TF-30 parameter was calculated and then compared to the flight manual data to determine calculation accuracy. Errors due to the engine installation differences between the F-111 and F-14 airplanes should be small because both airplanes are similar and the engine-airframe integration was optimized for maximum performance.

III. RESULTS AND ANALYSIS

TAKEOFF PERFORMANCE

Takeoff performance was evaluated during three normal takeoffs under the conditions listed in appendix B, table B-I. Average takeoff distance was approximately 3,000 feet from brake release. Figure 3 represents the forces typically acting on an aircraft during takeoff roll (reference 8).

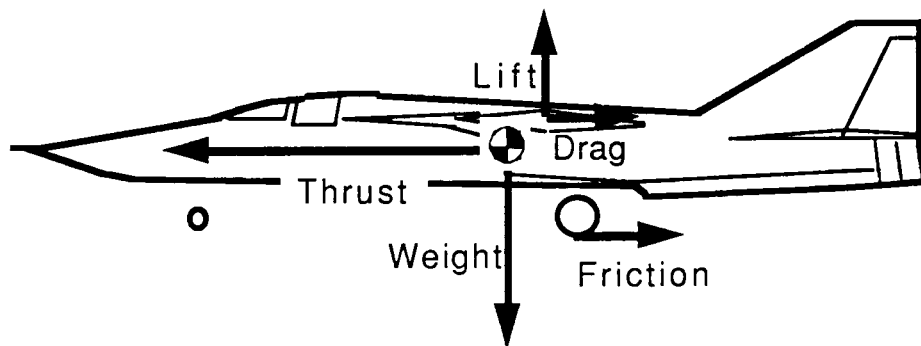


Figure 3

FORCES DURING TAKEOFF ROLL

Newton's second law states that acceleration on a body equals the applied resultant force divided by the mass:

$$a = F/m \quad (\text{eq. 1})$$

Assuming a horizontal thrust vector during takeoff on a level runway, the forces in the takeoff direction are thrust, drag and rolling friction. Any change in engine thrust will cause a corresponding change in takeoff acceleration. Over a short time period this acceleration can be considered

constant, which allows velocity and distance to be simply calculated as a function of the initial condition, acceleration and time:

$$v = v_0 + at \quad (\text{eq. 2})$$

$$\Delta x = v_0 t + \frac{1}{2} at^2 \quad (\text{eq. 3})$$

Where t is the elapsed time since the initial condition of each step, and v_0 is the velocity at that condition. The distance traveled during the time interval is Δx . Starting at zero velocity and using 20 kt increments (drag index of 45) on the takeoff acceleration time-check chart, appendix C, figure C-2, takeoff distance was determined as follows:

1. The time to increase 20 kt was calculated from the chart by subtracting the time at the end velocity from the time at the beginning velocity.
2. Equation 2 was used to determine the acceleration of the F-111 with the TF-30 engines at each speed.
3. Using the thrust versus Mach number charts, appendix C, figures C-3 and C-4, the increased thrust due to the F-110 engines was calculated.
4. From this thrust increment, incremental acceleration was calculated from eq. 1.
5. Total acceleration was calculated by adding the incremental acceleration to the acceleration determined from the time-change of velocity.
6. Using the new total acceleration and solving eq. 2 for the time increment, allowed an incremental distance to be determined, eq. 3.

This iteration was repeated until takeoff speed was reached and then the incremental distances summed. The results are shown in table V. The same iteration was performed using the takeoff acceleration time-check data and compared to the charted takeoff distance as a indicator of reliability. The distances were identical.

Table V
TAKEOFF DISTANCE

Engine	Distance (ft)
TF-30	2700
F-110	1600 (41%) ¹

Note: 1. Change from F-111 with TF-30 engines installed.

The 41% reduction in takeoff distance would provide exceptional flexibility in basing and continued capability during post-attack damaged runway operations. The F-110 engine is clearly superior for the takeoff flight phase.

CLIMB PERFORMANCE

Climb performance was evaluated during flight test for time and fuel to climb under the conditions listed in appendix B, table B-I. Time to climb from 5000 to 20000 ft MSL was 46 seconds and used only 3% of total mission fuel. There was excellent correlation to the values shown in the flight manual (reference 5).

Figure 4 shows the forces acting on an airplane in stabilized climbing flight.

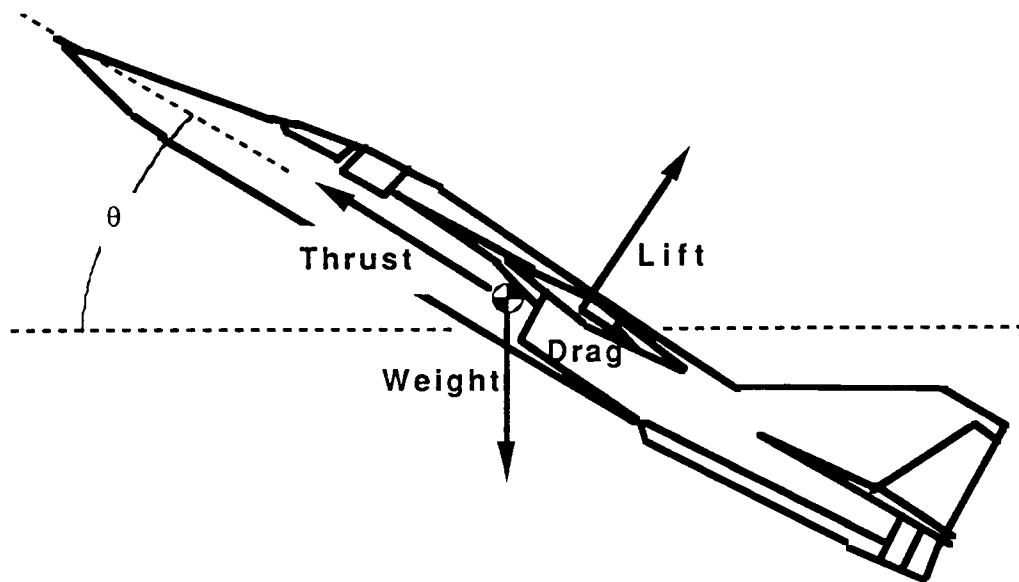


Figure 4

FORCES DURING STABLE CLIMB

Reference 8 shows the rate of a stable climb (ROC) to be the product of the velocity divided by weight multiplied by the difference of thrust and drag:

$$\text{ROC} = (T-D) V/W \quad (\text{eq. 4})$$

Using 5,000 foot intervals on the climb chart shown in appendix C, figure C-5 (aircraft weight of 87,000 lb and drag index of 60), elapsed time to climb was determined and from that, a rate of climb was calculated at each altitude. The additional thrust available from the F-110 engines was determined using the thrust charts shown in appendix C, figure C-3 and C-4 for both engines. Equation 4 shows that an increase in thrust results in a proportional increase in climb rate. The proportionality factor is velocity divided by weight.

$$\Delta \text{ROC} = \Delta T V/W \quad (\text{eq.5})$$

A rate of climb with the F-110 engine was determined by considering airplane weight to remain constant and calculating velocity from the product of the Mach number and the standard-atmosphere speed of sound. From this rate of climb, a time to climb the 5,000 foot block was determined. This process was repeated to 25,000 feet and then the incremental times were totaled. At each altitude, fuel flow was determined using appendix C, figure C-6 and C-7, for both the TF-30 and F-110 engines. Fuel used during the climb was then calculated by the sum of the incremental times, multiplied by the fuel flow at each altitude. The calculated fuel for the TF-30 was within 4% of the reference 5 charted fuel used. The results are shown in table VI.

Table VI
25,000 FOOT CLIMB PERFORMANCE

Engine	Time to Climb (s)	Fuel Used (lb)
TF-30	114	2700
F-110	94 (17.5%) ¹	3000 (-11.1%)

Note: 1. Change from F-111 with TF-30 engines installed.

The 17.5% decrease in the time to climb to optimum cruise altitude with only a 11% increase in consumed fuel, would allow closer interval departures during wartime alert launches, ensuring that the maximum number of aircraft are off the ground before an enemy airstrike can destroy the runway.

LEVEL FLIGHT PERFORMANCE

RANGE

Maximum range was flight tested under the conditions listed in appendix B, table B-I. Maximum unrefueled range at 20000 ft MSL was calculated to be greater than 1700 nm (3000 lb reserve). These results correspond with flight manual data within 8%. For the range comparison with the F-110 engine, a 26° wing sweep, optimum cruise profile of 0.73 M and increasing altitude was used (initial weight of 87,000 lb and drag index of 40). Using the procedure outlined in reference 5 with an altitude factor of 23 (altitude factor is a normalized chart parameter based on airplane weight and pressure altitude) and range factor of 59 (range factor is a normalized chart parameter based on initial airplane cruise weight and cruise Mach number), a 5,000 lb weight decrease interval was used to determine pressure altitude and Specific Range (SR - nautical miles per pound) from the charts shown in appendix C, figures C-8 and C-9, respectively. Fuel flow was then calculated as the product of cruise Mach number, speed of sound and inverse specific range.

$$\text{Fuel Flow} = M (a) (1/\text{SR}) \quad (\text{eq.6})$$

For each weight, a TF-30 engine thrust was determined by using fuel flow for the specific altitude found on a chart of the type shown in appendix C, figure C-10. This thrust was then used on the type of chart shown in appendix C, figure C-11, to determine fuel flow for the F-110 engine at the same altitude. Time between successive weights was calculated by dividing the weight

change by the calculated fuel flow. Incremental distance was then calculated from the product of time, cruise Mach number and the speed of sound.

$$t = \Delta W / \text{Fuel Flow} \quad (\text{eq. 7})$$

$$\Delta x = t (M) a \quad (\text{eq. 8})$$

When the air refueling weight of 58,000 lb was reached the incremental range was summed. Cross-check data was not available for range calculation. The results are presented in table VII.

Table VII
OPTIMUM CRUISE PERFORMANCE

Engine	Distance (nm)
TF-30	2190
F-110	2070 (-5.5%) ¹

Note: 1. Change from F-111 with TF-30 engines installed.

The F-111 airplane with the F-110 engines would suffer a slight range decrease over the current TF-30 engine installation. However, this range decrease would only be significant for unrefueled, extremely deep-strike missions.

LOW LEVEL INGRESS

The calculations for low level ingress phase used identical procedures as outline in RANGE above. The refueled weight was 83,000 lb with a cruise Mach

number of 0.9 at sea level. This resulted in an altitude factor of 8 and range factor of 2.15 (drag index of 60). Wing sweep was approximately 65°. The useable ingress fuel was assumed to be 10,000 lb. This would allow sufficient fuel for the aircraft to complete the attack run, perform defensive air-combat-maneuvering and return to the tanker. The maximum ingress distance was calculated to be 271 nm for the F-110 engine which was a negligible 3.2% decrease from the TF-30 engine.

ACCELERATION

Level flight acceleration was evaluated during flight test under the conditions listed in appendix B, table B-I. Total time to accelerate from 0.9 to 1.4 M was 104 seconds, requiring 1800 lb of fuel. Acceleration from 1.1 to 1.4 M occurred quickly and was nearly constant. Good correlation exists between flight-test and the flight manual data.

To determine the improvement provided by the F-110 engine, the supersonic acceleration chart shown in appendix C, Figure C-12, was used. The calculations assumed that the airplane weighed 80,000 lb and was at 10,000 ft after delivering its ordinance. Charted time to achieve 0.1 M intervals from 0.7 to 1.4 M were calculated and the method used for takeoff distance determination was repeated. Additionally, acceleration time with the F-110 engine was determined by summation of incremental times from 0.7 to 1.4 M. A cross check using the TF-30 engine data to calculate distance required was within 4.0% of the flight manual charted value. The results are presented in table VIII. The dramatic reduction in time to accelerate to 1.4 M is an exceptionally enhancing characteristic for this type of mission. Enemy

targets are typically well defended. The time spent in the target area after attack or reattack is the most vulnerable aspect of the F-111's mission. The rapid acceleration afforded by the F-110 engine may significantly reduce susceptibility to enemy ground fire which would reduce the F-111 combat attrition rate.

Table VIII
10,000 FOOT LEVEL ACCELERATION: 0.7 TO 1.4 MACH

Engine	Time Required (s)	Distance required (nm)
TF-30	198	41
F-110	68 (66%) ¹	13 (68%)

Note: 1. Change from F-111 with TF-30 engines installed.

MAXIMUM AIRSPEED

Analysis of the maximum airspeed with the F-110 engine used a linear interpolation of thrust required from the flight manual performance data (reference 5). Using the charts shown in appendix C, figures C-13 and C-14, with a weight of 50,000 lb, a 72.5° wing sweep and 30,000 ft MSL for a clean airplane, a maximum Mach number was obtained for both minimum and maximum afterburner. Since these are stabilized conditions the thrust required can be determined from the engine thrust curves, shown in appendix C, figures C-3 and C-4. The thrust available from the F110 engine at 30,000 ft MSL was then plotted with the TF-30 thrust required data. Since data were not available to precisely indicate the supersonic drag, and hence thrust required,

a simple linear interpolation of the TF-30 was used. Although a linear drag profile over the entire transonic and supersonic region is not likely, it should provide a reasonable estimate in the vicinity of the maximum Mach number. The intersection of the two lines shown in figure 5, at 2.0 M is an estimate of the maximum attainable with F-110 engines.

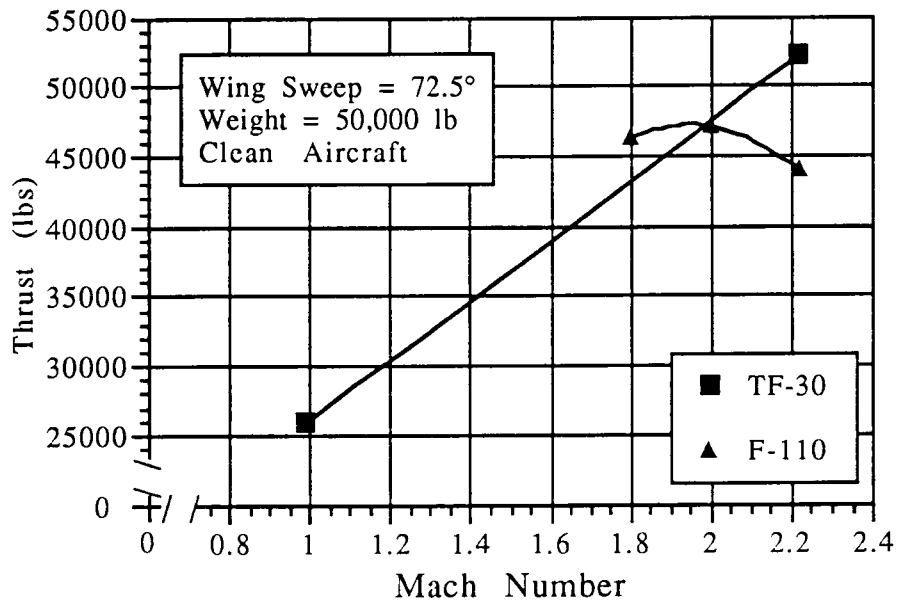


Figure 5

F-111 MAXIMUM MACH NUMBER CAPABILITY

The 9.1% decrease in maximum Mach number is consistent with results of the F-14 re-engine program (references 9 and 10) and can most likely be attributed to the higher pressure ratio of the F-110 engine. While substantial, the reduction in maximum Mach number for the F-111 is not of great significance for the current low altitude, terrain-following strike mission. If the F-111 were to be used as a interceptor or missile launching platform the maximum Mach number decrease would be undesirable.

TURN PERFORMANCE

Sustained turn performance is important for the all-weather, low-level attack mission primarily for two reasons. First, the distance that must be traversed to accomplish turns while on ingress or egress, and to maneuver to deliver weapons onto the target, is determined by the maximum sustained turning capability. Second, if fired upon by enemy missiles the turn radius of the aircraft must be smaller than the missile's to avoid being destroyed. The aircraft could bleed energy in both cases, maneuvering up to its aerodynamic limit. This type of maneuver however, would result in the airplane becoming vulnerable as airspeed/altitude is lost in successive or continuous maneuvers. Ideally, the thrust characteristics of the airplane would allow turns to be sustained at the aerodynamic and/or structural limit.

Sustained turn performance was evaluated in flight under the conditions listed in appendix B, table B-I. Sustained turn performance in military power was meager at all altitudes tested. The maximum sustained rate of turn with 40° wing sweep at 15000 ft MSL in military thrust was less than 3.6 degrees per second and required over 2 nm to complete a 180° turn. Sustained turn performance in maximum afterburner was paltry at all altitudes tested. The maximum sustained rate of turn with 40° wing sweep at 15000 ft MSL in maximum afterburner thrust was only 7 degrees per second and required over 1.5 nm to complete a 360° turn. The flight manual correlated well with the flight test data.

To begin the analysis with the F-110 engine, the maximum load factor charts from the F-111 flight manual, shown in appendix C, figures C-15 and C-16, were used to determine sustained load capability at 26° wing sweep and

5,000 ft MSL for both military and maximum afterburner thrust. Maximum loading for both thrust settings occurred at approximately 0.75 M. Next, the sustained rate of climb was calculated at the same conditions of altitude, wing sweep and thrust settings. This was done by using the flight manual climb charts, shown in appendix C, figures C-17 and C-18, by the technique previous described for normal climbs. This gave a nominal 5,000 and 20,000 ft/min rate of climb, in military and maximum afterburner thrust, respectively.

Assuming a parabolic drag polar for the F-111 allows a very direct means to calculate the increased sustained turning performance provided by the greater thrust of the F-110 engine. The high aspect ratio, and moderately tapered planform of the F-111 in the 26° wing sweep position should allow the parabolic drag assumption to provide representative performance characteristics. Using the specific excess power analysis method described in reference 11, specific excess power (P_s) versus the square of sustained normal load factor (N_z) is plotted. Specific excess power is defined as the difference of the thrust and drag, multiplied by the velocity to weight ratio.

$$P_s = (T-D) V/W \quad (\text{eq. 8})$$

During a stabilized climb the rate of climb equals the specific excess power. Also, for any stabilized (non-accelerating) condition the P_s equals zero. Lastly, from examining eq. 8 it can be seen that a change in thrust will result in a change in P_s by a factor of the velocity to weight ratio. This allows the graphs shown in figure 6 to be constructed.

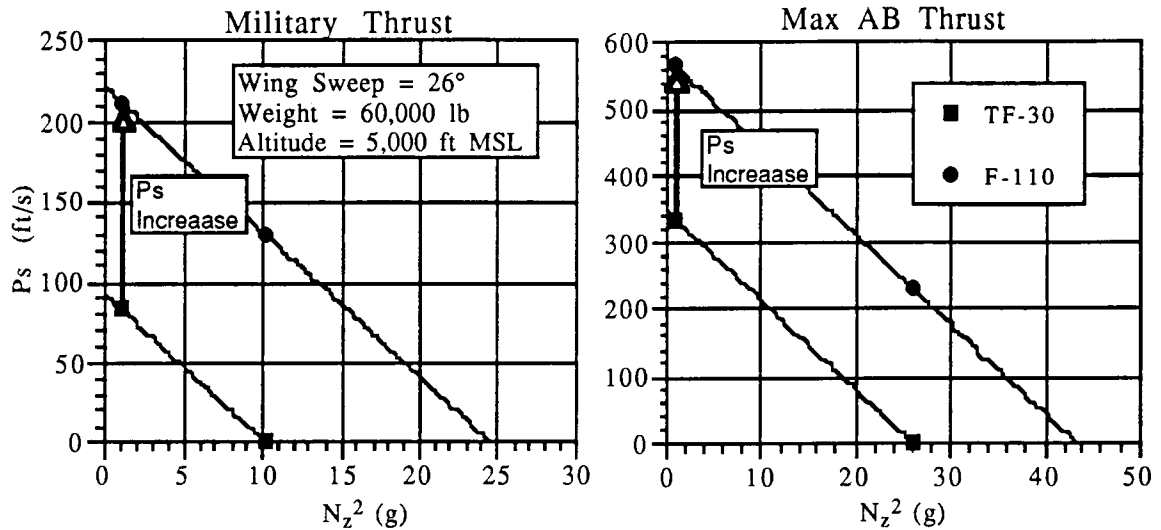


Figure 6

F-111 SUSTAINED NORMAL LOAD FACTOR CALCULATION

As described in reference 11, turn radius (R) can be calculated from the sustained normal load factor, flight velocity and the gravity constant. Turn rate (ω) is then given by the velocity divided by the radius. The sustained turn results are presented in table IX.

$$R = V^2 / [(n_z^2 - 1)^{1/2} g] \quad (\text{eq. 8})$$

$$\omega = V/R \quad (\text{eq. 9})$$

In order for the sustained turn performance predictions to be meaningful the airplane must be at or below its aerodynamic limit for the predicted maximum sustained load factor. The F-111 aerodynamic limit turn performance was evaluated in-flight under the conditions listed in appendix B, table B-I. The maximum instantaneous (aerodynamic) turning capability with

40° wing sweep at 5,000 ft MSL and 60,000 lb was calculated using the technique described in reference 11. Data are presented in figure 7.

Table IX
SUSTAINED TURN PERFORMANCE AT 5,000 FT MSL AND 0.75 MACH

Engine/ Thrust Setting	Normal Load Factor (g)	Turn Radius (ft)	Turn Rate (°/s)
TF-30 Military	3.20	6924	6.81
F-110 Military	4.95 (54.8%) ¹	4339 (37.3%)	10.9 (59.6%)
TF-30 MAX AB	5.10	4209	11.2
F-110 MAX AB	6.58 (29.0%)	3236 (23.1%)	14.6 (30.1%)

Note: 1. Change from F-111 with TF-30 engines installed.

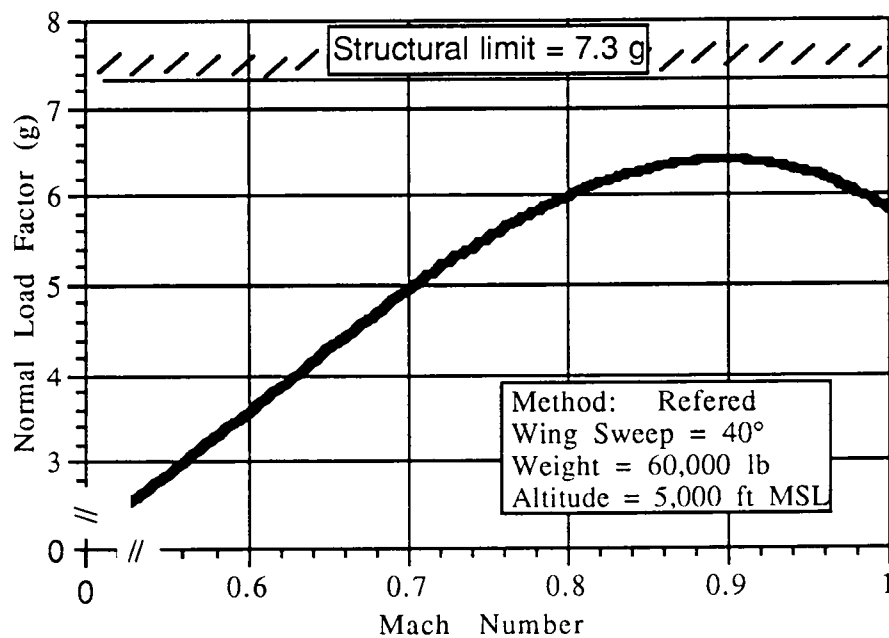


Figure 7

F-111 MAXIMUM INSTANTANEOUS NORMAL LOAD FACTOR

The maximum instantaneous normal load factor for the this condition was 6.4 g. While no direct information on instantaneous turn capability was available for the optimum 26° wing sweep angle, reference 8 indicates that decreasing the sweep angle, increasing the aspect ratio and increasing the wing area will raise the maximum lift coefficient; all three occur when the wing is unswept from 40 to 26°. Since lift and therefore load factor is linear with the lift coefficient it is highly probable that the maximum instantaneous normal load factor for 26° wing sweep will reach the 7.3 g structural limit. Furthermore the maximum aerodynamic capability for a 26° wing sweep angle of the F-111, as seen in flight test and in reference 5 occurs at approximately 0.75 M. It is therefore reasonable to assume that the F-111 sustained turning capability with the F-110 engine as described above is aerodynamically achievable.

The increased sustained turn performance provided by the higher thrust of the F-110 engine would dramatically enhance the F-111's mission performance capability and overall survivability. Currently the F-111 would have to select maximum afterburner to evade a battery of French made Roland surface to air missiles (reference 12). With the F-110 engine this could be accomplished in military power, thus avoiding the huge infra-red signature associated with afterburner selection. Evading air-to-air missiles in the South African Standard class (reference 12), requires the TF-30 equipped F-111 to decelerate, making it vulnerable to reattack. The F-110 engine would allow the missile to be successfully evaded while commencing a high speed dash to depart the danger area.

IV. CONCLUSION

GENERAL

The F-111 airplane with advanced technology General Electric F-110 engines would provide excellent performance benefits in several mission critical flight phases. These include: shortened takeoff ground roll, decreased time to climb, tighter sustained turns and quicker acceleration. The mission capability and overall airplane survivability during the low-level, all-weather attack missions would be significantly enhanced by the greater thrust capability of the F-110 engines.

SPECIFIC

A summary of performance characteristics for the F-111 airplane with either the TF-30 or F-110 engines is presented in appendix B, table B-II. The 41% improvement in takeoff distance would provide exceptional flexibility in basing and continued capability during post-attack damaged runway operations. The 17.5% decrease in the time to climb to optimum cruise altitude with only a 11% increase in consumed fuel, would allow closer interval departures during wartime alert launches, ensuring that the maximum number of aircraft are off the ground before an enemy airstrike can destroy the runway. The slight range decrease would be insignificant except for unrefueled extremely deep-strike missions. The rapid acceleration afforded by the F-110 engine may significantly reduce susceptibility to enemy ground fire which would reduce the F-111 combat attrition rate. The reduction in maximum Mach number for the F-111 is not of great significance for the

current low altitude strike mission. The increased sustained turn performance would dramatically enhance the F-111's mission performance capability and overall survivability. Roland surface-to-air missiles could be evaded in military power, thus avoiding the huge infra-red signature associated with afterburner selection. Air-to-air missiles in the Standard (South African) class could be evaded while commencing a high-speed dash to depart the danger area.

REFERENCES

REFERENCES

1. Flight Manual, T.O. 1F-111A-1, 12 December 1983, with change 6, 11 December 1989.
2. "Jane's All the World's Aircraft 1975-76", Mcdonald & Jane's, London, 1975.
3. "Jane's All the World's Aircraft 1990-91", Jane's Information group LTD, London, 1990.
4. USNTPS Flight Test Manual Number 104, July 1977.
5. Flight Manual, Performance Data, T.O. 1F-111A-1-1, 27 September 1974, with change 12, 11 December 1989.
6. F-14/TF-30-P-414A Installed Performance and Operating Characteristics, Grumman A51-333-I-83-01, November 15, 1983.
7. F-14D/F-110-GE-400 Installed Performance and Operating Characteristics, Grumman A55-333-R-84-05, November 1984.
8. McCormick, Barnes W., "Aerodynamics, Aeronautics, and Flight Mechanics", John Wiley & Sons, Inc., New York, 1979.
9. NATOPS Flight Manual Performance Charts Navy Model F-14A Aircraft, NAVAIR 01-F14AAA-1.1, 1 January 1986, with change 1, 15 June 1987.
10. NATOPS Flight Manual Performance Charts Navy Model F-14A (Plus)/F-14D Aircraft, NAVAIR 01-F14AAP-1.1, 15 September 1990.
11. USNTPS Airplane Performance: Fixed Wing Flight Mechanics, Classroom Notes, January 1989.
12. "Jane's Weapon Systems 1987-88", Jane's Publishing Company LTD, London, 1987.
13. Thomas Griffin and Oscar Bryan, "Re-engining the F-14 with the F110-GE-400 Turbofan Engine", brief given at NATC Patuxent River, Maryland on June 8, 1989.

APPENDIX A

LIST OF SYMBOLS AND ABBREVIATIONS

LIST OF SYMBOLS AND ABBREVIATIONS

a.....	acceleration, speed of sound
AB.....	Afterburner
AGL.....	Above Ground Level
C.....	degrees Centigrade
D.....	Drag
F.....	force
F-14.....	Grumman F-14 airplane
F-110.....	General Electric F-110 turbofan engine
F-111.....	General Dynamic' F-111 airplane
FT, ft.....	Feet
G, g.....	maneuvering load factor
g.....	gravity constant of acceleration
in.....	inches
KCAS.....	Knots Calibrated Airspeed
kt.....	nautical-miles per hour
lb.....	pound(s)
M.....	Mach number
m.....	mass
MAC.....	Mean Aerodynamic Chord
MSL.....	Mean Sea Level
nm.....	nautical mile(s)
N_z, n_z	Normal load factor
P_s	Specific Excess Power
R.....	Radius of turn
ROC.....	Rate Of Climb
s.....	second(s)
SFC.....	Surface
SR.....	Specific Range
t, T.....	time, Thrust
θ	climb angle
TF-30.....	Pratt & Whitney TF-30 turbofan engine
v, V.....	velocity
v_0	initial velocity
W.....	weight
ω	turn rate
x.....	distance

APPENDIX B

TABLES

Table B-I

F-111 TEST AND TEST CONDITIONS

Test	Configura- tion ¹	Altitude (ft MSL)	Airspeed/ Mach (KCAS/ M)	Ave. Gross Weight (1000 lb)	Ave. C.G. (% MAC)
TAKEOFF	TO	SFC-3000	0-375	80.5	29
CLIMB	CL	5000-20000	0.95	77.7	33
RANGE	CR40, CR54, CR72.5	15000, 20000, 25000	300, 400, 500 1.4	--	--
SUSTAINED TURN PERF	P40/54 CO40/54	8000 15000 20000	300 400 500	--	--
INST. TURN PERF	CO40	8000 15000 20000	300 400 500	--	--
LEVEL ACCEL	CO72.5	25000	0.9-1.4	72.7	34

Note: 1. Configurations are defined in Table IV.

Table B-II

TF-30 AND F-110 ENGINE PERFORMANCE SUMMARY

Parameter	Engine	
	TF-30	F-110
Takeoff Distance (ft)	2700	1600 (41%) ¹
Time to Climb (s)	114	94 (17.5%)
Fuel to Climb (lb)	2800	3000 (-11.1%)
Optimum Range Distance (nm)	2190	2070 (-5.5%)
Ingress Distance (nm)	280	271 (-3.2%)
Acceleration Time Required (s)	198	68 (66%)
Acceleration Distance required (nm)	41	13 (68%)
Maximum Sustained Load Factor (g)		
Military Thrust	3.20	4.95 (54.8%)
Max AB Thrust	5.10	6.58 (29.0%)
Maximum Sustained Turn Radius (ft)		
Military Thrust	6924	4339 (37.3%)
Max AB Thrust	4209	3236 (23.1%)
Maximum Sustained Turn Rate (°/s)		
Military Thrust	6.81	10.9 (59.6%)
Max AB Thrust	11.2	14.6 (30.1%)

Note: 1. Change from F-111 with TF-30 engines installed.

APPENDIX C

FIGURES

Appendix C: Figures

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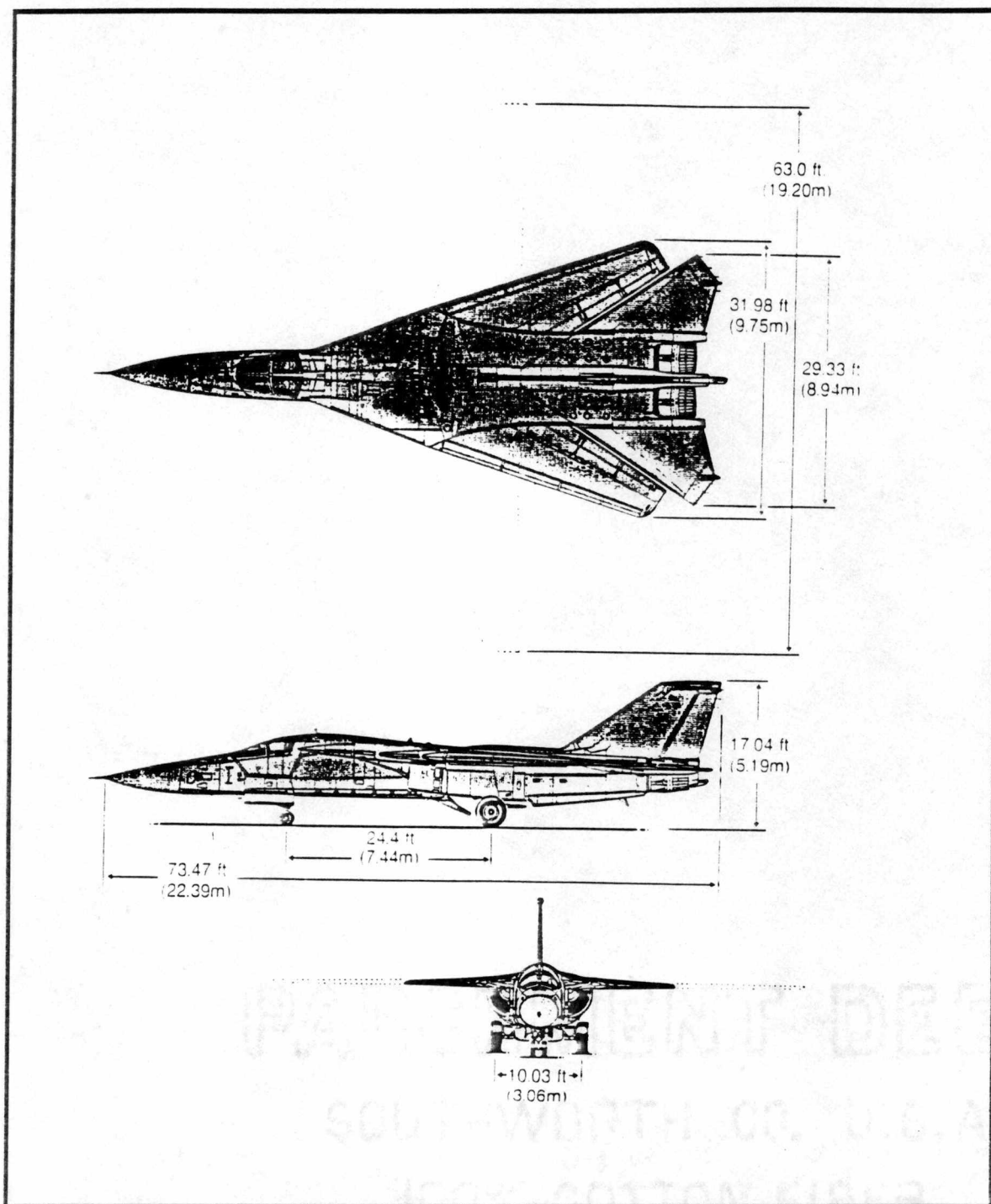


Figure C-1

F-111 THREE-VIEW

Source: Flight Manual, T.O. 1F-111A-1, 12 December, 1983, with change 6, 11 December, 1989.

Acceleration Check Speed

DATA BASIS: ESTIMATED
DATE: 13 SEPTEMBER 1974

CONFIGURATION:
WING SWEEP = 16 DEGREES
FLAPS = 25 DEGREES

CONDITIONS:
MAXIMUM AB

FUEL GRADE: JP-4
ENGINES: TF30-P-3

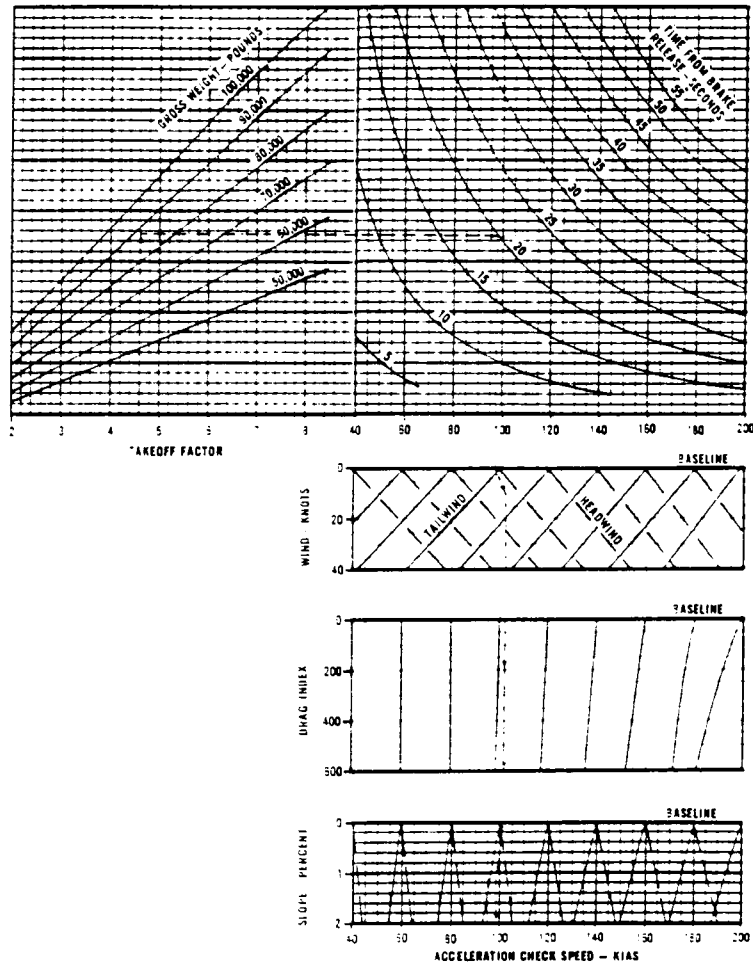


Figure A2-10.

AE0001AP-F033

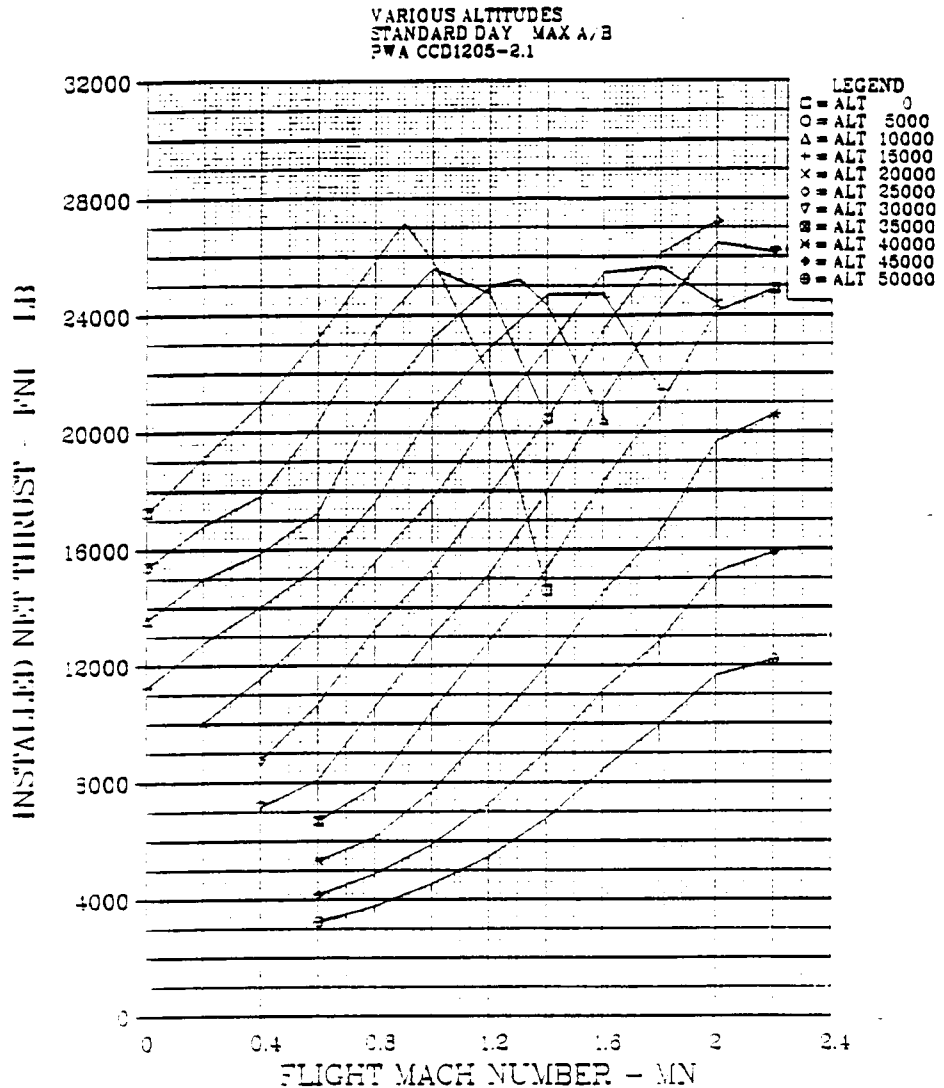
A2-20

Figure C-2

F-111 TAKEOFF ACCELERATION TIME CHECK

Source: Flight Manual, Performance Data, T.O. 1F-111A-1-1, 27 September, 1974, with change 12, 11 December, 1989.

TF30-P-414A ENGINE IN F-14A AIRCRAFT NET THRUST vs MACH NUMBER



NOV 4.1983

FIGURE 1.1

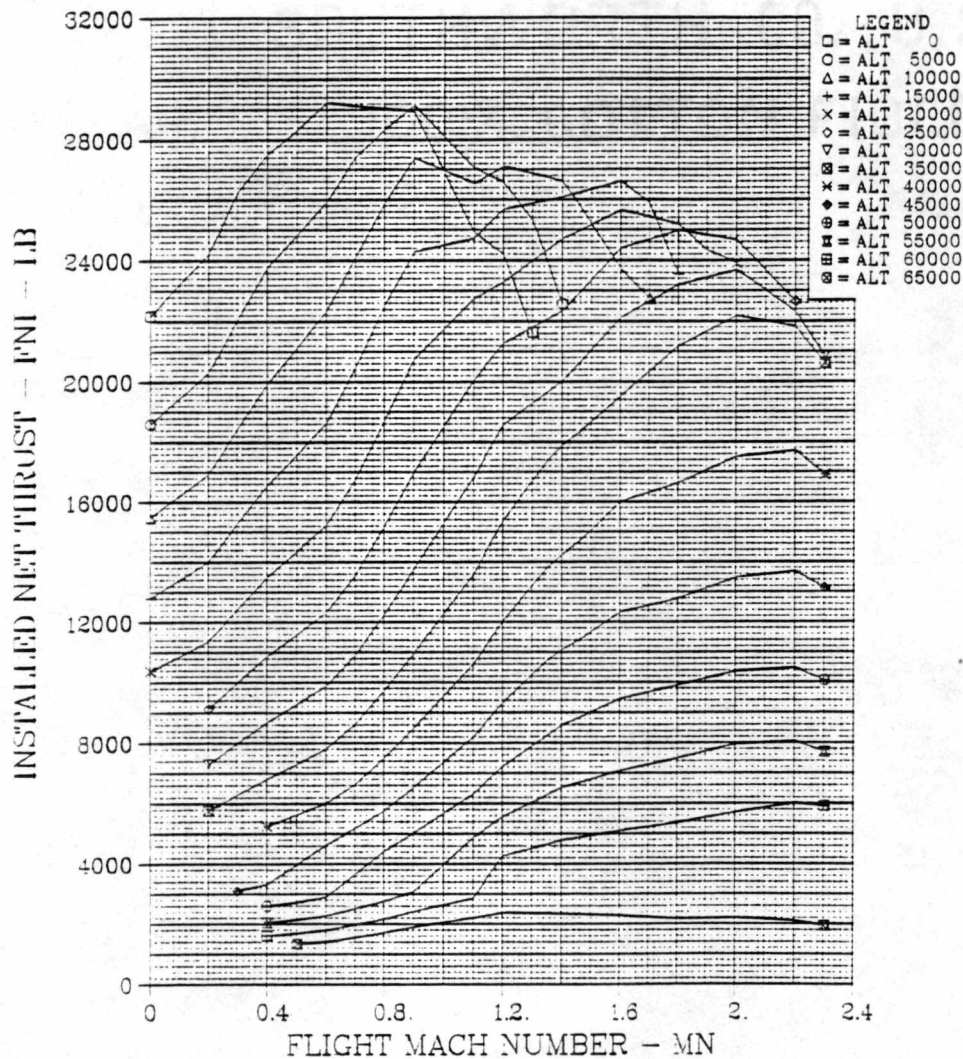
Figure C-3

TF-30 ENGINE THRUST VS. MACH

Source: F-14/TF-30-P-414A Installed Performance and Operating Characteristics, Grumman A51-333-I-83-01, November 15, 1983.

F110-GE-400 ENGINE F-14D AIRCRAFT NET THRUST vs MACH NUMBER

VARIOUS ALTITUDES
STD DAY MAX A/B POWER
MINIMUM ENGINE PERFORMANCE
COMPUTER PROGRAM REF. NO. G0077E-15F



SEPT 5.1984

FIGURE A1

Figure C-4

F-110 ENGINE THRUST VS. MACH

Source: F-14D/F-110-GE-400 Installed Performance and Operating Characteristics, Grumman A55-333-R-84-05, November, 1984.

Maximum Afterburner Climb

DATA BASIS: ESTIMATED
DATE: 23 OCTOBER 1970

CONFIGURATION:
WING SWEEP = 54 DEGREES

CONDITIONS:
STANDARD DAY

FUEL GRADE: JP-4
ENGINES: TF30-P-3

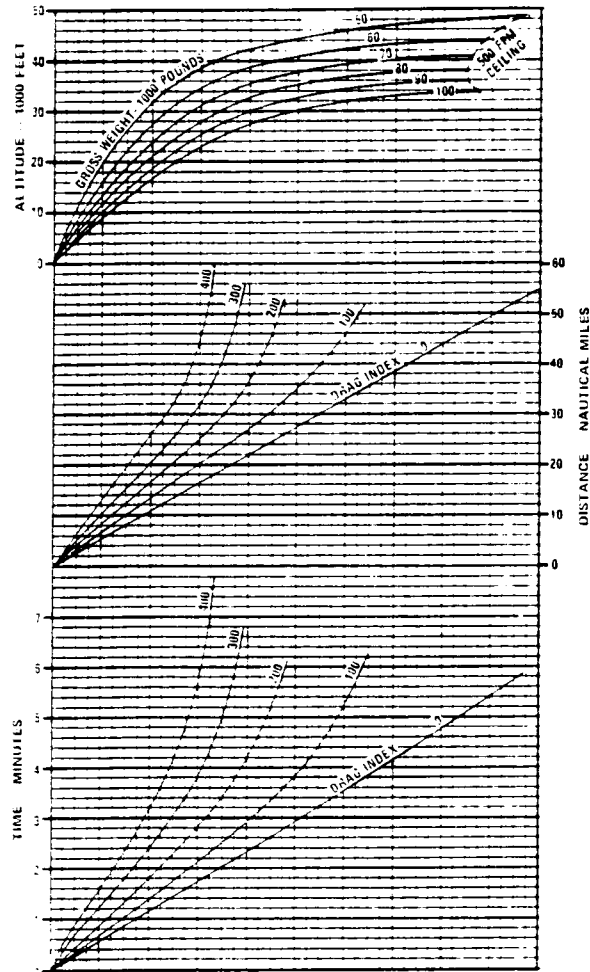


Figure A3-6. (Sheet 2)

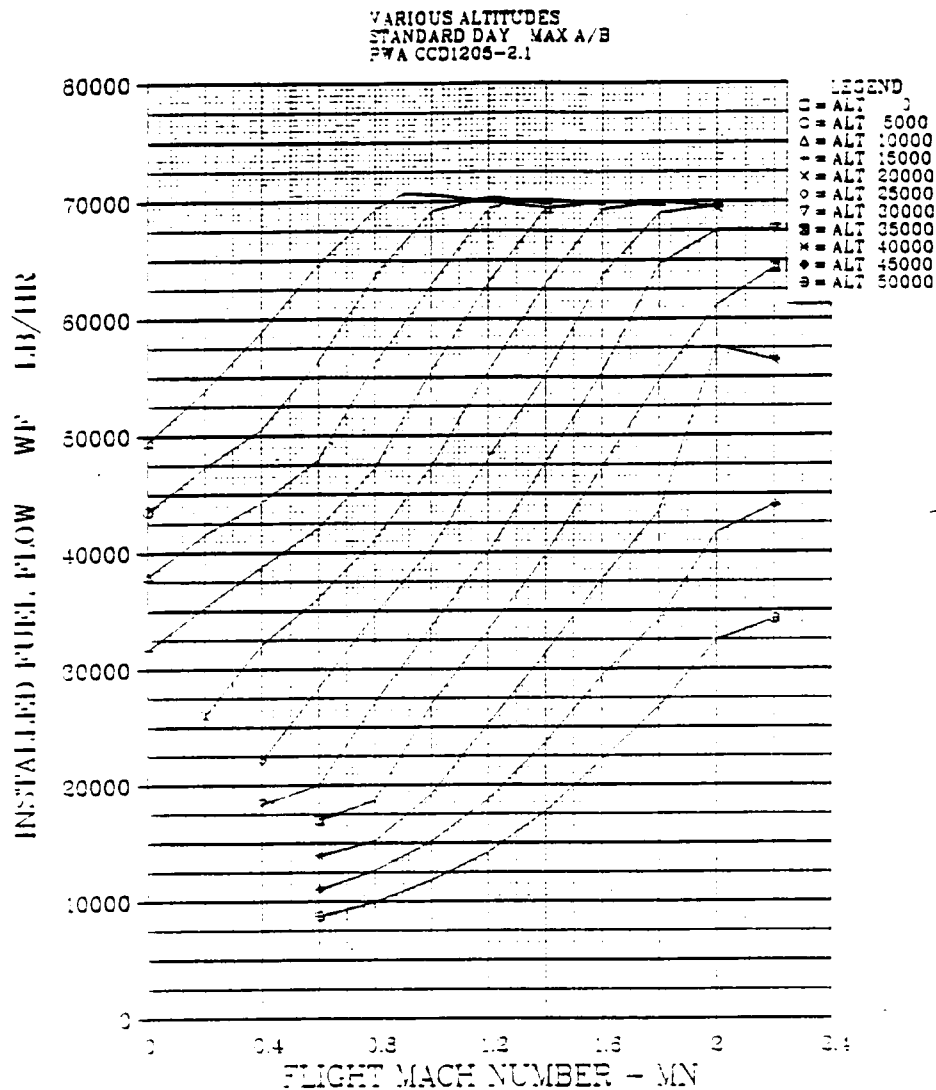
A3-10

Figure C-5

F-111 CLIMB CHART

Source: Flight Manual, Performance Data, T.O. 1F-111A-1-1, 27 September, 1974, with change 12, 11 December, 1989.

TF30-P-414A ENGINE IN F-14A AIRCRAFT
FUEL FLOW vs MACH NUMBER



NOV 4 1983

FIGURE C-6

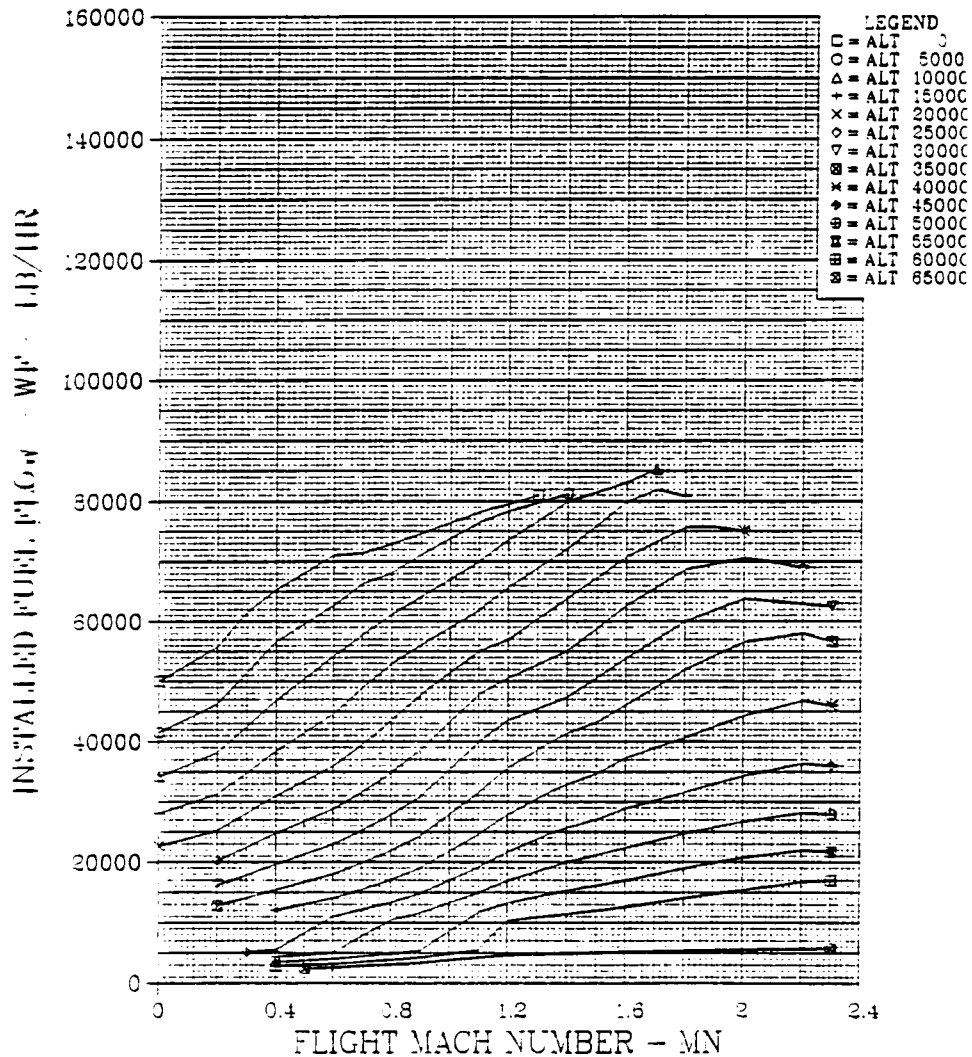
Figure C-6

TF-30 FUEL FLOW VS. MACH: MAX AB

Source: F-14/TF-30-P-414A Installed Performance and Operating Characteristics, Grumman A51-333-I-83-01, November 15, 1983.

F110-GE-400 ENGINE F-14D AIRCRAFT FUEL FLOW vs MACH NUMBER

VARIOUS ALTITUDES
STD DAY MAX A/B POWER
MINIMUM ENGINE PERFORMANCE
COMPUTER PROGRAM REF. NO. G0077E-15F



SEPT 5, 1984

FIGURE A7

Figure C-7

F-110 FUEL FLOW VS. MACH: MAX AB

Source: F-14D/F-110-GE-400 Installed Performance and Operating Characteristics, Grumman A55-333-R-84-05, November, 1984.

Altitude Factor

DATE: 23 OCTOBER 1970

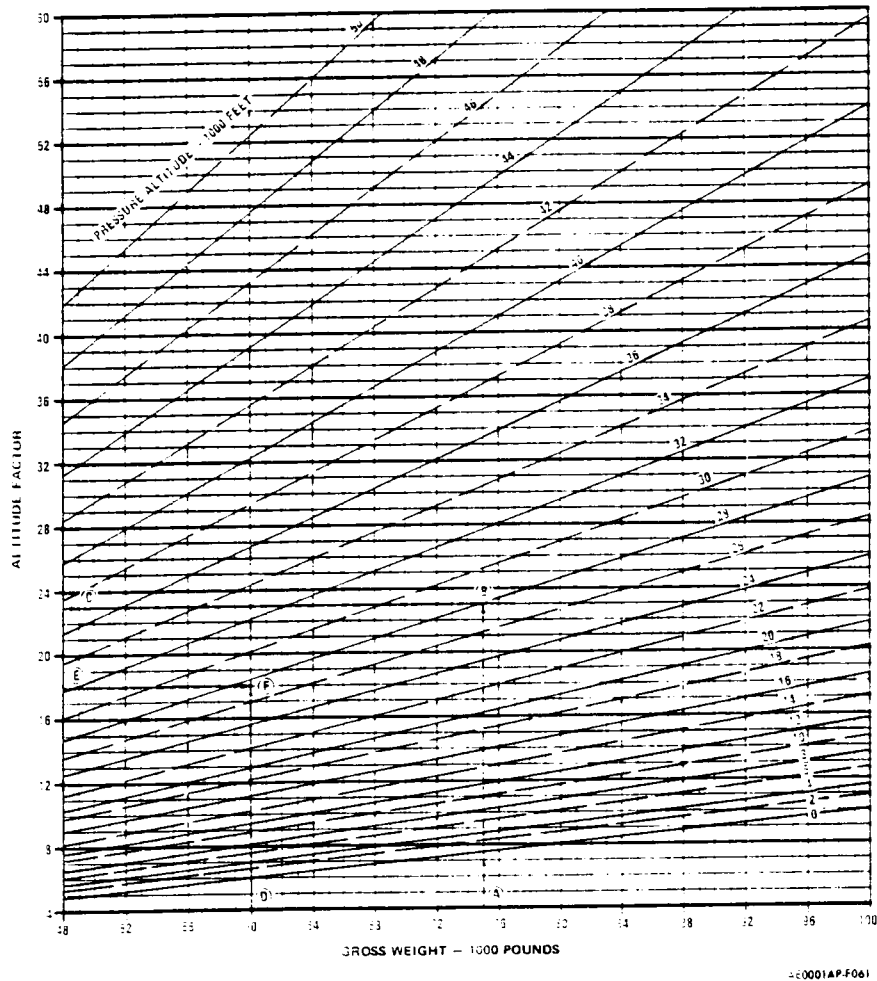


Figure A4-1.

A4-8

Figure C-8

F-111 RANGE: ALTITUDE FACTOR VS. GROSS WEIGHT

Source: Flight Manual, Performance Data, T.O. 1F-111A-1-1, 27 September, 1974, with change 12, 11 December, 1989.

Specific Range

DATE: 23 OCTOBER 1970

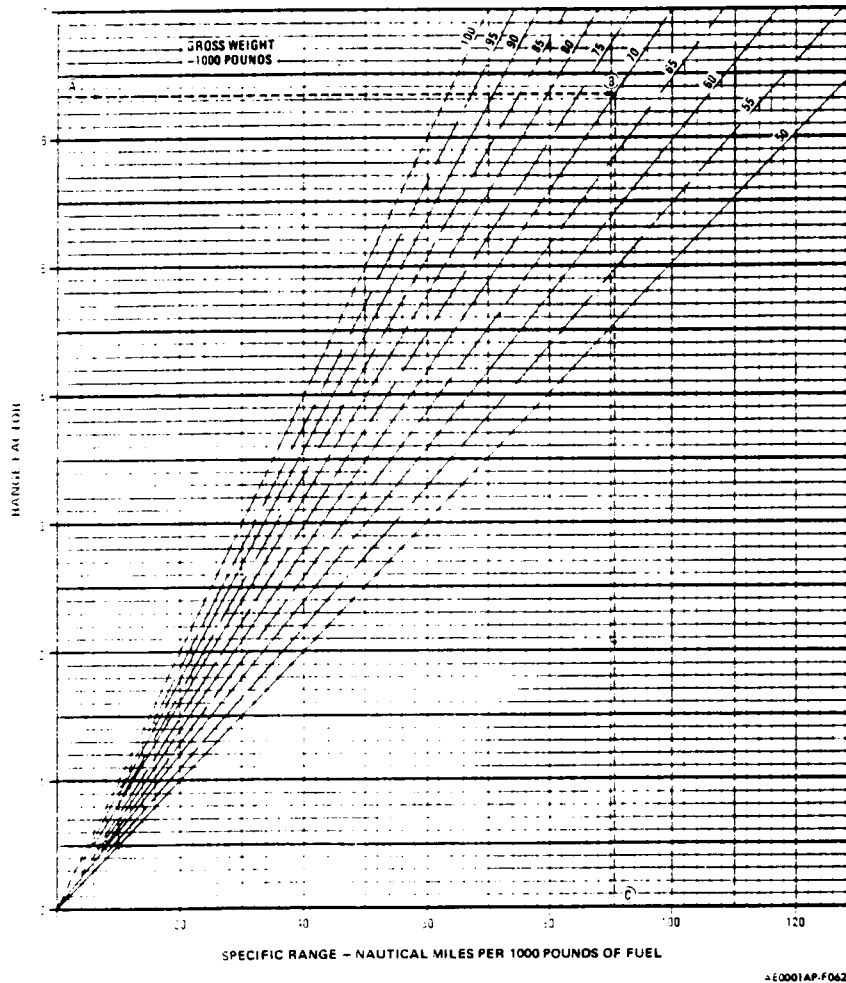


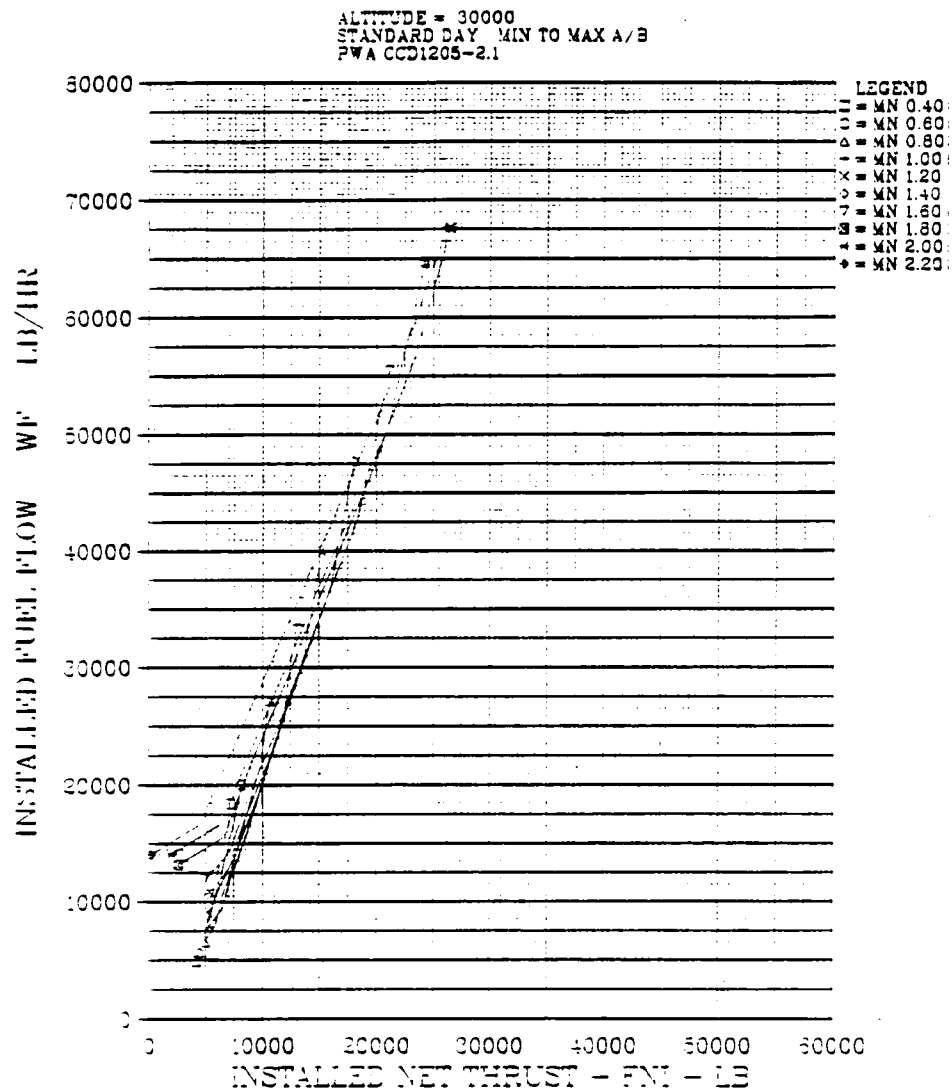
Figure A4-2.

Figure C-9

F-111 RANGE: RANGE FACTOR VS. SPECIFIC RANGE

Source: Flight Manual, Performance Data, T.O. 1F-111A-1-1, 27 September, 1974, with change 12, 11 December, 1989.

TF30-P-414A ENGINE IN F-14A AIRCRAFT FUEL FLOW vs NET THRUST



NOV 4 1983

FIGURE C-10

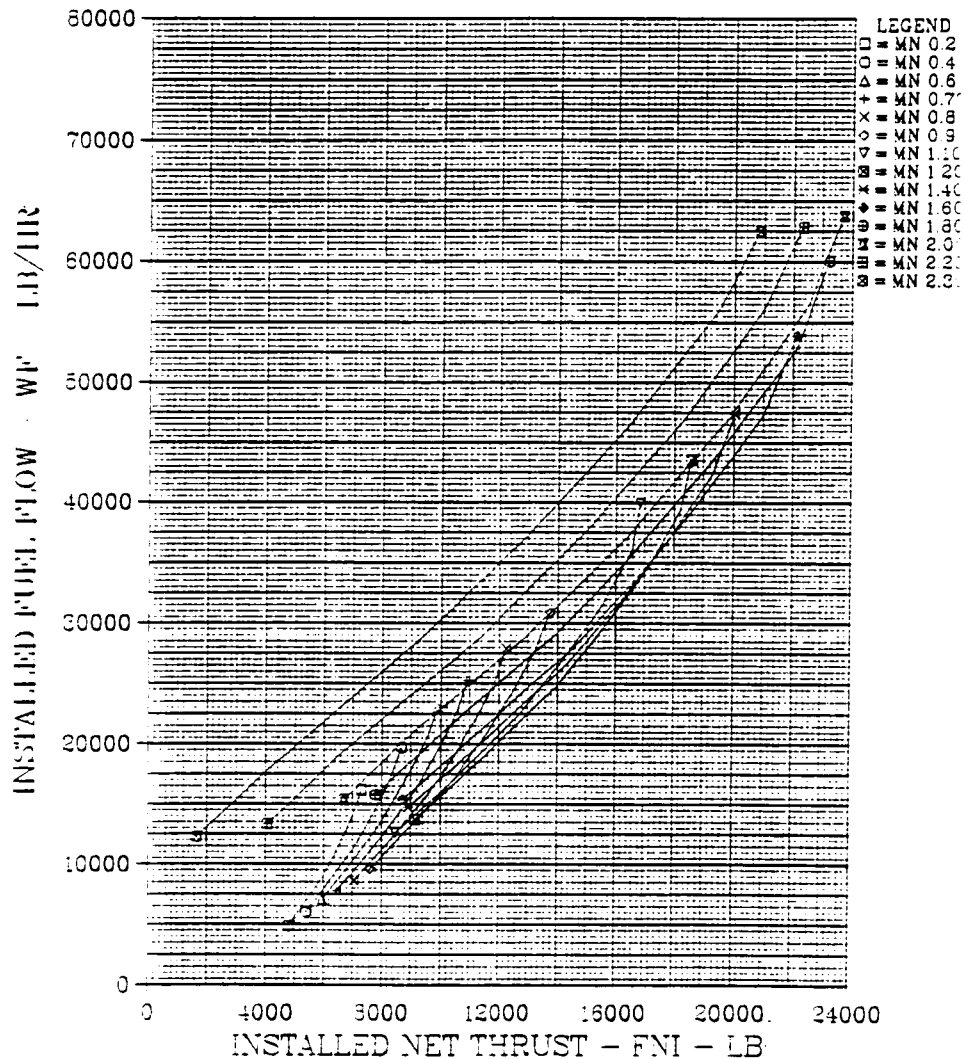
Figure C-10

TF-30 INSTALLED FUEL FLOW VS. THRUST (TYPICAL)

Source: F-14/TF-30-P-414A Installed Performance and Operating Characteristics, Grumman A51-333-I-83-01, November 15, 1983.

F110-GE-400 ENGINE F-14D AIRCRAFT FUEL FLOW vs NET THRUST

ALTITUDE = 30000
STD DAY MIN TO MAX A/B POWER
MINIMUM ENGINE PERFORMANCE
COMPUTER PROGRAM REF. NO. G0077E-15F



SEPT 5, 1984

FIGURE A17

Figure C-11

F-110 INSTALLED FUEL FLOW VS. THRUST (TYPICAL)

Source: F-14D/F-110-GE-400 Installed Performance and Operating Characteristics, Grumman A55-333-R-84-05, November, 1984..

Supersonic Acceleration - 10,000 Feet Optimum Sweep and Thrust

FUEL GRADE: JP-4
ENGINES: TF30-P-3

CONDITIONS:
STANDARD DAY

DATA BASIS: FLIGHT TEST
DATE: 24 DECEMBER 1976

- NOTES:
1. FOR B 57 B 61 WEAPONS
2. REFER TO SHEET 1 OF THIS FIGURE FOR WING SWEEP AND POWER SCHEDULE

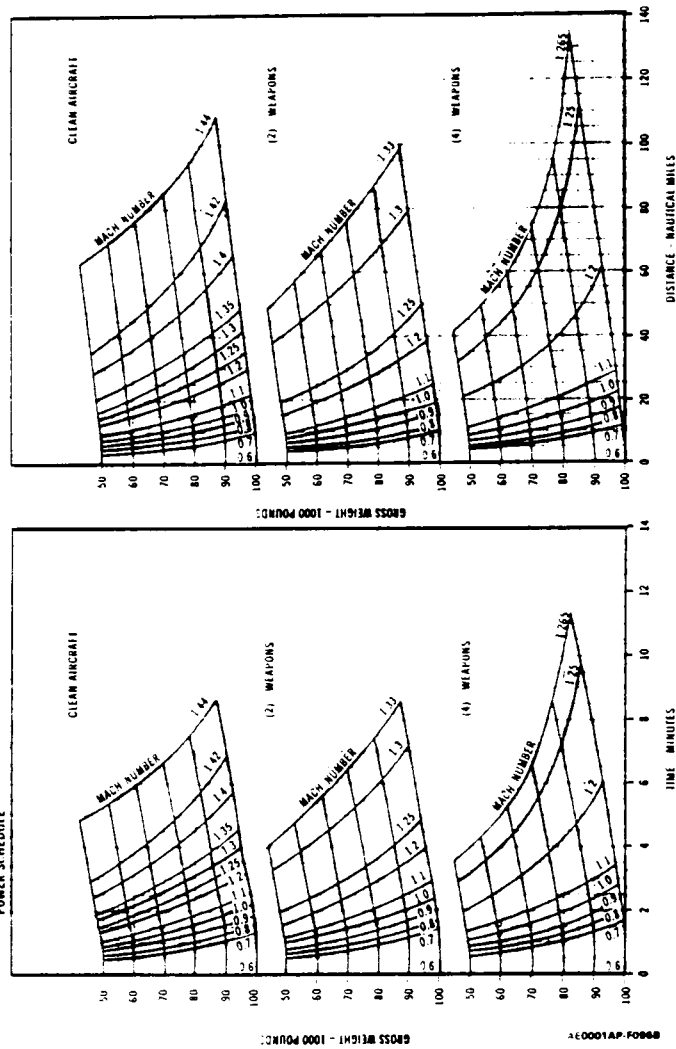


Figure A6-8. (Sheet 2)

Change 12 A6-13

Figure C-12

F-111 SUPERSONIC ACCELERATION

Source: Flight Manual, Performance Data, T.O. 1F-111A-1-1, 27 September, 1974, with change 12, 11 December, 1989.

Maximum Level Flight Speed - Minimum Afterburner Thrust

DATA BASIS: ESTIMATED
DATE: 23 OCTOBER 1970

CONDITIONS:
STANDARD DAY

FUEL GRADE: JP-4
ENGINES: TF30-P-3

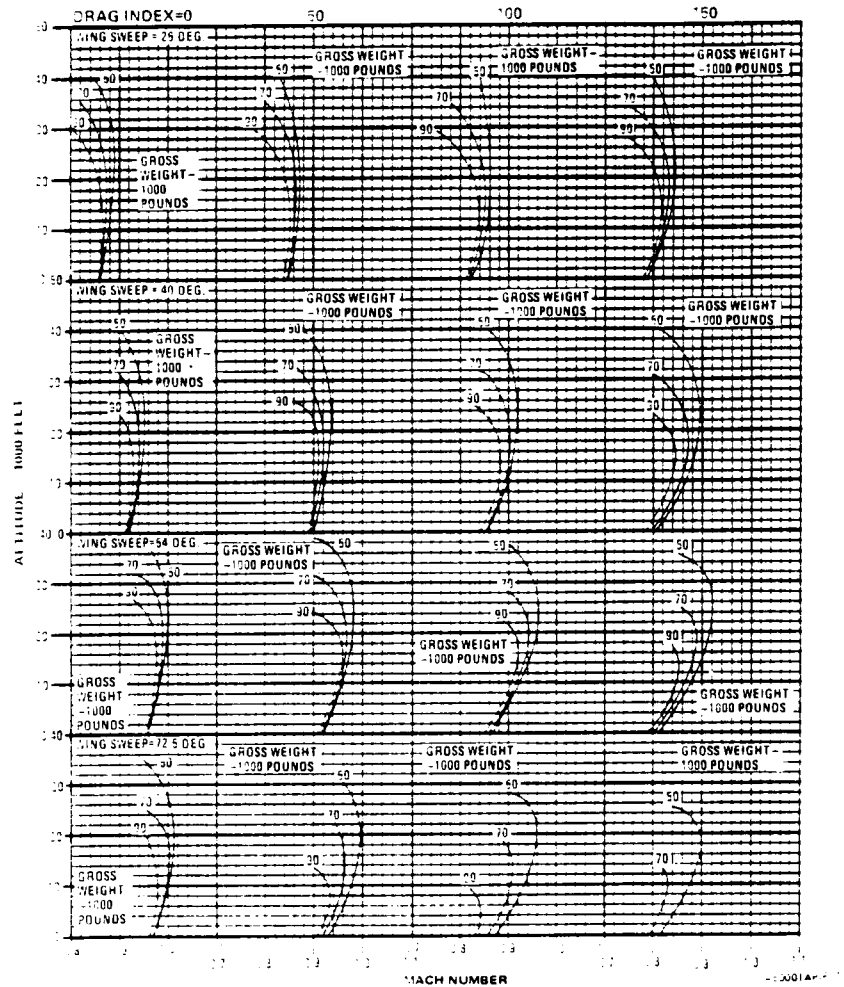


Figure A11-10.

A11-13

Figure C-13

F-111 MAXIMUM LEVEL FLIGHT SPEED: MINIMUM AB

Source: Flight Manual, Performance Data, T.O. 1F-111A-1-1, 27 September, 1974, with change 12, 11 December, 1989.

Maximum Level Flight Speed - Maximum Afterburner Thrust

NOTE: FOR F-111E ADD 60 TO DRAG INDEX
FOR SPEEDS OF MACH 1.2 OR ABOVE.

DATA BASIS: FLIGHT TEST
DATE: 24 DECEMBER 1976

CONDITIONS:
STANDARD DAY

FUEL GRADE: JP-4
ENGINES: TF30-P-3

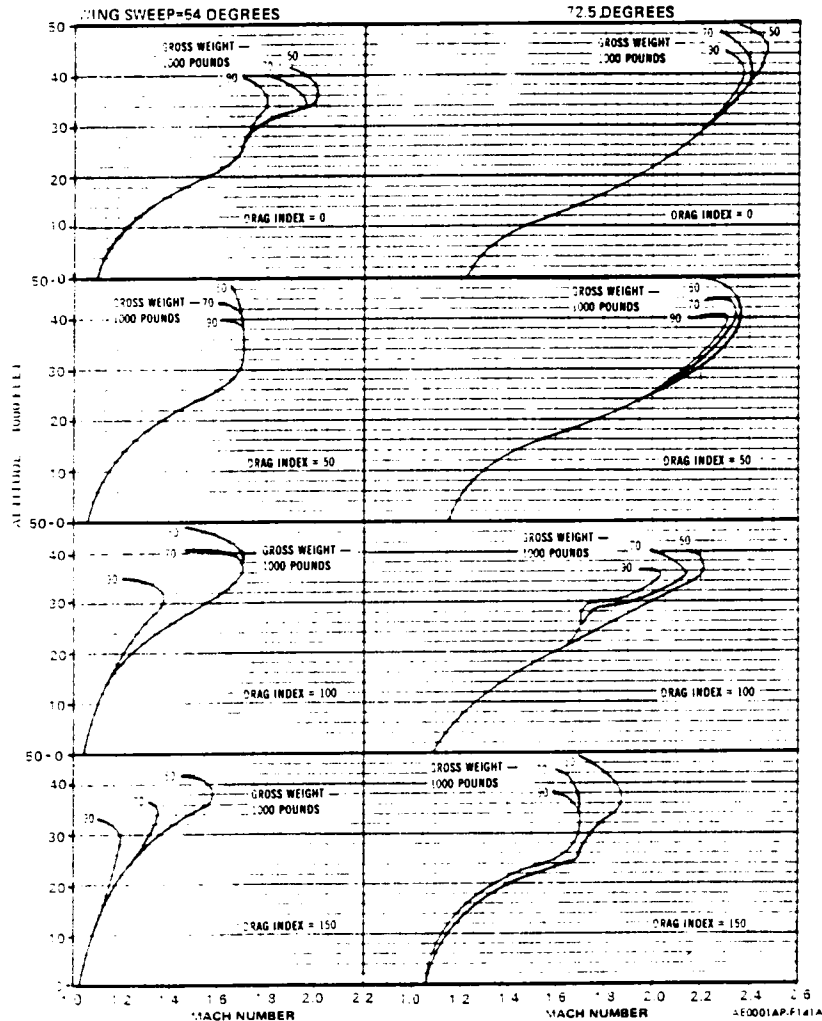


Figure A11-12. (Sheet 2)

A11-16 Change 2

Figure C-14

F-111 MAXIMUM LEVEL FLIGHT SPEED: MAXIMUM AB

Source: Flight Manual, Performance Data, T.O. 1F-111A-1-1, 27 September, 1974, with change 12, 11 December, 1989.

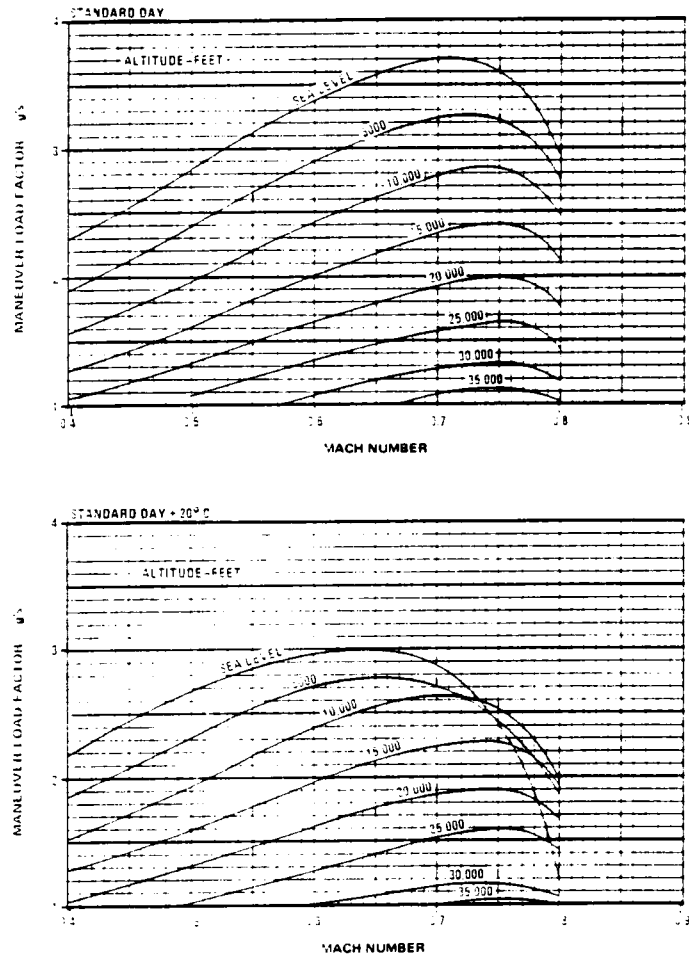
Maneuver Load Factor - Military Thrust

DATA BASIS: ESTIMATED
DATE: 23 OCTOBER 1970

CONFIGURATION:
WING SWEEP = 26 DEGREES
CLEAN AIRCRAFT
GROSS WEIGHT = 60,000 POUNDS

CONDITIONS:
CONSTANT ALTITUDE

FUEL GRADE: JP-4
ENGINES: TF30-P-3



FE0001AP-F129

Figure A11-1.

A11-4

Figure C-15

F-111 MANEUVERING LOAD FACTOR: MILITARY

Source: Flight Manual, Performance Data, T.O. 1F-111A-1-1, 27 September, 1974, with change 12, 11 December, 1989.

Maneuver Load Factor - Maximum Afterburner Thrust

DATA BASIS: FLIGHT TEST
DATE: 24 DECEMBER 1976

CONFIGURATION:
CLEAN AIRCRAFT

CONDITION:
GROSS WEIGHT = 60,000 POUNDS
STANDARD DAY
CONSTANT ALTITUDE

FUEL GRADE: JP-4
ENGINES: TF30 P-3

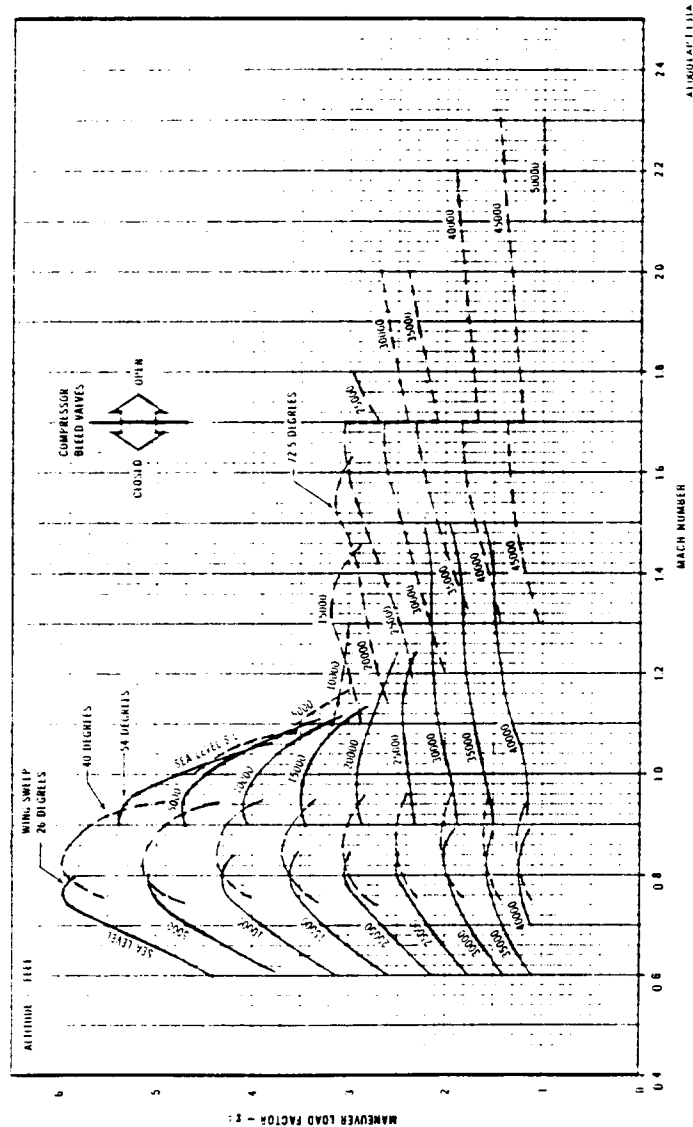


Figure A11-3.

A11-6 Change 2

Figure C-16

F-111 MANEUVERING LOAD FACTOR: MAXIMUM AB

Source: Flight Manual, Performance Data, T.O. 1F-111A-1-1, 27 September, 1974, with change 12, 11 December, 1989.

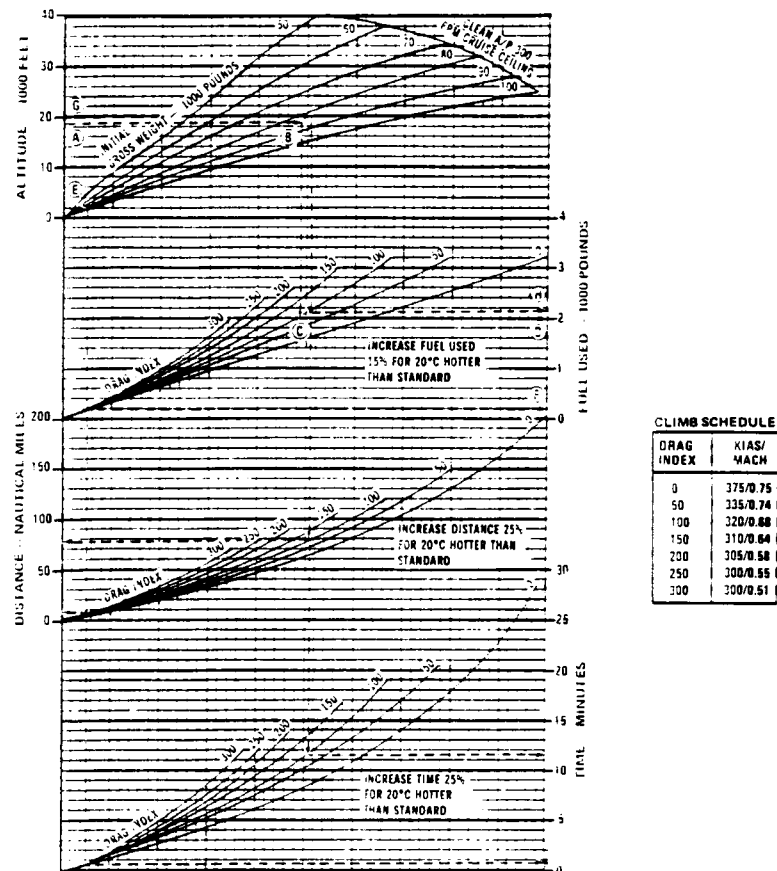
Military Thrust Climb

DATA BASIS: ESTIMATED
DATE: 24 DECEMBER 1976

CONFIGURATION:
WING SWEEP = 26 DEGREES

CONDITIONS:
STANDARD DAY

FUEL GRADE: JP-4
ENGINES: TF30-P-3



AE0001AP.F040A

Figure A3-3.

A3-6 Change 2

Figure C-17

F-111 MILITARY THRUST CLIMB

Source: Flight Manual, Performance Data, T.O. 1F-111A-1-1, 27 September, 1974, with change 12, 11 December, 1989.

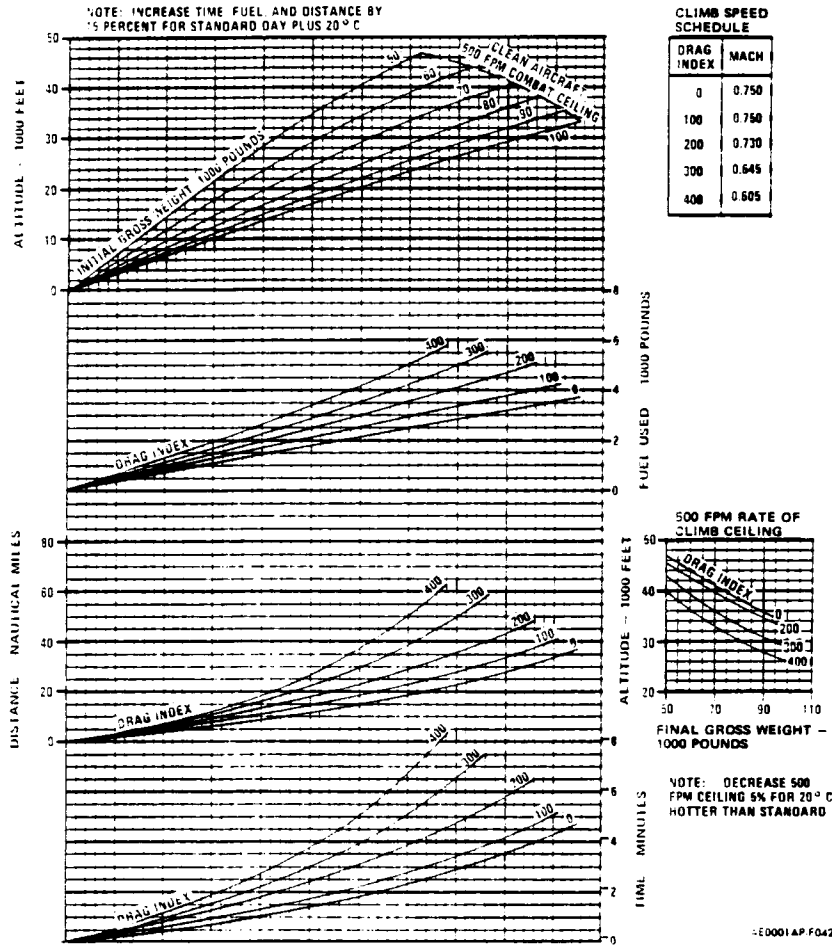
Maximum Afterburner Climb

DATA BASIS: FLIGHT TEST
DATE: 23 OCTOBER 1970

CONFIGURATION:
WING SWEEP = 25 DEGREES

CONDITIONS:
STANDARD DAY

FUEL GRADE: JP-4
ENGINES: TF30-P-3



A3-8

Figure C-18

F-111 MAXIMUM AB THRUST CLIMB

Source: Flight Manual, Performance Data, T.O. 1F-111A-1-1, 27 September, 1974, with change 12, 11 December, 1989.

VITA

Patrick Martin Leard was born in Columbus, Ohio on May 22, 1961. He attended Holy Name elementary school and graduated from Bishop Watterson High School in June, 1979. The following September he entered The Ohio State University and the Navy Reserve Officer Training Corps. In June, 1983 he received the degree of Bachelor of Science in Aeronautical and Astronautical Engineering and was commissioned an Ensign in the United States Navy. He completed flight training instruction and was awarded Navy pilot wings in February, 1985. After completing a three year airborne strategic communication assignment, he attended the United States Naval Test Pilot School and graduated in December, 1989. In September, 1990 he entered the University of Tennessee, Knoxville and in December, 1991 received a Master of Science degree in Aviation Systems.

He is presently completing an assignment as test pilot for naval airborne strategic communication at the Naval Air Test Center, Patuxent River, Maryland.