# F-16XL Demonstrates New Capabilities in Flight Test at Edwards Air Force Base

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**The F-16XL was an evolutionary aircraft developed by building on the proved capabilities of the F-16's fly-by-wire flight control system, relaxed static stability, and vortex flow control. Two F-16 fuselages were stretched and modified with a new cranked arrow wing that included a low-drag conformal weapon carriage. The goal was to provide improved operational effectiveness of the F-16 in the air-to-ground role without degrading the F-16's air-to-air capabilities. Design goals also included survivability enhancement through increased speed, maneuverability, and reduced radar signature along with retention of the F-16's reliability and maintainability through 80% commonality with the F-16. The F-16XL successfully met most of these goals. Improvements in air-to-ground effectiveness were a 35–65% increase in mission radius, an increased external weapons payload capability of 15,000 lb, increased speed, and outstanding high-angle-of-attack flying qualities with air-to-ground weapons. Areas identified for improvement were primarily related to the low thrust-to-weight ratio of the XL during heavyweight takeoff and sustained maneuvering. The concepts demonstrated by the F-16XL will impact all future fighter aircraft design programs.**

## Nomenclature

| | |
|---|---|
| AOA | = angle-of-attack |
| $\mathcal{R}$ | = aspect ratio |
| $C$ | = specific fuel consumption |
| $C_{l_\beta}$ | = variation of rolling moment coefficient with sideslip angle |
| $C_{m_\alpha}$ | = variation of pitching moment coefficient with angle of attack |
| $C_{n_\beta}$ | = variation of yawing moment coefficient with sideslip angle |
| $C_{n_{\beta_{\mathrm{dynamic}}}}$ | = $[C_{n_\beta}\cos\alpha - (I_{zz}/I_{xx}C_{l_\beta})\sin\alpha]$ |
| c.g. | = center of gravity |
| $g$ | = acceleration of gravity |
| KCAS | = knots calibrated airspeed |
| $L/D$ | = lift-to-drag ratio |
| MAC | = mean aerodynamic chord |
| $P_s$ | = specific excess power |
| SR | = specific range |
| TED | = trailing edge down |
| TEU | = trailing edge up |
| $T/W$ | = thrust-to-weight ratio |
| $V$ | = velocity |
| $W_f$ | = aircraft weight, final |
| $W_i$ | = aircraft weight, initial |

## Introduction

THE F-16XL flight demonstration program began in December 1980 at General Dynamics Corporation, Fort Worth, Texas to meet the U.S. Air Force need for an improved air-to-ground fighter.[1,2] The F-16XL is an advanced version of the highly successful F-16 Fighting Falcon. The XL was designed to improve the air-to-ground operational effectiveness and to maintain the outstanding air-to-air capability of the F-16. The F-16XL flight demonstration program was the product of growth programs initiated in 1974 following F-16A/B full-scale development (FSD). These programs were undertaken to meet the requirements generated by the inevitable changes that occur in missions and threats and to take advantage of the leverage provided by new technologies. The final configuration, designated the F-16E by the USAF (the F-16F following the derivative fighter competition), has undergone significant refinement since its inception in 1975.[1,2] The refinements resulted from new operational concepts associated with revisions in mission emphasis and evolved through 3600 h of cooperative wind-tunnel testing of 149 different configurations by General Dynamics and the NASA Langley Research Center.[3,4] The F-16XL prototype demonstration program ended on Oct. 1, 1985, accumulating over 800 h in its three year flight test program at Edwards AFB, California.[5] Many of the design goals and concepts validated in this program are applicable to future fighter aircraft programs.

Evolution of the F-16XL was made possible by the F-16's unique combination of fly-by-wire, relaxed static stability, vortex flow control, modular component structure, and recent developments in wing design technologies not available for the original F-16. These developments combined maturing composite materials with the results of extensive work by NASA Langley in efficient subsonic and supersonic aerodynamics and low-speed flying qualities stemming from their supersonic transport (SST) programs.[6] The XL modification consisted of two fuselage stretches totaling 56 in., a 48,000 lb gross weight capability, a 663 ft$^2$ cranked arrow wing with composite skins, and increased fuel capacity. These modifications could be accomplished while maintaining 80% commonality with the basic F-16 production aircraft. The magnitude of the predicted performance benefit were so significant that General Dynamics proposed a prototype program to demonstrate the increased operational effectiveness and suitability to the USAF.[4,5] General Dynamics invested $49 million of independent research and development funds to design and modify two F-16 airframes with the USAF funding the flight test program.

The F-16XL was designed to meet the need for improvement in the capabilities and characteristics of the fighters being introduced into the Tactical Air Forces (TAF) for the air-to-ground role. History has shown that the aerodynamic gains achieved in tactical fighter aircraft are substantially negated when weapons and external fuel are loaded.[1,7] Typically, there is up to a 50% increase in external drag and severely degraded flying qualities. General Dynamics' goals for the XL growth program were to provide increased range

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and payload without reliance on external fuel, increased survivability through increased speed of penetration, reduced radar signature, and increased maneuverability with air-to-ground weapons. Additional goals were improved handling qualities (including high-angle-of-attack flying), improved ride qualities, and the reliability and maintainability of the F-16 production aircraft. The resultant aircraft would provide enhanced air-to-ground capabilities at a moderate cost over the F-16C/D, the current production aircraft.[4,5,8,9]

The recent literature discusses the need for improvements in these very same areas to meet the continuing force requirements of 1990's fighters. Many authors have pointed out the need for efficient supersonic maneuver, weapon carriage, and delivery for threat avoidance and survivability.[7,10,11] Also, additional mission flexibility must be obtained through increased speed, payload, and mission radius. A RAND Corporation report discussed the need for increased combat range to provide improved survivability through increased basing options for future tactical fighters.[12] Contingency operations in the Middle East/Persion Gulf region need two to three times more combat radius than aircraft developed for Central Europe because of the geography and the scarcity of air bases.[1,7] The need for improved supportability, reliability, and maintainability will carry equal weight with performance in the next generation fighter.[13] The F-16XL design integrates most of these individual elements cited as required for future tactical aircraft, making the results of the F-16XL fight test demonstration program important to the advanced fighter aircraft programs underway in the United States and Europe.

## F-16XL Program

### Goals

The F-16XL is an advanced version of the F-16 and is a result of studies initiated in 1974 at General Dynamics to address three potential categories of improvements to the basic F-16. The studies examined model improvements such as those in the F-16C/D, expanded mission applications such as reconnaissance, and advanced versions or derivative configurations such as the XL. The improvements sought in the advanced versions would result from external changes that would provide significant leverage in providing the TAF measurable air-to-ground and air-to-air benefits while maintaining maximum commonality with the F-16. A critical examination of the operational capabilities and characteristics of the fighters being introduced into the TAF led to General Dynamics' proposal for further improvements in a number of areas,[1] as outlined in the following subsections.

#### *Weapon Carriage*

Penetration speed in most fighters is limited at military power by weapon and carriage drag. This increased drag reduces both dry-power penetration speed and mission radius. These reductions usually result in the requirement for external fuel, which increases mission radius but further reduces penetration speed. Also, the addition of air-to-ground weapons usually degrades flying qualities and reduces the maneuver capability by imposing the structural limits of the suspension system. Increasing the penetration speed with weapons would provide significantly increased survivability in heavily defended areas. Consequently, concepts were sought that would minimize and reduce the penalties of multiple weapon carriage on drag, flying qualities, and structural limits.

#### *Fuel*

The need to maintain mission radius with external stores increases the dependence on external fuel tanks for primary missions. Many aircraft, for example, require centerline tanks for all air-to-ground missions. The centerline tank effectively becomes "hard installed." In addition to drag, external tanks often occupy a store location. This further impacts the number of weapons that can be employed and reduces the useful payload. Mission accomplishment utilizing only internal fuel is desired.

#### *Range/Payload*

The cumulative effect of weapons and external tank carriage has been discussed. If this can be overcome, the increased range and payload afford real increases in combat effectiveness and operational flexibility. The additional range relaxes the need for forward basing. It provides increased combat and weapon persistence over the battle area. The flexibility is available, with appropriate payloads, to perform the deep-strike mission. Divert and delayed recovery options are expanded.

#### *Combat Maneuvering*

The concept of improved dynamic maneuvering through instantaneous turn rate, acceleration/energy recovery, and maneuver response (agility) was considered by General Dynamics as more important than just improved sustained capabilities. All-aspect missiles and improved launch fire control systems offer the option of a "quick kill" via pointing at the target. An aircraft optimized for instantaneous turns can utilize the option of quickly pointing and firing at a target. The ability to quickly reverse course during and after weapon delivery improves survivability in the air-to-ground role.

#### *Radar Signature*

A reduction in radar signature, particularly when combined with higher penetration speed, can greatly enhance penetration survival at any altitude by decreasing the detection range and time available to detect, lock on, and track.

#### *Takeoff and Landing*

Significant basing advantages result from takeoff and landing rolls of 2000 ft or less. Short takeoff and landing capability also allows improved operation on wet or iced runways and reduced vulnerability to airbase attack.

### Configuration Evolution

According to Hillaker, designer of the F-16XL, the low-aspect planform of the cranked-arrow wing evolved to give the XL all the advantages of the tailless delta wing, while minimizing the normal penalties of high drag during maneuvering flight.[4] The XL design was made possible by recent developments in the technologies of wing design and composite materials. Composites allow increased area and aspect ratio at a weight equal to a smaller wing. NASA Langley's supersonic cruise aerodynamic research (SCAR) program provided extensive data on efficient high-speed aerodynamics and low-speed flying qualities. This work was the basis for a new wing planform and camber design with a much better balance between subsonic and supersonic aerodynamics.[1,4,6]

General Dynamics considered four wing planform designs constrained to a common F-16 fuselage, with a stretch if necessary, to meet their goals. The baseline wing for comparison was the F-16A.[1,2] The four candidates are compared in Table 1.

**Table 1 Comparison of the four candidate wing planforms considered by General Dynamics during the F-16XL design program**

| Type | Æ | Area, ft$^2$ | Sweep, deg | Unit weight | Unit volume |
|---|---|---|---|---|---|
| Baseline | 3.0 | 300 | 40 | 1.00 | 1.00 |
| Equal-weight composite | 3.28 | 338 | 40 | 1.00 | 1.07 |
| Swept forward | 4.15 | 300 | −15 | 1.21 | 1.02 |
| Cranked arrow | 1.62 | 646 | 70/50 | 0.85 | 2.16 |
| Delta/canard | 1.87 | 414 | 60 | 0.92 | 1.61 |

The equal-weight composite wing (EWC) is a version of the F-16A wing with increased area and aspect ratio at an equal weight. Hillaker reported on the aerodynamic comparison of these designs.[1,2] At subsonic speeds, the EWC and the swept-forward wing (SFW) were equal and offered better lift/drag ($L/D$) ratio at moderate- and high-lift conditions. This increased $L/D$ would improve the takeoff and landing and sustained maneuver performance when compared to the others. The $L/D$ ratios of the cranked arrow, delta/canard, and baseline wings are essentially equal at these speeds. At supersonic speeds (up to 1.2 Mach), the cranked-arrow wing offered improved $L/D$ in the midlift range over all the other planforms. At supersonic speeds and high-lift conditions, the cranked-arrow wing is also equal to the other planforms in advantage over the F-16 baseline. The cranked-arrow planform has comparable drag at acceleration lift (1 $g$ flight) to the baseline F-16, EWC, and delta/canard and is significantly better than the SFW. At Mach 2.0, only the delta/canard and cranked-arrow planforms offer potential for increased $L/D$ ratio. In terms of cruise efficiency ($L/D_{max}$), the delta/canard and the cranked arrow show little difference at all speeds of Mach 0.9–2.0. The delta/canard and cranked arrow are equal to the baseline at Mach 0.9 and improved at all supersonic speeds. In addition, refinements in the location of the crank or breakpoint in the wing's leading-edge sweep angle produced improvements in the subsonic and transonic $L/D$. The cranked-arrow wing was optimized to retain the F-16's subsonic efficiency and it offered very significant design integration advantages (increased volume for fuel, increased chord for weapon carriage, increased area for takeoff and maneuver at minimum weight). Selection of the cranked-arrow wing traded improved sustained maneuver for decreased drag at acceleration lift, high-speed $L/D$, and cruise efficiency.

The emphasis on the air-to-ground mission dictated further refinements in the cranked-arrow wing to improve the subsonic $L/D$ and lateral directional stability. A wide variety of wing cambers, twists, and trailing-edge reflexes were tested to achieve improvement in the drag polar at Mach 0.9. The final camber design improved the drag at cruise at both Mach 0.9 and 1.6. It also improved the maneuver lift at these speeds. The shape of the forebody blend improved the high-AOA and lateral-directional stability and provided maximum lift at all flight conditions and loadings by means of vortex lift control. Leading-edge flaps are used on the outboard crank to enhance flow over the ailerons and provide resistance to yaw divergence at high AOA.

**Prototype Proposal**

The magnitude of the predicted performance increases obtainable through the XL modification and the unfavorable delta wing perceptions led General Dynamics to propose to the USAF a full-scale prototype evaluation.[4,5] The F-16XL is, as was the YF-16 lightweight fighter prototype, an example of the unique role flight testing can play in the advancement of new technologies.[5] In both of these programs, flight testing played a leading and not a following role in the program decision. Documented flight data and not paper study results were available for FSD decisions.

Using corporate discretionary funds, General Dynamics modified two F-16A airframes leased from the USAF into the one- and two-place F-16XL-1 and 2 configurations (Fig. 1). F-16XL-1 was modified from tail no. 75-0749, the fifth FSD F-16 aircraft, with 401.5 h of flight and was powered by a production Pratt & Whitney F-100-PW-200 engine. F-16XL-2 was modified from F-16A tail no. 75-0747, the third FSD aircraft, with 1212.2 h of flight. The single-seat A model airframe was modified with a production two-seat unit that replaced components damaged in a landing accident. The aircraft was powered by a General Electric F110-GE-100 (originally designated F101 DFE) engine.

Figure 2 is a schematic showing the XL modification to a F-16 airframe. The modification consists of a 56 in. fuselage

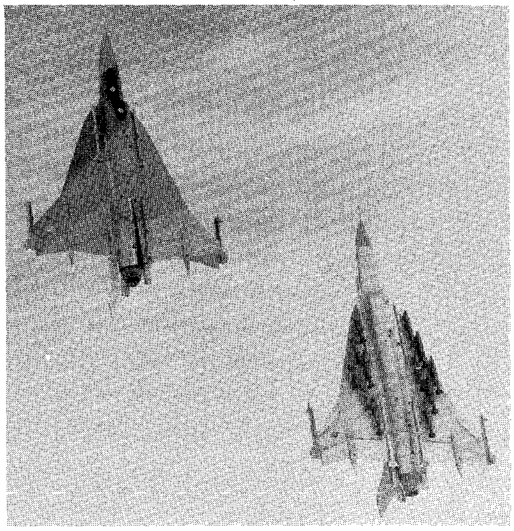

Fig. 1 XL-1 loaded with 12 MK-82 500 lb bombs and air-to-air missiles and XL-2 with the air-to-air missiles.

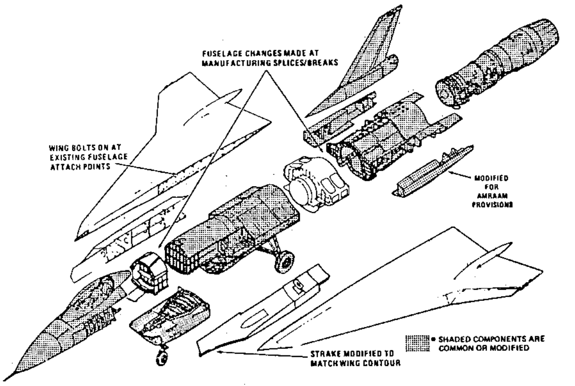


Fig. 2 Schematic showing the modification required to a F-16 fuselage to incorporate the XL modification.

stretch (30 in. forward and 26 in. aft of the main landing gear) and replacement of the F-16 conventional wings and tail with a 663 ft$^2$ cranked-arrow wing. The wing was constructed from graphite-polyamide composite skins and an aluminum substructure. The composite skin was tooled to the inside mold line, ensuring the best possible fit to the understructure, with a variation in fiber thickness of 0.25–0.75 in. A production F-16 Norwegian drag chute was incorporated into the vertical tail and the F-16 ventral fins were eliminated. The landing gear was upgraded to 48,000 lb maximum gross weight capability (F-16A is 35,400 lb). The rudder was strengthened for a 50% increase in hinge moment capacity. Armament included a fuselage-mounted M61A1 20 mm Vulcan gun and six air-to-air missiles (four fuselage-mounted semisubmerged AMRAAM's and two wing-tip-mounted AIM-9L's). In addition, the XL was configured with five 2000 lb and sixteen 1000 lb hardpoints and two Lantirn pod stations.

The primary flight control system incorporated the F-16 full analog fly-by-wire system modified for the XL control surfaces. Figure 3 is a drawing of the F-16XL, showing three views and a table of the control surface authority limits. Pitch was controlled by symmetric deflection of the elevons mounted on the inboard trailing edge of the wing and by symmetric deflection of the outboard ailerons. The pilot commanded the normal load factor throughout most of the flight envelope. In the power approach configuration, and above 19 deg AOA in the cruise configuration, the flight control system reverted to a blended load factor and AOA command to provide speed stability. The XL incorporated an AOA limiter, which was similar to the F-16A/B but with an envelope ex-

AIRCRAFT DATA

| | |
|---|---|
| **WING** | |
| AREA | 663 259 FT² |
| SPAN (THEO) | 32 FT 4 84 IN |
| ASPECT RATIO | 1 583 |
| TAPER RATIO | 0.128 |
| LE SWEEP (INBD. OUTBD) | 70°. 50° |
| INCIDENCE | -0 65° AT BL 41 50 |
| | -4 104° AT 136 1 & TIP |
| DIHEDRAL | 0° |
| M A C (REF) | 296 398 |
| L E M A C (REF) | FS 19066 (APEX FS 16) |
| T C DISTRIBUTION | 297% - 4 50% - 4 50% |
| AIRFOIL | NACA 64A (SS 41 5 - 136 1) |
| | MOD BICON (136.1 - TIP) |
| | CRUISE ACCEL CAMBER |
| ELEVON AREA | 44 056 FT² (TOTAL) |
| AILERON AREA | 29 445 FT² (TOTAL) |
| LE FLAP AREA | 18.197 FT² (TOTAL) |
| **VERTICAL TAIL** | |
| AREA | 54 75 FT² |
| SPAN | 101.00 IN. |
| ASPECT RATIO | 1 294 |
| TAPER RATIO | 0 437 |
| LE SWEEP | 44 5° |
| AIRFOIL | BICON-5 3% ROOT. 3% TIP |
| RUDDER AREA | 11 65 FT² |
| **SPEEDBRAKES** | |
| AREA | 14 26 FT² |
| **CONTROL-SURFACE AUTHORITY (NORMAL TO H L)** | |
| ELEVONS | 30° UP & DOWN |
| AILERONS | 20° UP & 30° DOWN |
| LE FLAPS | 6.4° UP. 36 5° DOWN |
| RUDDER | 30° LEFT & RIGHT |
| SPEEDBRAKES | 60° UP & DOWN |
| **STALL HINGE MOMENTS (IN-LB)** | |
| ELEVONS | 259,525 |
| AILERONS | 115 000 |
| LE FLAPS | 165,000 |
| RUDDER | 115,000 |
| SPEEDBRAKES | 144,000 |
| **CONTROL-SURFACE RATES (°/SEC @ ZERO LOAD)** | |
| ELEVONS | 60 |
| AILERONS | 60 |
| LE FLAPS | 31 |
| RUDDER | 90 |
| SPEEDBRAKES | 30 (PER PANEL) |
| **LANDING GEAR (48,000 LB TOGW CAPACITY)** | |
| MAIN-GEAR TIRE SIZE | 27 75 x 8 75 - 14 5 |
| NOSE-GEAR TIRE SIZE | 18.0 x 5.7 - 8.0 |
| **UNALLOCATED VOLUME (WATER VOLUME)** | |
| F-16 AFT AVIONICS BAY | 11.2 FT³ |
| FORWARD STRETCH | 11.6 FT³ |
| STRAKE | 6.0 FT³ |
| AFT STRETCH | 9 8 FT³ |
| **PROPULSION** | |
| ENGINE | (1) F100-PW-200 |
| | (2) F101 DFE |

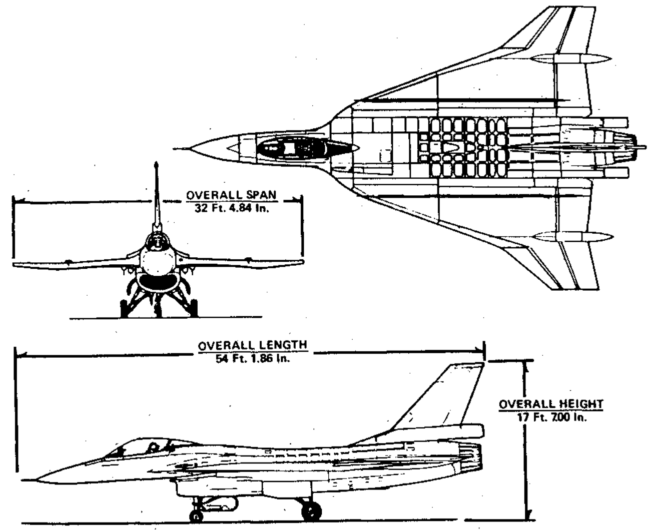


**Fig. 3 Schematic of the F-16XL showing three views with aircraft data and control surface authority limits.**

panded to 29 deg at low speeds and 26 deg above Mach 0.9.

Roll rate was commanded by asymmetric deflection of the ailerons and was assisted by elevon deflection. The maximum rate commanded was 308 deg/s and was scheduled as a function of AOA. Yaw control was by deflection of the rudder with an aileron rudder interconnect to provide coordination during rolls.

Secondary flight control surfaces included the outer wing panel leading-edge flaps (LEF) and F-16 clamshell-opening speed brakes. The LEF's were scheduled symmetrically for improved performance and pitch trim assistance at high dynamic pressures. They deflect the leading edge up during high-speed level flight. The LEF's were also deflected asymmetrically to assist the rudder and ailerons for lateral-directional stability at high AOA and were used for postdeparture yaw rate limiting between 35 and 50 deg AOA. The XL, like the F-16A/B, had a manual pitch over-ride (MPO) capability in the event of a deep stall. The MPO by-passed the AOA limiter and provided the pilot with full pitch surface command authority. For flight test, the XL also had an automatic pitch over-ride system. This system was designed to input a pitch rocking command to the flight control computer to break a deep-stall condition.

## Flight Test

### Organization

The flight demonstration program was conducted from July 1982 to October 1985 in three phases by the F-16E Combined Test Force (CTF) at Edwards AFB. Initially, the goals of the test program were to demonstrate that the configuration changes in the XL modification, when fully developed, would achieve a major improvement in the operational effectiveness in both the air-to-ground and air-to-air roles. During phase I testing (conducted from July 1982 to June 1983), the program goals were modified to provide data to the Aeronautical System Division's (ASD) Derivative Fighter Steering Group (DFSG) for selection of the dual-role fighter. The USAF conducted a flight evaluation of the F-16XL and a modified F-15 for selection of a dual-role tactical fighter derivative capable of night, all-weather air-to-air and air-to-surface combat operations.[14] The test program included both development test and evaluation (DT&E) and operational utility evaluation (OUE) to support a FSD decision. During phase I, the CTF was composed of test pilots and engineers from General Dynamics and the Air Force Flight Test Center (AFFTC), with additional members from the Air Force Operational Test & Evaluation Center (AFOTEC), Tactical Air Command, and ASD.

Phase II testing followed the F-15 dual-role fighter selection and ran from June 1983 to November 1984. Flight testing con-

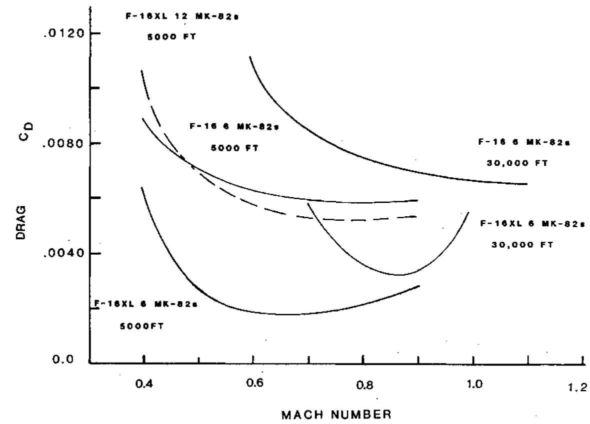


**Fig. 4 Comparison of the drag change when MK-82 500 lb bombs are carried on the F-16A and F-16XL.**

tinued to accomplish DT&E of the F-16XL modification. The AFOTEC representatives did not formally participate in the testing after the dual-role fighter decision.

Phase III was conducted from December 1984 to the end of the test program. The testing was structured to continue DT&E in anticipation of a growth version F-16F based on the XL derivative FSD program—the original goal at the program inception in 1981.[15] During this period, XL-2 was modified with a large normal shock inlet (LNSI) with increased airflow capability to utilize the full capacity of the General Electric F110-GE-100 engine. The test program ended in October 1985 and both XL's were placed in flyable storage.

### Results

In order to make a valid aerodynamic comparison between the baseline F-16 planform and the F-16XL derivative, F-16XL data (except where noted—takeoff and landing) were limited to F-16XL-1. This aircraft had the same engine and inlet as the F-16. The F110 engine installed in F-16XL-2, especially with the LNSI, improved the thrust-to-weight ratio and significantly improved the performance of the XL.

#### *Weapon Carriage*

The large wing chord of the cranked-arrow planform allowed weapons to be carried conformally in a low-profile, tandem, staggered arrangement on the wing's lower surface as shown in Fig. 1. Conformal weapon carriage provided significant drag reduction resulting in increased speed capability. Figure 4 graphically shows the reduction in drag resulting

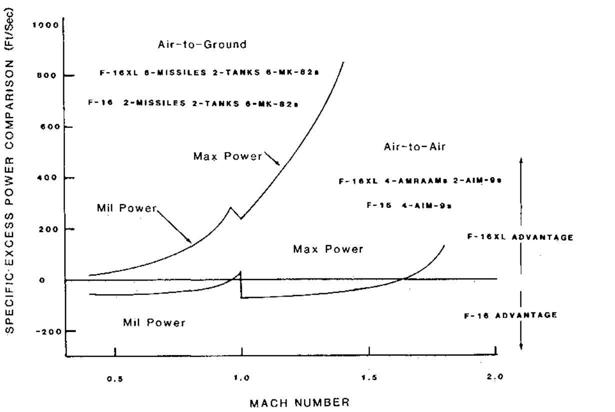


**Fig. 5 Relative comparison of the specific excess power $P_s$ of the F-16XL to the F-16A with air-to-air and air-to-ground weapon loads.**

from low-profile weapon carriage. Conformal carriage of 12 MK-82 bombs on the F-16XL using the low-profile LODE-14 type of ejectors is comparable in drag to 6 MK-82's in the triple-ejector TER-9A racks on the F-16A. Conformal carriage of an equal number of MK-82's on the XL reduces drag by 66% compared to the F-16A. The Maverick air-to-ground missile (AGM-65) carriage shows a similar reduction in drag. The XL's semisubmerged ejector launcher carriage of four advanced medium-range air-to-air missiles (AMRAAM) also produced a drag reduction over 70% when compared to pylon-mounted AMRAAM's. The effect on the level flight acceleration performance of the XL is dramatic. Figure 5 is a plot comparing the difference in specific excess power $P_s$ (the acceleration capability defined in ft/s) of the F-16XL to the F-16A ($P_s$F-16XL vs $P_s$F-16). A positive $P_s$ in Fig. 5 shows superior XL performance and a negative $P_s$ the F-16 advantage. The performance advantage of the F-16XL with an air-to-ground weapon load ranges from 20 ft/s at Mach 0.4 to 820 ft/s at Mach 1.4. With the air-to-air load, the XL has the advantage only at high supersonic speeds. Low-profile weapon carriage also provided increased speed of penetration. At 500 ft, the F-16XL loaded with two external tanks, six MK-82 bombs, four AMRAAM's, and two AIM-9L's achieved a military power speed increase of 65 knots over a comparably loaded F-16A.

Conformal weapon carriage also saves weight. Multiple ejector racks (MER) and pylons to carry 12 MK-82 bombs weigh 1039 lb compared to 516 lb for conformal low-profile carriages. The horizontal separation of all the stores eliminates interference from hung stores. The wing hardpoint loads are reduced by elimination of bomb clusters on MER's. The cranked-arrow wing improved the distribution of weapons with a balanced load fore and aft of the center of gravity. This distribution of weapons allowed higher roll rates and higher maneuver limits. Weapon separation tests to validate the conformal carriage concept on the cranked arrow wing included release of 500 lb MK-82 and 2000 lb MK-84 bombs, firing of an AGM-65 guided munition, and release of tactical munition dispenser (TMD) weapons. The largest single release was a 50 ms ripple of 12 MK-82 bombs.

*Fuel/Range*

The F-16XL's ability to carry 11,200 lb of internal fuel, coupled with its low-drag design, provides increased range capabilities. Examination of the range equation shows that range is increased by minimizing the specific fuel consumption $C$,

$$\text{Range} - \int_{W_f}^{W_i} \left(\frac{1}{C}\right) V \left(\frac{L}{D}\right) \frac{\mathrm{d}W}{W} \tag{1}$$

and maximizing the lift-to-drag ($L/D$) ratio, velocity $V$, and

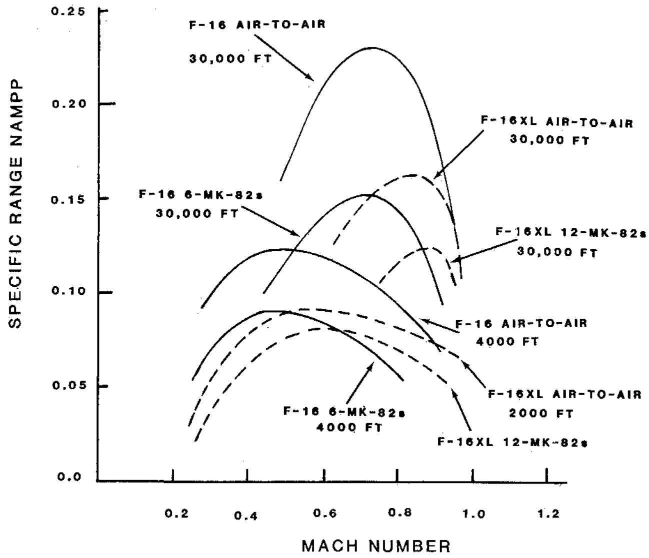


**Fig. 6 Specific range (NAMPP) vs Mach number for F-16XL-1 at 2000 and 30,000 ft, showing the effect of 12 MK-82 weapons on cruise (F-16A data at comparable conditions are also shown).**

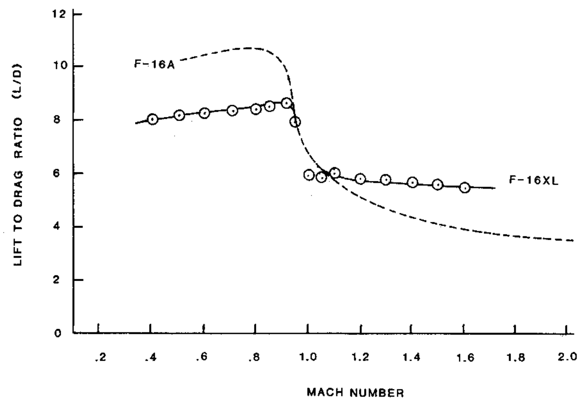


**Fig. 7 Maximum lift/drag ratio vs Mach number for the F-16XL compared to the F-16 (air-to-air loading).**

fuel capacity $W_i/W_f$. $W_i$ and $W_f$ are the aircraft gross weight at the start and end of mission, respectively ($W_i - W_f$ = fuel weight). The F-16XL with the cranked-arrow wing and fuselage stretch has a fuel fraction of 0.32. This is a 14% increase over the F-16's 0.28 and approaches the F-111's fuel fraction of 0.38. Figure 6 plots specific range (SR) vs Mach number for the F-16XL and F-16A. SR is velocity divided by fuel flow giving the units of nautical air mile per pound (NAMPP) and is a direct measure of the distance obtained per pound of fuel burned. At 2000 ft with 12 MK-82's the F-16XL has a peak SR of 0.08, which is lower than the F-16A's SR of 0.092. However, at these conditions, the XL's peak specific range occurs at a higher speed, Mach 0.6, compared to Mach 0.45 for the F-16A. At higher speed (>0.65 Mach) and low altitude, the XL has a greater SR than the F-16A. At high altitude, the XL's peak SR was less than the F-16's. This is primarily due to the lower fuel flows required in the smaller aircraft and a speed differential that is not as great. Again, at higher speeds at this altitude where the fuel flows are equivalent, the XL's SR with external stores was higher than the F-16's.

The third term in Eq. (1) is the maximum $L/D$ ratio. Figure 7 compares the $L/D$ ratio of the XL to that of the F-16A. Subsonically, the F-16A has better cruise efficiency. As the speed approaches supersonic flight, the XL has improved cruise efficiency. At Mach 1.4, the XL has a 25% higher $L/D$ ratio. The other factor to be seen from Figs. 6 and 7 is the dramatic effect

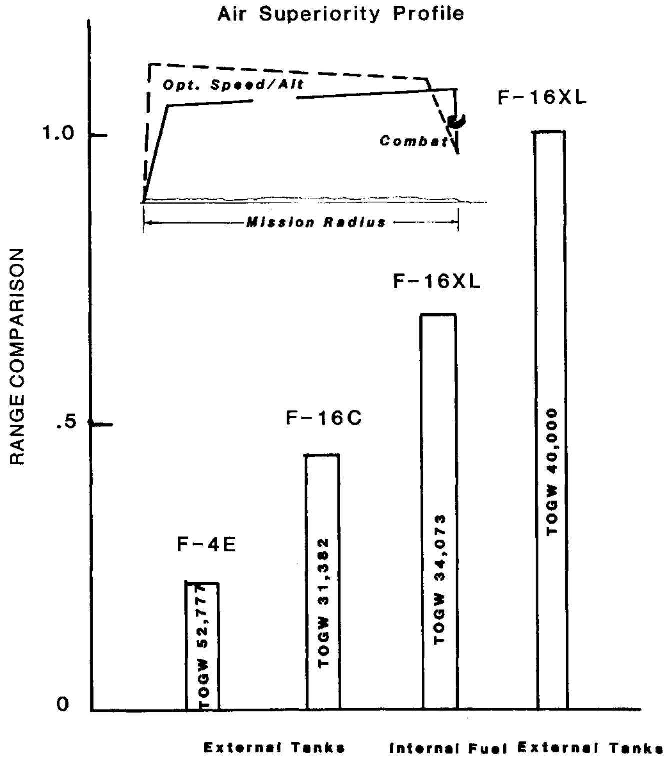


**Fig. 8 Relative increase in range for the F-16XL compared to the F-16 and F-4 aircraft with comparable fuel and air-to-air weapon loads.**

external stores have on an otherwise very aerodynamically efficient fighter. The effect of external stores on the F-16 is three times that of the XL (Fig. 6).

Figure 8 shows a comparison of the relative range for the F-16XL, F-16C, and F-4E configured for the air-to-air mission. Compared to the F-16C, with internal fuel only, the XL shows a 53% increase in range; with external fuel, the increase is 124%. The F-16XL also showed similar results with air-to-ground weapons. With twice the payload, 12 MK-82's on the F-16XL compared to six MK-82's on the F-16A, the XL had a 44% increase in range. The ferry range of the F-16XL with two 600 gal external fuel tanks was 2245 n.m.

*Maneuver Capability*

The F-16XL modification increased the maneuvering flight envelope and allowed relatively unlimited maneuvering for all store loadings tested. The AOA capability of the XL was increased to 29 deg at low speed (26 deg above Mach 0.9). There was an increased structural load capability with external stores to 7.2 *g* (5.86 *g* with external tanks) vs the F-16A limits of 5.5 *g* with air-to-ground stores. Both aircraft have a 9 *g* capability in the air-to-air configuration. The F-16XL's handling qualities were not degraded by external stores. No pilot action was required to recover the aircraft from intentional departures.

*Longitudinal Maneuvering Characteristics*

These characteristics were evaluated with constant Mach number turns and maximum *g* slow down turns. Static stability was evaluated by 1 *g* accelerations and decelerations. In the air-to-air configuration, the normal aircraft fuel burn resulted in a center of gravity (c.g.) range of 44.7-46.4% mean aerodynamic chord (MAC). The allowable c.g. range tested (43.5-47.5% MAC) permitted flight both forward and aft of the neutral point of the XL. Figure 9 shows the neutral point and maneuver point (in percent of MAC) as a function of Mach number. For subsonic Mach numbers, external stores did not cause a shift in the neutral or maneuver points. The effective pitch surface deflections required to trim the aircraft, as a function of Mach number, are shown in Fig. 10. As seen

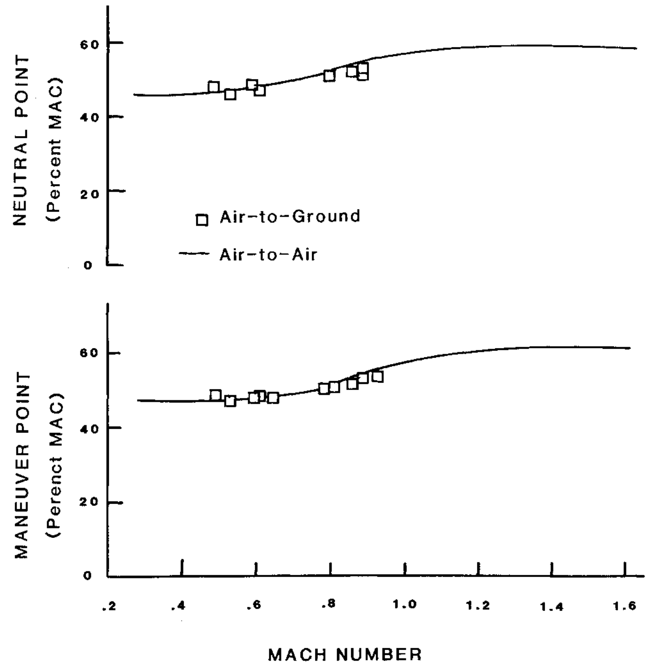


**Fig. 9 Shift in the neutral and maneuver points in percent MAC as a function of Mach number for the air-to-air and air-to-ground store loadings (F-16XL, 30,000 lb gross weight).**

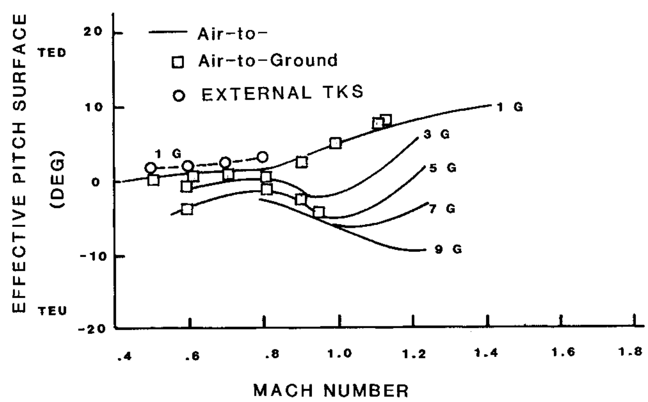


**Fig. 10 Effective pitch trim requirements for 1 *g* and elevated *g* flight as a function of Mach number (F-16XL, 30,000 lb gross weight, 45% MAC, 10,000 ft altitude).**

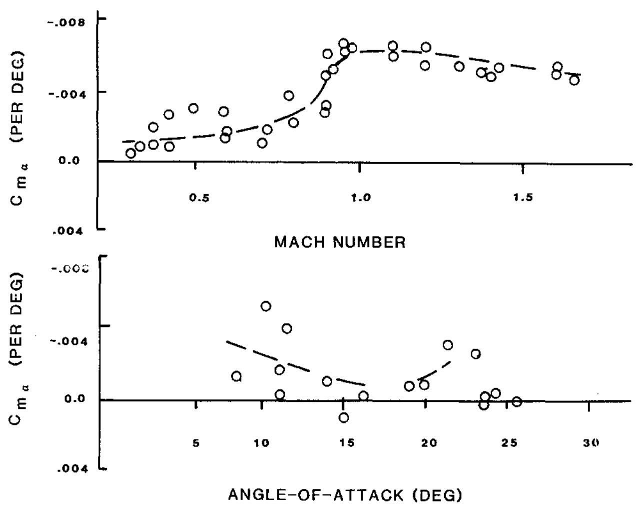


**Fig. 11 Plot of $C_{m_\alpha}$ showing longitudinal stability as a function of Mach number and angle of attack (F-16XL, air-to-air loading, 45% MAC, c.g. pitch stability).**

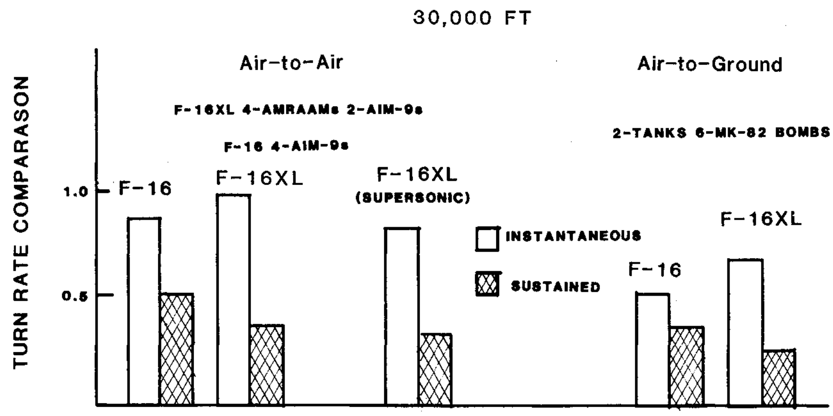


**Fig. 12 Instantaneous and sustained turn capability of the F-16XL vs F-16A at 30,000 ft.**

from Fig. 10, an increase in pitch surface deflection was required for 1 $g$ trim above 0.95 Mach number. This was caused by a decrease in the pitch surface effectiveness and the aft shift of the neutral point. The trim requirements without external tanks were similar for all weapon loadings. With external tanks, 2-3 deg of additional trailing-edge-down (TED) pitch surface are required for trim for a given c.g. The aft c.g. limit tested with tanks was 47% MAC. Figure 11 is a plot of $C_{m_\alpha}$ vs Mach number and AOA. While the XL had positive static longitudinal stability (negative $C_{m_\alpha}$) for all Mach numbers tested, at elevated angles of attack (16–24 deg) and low airspeeds, pitch stability was very low.

The F-16XL was designed to improve dynamic maneuvering (instantaneous turn rate) capability rather than sustained maneuver capability.[1] Figure 12 compares the instantaneous and sustained turn capability of the F-16XL to that of the F-16A. The F-16XL is given an order of merit of one to provide a relative comparison. The F-16XL instantaneous turn rate is 30% higher with the air-to-ground loading and 14% higher than the F-16A with the air-to-air load for the conditions shown. Reported instantaneous turn rate performance for the newer USSR MiG-29 and Su-27 is 20 and 34% higher than the F-16A and F-15 aircraft.[16] Also, the F-16XL has a significant supersonic turn capability. The loss of sustained turn capability, shown in Fig. 12, was a result of the induced drag of the cranked-arrow wing and low $T/W$ ratio as compared to the basic F-16. Pilot comments generally expressed concern about the loss of energy that resulted during high $g$ maneuvers with the XL. Typically, in a hard 180 deg heading change turn, the XL would lose 180 KCAS. The operational utility of the gain in instantaneous turning capability was masked by this loss of energy. The $T/W$ of the F-16XL with half-fuel in the air-to-air loading is 0.7. This is below the historical trend that US fighter aircraft have been following.[16] The major exceptions are the F-111A and the F-14, which also fall below this trend at 0.5 and 0.7, respectively. The exceptional rolling ability of the XL was used to offset this loss of sustained maneuver capability in simulated combat, but the lack of sustained maneuver capability was always raised as a primary concern by the pilots attached to the test program.

*Lateral-Directional Maneuvering*

Evaluation of the F-16XL's static lateral-directional stability was accomplished by performing wings level sideslips to maximum rudder or maximum lateral control required to maintain wings level. Directional control of the aircraft was satisfactory at all conditions and store loadings tested. Lateral-directional stability was not significantly affected by external stores. At AOA's greater than 20 deg, with both air-to-air and air-to-ground store loadings, static directional stability $C_{n\beta}$ was reduced and approached zero at 24 deg AOA (Fig. 13). This reduction in directional stability was not evident to the pilot. The dynamic directional stability parameter

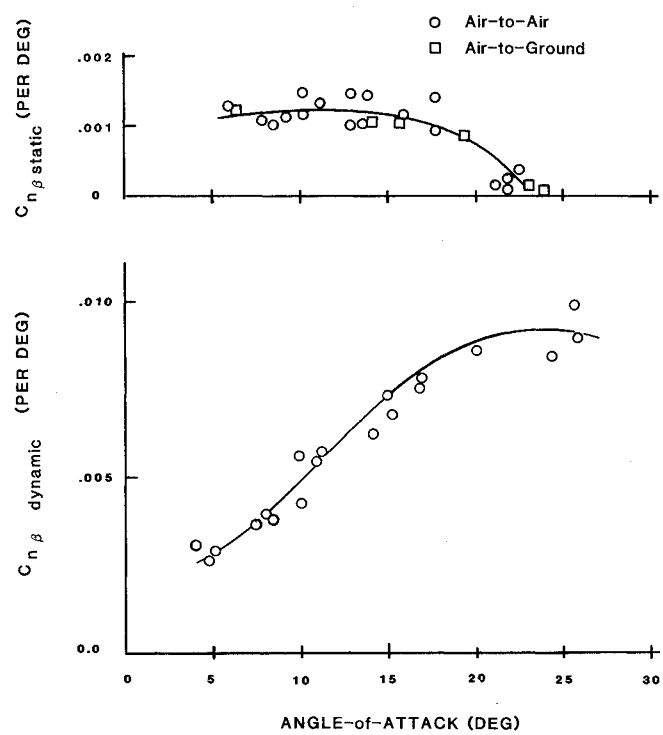


**Fig. 13 Lateral directional stability, $C_{n_\beta}$ and $C_{n\beta_{\mathrm{dynamic}}}$ as a function of Mach number (30,000 lb gross weight, 45% MAC).**

$C_{n\beta_{\mathrm{dynamic}}}$ increased positively with AOA (Fig. 13) and was due to a larger negative increase in $C_{l_\beta}$.

The lateral control power and rolling performance of the F-16XL were excellent both with and without external stores. The XL met or exceeded all of the MIL-F-8785C requirements except at high dynamic pressures where the aircraft was hinge moment limited. The outstanding roll performance was a result of the flight control system, cranked-arrow wing, and conformal carriage of external stores. Table 2 compares the roll performance of the F-16XL and F-16A with air-to-air and air-to-ground stores at equivalent conditions of speed, altitude, and angle of attack. Roll accelerations and roll time constants were consistently better for the F-16XL.

The subsonic roll performance with air-to-ground stores was the same with or without external tanks. The roll performance at high dynamic pressures was reduced because the large hinge moments prevented the aileron actuators from producing the surface deflections commanded by the flight control computer (FLCC). Roll termination was crisp and there was little or no tendency to overshoot the desired bank angle.

Table 2 Comparison of 1 g roll performance of F-16X and F-16A[a]

| Airspeed, Mach no. | Altitude, ft | Maximum roll rate, deg/s | Time to roll thru 90 deg, s | Time to roll thru 180 deg, s |
|---|---|---|---|---|
| | | Air-to-air loading | | |
| 0.6 | 10,000 | 230 (220) | 0.8 (1.0) | 2.1 (2.2) |
| 0.8 | 10,000 | 240 (210) | 0.8 (1.0) | 2.0 (2.25) |
| | | Air-to-ground loading | | |
| 0.6 | 10,000 | 160 (155) | 1.15 (1.45) | 2.8 (NA)[b] |
| 0.8 | 10,000 | 170 (160) | 1.0 (1.25) | 2.7 (NA) |
| 0.8 | 30,000 | 170 (150) | 1.0 (1.45) | 2.7 (NA) |
| | | High-angle-of-attack roll performance | | |

| Angle of attack, deg | Max roll rate air-to-air, deg/s | Max roll rate air-to-ground, deg/s |
|---|---|---|
| 16 | 130 (94) | 120 (NA) |
| 24 | 100 (66) | 60 (NA) |

[a]F-16A results in parentheses. [b]Not available.

*High-Angle-of-Attack Maneuvering*

The high-angle-of-attack flying qualities both with and without external stores was found outstanding and in many respects superior to the F-16A. No placard airspeed or AOA limits were identified for the F-16XL at c.g. positions as far aft as 47.5% MAC. When AOA excursions did occur, no pilot action was required to recover the aircraft. The XL had excellent control response at very low airspeeds while returning to a lower AOA.

The high-AOA testing was accomplished using an XL-1 equipped with a spin recovery parachute system. The maneuvers flown followed a progressive buildup in AOA and aggressiveness. Maneuvers included pitch-yaw-roll doublets, sideslips, 1 *g* and maximum *g* decelerations, maximum command rolls, and roll reversals. Maneuvers from high-pitch attitude climbs (up to 90 deg) included maneuvers with a 180 deg roll followed by a full-aft stick pull, forward-push maneuvers, and full-aft stick maneuvers. The means to obtain uncommanded AOA excursions above the AOA limiter were, with the upright and inverted constant-pitch attitude climbs to minimum airspeed and repeated roll reversals at aft c.g.'s in the AOA range of low-pitch stability, 16–24 deg AOA. Unlike the F-16A/B,[17] AOA excursions were the only type of departure experienced with no deep-stall or spin conditions encountered at c.g.'s as far aft as 47.5% MAC. Figure 14 is a time history plot from a typical 60 deg pitch attitude climb with the roll and pull maneuver initiated at 125 KCAS. The aircraft had two AOA excursions with a maximum AOA of 40 deg. The aircraft quickly falls to a nose-down (−90 deg) pitch attitude, followed by a rapid increase in airspeed, a reduction in the AOA, and a rapid recovery. Figure 15 presents a time history of a 90 deg pitch attitude climb to 0 KCAS (tail slide). The aircraft generated AOA excursions greater than +120 and −90 deg. The aircraft quickly recovered to a nose-down pitch attitude and after two AOA oscillations fully recovered. Only 20 s were required from the start of the tail slide to the point where AOA was 29 deg with the pilot flying the aircraft. When AOA excursions did occur, no pilot action was required to recover the aircraft. Similar maneuvers were also performed with the 12 MK-82 loading and limited testing with external tanks. As in the air-to-air loading, the aircraft exhibited excellent longitudinal flying qualities at high AOA, with slightly increased resistance to AOA excursions during high-pitch attitude climbs. The aft c.g. was restricted to 47% MAC with external tanks due to early program termination.

*Takeoff and Landing*

In the power approach configuration, the F-16XL was smooth, responsive, and stable. Approach and landing handling qualities were similar to the F-16. The landing distances with the XL modification were not improved over the F-16A. Maximum power was normal procedure for all takeoffs. Takeoff performance in XL-1 was degraded at high gross weights and temperatures. The F110 engine installed in XL-2 noticeably improved the hot-day takeoff performance.

For takeoff, the aircraft was rotated to 10 deg AOA at approximately 25 KCAS below the computed takeoff speed. With air-to-ground loadings (heavy weight), the aircraft was

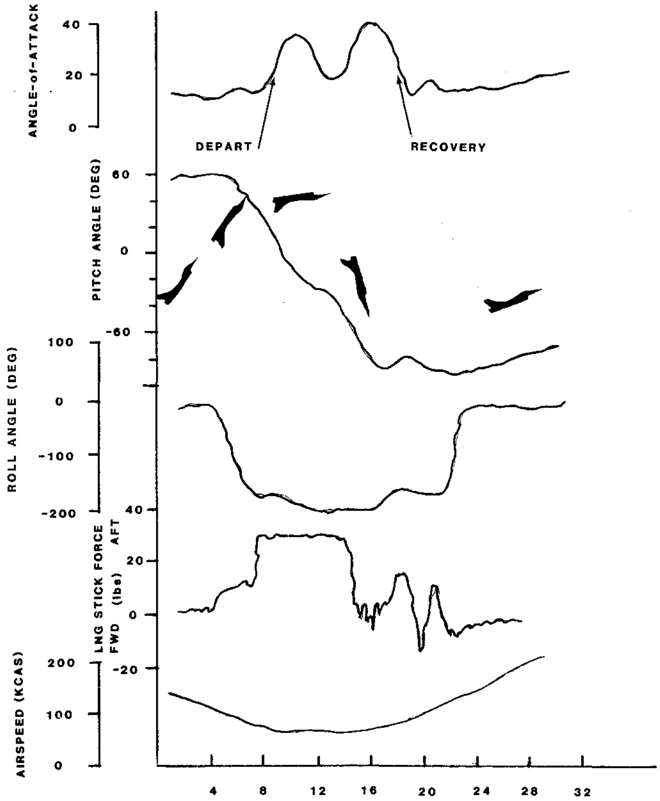


Fig. 14 Time history plot of a 60 deg pitch attitude climb with a roll and pull maneuver initiated at 125 KCAS.

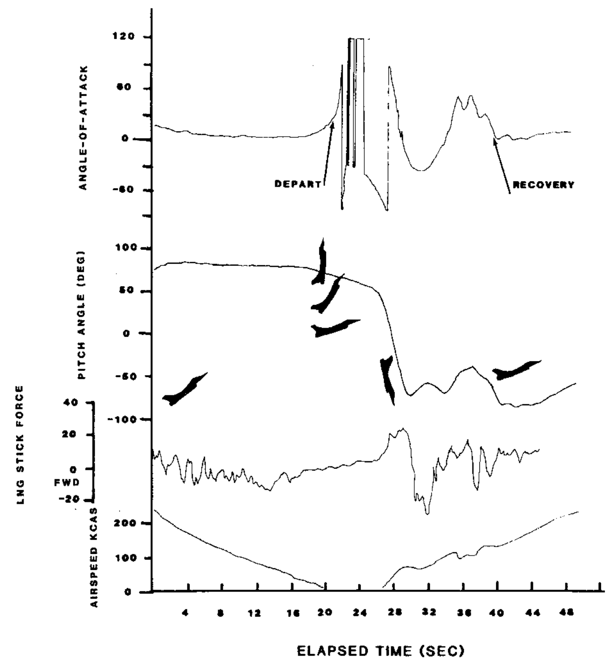


Fig. 15 Time history plot of a vertical climb (90 deg pitch attitude) to zero airspeed (air-to-air loading).

**Table 3 Takeoff performance of XL-1 and XL-2 compared to the F-16A**

| Aircraft | Temp, °F | Weight, lb | Pressure altitude, ft | Distance, ft | Thrust/weight ratio |
|---|---|---|---|---|---|
| F-16XL-1 | 100 | 44,000 | 2300 | 6,250 | 0.33 |
| F-16XL-2 | 100 | 44,000 | 2300 | 3,800 | 0.40 |
| F-16XL-2 | 67 | 35,000 | 2300 | 2,270 | 0.48 |
| F-16A | 100 | 34,500 | 2300 | 4,200 | 0.42 |

**Table 4 Landing distance of the F-16XL**

| Aircraft | Fuel/stores, lb | Aircraft weight, lb | Drag chute | Distance, ft |
|---|---|---|---|---|
| F-16XL | 10,000 | 34,990 | No | 6700 |
| F-16XL | 11,980 | 35,213 | Yes | 5100 |
| F-16XL | 1,100 | 28,206 | No | 2900 |

rotated to 12–14 deg AOA 25 KCAS below takeoff. At main gear liftoff, the AOA was increased to 15 deg. This procedure was used to minimize takeoff distance. The aircraft had a tendency to settle back toward the runway as the aircraft left ground effect. With heavy weight, the aircraft would touch down again if the settling was not countered by the pilot with the aft stick. Table 3 presents typical takeoff distance data for several different conditions and compares the XL-1 and XL-2 (F100 and F110 engines) to a F-16 aircraft. The long takeoff distance of the F-16XL-1 (6250 ft), with heavy weight on a hot day, was due to the low $T/W$ ratio. At comparable thrust-to-weight ratios, the cranked-arrow wing did reduce the required takeoff distance and provided better takeoff performance than a heavyweight F-16 (3800 and 2270 vs 4200 ft). The design goal of improving the takeoff distance, while realized for comparable $T/W$ ratios when compared to the F-16, did not meet the goal of 2000 ft.

The landing approach was flown at 13 deg AOA to touch down. The aircraft has a natural affinity for 13 deg and the airframe provided a useful cue by a slight buffet above 10 deg AOA. External stores did not change this cue. At touchdown, the aircraft was held at 14 deg AOA to 100 KCAS for aerodynamic braking. The nose gear would then be put on the runway and the brakes applied. The visibility over the nose of the XL was very limited for approaches at or above 13 deg AOA. Most pilots raised their seats to increase visibility at this approach AOA. In comparison, the F-16 flew its approach at 11–13 deg AOA. The large XL wing increased ground effect and a flared landing resulted in a smooth touchdown. Although not quite the problem in XL-2, high sink rates during heavyweight approaches could develop due to the induced drag of the wing and the slow response of the turbofan engine. This required the pilot to anticipate power changes and increased the pilot's workload. The improved brakes and aerobraking provided adequate stopping power for routine operation at normal landing gross weights. For adverse and heavyweight conditions, the XL was equipped with an adaptation of the Norwegian drag chute. Table 4 presents typical landing distances for the XL.

The XL did not meet the goal of decreased landing distance. With full internal fuel (35,000 lb), the XL had a landing distance of 6700 ft; with the drag chute, the distance is 5100 ft. For comparison, the F-16 with full internal fuel had a landing distance of 4500 ft. The XL's high approach speed (200 KCAS) at heavyweight conditions contributed to this long landing distance. The aircraft was limited to a 13 deg AOA approach by tail clearance requirements and over-the-nose visibility. Several methods were proposed to increase the lift coefficient while holding AOA constant and thus reducing the approach speed. These included vortex flaps on the inboard leading edge of the wing and changes to the pitching moment to allow the pitch trim surfaces to trim TED. Wind-tunnel evaluations were underway at the time of the program cancellation.

**Table 5 Comparison of the reliability and maintainability of the F-16 and F-16XL aircraft, MMH/FH**

| System | FSD F-16A/B | F-16XL-1 | F-16XL-2 | F-16A fleet |
|---|---|---|---|---|
| Airfame | 0.5 | 0.4 | 0.1 | 0.05 |
| Flight controls | 1.6 | 1.7 | 0.5 | 0.8 |
| Engine | 1.4 | 0.8 | 0.1 | 0.8 |
| Fuel system | 2.6 | 0.9 | 0.4 | 0.9 |
| Weapons | 0.6 | 0.3 | 0.1 | 0.5 |
| Landing gear | 1.2 | 0.8 | 0.4 | 0.4 |
| Hydraulics | 0.4 | 0.4 | 0.2 | 0.1 |
| Total aircraft | 11.6 | 6.8 | 2.9 | 7.1 |

*Radar Signature Reduction*

The cranked-arrow wing and the fueslage stretch provided significant advantages over the F-16 in the reduction of radar signature. Some of the design advantages contributing to this reduction were composite wing skins, longer inlet duct, higher leading-edge wing sweep angle, elimination of the ventral surfaces, and low-profile conformal weapon carriage. Extensive tests on a 40% model showed a reduction in the radar signature over a similarly loaded F-16 aircraft.

*Reliability and Maintainability (R&M)*

The CTF concurrently conducted a limited R&M program during DT&E testing. The aircraft was maintained by the contractor with Air Force maintenance personnel assigned to work closely with the contractor personnel. All deficiencies noted were recorded and passed to the contractor for investigation. Following action by the contractor for investigation, the item was either closed out or held open for a fix at FSD. Table 5 compares the F-16XL and its major systems to the F-16 during its FSD test program and F-16 fleet experience. The comparison is made in maintenance manhour per flight hour (MMH/FH). The F-16XL-1 was comparable to the FSD F-16 in airframe, flight controls, and hydraulics. There was growth in reliability from XL-1—the first prototype—to XL-2. XL-2 matched or exceeded the F-16 fleet experience in flight controls, engine, fuel systems, weapons, and landing gear. Overall, the XL showed the effect of 80% commonality and growth in maturity of the F-16 systems. The overall reliability of the XL was higher than the F-16 fleet experience.

One maintainability area of interest with the XL's unique weapon carriage was the loading of weapons and fuel in a surge environment. During operational testing, the XL was quick-turned with 12 MK-82's, 500 rounds of 20 mm ammunition, 2 AIM-9L's, refueled, and preflighted. The aircraft was ready for pilot acceptance in 16 min and to taxi with self-test of the flight controls complete in 24 min. This met present Tactical Air Force requirements.

## Conclusions

The F-16XL accomplished air-to-ground missions better than the F-16A/B. This flight demonstration program validated many new design concepts that will have far-reaching effects on future fighter aircraft design. The XL modification to the F-16 stretched airframe provided increased payload and range. The XL had significant increased speed capability with more than twice the air-to-ground weapon load when compared to the F-16A. The F-16XL provided the capability to economically carry a large air-to-ground weapon load while maintaining a potent air-to-air capability (four AMRAAMs and two AIM-9L's) for extended ranges.

The XL modification provided many improvements in the air-to-air maneuver region. The XL had outstanding high-angle-of-attack flying qualities and departure-resistant characteristics. The pilot could recover from departures with hands-off control. The high-angle-of-attack flying characteristics were not degraded by air-to-ground weapons. The XL had increased AOA and *g* capability with external stores. The roll performance both at elevated AOA and with external stores and tanks was improved, including the ability to roll 360 deg with bombs. Supersonic performance was significantly improved over the F-16A with external stores.

Areas of deficiencies were primarily related to thrust and weight requirements. At low thrust-to-weight ratios, the takeoff distance was significantly increased. The F110 engine provided greater thrust on hot-day conditions and the takeoff distance was noticeably improved. The low thrust-to-weight ratio negated the advantage of increased instantaneous maneuver potential compared to the F-16, since the increased drag caused the XL to rapidly lose energy during hard maneuvers. The heavyweight approach and landing performance was not acceptable. The heavyweight approach speed of 200 KCAS required a drag chute for routine operations (to minimize brake wear) and resulted in increased landing distances. The requirement to fly 13 deg AOA approaches reduced visibility over the nose of the aircraft. The test program to reduce the approach and landing speed was not completed due to program termination.

## Acknowledgments

The authors wish to acknowledge the outstanding cooperation and dedication of all the past members of the F-16E CTF. This group set the example at the Air Force Flight Test Center on how the combined contractor Air Force DT&E team should work. A special note of thanks for help in preparation of this paper goes to the following individuals: Lt. Col. Edwin A. Thomas, past CTF Director, Mr. Mark Crawford, Lead Flight Dynamics Engineer, and Ms. Lynn Herzog and Ms. Marion Socci, Performance Engineers.

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