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THE X–31A AND ADVANCED HIGHLY MANEUVERABLE AIRCRAFT

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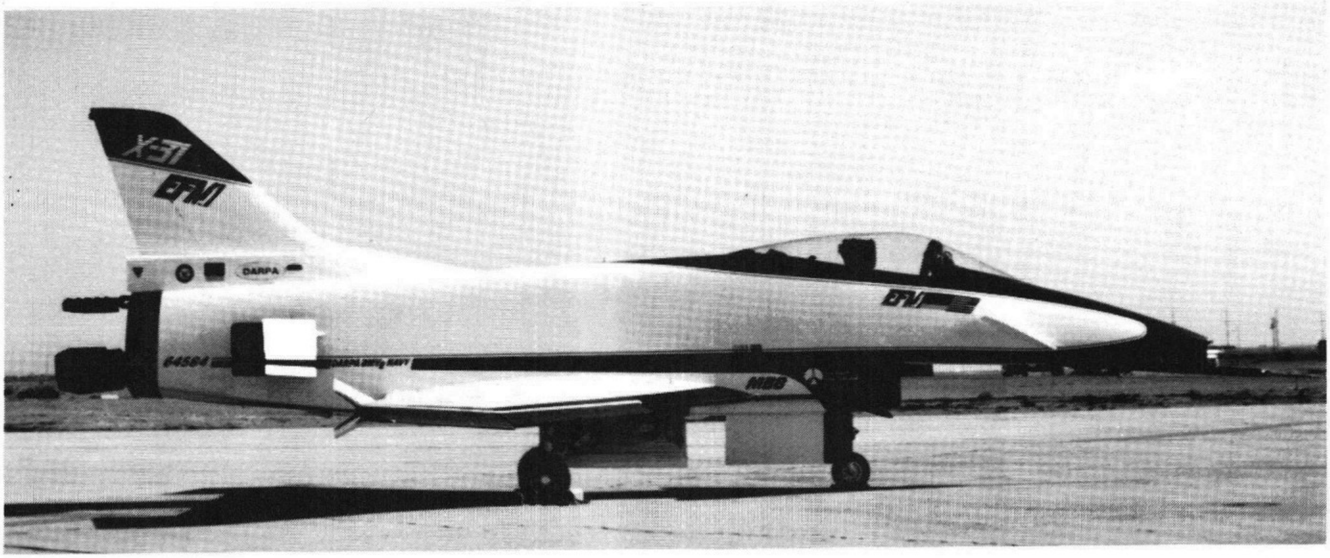


Abstract

The X–31A Enhanced Fighter Maneuverability Program is unique in that its purpose is the demonstration of the tactical utility of Enhanced Fighter Maneuverability (EFM) rather than the generation of in-flight technical data. The genesis of the X–31A vehicle is briefly discussed.

The design criteria are presented, portions of the design effort and the impacts of the low cost requirement are described, and the end result is quantified.

The aerodynamics of this vehicle are described, as are some of the interesting aerodynamic problems and their solutions.

The program is a unique form of collaboration between the U.S. and German governments. Rockwell International Corporation and Messerschmitt-Bolkow-Bohm (MBB). This successful arrangement could form the basis for future international collaborations.

Program Overview

Background

Rockwell and MBB first discussed joint technological collaboration in 1981. After several successful small studies it became apparent that there was mutual interest in improved fighter effectiveness concepts. MBB had been working on a "Post-Stall" maneuvering (PST) concept since 1977. Though radical in comparison to conventional air combat tactics the concept showed high potential payoff. After conducting additional company funded studies to show the potential pay off for both U.S. and German tactical forces a study proposal was presented to the U.S. Defense Advanced Research Projects Agency (DARPA) in February 1983. The proposal was to further quantify the potential of PST, show what additional attributes the PST enabling technologies would bring to future fighters, and to define the best method to mature and demonstrate the new combat capabilities. In late 1984 Rockwell was awarded the proposed study contract with MBB as its team member. This in turn prompted German Ministry of Defense interest and they agreed to match funds for MBB subcontract share for the study. After 12 to 13 months the study results showed that PST had high promise and once implemented in a fighter an additional 5 capabilities could be implemented for no penalty. The resulting six capabilities became known as Enhanced Fighter Maneuverability (EFM).

At the same time it was recommended that a new demonstrator was the only practical course to bring acceptance of the EFM concepts. Luckily, two developments in the U.S. made this proposition attractive and viable. First the Presidents Blue Ribbon Panel on Defense Developments (The Packard Commission) recommended increased prototyping as a "way of life" and recommended DARPA take the lead role. Secondly the U.S. Congress passed the "Nunn-Quayle" Defense Cooperation Iniative to foster and fund joint R&D between the U.S. and its NATO allies.

Program Evolution

Thus the first international X–aircraft development program was formally recognized in a joint agreement between the U.S. and Germany in June 1986 then again on February 23, 1987, when the U.S. Department of Defense assigned the X–31A designation to the Enhanced Fighter Maneuverability demonstrator aircraft. The program is one of the first NATO cooperative efforts initiated under the provisions of the United States Congress Nunn-Quayle Research and Development Initiative and is the first to bear hardware.

The Enhanced Fighter Maneuverability (EFM) program is a joint U.S. and Federal Republic of Germany program. DARPA, sponsors and funds the U.S. part of the program through its agent, the U.S. Naval Air Systems Command, who in turn has contracted Rockwell.International Corporation to build the test aircraft and to develop the new fighter capabilities. Similary, the German Federal Ministry of Defense (FMoD) funds the remaining portion and contracts directly with MBB in Munich, Federal Republic of Germany to conduct the German portions of the effort.

The programmatic relationship between the two countries is governed by a Memorandum of Understanding signed by both parties. This document governs the top level policies for the program and specifies that DARPA provides the overall Program Manager, while FMoD provides the Deputy Program Manager. Rockwell and MBB have established a set of Associate Contractor Agreements governing the operation of the contractors' efforts. This business approach absolutely minimized management layers and duplication of administrative efforts which in turn minimize cost.

The X–31A is an experimental aircraft dedicated to explore controlled flight beyond stall and enhanced agility. It is the first aircraft utilizing thrust vector control in pitch *and* yaw and blending that control with conventional aerodynamic control such that it is transparent to the pilot. The X–31A has the potential of demonstrating superior close-in air combat capability (without sacrifice to supersonic performance) as well as superior beyond-visual-range combat effectiveness. It will be a supersonic capable aircraft with the option of effective low-speed characteristics. It will be superior to any existing fighter in terms of the ability to make quick and tight turns.

The X–31A will offer a unique challenge for pilots. The aircraft will not depart and spin but will be fully maneuverable during and beyond stall conditions. It will be controlled with the stick only, without noticeable sideslip even at very high angles of attack—up to 70° AOA. Rudder pedals will be unnecessary except for intended sideslips and cross wind landings. In high performance post-stall (PST) maneuvers very peculiar attitudes and angular motions will be encountered, however, a new flight display will keep the pilot from getting disoriented and help him to maintain flight path control. For an opponent the maneuvering of a fighter with X–31A capabilities will be hard to predict due to its attitude during PST maneuvers and the quickness to roll and pitch into an unexpected new attitude. Additionally, thrust vector enhanced sideslip maneuvers will allow head-on gun attacks to very short closure at safe collision distances providing more and longer shooting opportunities during close-in air combat.

Program Schedule

The EFM program consists of four phases.

Phase I was the conceptual design phase. During this phase the payoff expected from the application of EFM concepts in future air battles was quantified and the technical requirements for a demonstrator aircraft defined.

Phase II carried out the preliminary design of the demonstrator and detailed the manufacturing approach to be taken. Then completed the detailed design. Three Governmental design reviews were held during Phase II to thoroughly examine the proposed design. Technical experts from the U.S. Navy, FMoD, USAF, and NASA all contributed to the careful examination of all aspects of the design.

Phase III carried out the fabrication of the two experimental vehicles. This phase also required that both aircraft fly a limited flight test program. The first aircraft was rolled on March 1, 1990 and completed low-speed taxi test on June 6, 1990. The first flight will occur in the third quarter of 1990.

Phase IV is the comprehensive flight test phase. During these flight tests the feasibility of controlled flight in the post-stall region will be established and correlations will be made with the Operations Analysis data previously derived. During this phase, close-in combat will be conducted between both similar and dissimilar aircraft, and tactics for the successful employment of EFM will be evolved from tactics generated by ground-based studies.

The four phases of the program are summarized in Figure 1.

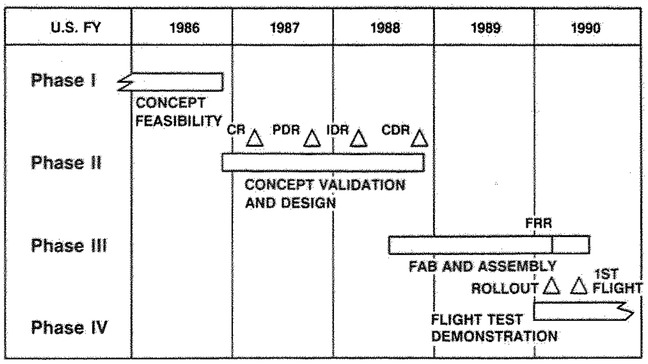


Figure 1. Program Schedule

Program Management Approach

Cooperation Model

The most important factors that enable companies to overcome the hurdles of international cooperation are:

1. To understand the national character of your partner

There are countries which have a very flexible way of thinking and acting, and others tend to be more pragmatic.

If you set up a program with heterogeneous partners, write a Memorandum of Agreement which does not clearly define the rules and goals, and pick the wrong cooperation model—disaster and disenchantment are inevitable.

2. Understand the national policies and procedures

If you are a manager in an international program do not forget that you have to comply with the different national decision milestones. This means that your life will be interesting—even when your program is technically and financially on a sound base.

3. Use the appropriate cooperation model:

   - The integral solution
   - The pilot solution or
   - The cooperative solution

The integral model is often used for major weapon systems (e.g., *Tornado*, EFA). The model is frequently used in European collaborative programs.

It has the advantage that all program partners are represented according to their share. It helps to ease the problem of national sensitivities but requires rather cumbersome, redundant offices in industry as well as in government.

In the pilot model one country takes the lead. This means short line of command and communication—but you have to put aside national pride. Basically one country becomes a subcontractor to another. This has been typical of U.S.–European joint efforts to date.

The cooperative solution is the simplest but sometimes the most dangerous one. Each country is responsible for its work share and budget. Program coordination is done in committees (hopefully very small ones). This model only works when the "national characters" are similar and the parties are willing and mutually motivated.

The EFM Government and Industry team decided to use the cooperative model for this program. The dangers were recognized at the outset, however, evaluation showed that if the low cost prototyping program goals were to be met the elimination of duplication of management, administrative, technical, documentation, and fabrication efforts were a must. This international collaborative approach is clearly best suited to the EFM program goal but it depended upon careful and close co-ordination. All this said the MoA was a relatively loosely defined document.

By limiting specific agreements to key areas, the program management has the flexibility to respond to the changing requirements and new information became available. Potential disadvantages were the potential for misunderstandings and/or misinterpretations which would result from not defining and maintaining a detailed agreement.

It was recognized that misunderstandings are inevitable due to the language barrier, thus a special "program glossary" was developed and proved to be a very useful tool.

Even in a relatively short R&D program such as this new team players tended to come in. A "program management plan" with an update task description, management hierarchy, etc. proved a must .

Both Government and Industry team members feel that the X–31 program serves as an example that one can reduce the negative effects of international cooperation to close to zero while capitalizing on the positive aspects.

This was possible due the professional knowledge, mutual motivation, and sincerity on both sides. We have created international ties which will outlast this program—the X-31A cooperative family should have a long life.

Program Goals

The EFM program has four distinct goals which have remained constant since the program was first proposed. These are:

Rapid Demonstration of EFM: This requires the rapid design and fabrication of two demonstrator aircraft which are to fly under full control in the post-stall regime. While this is a severe challenge itself, the aircraft are also expected to demonstrate other aspects of EFM such as increased agility and roll-coupled fuselage aiming.

Investigate EFM Tactical Exchange Ratios: This requires that the demonstrators be used in simulated close-in combat to verify that the operations analysis results generated earlier were correct. Three stages of tactical flying will be used; (1) flying computer generated post-stall trajectories, (2) flying one X–31 with post-stall capability enabled against the other with the post-stall capability disabled, and (3) flying the X–31 with post-stall capability enabled against a dissimilar operational aircraft.

Develop Design Requirements and Data Base for Future Aircraft: The work generated in support of the first two goals is to be collected, correlated, and prepared for use in applying the EFM concepts to advanced fighter designs. This will be a joint effort of the flight test, design, and operations analysis teams.

The Development and Validation of Low Cost Prototype Concepts: This goal is on a par with the other goals and is one of the unique features of this program. The aircraft Government industry community as a whole needs faster and less expensive methods for generating prototype aircraft. The X–31 team was given a liberal charter to explore some promising avenues for cost and schedule reduction.

The EFM Concept

The concept of supermaneuverability was originated around 1977 in response to the developing all-aspect capability of short range missiles. The ability to successfully launch a missile in almost any clockwise position against an opponent seemed likely to alter the tactics of air combat and thus the performance requirements of fighter aircraft. It was found in extensive manned and computerized air combat simulations that appropriate tactics actually would result in mutual head-on launch opportunities and thus in the dilemma of potential mutual kills amongst equal high performance aircraft. The analysis of such engagements revealed a new maneuver cycle (Figure 2) characterized by dominance of instantaneous maneuvers and a tendency to slow speed. At slower speed an aircraft would achieve a smaller radius of turn at a given rate of turn and, obviously, a tighter turn in a developing mutual head-on situation would allow for an earlier weapon launch at any give off-boresight angle (Figure 3).

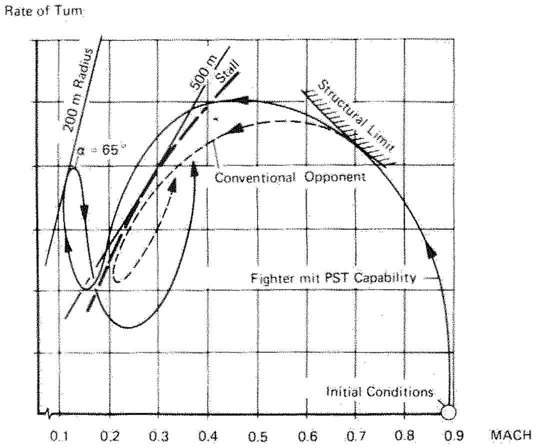


Figure 2. Maneuver Cycle in Future Short Range Air Combat as Experienced in Combat Simulation

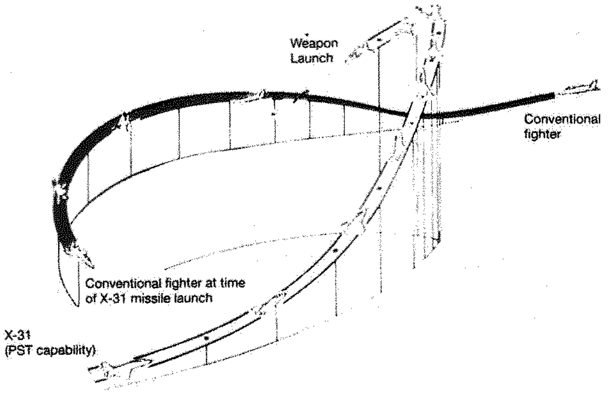


Figure 3. Importance of Turn Radius in Future Air Combat

Conventional aircraft, however, have limited controllability at slow speed and may even get uncontrolled at stall speed just as they are achieving the smallest radius-of-turn. Any significant reduction of radius-of-turn could only be achieved by deeply penetrating the post-stall regime. With thrust vector control and a proper aerodynamic design it was anticipated that an aircraft could be maneuvered safely within and beyond stall limits. Very soon it was found that the biggest design challenge was to roll the aircraft at high angles of attack around its velocity vector quickly enough to achieve the desired tight turn performance.

Generic fighter aircraft with post-stall capability were evaluated first in manned combat simulations at the German IABG in 1977 (1 vs. 1) and in the U.S. during 1978 (1 vs. 2). At that time about 15 operational pilots of USAF and GAF had the opportunity of familiarizing themselves with this new capability and to generate statistical data about its effectiveness. Many technical features now being installed in the X–31A have been empirically developed during those simulations, for example

- Mechanization of lateral stick input to roll the aircraft around the flight path at zero sideslip angle rather than around the familiar aircraft body axis
- Angle of attack and n_z demand with proper blend-over
- PST entry mechanization of the flight control system
- Gravity and gyroscopic moment compensation
- Consideration of inertia coupling
- Scheduling of control surfaces and thrust vectoring blend-in
- Response characteristics and maximum deflection of the thrust vectoring system in pitch and yaw and the criteria for body axis roll

All pilots had to go through a learning process of how to use the new capability in order to achieve a tactical advantage. Many of the maneuver characteristics now being defined as "PST–performance" in X–31A have been developed during manned simulation. This includes the effect of weapons and fire control and as an overall result, it was found

- That combat effectiveness in one vs. one engagements can be expected to be improved by a factor of at least two
- That super-maneuverability would provide a fair chance to survive against two opponents of similar conventional performance
- That the benefit of super-maneuverability tends to increase in multi-bogey situations

These results formed the basis of the acceptance of the program to develop the X–31A test aircraft.

Flight Test Objectives and Expectations

Accordingly the objective of the X–31A aircraft and their test program is to evaluate in flight the technical feasibility of

- Maneuvering at and beyond stall limits
- Agility enhancement by thrust vectoring
- Flight path decoupling (RCFAM) enhancement by thrust vectoring
- Rapid deceleration and corresponding rapid reaccelerations

As the program developed a need developed to evaluate the tactical advantages of these objectives against the previously observed simulated results. Thus the flight test plan was developed to measure X–31A flight performance for each individual capability described above after clearing the aircraft for its design envelope. Finally the program will develop maneuvers to exploit maximum performance. It is anticipated that modifications will have to be made to the flight control system in order to actually achieve maximum performance. The modifications will be based on flight experience related to projected capabilities that were the basis for the original flight control laws.

Expected performance is summarized in Figure 4. Emphasis is on instantaneous turn performance which will have to be achieved within certain types of three-dimensional maneuvers (Figure 5) aimed at turning the direction of flight (velocity vector) at a high angular rate and within a small air space, i.e., to perform instantaneous quick and tight turns. The aircraft needs a roll-rate around the flight path as high as the expected turn rate in order to achieve the desire maneuver performance level. To safely roll the aircraft at a high rate and a high angle of attack is the most demanding capability for the X–31A.

Thrust / t.o.weight (s. l. st. uninst. / t.o. weight)	~1.1
Wing loading	65 lb/ft²
Fuel / t.o. weight	23 %
Empty weight / t.o. weight	75 %
Structure / t.o. weight	36 %

Conv.	Max. SEP	740 ft/s
	Max. sust. turn rate	17 °/s
	Max. inst. turn rate / turn radius	28°/s 1100 ft
	Approach speed	134 Kts
	Max. speed (potential), 36 K	1.6
	Max. decelleration at M ≈ 0.6 / 10 K	0.8 g
EFM	Max. inst. turn rate / turn radius	looking forward to flight testing
	Agility	
	Fuselage aiming	
	Max. decelleration at 70°	

Figure 4. X–31A Performance

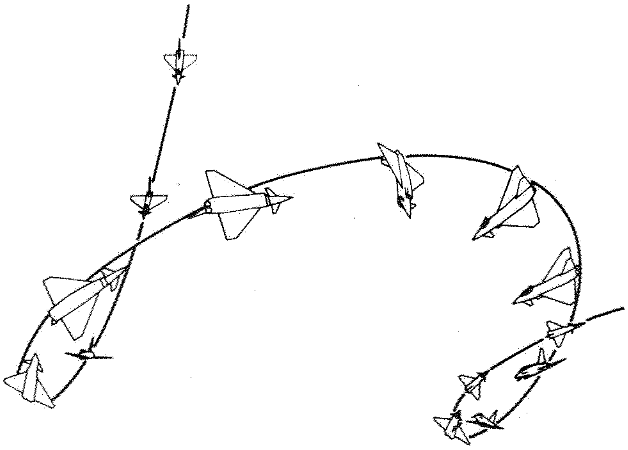


Figure 5. Typical Post-Stall Maneuver

Flight testing in the post-stall regime will also include the evaluation of a special flight attitude symbology displayed on the HUD (and eventually a helmet mounted display). This will allow the pilot to closely control the aircraft trajectory (velocity vector) even at unusual aircraft attitudes while experiencing unusual body motions.

Agility is currently a widely discussed subject, and there are a number of interpretations and engineering definitions in use. The EFM program is proud to have been the originator of these efforts. From the outset the EFM program defined, agility as the ability to quickly change the state of maneuver and/or to rotate the plane of maneuver. Thus, agility is very much related to control power and handling performance. Agility is therefore important to the conventional fighter envelope performance as well as to post-stall performance. In the conventional flight regime, agility is particularly important approaching the aerodynamic stall or control limits. The thrust vectoring system of the X–31A is activated at certain flight conditions in the normal flight regime and therefore contributes to the agility before entering the post-stall regime. Figure 6 depicts a maneuver in which agility will be measured. It is comprised of a maximum performance level wind-up followed by maximum performance reversal. Fine tuning of the flight control system will be necessary in order to maximize both inherent and thrust vector enhanced agility.

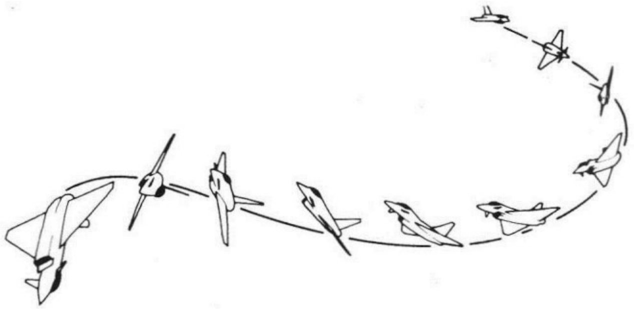


Figure 6. Typical Agility Maneuver

Flight path decoupling (RCFAM) is a special mode of the flight control system by which the pilot can point the aircraft nose (or gun) independently from its trajectory. Upon a stick input by the pilot the aircraft in RCFAM mode will react adversely in pitch and yaw. Of course, the angular range of such decoupling is aerodynamically and structurally limited, however, this limit is increased by thrust vectoring (Figure 7).

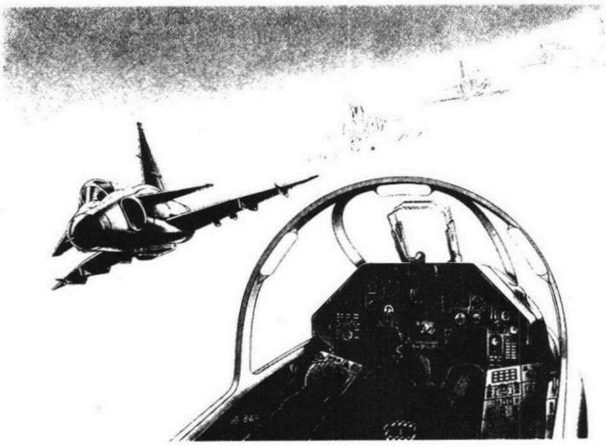


Figure 7. Typical Fuselage Aiming Maneuver

Longitudinal deceleration is important for any aircraft to quickly reduce speed for best turn performance. On EFM aircraft such as the X–31A this capability is used to effectively enter the post-stall regime. The thrust deflection devices can be deployed outwards on the X–31A to act as additional deceleration devices to the conventional speed brakes.

Tactical flight evaluation, at this time, is still in a definition stage. The current aircraft configuration is not equipped with a fire control system, weapons representation or suitable cockpit facilities. However, once the flight envelope has been thoroughly expanded, there is a strong desire to substantiate the expected tactical utility by actual flight experience.

X–31A Design

Configuration Development

The aerodynamic design of the X–31 is based on a combination of MBB's proposed configuration for the European Fighter Aircraft (EFA) and Rockwells high maneuvering fighter demonstrator the HIMAT. For instance the original MBB EFA wing planform, used on the X–31, was a compromise solution to competing requirements of low drag at supersonic speeds, maximum lift at corner speed, minimum induced drag at the design maneuver points, and a balance between relaxed stability at low angle of attack and pitch down recovery moment from high angle of attack. The wing section twist and camber were defined by Rockwell as the best compromise between low speed handling qualities, transonic maneuver performance and supersonic lift to drag ratio.

Configuration studies then evaluated how the resulting levels of required control power could be provided. These studies showed that the aerodynamic controls could provide sufficient nose up pitch control but that nose down pitch control and roll control were marginal above the stall. Yaw from the rudder was inadequate to meet the goals at large angles of attack. It was apparent that thrust vectoring was needed to provide the missing authority necessary for enhanced maneuvering. The two key areas of concern for the aerodynamic design and development of the X–31A were aileron roll control and pitch-down recovery moment without thrust vectoring assistance should there be a system failure.

Wing Design

Successful post-stall maneuvering requires that velocity vector roll be achieved at zero sideslip angle by combining body axis yaw with body axis roll. Since the single engine thrust vectoring of the X–31A can provide no rolling moment, all body axis roll during post-stall must be provided by the ailerons. Careful attention was paid to high alpha aileron effectiveness in designing planform, thickness twist and camber of the outboard wing.

The successful demonstration of the operational effectiveness of the X–31 depends on the conventional maneuvering and supersonic cruise performance of the aircraft as well as performance in the enhanced flight regimes. It was considered imperative that a simplified multipoint wing design be conducted to optimize the X–31 conventional performance. The design goal was to select wing and canard twist distributions, a fixed canard camber, and a compromise wing camber that could be varied using the leading and trailing edge flaps.

The approach was to minimize the drag due to lift at selected operating points in the design envelope. Two points, one representing transonic maneuvering "corner point" and the other representing supersonic cruise were chosen. At each design point, an optimum fixed wing and canard camber was identified. A compromise configuration was then developed, using the optimum cambers and their associated induced drag values for guidance. The resulting compromise was a fixed-camber wing box that could be additionally cambered for transonic maneuvering or de-cambered for super-cruise. Canard twist and camber were then selected to enhance the compromise wing design. Wing flap deflections for optimum performance were used in establishing control surface schedules.

The resulting wing is a clipped double delta planform with 56.6 degrees of leading edge sweep inboard, and 45 degrees outboard. Rockwell applied a proprietary transonic airfoil of 5% thickness in combination with the compromise twist and camber distribution to this wing. This airfoil has a generous leading edge radius which benefits the high angle of attach performance.

The use of graphite epoxy wing skins, and the method of attaching the wings resulted in the requirement that the wing skin loads be taken out in line with the center of the wing skin thickness. Thus, a fairing was necessary to cover the wing attachment fittings at the root of the wing. This became a 7% thick transonic section at the fuselage which faired out to become tangent to the original outer mold line about 25 inches out from the fuselage.

MBB was selected to build the wing.

The Wind Tunnel Development Program

The development of the final X–31 configuration from the initial concept was paced by the wind tunnel test program outlined in Figure 8.

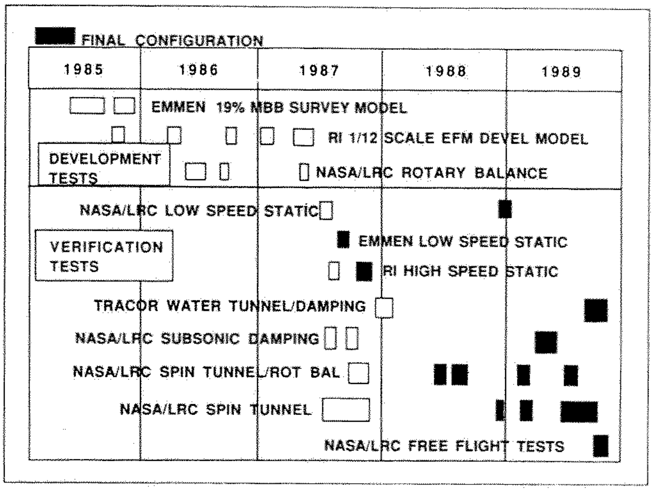


Figure 8. Summary of X–31 Wind Tunnel Tests

The initial "P–20" configuration was tested in the Swiss Federal Aircraft Factory low-speed wind tunnel at Emmen, Switzerland in 1985. A 19% scale model of an MBB fighter design was modified to approximate the X–31A single engine design and fitted with a flat plate wing. This test verified the basic design concept and provided the first opportunity for tuning the aircraft static aerodynamics development.

The results of this tests were used to generate an aerodynamic data set representing the P–20 aerodynamics, and the data set was in turn used in early digital simulations to evaluate the potential performance and maneuverability of the aircraft. Since the simulation results were satisfactory, many of the P–20 aerodynamic values became goals to maintain as the X–31A design matured.

A model of the P–20 was built and tested on the rotary rig balance in NASA Langley Research Center spin tunnel to provide early evaluation of departure, spin susceptibility and recoverability, and an indication of aerodynamic damping dynamic characteristics. The high angle of attack flight regime intended for the X–31 made it imperative that these effects be considered early in the design of the aircraft rather than accepted as a fallout of the configuration.

Configuration work at Rockwell resulted in a significantly modified configuration. A model of this version was manufactured and tested in the Rockwell low speed wind tunnel. This model also used flat plate wing and tail surfaces and was used to check on the development of the overall configuration changes. Notably a fuselage length increase became necessary, to provide fuel volume and to realistically emulate modern fighter fineness ratios; thus the model was modified to reflect the changes. The wind tunnel data confirmed that the aerodynamics from this modified configuration were acceptable.During this series of tests in the Rockwell low speed wind tunnel, the effects of wing location (fore and aft, and up and down) were defined, as well as effectiveness of the proposed speed brakes and strakes. However, an even more significant finding was made-model scale for high angle of attack aircraft design was the driver in obtaining credible, reliable wind tunnel data. As a result a common low speed model scale of about 0.2 was selected for all further testing.

The NASA 14 by 22 feet VSTOL tunnel was used to test the first of these constant scale models. Considerable development on details of the configuration were carried out during this test series. An interesting phenomena uncovered during this test series was the lateral/direction destabilization of the configuration due to the location of the nose boom. It was found that the placement of the nose boom on the center line of the radome or above had a detrimental effect upon the lateral/directional stability. It had been expected that the boom would have to be moved from the center line position, but the upper location was expected to be the favored site. These tests showed that the best location for this boom was essentially underneath the radome.

A high speed model was fabricated and tested in the Rockwell Transonic Wind Tunnel (TWT). These tests measured the aerodynamics of the configuration up to 1.6M. These tests derived the Mach number effects used in the development of the aerodynamic data base thus, design loads and the control system.

A series of tests were run in the Tracor (Greenbelt MD, USA) water channel to determine the damping derivatives at large angles of attack. The basic data from these tests correlated closely with the data from the Langley 30 by 60 tests. The Tracor tests were beneficial in that they separated out the C_{mq} and $C_{malpha\ dot}$ values which cannot be done in a conventional wind tunnel. It was shown that the sum of the two values generated in the Tracor tests does not correspond with the summed value measured in the wind tunnel at high angle of attack. This may become important in the departure simulation.

At this point in the program a configuration change occurred. The F–16 canopy was replaced by the F–18 canopy in order to save weight. The change was not limited to the canopy but spread to the entire upper fuselage from the canopy to the vertical tail. Obviously this change required additional wind tunnel tests to ensure that the change did not interfere with the generally good high angle of attack aerodynamics.

The tests of the revised configuration showed only minor differences between configuration. The principal change was a small reduction in the static directional stability.

Thrust Vectoring System

The thrust vectoring system used on the X–31A is the result of a joint development between Rockwell and the U.S. Navy's David Taylor Research and Development Center. At that time Navy interest was for a yaw-producing paddle system fitted to the F–14. As an aside this concept was eventually tested on an F–14 spin test aircraft. Rockwell's early IR&D studies showed that only 10 to 15 degrees of thrust vectoring of the F404 engine maximum afterburner thrust were required to achieve the control requirements for EFM maneuvering..

A series of subscale nozzles and thrust vectoring vanes were tested under this IR&D program in the Langley Research Center blow down facility. These tests included rectangular and rotational symmetric nozzles. The rotationally symmetric nozzle tests included both three and four paddles equally spaced around the nozzle exit. Since no such concept had been previously tested there was doubt as to scale and Reynolds Number Effects of such small scale testing.

As a result full scale test of the thrust vectoring system was carried out at the Naval Air Test Center, Patuxant River MD, USA. Since the Navy's F-18 utilized the same engine as the X-31A one of the test F-18's was set up in the same proximity to the thrust vector vances as the X-31 test. Figure 9 shows the A–frame that was built to carry the three thrust vectoring paddles and the loads generated on them. This A–frame was located just behind the "center field" thrust measurement stand so that the aircraft net thrust could be measured at the same time as the forces and moments on the paddles were being measured. The A–frame was instrumented so that all the forces and moments on one paddle could be measured. All three paddles were remotely actuated so that the paddle deflections could be changed from the control van during the course of an engine run.

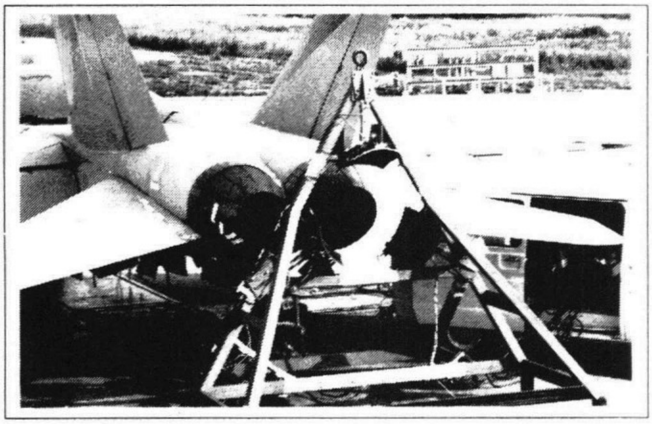


Figure 9. Full Scale Thrust Vectoring System Test Setup

The end result of these tests were that a high degree of confidence exists in the ability of the thrust vectoring system to generate the required forces and moments, and that the paddles can withstand the thermal environment. Even more important the results correlated with the small scale tests. The thrust vectoring paddles are manufactured from carbon/carbon composites, with steel inserts for the trunnions and actuator attachments. The paddles are attached to the base of the aircraft through the use of titanium fittings. The actuators and control valves are all contained within the base of the aircraft. The fabrication of the paddles was also assigned to MBB.

Fuselage

The design of the fuselage was a crucial element in the design of this aircraft since, like all modern aircraft, it carries the majority of the subsystems. From front to rear, the fuselage carries the flight instrumentation, the cockpit, the Flight Control Computers, the Environmental Control System (ECS), the Emergency Power Unit (EPU) and Emergency Air Start System (EASS) systems, the fuel tank, the Aircraft Mounted Accessory Drive (AMAD), the engine, the spin recovery parachute system, and the thrust vectoring controls. The fuselage also provides mounts for the wing, canard, fin, and landing gear. The final positioning and selection of the various subsystems was the result of a long series of trade studies.

The cockpit uses many F/A–18 elements, such as the windshield, canopy, seal, stick, throttle, instrument panel, and the digital displays. The rudder pedals are F–16 equipment. This was a cost saving decision but imposed little or no technical penalities.

The center section of the fuselage is a sophisticated balance of aerodynamic and low cost design. From just aft of the canopy to just aft of the trailing edge, the upper fuselage has a constant cross section shape. This was done to allow the light metal frames to be manufactured from one single hydropress form. The upper center line of the fuselage has a negative slope in this region. This area reduction generates the area ruling needed to minimize the transonic drag rise. The vertical sides at the wing provide the optimum wing-fuselage joint and allow the wing glove to be a simple structure.

Rockwell was assigned responsibility for Fuselage Fabrication.

Canard

The X–31 canard is lightly loaded, and is not highly coupled with the wing aerodynamically. It is primarily a safety device to assure pitch down capability should the thrust vecter system fail at high angle of attack. Early trade studies looked at using the B–1B Structural Model Control Vane for this purpose. However, the B–1B vanes weighed over 50% more than the weight allowance for the canards, so the idea was dropped. However, the forged spindle for the B–1B vane was used as the structural foundation of the X–31 canard. Using this existing forging saved both money and time. Left and right canard panels are identical and can therefore be used on either side. Cambering and twisting the panels was examined but was dropped in favor of the lower cost uncambered panel concept. Rockwell also had canard fabrication responsibility.

Vertical Tail

The single vertical tail attachment is designed as a fail safe structure. Concerns over the unknown buffeting loads during high angle of attack flight and experience with current fighter aircraft dictated this as a prudent design approach. The composite vertical tail was another Rockwell responsibility.

Inlet and Duct

MBB-supplied an extensive inlet and duct data base for high angle of attack operation. These data were used for the development of the X–31 duct lines. The inlet includes a movable lower lip which significantly reduces the distortion at high angles of attack. A boundary layer diverter above the inlet was utilized to provide air to the ECS intake and to the fuel-oil cooler heat exchanger. Due to the geometric restrictions imposed on this design, this secondary inlet had to capture more airflow than was necessary to satisfy the two requirements described above. The excess airflow is dumped overboard. Again the metal inlet and composite ducts were Rockwell's fabrication responsibility.

Landing Gear

Choosing the landing gear for the X–31 was a difficult job, given the schedule, and financial constraints. Three types of main landing gear were considered: the F–16 type of tripod gear mounted in the fuselage, the AlphaJet type of fuselage-mounted cantilever landing gear, and the F–5 type of wing mounted gear. A spring steel cantilever gear was considered briefly but the lack of damping in such a design made it a non-competitior.

The F–16 landing gear was found to fit with some minor modification. For the main landing gear, a Cessna Citation main landing gear wheel and brakes and an A–7 tire were used. The nose landing gear uses the standard F–16 wheel and tire combination.

The use of the F–16 gear also allowed the program to take advantage of the known capability of the gear. Again the costs of a flight qualification test were minimized.

Fuel System

The fuel system for this aircraft has the difficult job of delivering the fuel to the engine over an extraordinarily wide range of attitudes and g's. In addition, the emphasis is on low cost dictated simple solutions. As a result, the entire fuel system was housed in one large gravity fed fuel tank centered over the aircraft center of gravity. The CG shift between full and empty is only about 2% MAC. The fuel cell caries two double-ended fuel pumps enclosed in negative g cells on the floor of the tank; one is in the forward left corner of the tank and the other is in the aft right corner.

The fuel tank uses machined surfaces and polysulfide sealant to preclude leaks. The location and arrangement of the tank is such that deflections in the structure have been minimized.

Structural Design

Structural Concept

Trade studies showed that the use of the Rockwell and MBB CADAM capabilities would result in the lowest airframe cost. Therefore, the design was structured to take advantage of these advanced tools.

The fuselage is made from eleven major bulkheads connected by four principal longerons. See Figure 10. Intermediate frames manufactured from sheet metal are added between the major frames. The forward skins around the cockpit area are graphite epoxy skins over honeycomb cores. The center section of the fuselage uses aluminum-lithium sheet draped over the constant cross section frames. The final 30 inches of the fuselage is built up from titanium frames and covered with titanium skin in order to withstand any unknown heat loads induced by the thrust vectoring system.

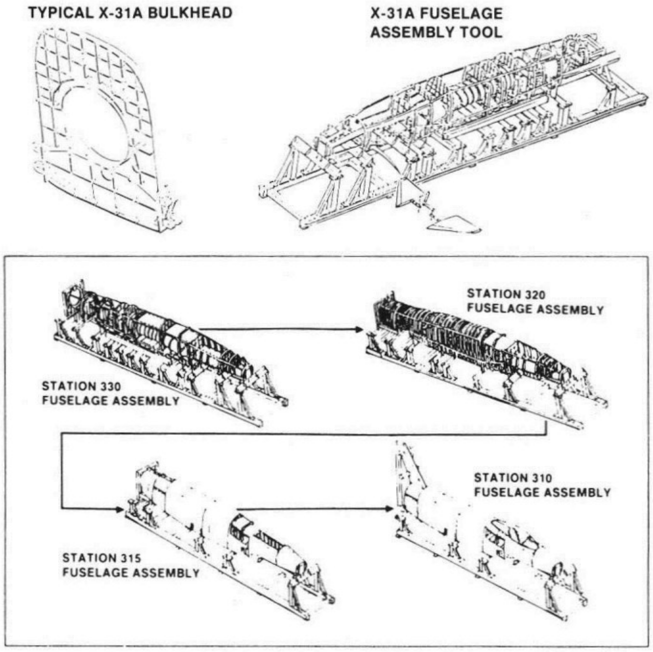


Figure 10. The Fuselage Assembly Process for the X–31

These bulkheads do double duty, serving both as part of the assembly tool and as part of the aircraft structure. All but two of the bulkheads were machined from single blocks of aluminum. These two bulkheads carry the wing bending ties and required that the lower sections be machined out of much thicker blocks than the upper part. Therefore, the two pieces were machined separately and then joined mechanically.

The wing structural configuration was the subject of a long trade study. The resulting configuration consists of two separate panels which are bolted onto the fuselage using two bending ties and two shear ties for each panel. In order to fair over the bending tie lugs, a thicker wing root section of some 7% thickness was generated using the same design philosophy as used for the main wing airfoil. This airfoil was then implemented as a glove over the structural wing box, and terminates at the fuselage side.

The canard is manufactured from graphite epoxy skins and honeycomb core bonded to the modified B–1B structural mode control vane spindle. The leading edge is a graphite epoxy shape bonded into place.

The vertical tail internal structure of five spars and five ribs is manufactured from aluminum. The outer skins and tip cap are made from graphite epoxy. The rudder consists of graphite epoxy skins over a honeycomb core.

The inlet is basically rectangular in cross section and is assembled from numerically controlled machined parts and sheet metal. The duct is manufactured from graphite epoxy skin over honeycomb core. It was manufactured in two sections to facilitate installation.

Structural Analysis

The principal analysis tool used for structural design was NASTRAN. Figure 11 shows the final structural analysis model which has some 20,000 degrees of freedom. This model evolved during the design process along with the design of the structure. Rockwell laid out the first coarse model, and electronically transmitted the wing portion to MBB in Germany. MBB then took this wing model and upgraded it to match the evolving wing design and returned the model to Rockwell, again electronically. Load estimates were transmitted both ways also. In this manner, the fuselage and wing designs were synchronized and matched.

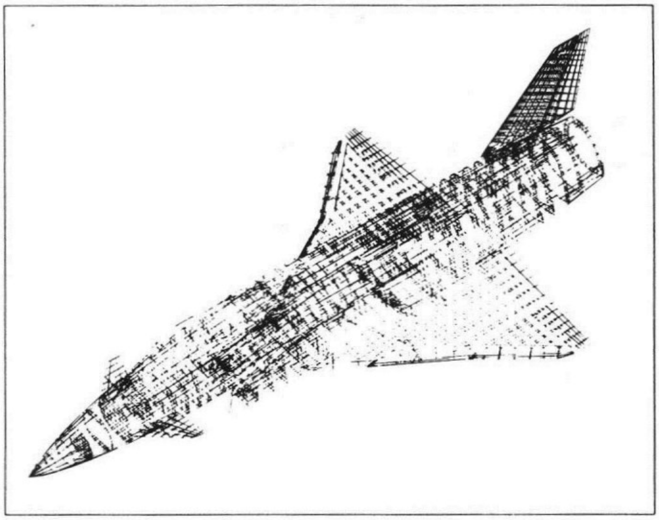


Figure 11. The Finite Element Model of the X–31

Results

The degree of success in designing and building a successful demonstrator is shown in Figure 12. This figure compares the material tooling, engineering, and fabrication costs for the X–31A to those of previous aircraft at the same point in their production cycle. The material costs for the two X–31A aircraft are on a par with those of the F–16 production program, which was able to achieve substantial discounts by virtue of volume purchases. The tooling costs for the X–31 are one-third of those for an equivalent completely new aircraft, the XF–100A, and 20% less than those of the XF–86A, which made use of experience and tooling from the XFJ–1 program.

The engineering and fabrication/assembly hours per pound follow the same trend; they are far less than those for a completely new aircraft, and considerably less than those for a derivative aircraft.

The final configuration of the X–31 is given in Figure 13. This aircraft has a normal takeoff gross weight of 15,935 pounds including 4,136 pounds of fuel. An additional 836 pounds of fuel can be accommodated if required.

Test flights are expected to commence during the summer of 1990. All indications are that this aircraft will meet the goals established for it.

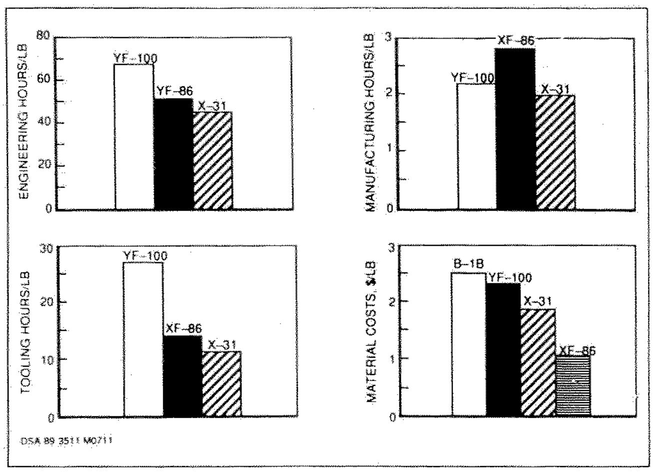
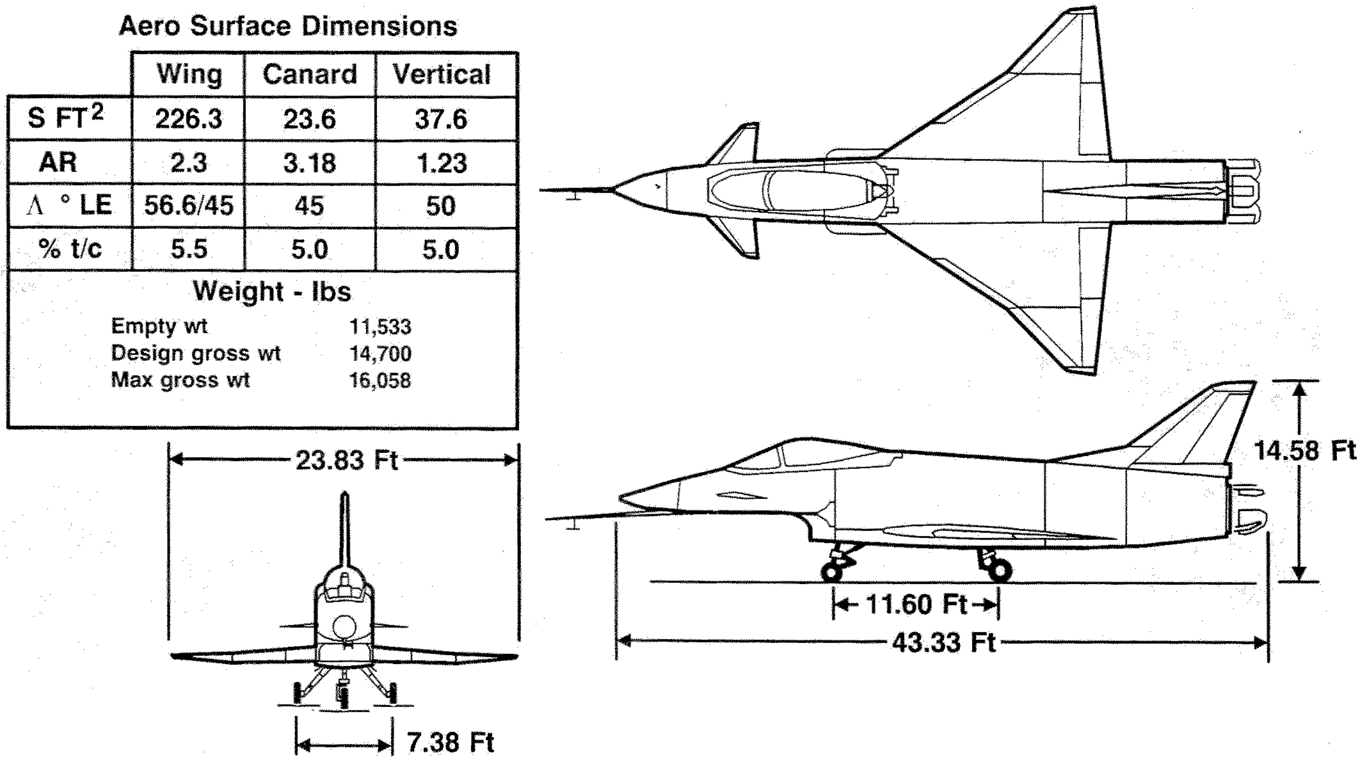


Figure 12. The X–31 Cost of Fabrication as Assembly

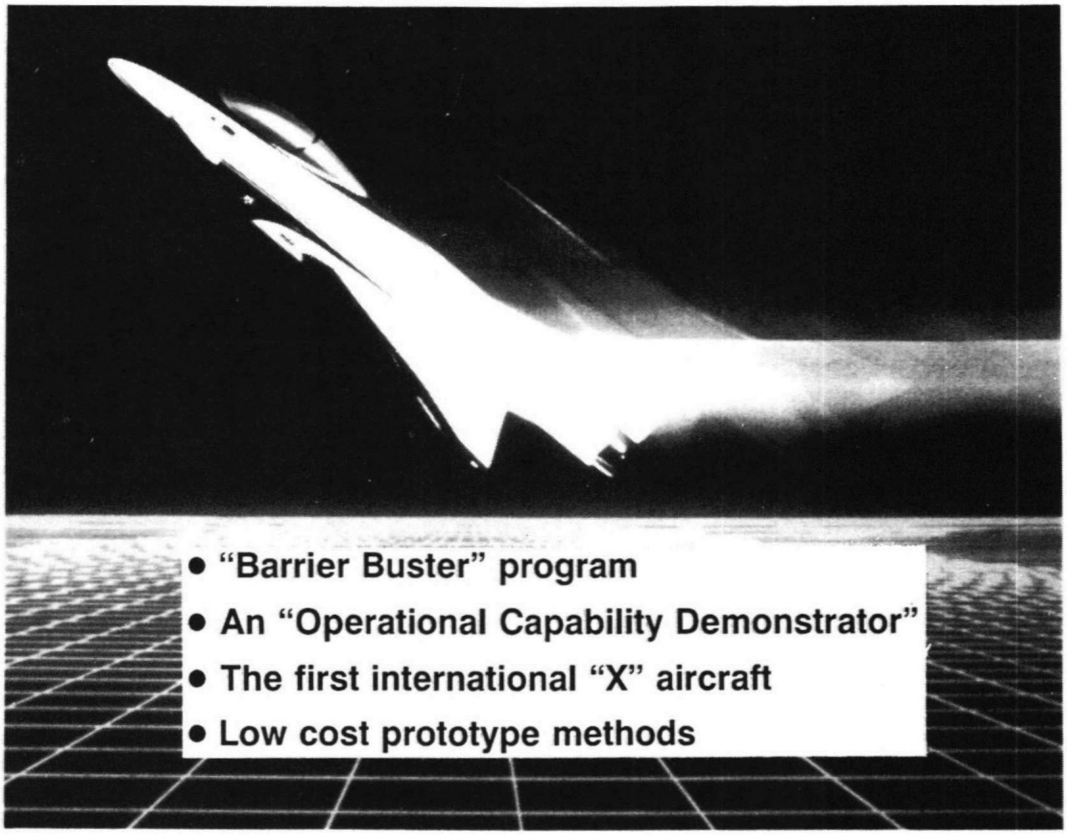

Aero Surface Dimensions

	Wing	Canard	Vertical
S FT^2	226.3	23.6	37.6
AR	2.3	3.18	1.23
Λ ° LE	56.6/45	45	50
% t/c	5.5	5.0	5.0

Weight - lbs

Empty wt	11,533
Design gross wt	14,700
Max gross wt	16,058

Figure 13. General Arrangement Drawing of the X–31



- "Barrier Buster" program
- An "Operational Capability Demonstrator"
- The first international "X" aircraft
- Low cost prototype methods

X–31 Rollout—March 1, 1990