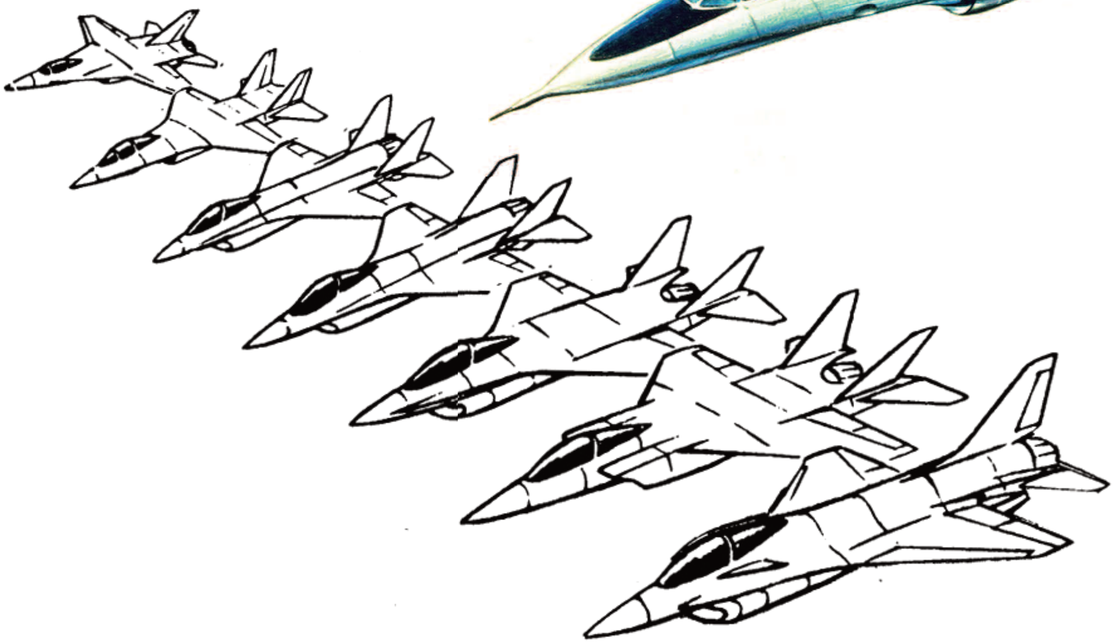
Evolution of the F-16

A Secret Projects Forum Study

Paul Martell-Mead



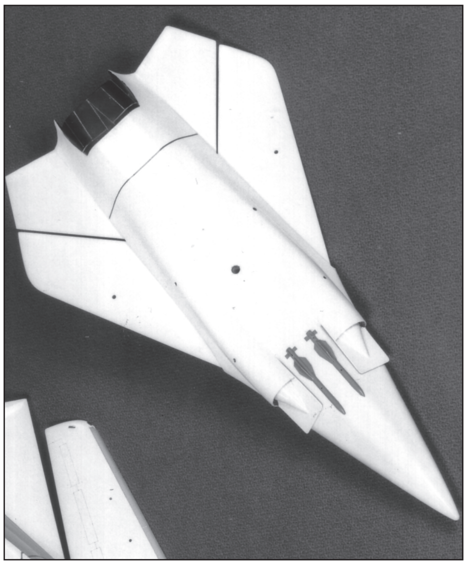
The F-16 has its first origins in 1962, when General Dynamics engineer Harry Hillaker visited the Eglin AFB O'Club and met US Air force officer John Boyd. On learning that Hillaker was working on the F-111, at that time supposed to be able to fill the fighter role. John Boyd ranted on about how the design was too large, underpowe red, and with a swing-wing mechanism too complex and liable to fatigue and stress cracks. His criticisms, partly rooted in early analysis he'd performed with mathematician John Christie working towards his definitive Energy Manoeuvrability theory, struck a chord with Hillaker, who shared many of Boyd's doubts about the utility of the F-111 as a fighter.

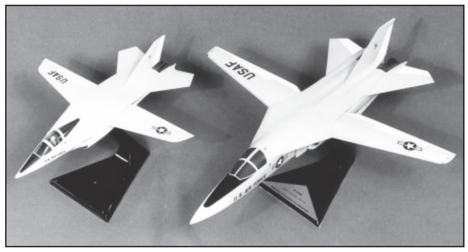
The two men sat down for a wide-ranging chat on aircraft design theory, by the of which Boyd and Hillaker had agreed that they would both like to develop a small manoeuvrable fighter.

Boyd and Hillaker weren't alone in this. Some Air Force and Navy pilots were convinced that manouverablity was far from irrelevant, and from 1962 an alliance of industry members, former and current pilots dubbed the "Air Superiority Society" were involved in a crusade to get a new lightweight air superiority fighter built. A key member was Charles ‘Chuck’ Meyers, who after retiring as a pilot was was working as a consultant for Lockheed trying (unsuccessfully) to sell the US Air Force on the F-104 as the ide air superiority solution.

After this chance meeting Hillaker went back to his day job on the F-111 at Forth Worth and spent some of his spare time on lightweight fighter ideas, while Boyd completed his Energy-Manoeuvring Theory and went on to analyse then-current Soviet aircraft manoeuvrability using his theories. He came to the un-

Below: *John Boyd.* **Below right:** *Harry Hillaker.*



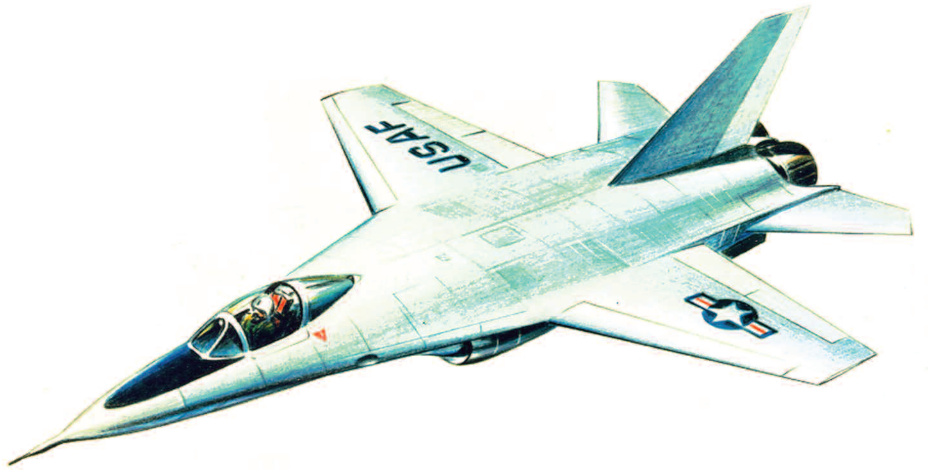


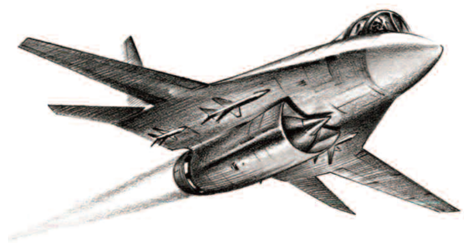
***Above and left**: General Dynamics variable geometry ADF design, 1965, seen next to an F-111 for size and shape comparison. Note the unusual AAMs and F-111 type intakes.*
via Scott Lowther

pleasant conclusion that the MiG-21 outmanoeuvred the F-4 Phantom II in most situations, whereas the F-111 was totally outclassed everywhere by any opponent in manouvring.

In early 1965 after some air combat problems faced by F-105 pilots, Boyd was sent to Vietnam to brief pilots about improved manoeuvring tactics. He followed this with a series of briefings to Air Force commanders where the problems with the F-111 as a fighter were highlighted. He kept up a postal correspondence with Hillaker on the lightweight fighter theme during his time in Vietnam.

In 1965, while development effort started on a big, complex Advanced Tactical Fighter that eventually became the F-15, the lightweight fighter group had gained sufficent momentum that the Air Force started concept formulation studies of an Advanced Day Fighter (ADF) with the goal of developing a 25,000 pound fighter with a thrust-to





Above: *Harry Hillaker's fixed wing ADF design (1965) shows F-111 influences in inlet and overall shape.* ***Right:*** *General Dynamics single engine F-X studies (1968) were close cousins to the earlier ADF design but with single engines and twin vertical tails.* **Code One, Bob Cunningham**

weight ratio high enough and wing loading low enough to outperform the MiG-21 by 25%.

Meanwhile at General Dynamics Fort Worth with his involvement on the F-111 tailing off Hillaker had managed to get internal development funding to start work on a small maneuvering fighter concept suitable for the ADF study.

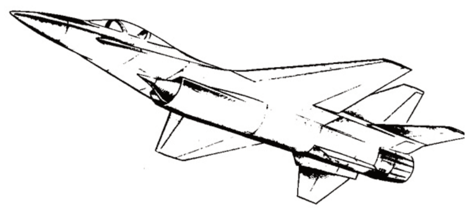
Hillaker said in an interview in 1991 'I don't think too many people within the company were aware of what was going on for a long time. It was three or four years before anyone outside of Bob Widmer and one or two other people knew what we were doing'.

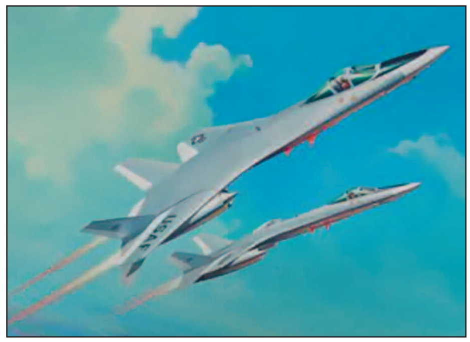
This was pretty far from their normal line of work - General Dynamics (Forth Worth) had previously specialised in bombers, producing the B-36 and B-58, while General Dynamics San Diego designed fighters (F-102, F-106). Fort Worth's latest design, the F-111, was huge, and unmanouverable, so a lightweight fighter design was not an obvious sell to the Air Force or to Forth Worth management.

In 1966, John Boyd was sent to the Pentagon to help analyse and define the requirements for the evolving F-X fighter program. While there, he met Pierre Sprey and, later on, Everest Riccioni, who would become influential members of a new "lightweight fighter" cabal, the infamous "Fighter Mafia".

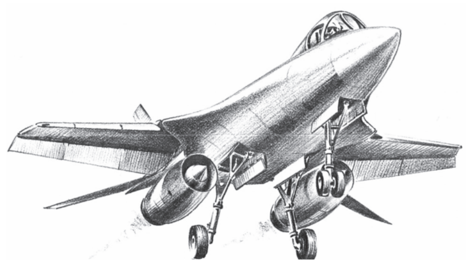
The lightweight ADF concept was never in total favour with the Air Force and when the MiG-25 'Foxbat' was unveiled in 1967 all money and effort was concentrated on the larger, faster, more complicated F-X to defeat this aircraft.

General Dynamics did not participate in the earliest concept exploration studies for Tactical Fighter / F-X in 1965 and 1966 but in 1967 won a contract for concept formulation studies alongside McDonnell-Douglas. While the air force was looking for a large, very complex, probably variable geometry fighter, as part of this contract Harry Hillaker worked on a single-engine, lighter weight concept alongside the more compliant large variable-geometry design. Both designs built on concepts already explored in the earlier ADF studies by Hillaker, most notably the blended fuselage tapering into a blunt

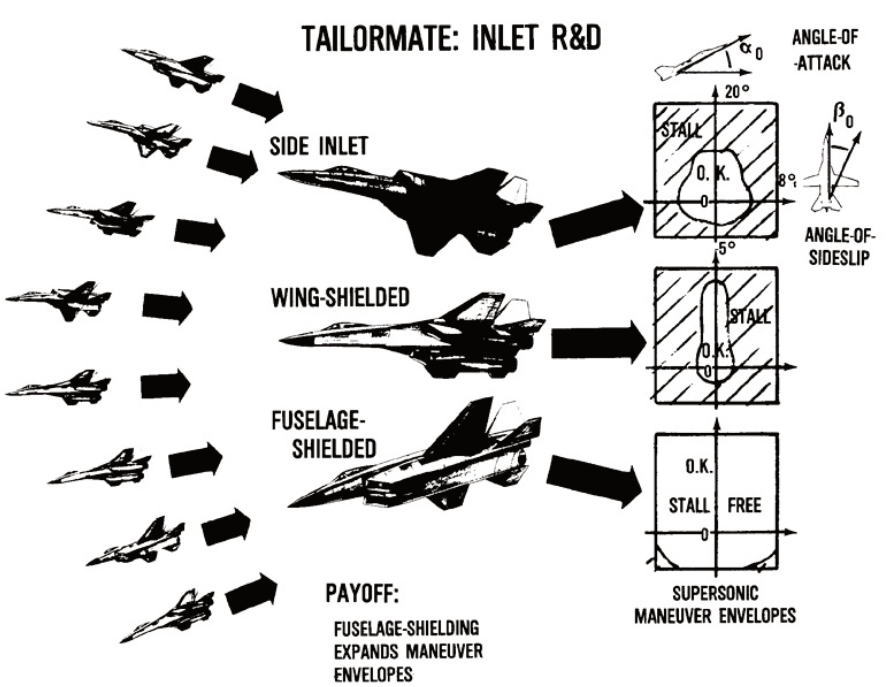




Below and right: *General Dynamics' variable geometry F-X effort (1968) was led by Harry Hillaker but placed flast from four submissions. Initially all F-X designs were variable geometry, but changing requirements meant the final 3 submissions were all fixed wing.*
Bob Cunningham



Above, left: ***Above, left:*** *Wind tunnel model of one Tailor-Mate study, B-3. The painting and markings are not original but were added by master model maker* **Allyson Vought,** who took these photos. The similarity to General Dynamics' F-X design is clear. ***Bottom left:*** *A diagram illustrating the various inlet locations studied in the program. The conclusions from Tailor-Mate fed into the fuselage-shielded location of the F-16's air intake.* **via NASA**



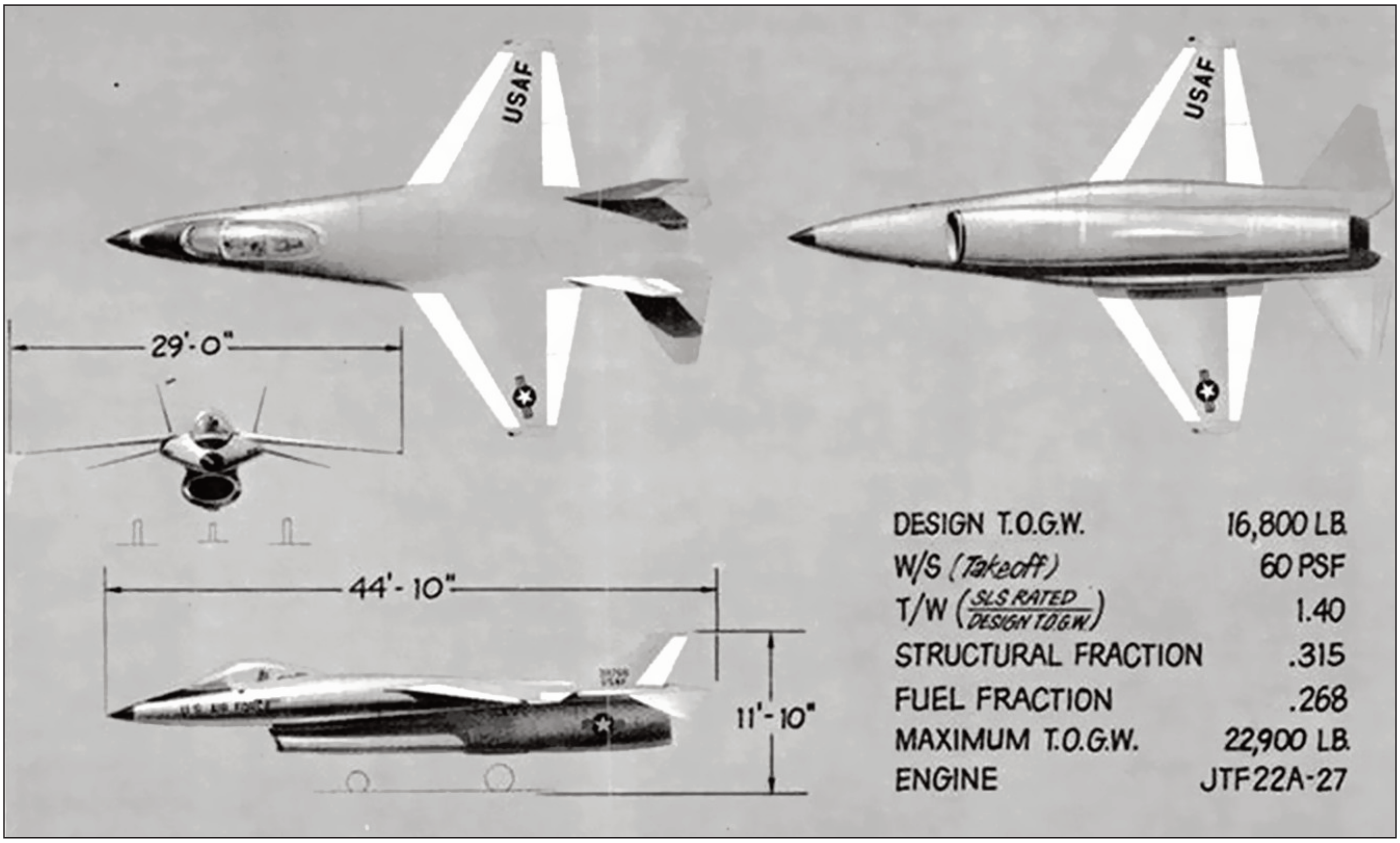
edged leading edge extension, mid wing and large bubble canopy, while the serious intake boundary layer issues encountered on the F-111 intakes might explain the unusual use of underslung axisymmetric engine pods on the large variable geometry designs.

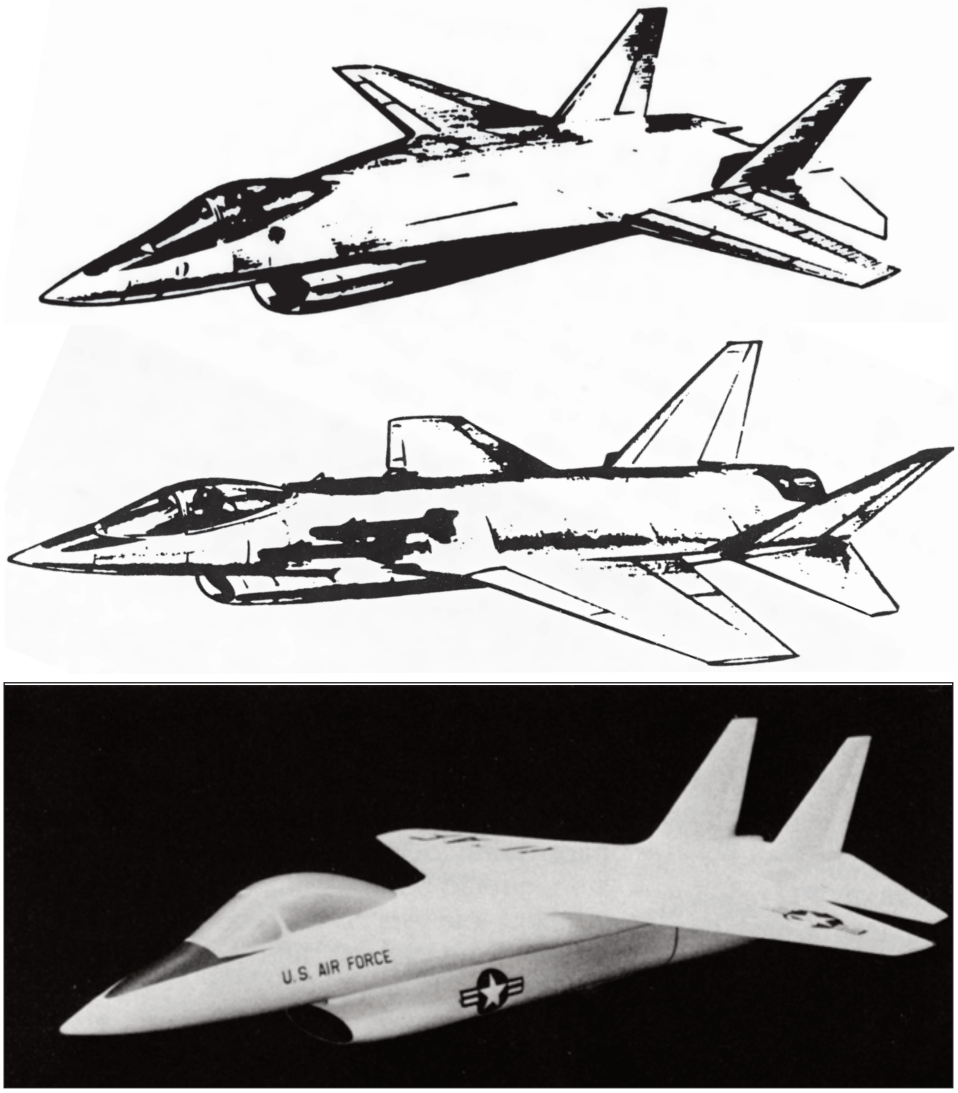
General Dynamics submitted a bid for F-X contract definition phase in 1968 but were unsuccessful, placing last of 4 submissions. Fairchild and North American were the frontrunners with eventual winners McDonnell-Douglas in third place.

Harry Hillaker had been given the task of selling the VG F-X design to the Air Force and after failing to gain a contract was despondent, on the verge of quitting General Dynamics.

in 1969, Everest Riccioni wrote a rather vaguely-worded budget request for a 'Study to Validate Energy-Manueverabilty Theory with Trade-Off Analysis' based on validation of Boyd's E-M theories and received $149,000 for performance and design studies. He split this funding between Northrop ($100,000) and General Dynamics ($49,000) to help them develop their respective lightweight fighter concepts. Lee Begin from Northrop was by this time another member of the "Fighter Mafia" alonside Hillaker, so this budget request was a way of funneling money to lightweight fighter studies promoting their agenda.

Additionally, General Dynamics in this





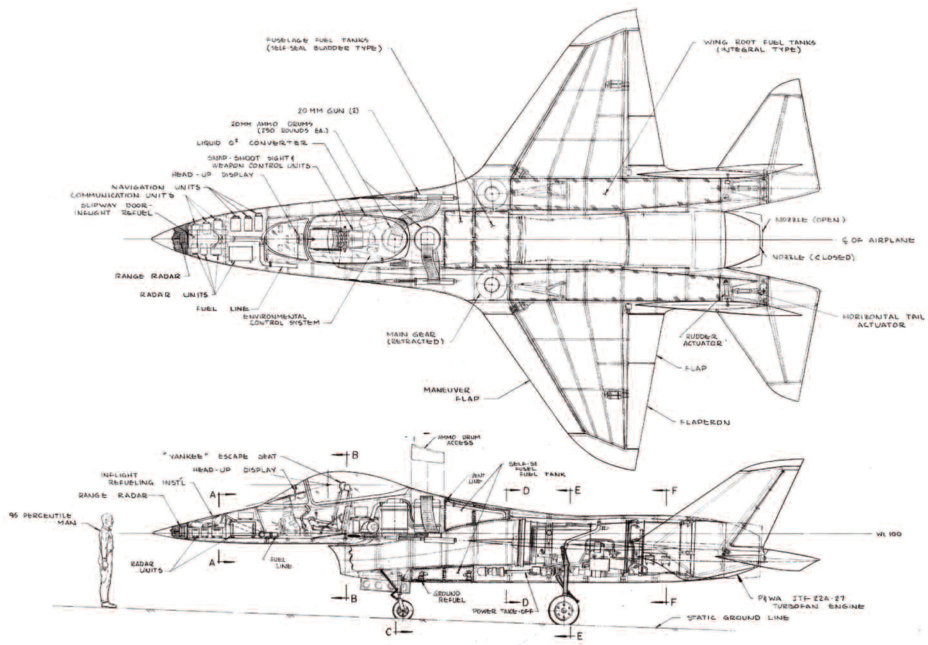
Above: *FX-404 drawing as presented in Riccioni's 'Falcon Brief' (Feb 1971)* **Code One**
Left: *3 FX-404 variants all share the twin vertical tails and anhedral horizontal tails.*

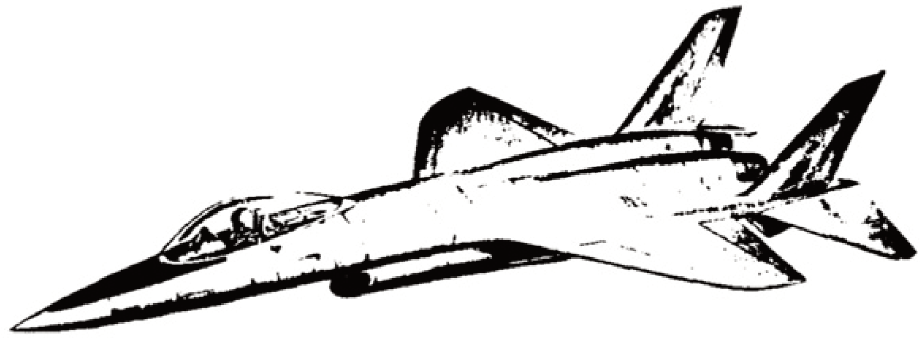
timeframe won several other study contracts that subsequently proved instrumental to formulating the F-16 design.

• **Supersonic Inlet Design and Airframe-Inlet Integration Program** (Project Tailor-Mate, 1969-70) was an experimental study of inlet types and locations. It used a fixed-wing design similar to the F-X to study a variety of intake designs in different locations and determine relative performance levels and projected inlet/engine compatibility. The fuselage-shielded two-dimensional inlet installation showed significantly greater potential for stall-free supersonic maneuvering flight than either the side-mounted or wing shielded configurations.

• **Wing Mounted Roll Control Devices for Transonic, High-Lift Conditions** (1969) studied leading and trailing edge devices, leading to the use of variable camber - automatic leading and trailing edge flaps - on the F-16. V ariable camber provided an 10- percent improvement in sustained turn capability over the best fixed-camber design.

• **Aerodynamic Contouring of a Wing-Body Design for an Advanced Air-Superiority Fighter** (1970) was an add on to the previous study and generated useful information on wing-body





Top: *Model 401B (April 1971) had complex wing shape, anhedral tailplanes and was exremely compact.* **Code One**

Above: *This early Model 401 study (unknown suffix) had twin engines fed by bifurcated pitot intakes.* **NASA**

blending.

In June 1969 Pierre Sprey wrote a a paper entitled "F-XX and VF-XX - Feasible High Performance Low Cost Fighter Alternatives" which used Northrop's P530 and General Dynamics FX-404 design to illustrate suitable Lightweight fighter concepts.

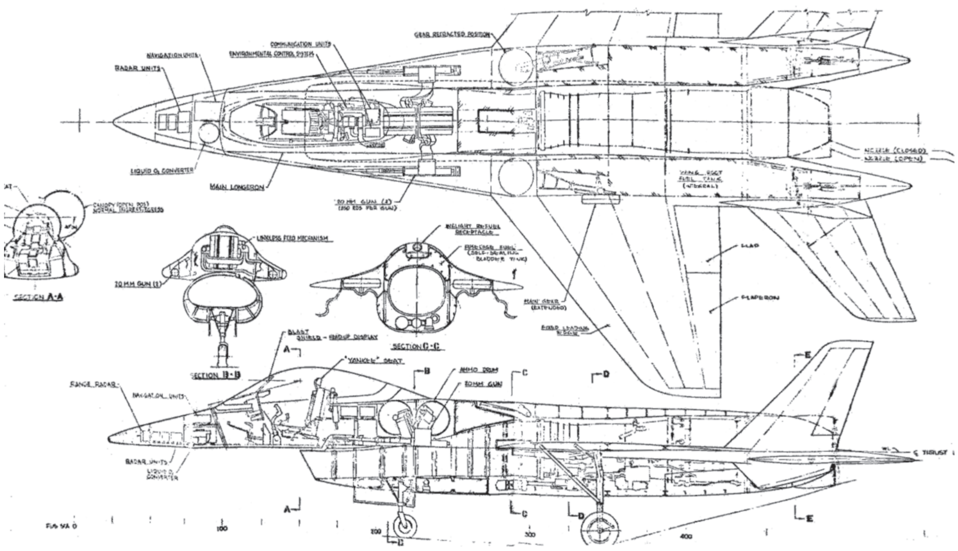
General Dynamics Model FX-404 (called 'Falcon 404F' in a 1971 Riccioni briefing entitled "Advanced Fighter Aircraft Study Avenging Falcons (AVFFX)") drew heavily on General Dynamics' previous FX studies with its long, blunt edged root extensions and horizontal tails with significant anhedral. It's primary characteristics were the blended wing/body design with small, unswept wings and fuselage shielded simple oval pitot intake. Length was just 44 ft, span 29ft, significantly less than the YF-16, and design thrust to weight ratio an incredible 1.4. Design takeoff weight was just 16,800lb, roughly equal to the empty weight of the eventual production F-16A. Hillaker would later say he borrowed an idea from Willy Messerschmitt and wrapped the smallest possible airframe around the biggest available engine.

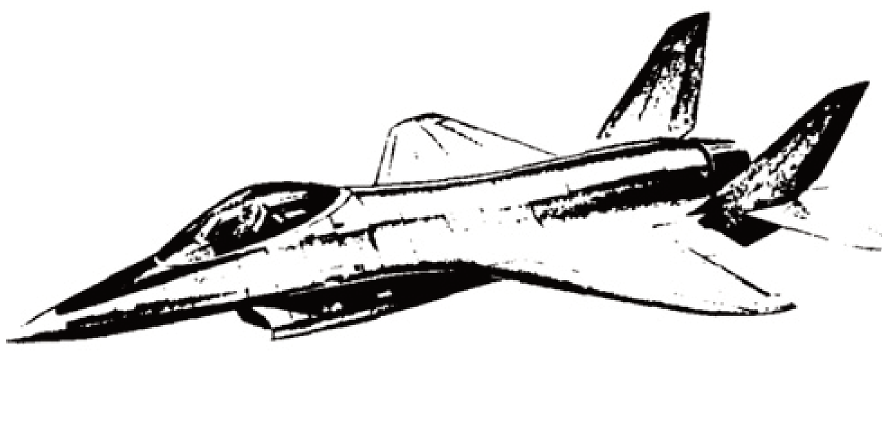
One interesting feature of the FX-404 design which were later to feature on Model 401 was its blunt leading edge root extensions. The rationale behind blunt LERX was to avoid causing vortices to be generated, and was seen on other contemporary designs like North American Rockwell's F-15 as well as General Dynamics' own fighter designs since the mid 1960s and windtunnel tested in 1966.

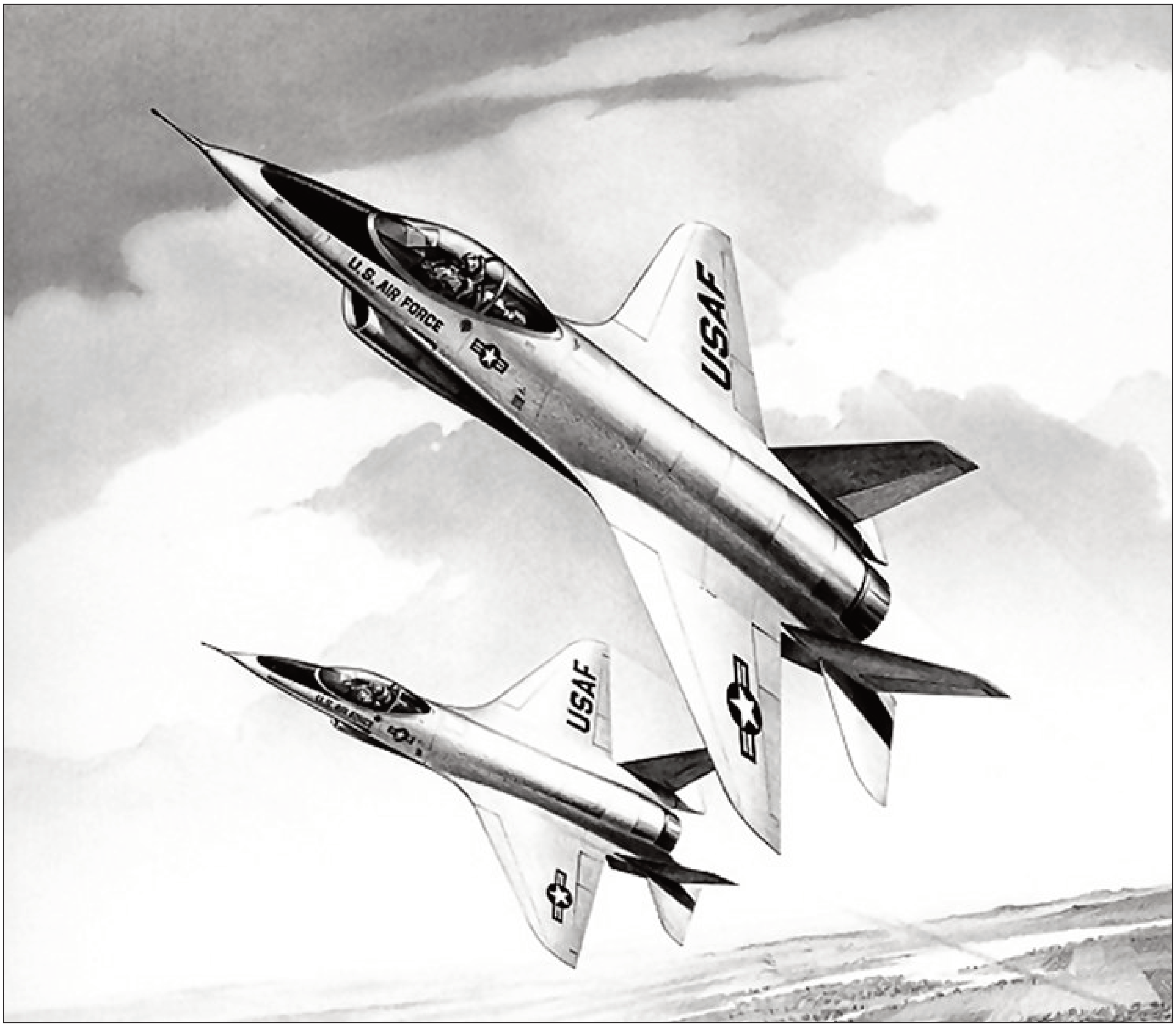
Work on the lightweight fighter started in earnest in late 1970. A new kind of mission and combat goal definition was being formulated, allowing combat performance to be a primary driver in configuration studies alongside range and speed; realistic combat tasks would replace arbitrary numbers in the RFP.

In anticipation of a possible requirement General Dynamics undertook a series of in-house analytical studies from late 1970 through 1971 primarily under the Model 401 designation. There were probably at least 7 versions (A through F) studied - B, C and F variant are illus-

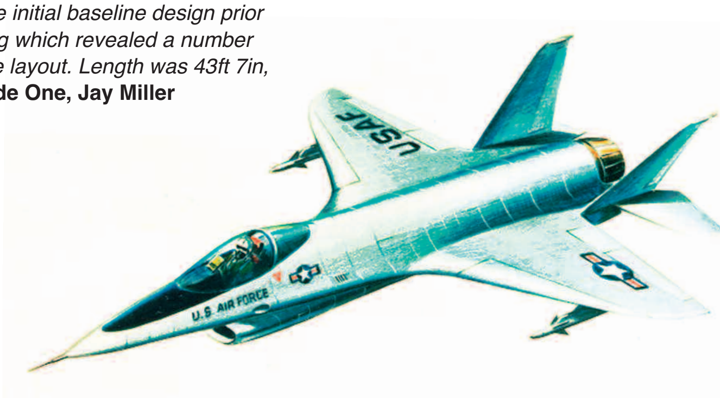
Below: *the Model 401C had swept-back tailfins and increased leading edge wing sweep.*
Richard Pugliese,

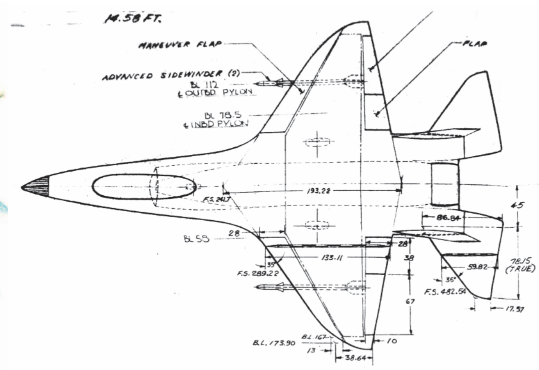


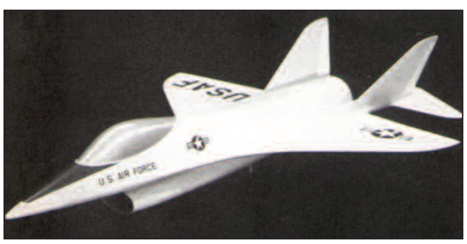


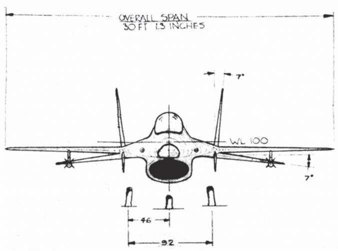


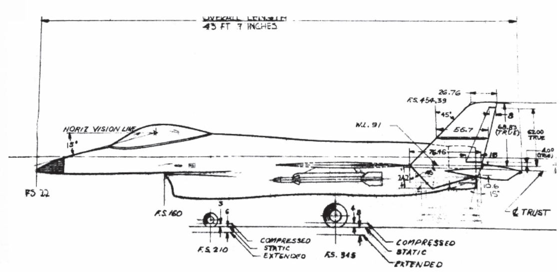
Model 401F was the initial baseline design prior to windtunnel testing which revealed a number of major flaws in the layout. Length was 43ft 7in, span 30ft 1.3in. **Code One, Jay Miller**

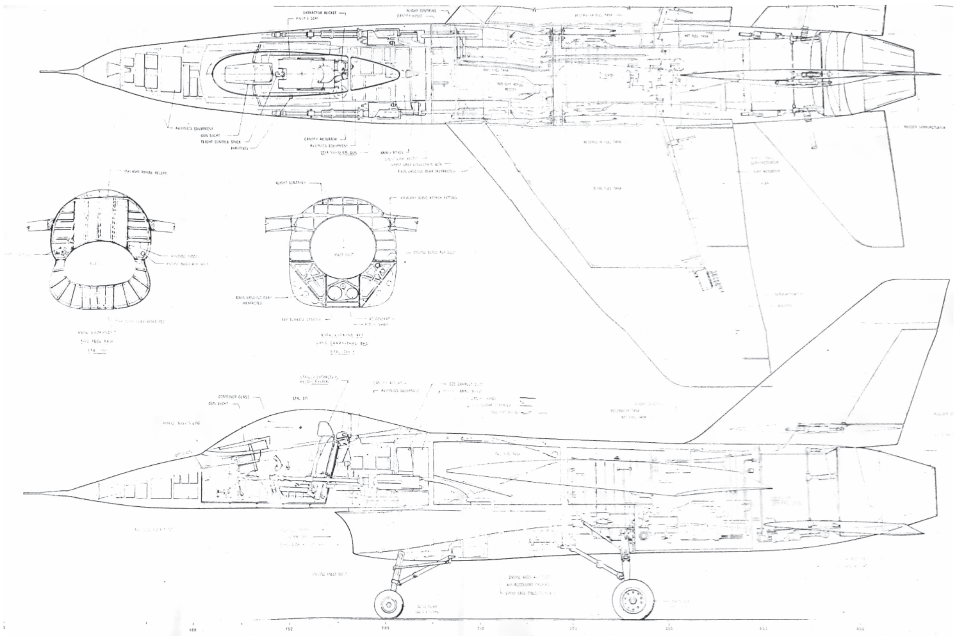












trated here. It featured large tail booms either side of the single engine mounting the twin vertical tails and ventral fins directly below forming a single surface above and below somewhat reminscent of NASA's LFAX-8 study and the early F-15 tail design.

The design philosophy for the in-house studies was simplicity, 'that is, install only those features that contribute directly to kill potential and leave off the "nice- to-have" features which add cost and weight but very little to the task of securing air superiority'.

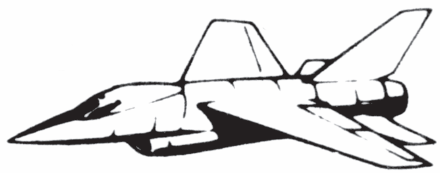
It therefore mounted the bare minimum of equipment for air-air combat with no extras - single seat, 20mm gun, Sidewinders, HUD and ranging-only radar.

The single seat came from General Dynamics F-X competition analysis, while Vietnam analysis showed the need to retain a gun.

The engine selected was the F100, because it was the most advanced engine available and would be operational and proven in the right timeframe.

The initial wing design seen on Model 401B was the result of the previously

Above: Model 785 inboard profile **Richard Pugliese**
Below: Model 785 drawing. right: strakes ntested on Model 785 **Jay Miller, NASA**



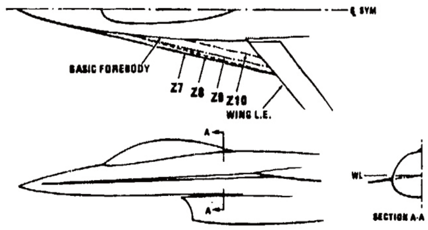
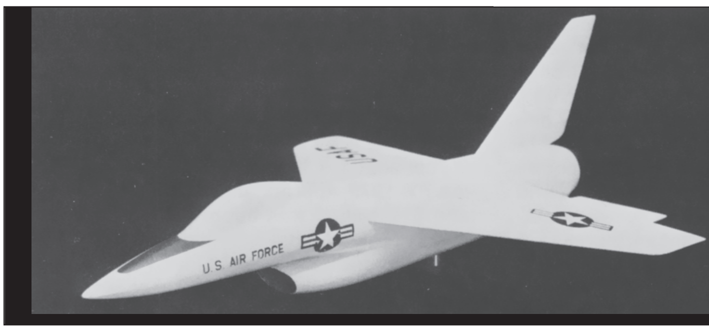
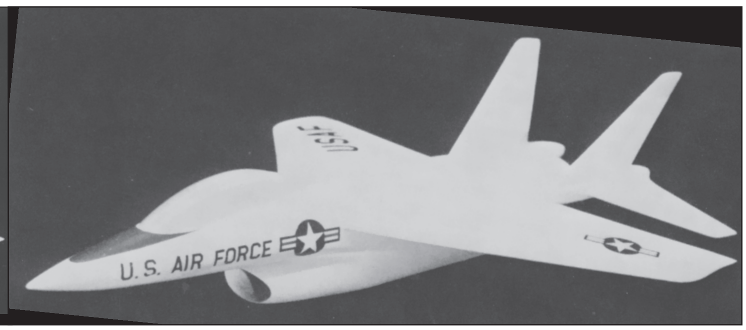
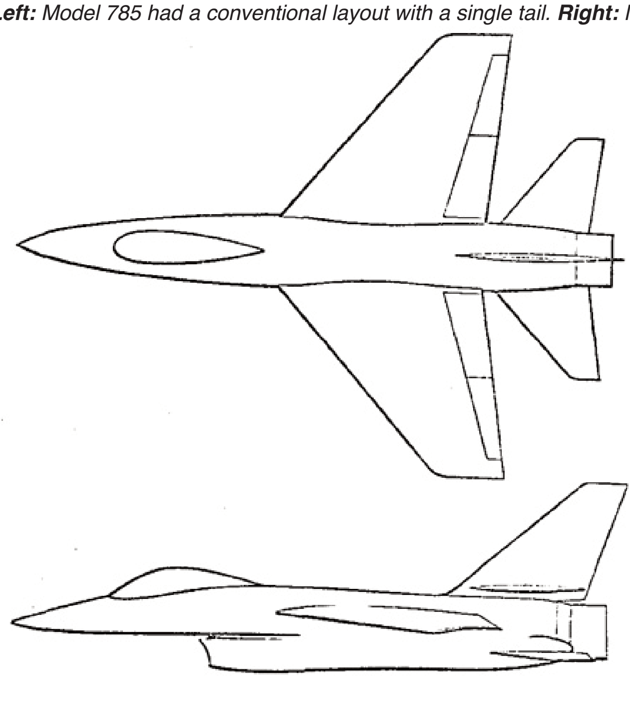


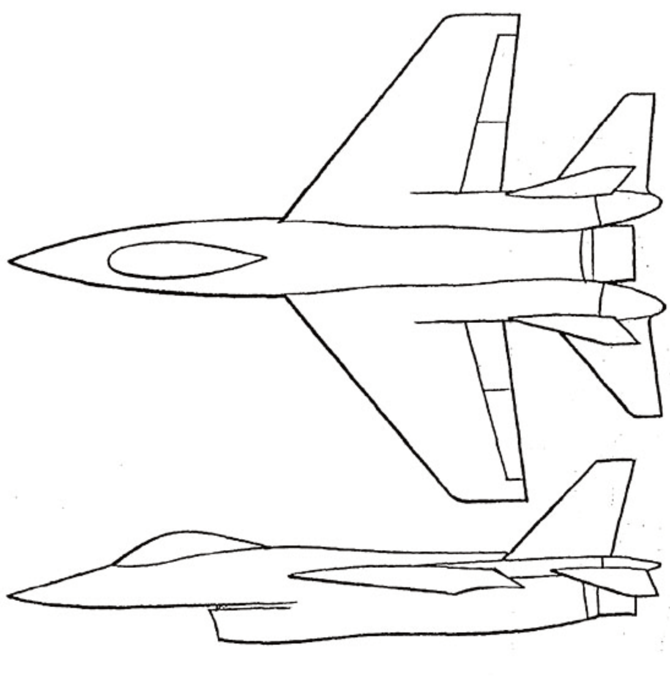
Figure 5 Delta Planform Strakes on Configuration 785





Left: *Model 785 had a conventional layout with a single tail.* ***Right:*** *Model 786 had twin tails mounted on significantly-sized tailbooms.* **NASA**





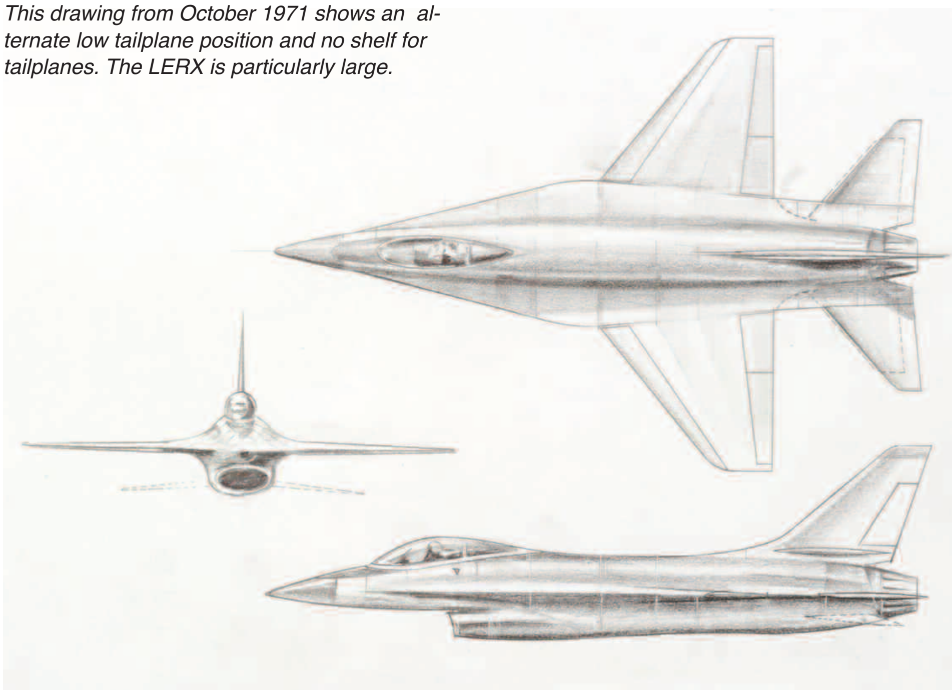
mentioned 1970 study of wing-body contouring. It used a 35 deg sweep leading edge, rounded tips, bi-convex profile and leading and trailing edge flaps. Horizontal tailplanes were identically shaped to the wing and had pronounced anhedral. The design used extensive wing-body blending with blunt leading edge root extensions intended to reduce vortex generation. 401C used an alternative, more conventional wing with 40 deg leading edge sweep, no trailing flaps and more conventional swept tail surfaces. The third design pictured here (unknown suffix) was a twin-engined version studied for comparison; it ended up heavier and lower performing than the single engine baseline.

The winning design from the initial studies was 401F. Longer and less dumpy in appearance, 401F was 43 ft 7in long with a wingspan of 30 ft 1.3in.

When wind tunnel testing started, two baseline designs were created from the parameters explored by the previous analytical studies. The first was Model 401F as already described, the second was designated Model 785 and was a simple design using a conventional swept wing initially with no leading edge flaps. 785 had a single vertical tail and featured a simple separate conventional fuselage with no blending, like Model 401C . A twin-tailed version was also developed as Model 786. Model 785/786 was a conventional baseline, to double check the more radical Model 401F was superior to a less radical approach.

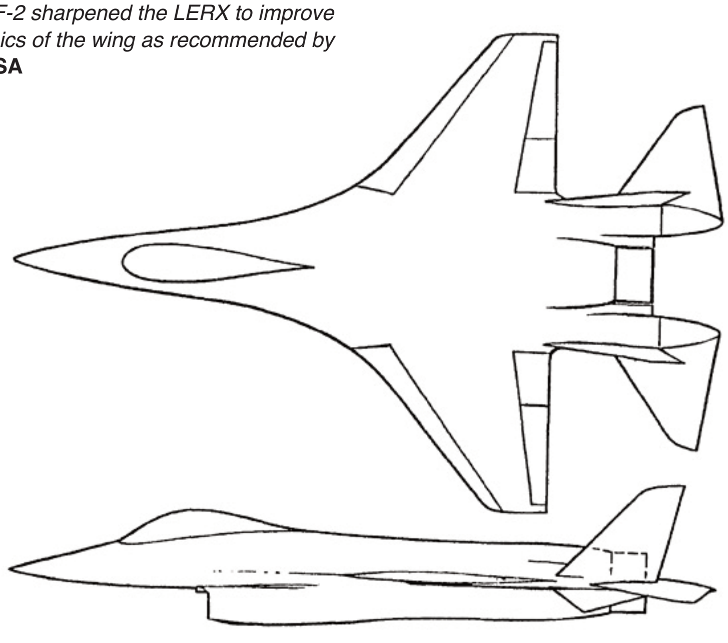
Different wings were tested on both Model 785 and Model 401F wind tunnel models. The 35 degree sweep wing with bi-convex profile was found inferior to the simple 40 degree sweep wing and was discarded, though the latter adopted the leading edge flaps of the former. Windtunnel tests soon revealed serious problems with the 401F design. A severe loss of directional stability at

This drawing from October 1971 shows an alternate low tailplane position and no shelf for tailplanes. The LERX is particularly large.



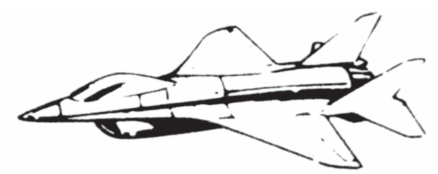
401FS-1 was an alternative design with simple bifurcated pitot intakes. Inlet performance at high angles of attack was very poor, leading to the later 401FS-2 configuration using F-15 style wedge intakes. **Code One**

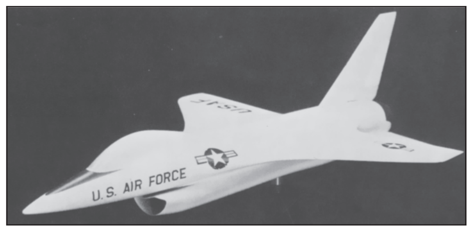
Model 401F-2 sharpened the LERX to improve aerodynamics of the wing as recommended by NASA. **NASA**

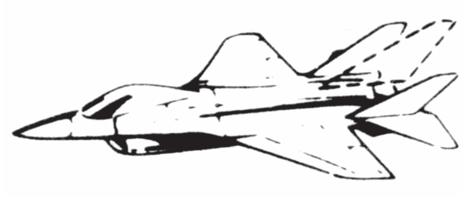


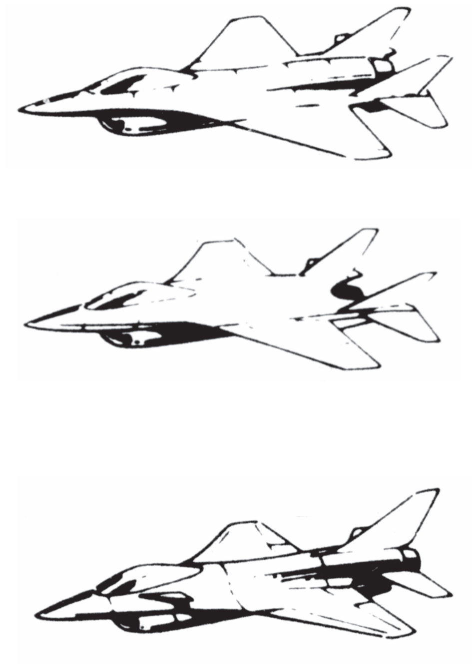
Below top: *401F-0 was the first configuration tested in the wind tunnel.* **Code One**

Below middle, bottom: *F401F-2 was tested in two configurations, the model illustrated here has a single fin, while the drawing at bottom shows both variants.* **Jay Miller, Code One**







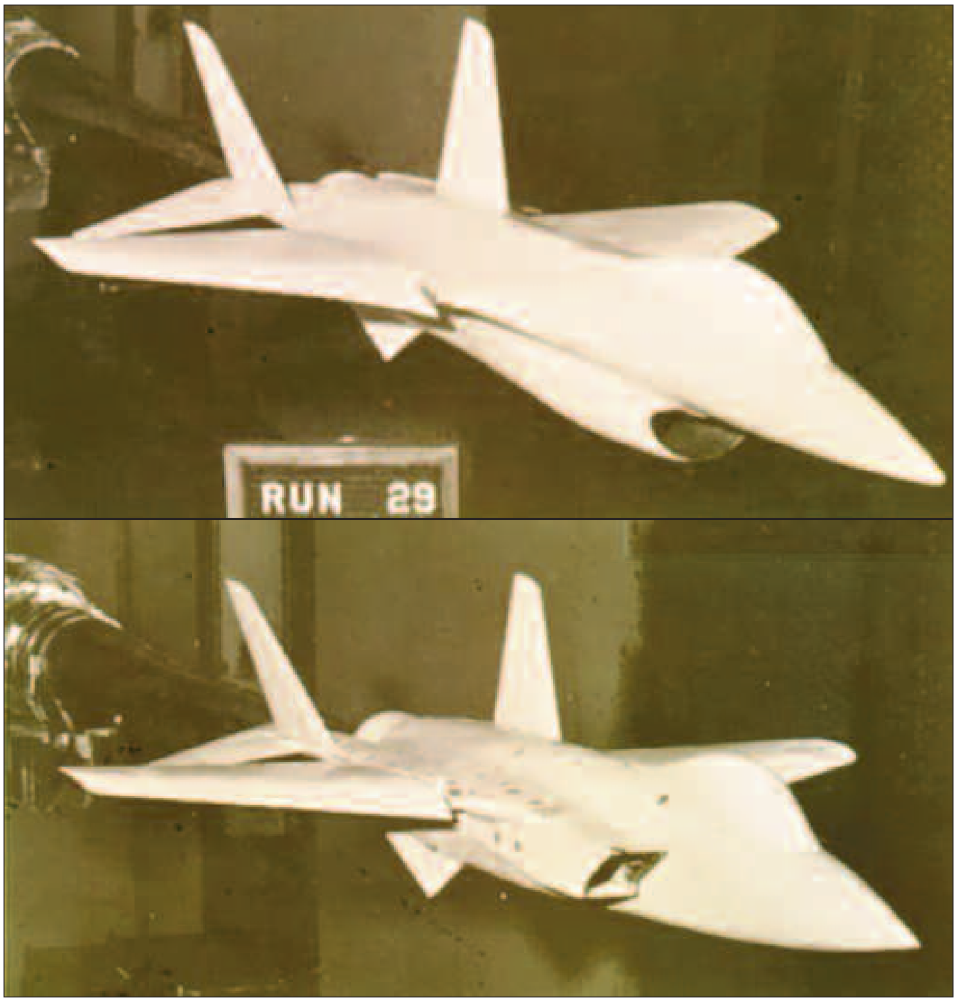


Above : 401F-3, 401F-4 refined the twin tailed design until the Model 401F-5 (bottom) finally ditched the twin tails in favour of a recognisably F-16 shape. **Code One**

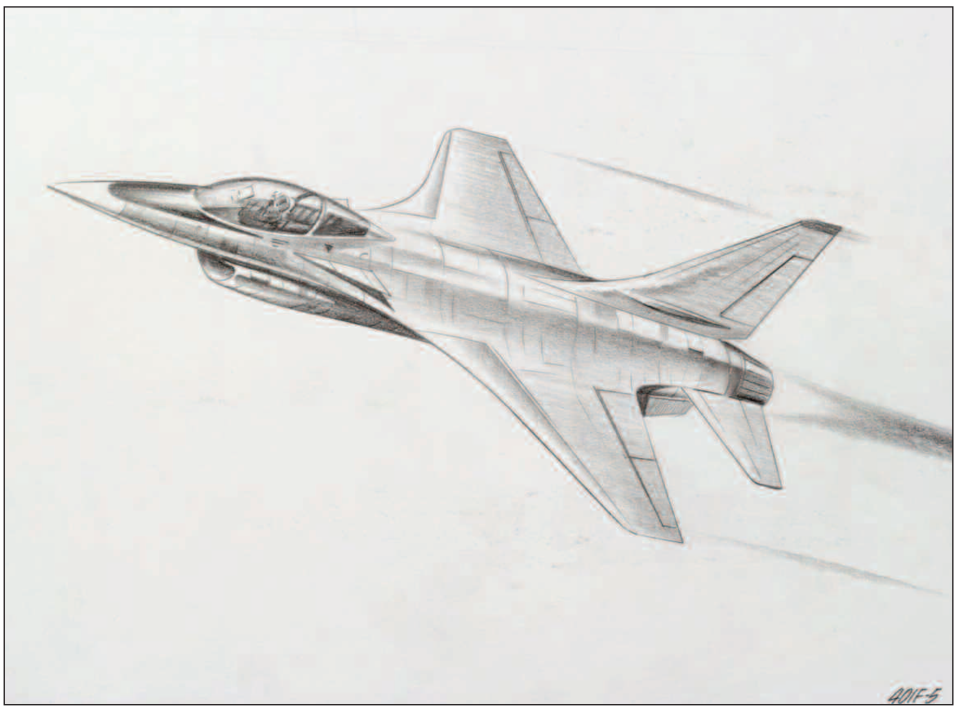
modest to high angle of attack was discovered, and subsonic drag polar "breaks" occurred much earlier in lift coefficient than expected. Further tests verified that leading edge flow separations from both the forebody and wing interacted to adversely affect the vertical tails at moderate angle of attack. Various palliative measures were tried with limited success. NASA Langley were consulted, who recommended that rather than use blunt forebody strakes to try to avoid vortex generation, it was better to control and exploit it. generating extra lift and strong forebody vortices which would actually help to stabilise airflow in high angle of attack flight. General Dynamics embarked on a series of tests of strake shapes, delta strakes on 785 and 786 wind tunnel models and curved strakes on the 401F-5 model, to identify the best shape. Tiny strake surfaces for vortex generation were featured on some LERX configurations as well.

Within three months of the first windtunnel tests of F401F-0, the aerodynamic problems of the initial configuration were broadly understood and solutions in hand. The configuration continued to evolve.

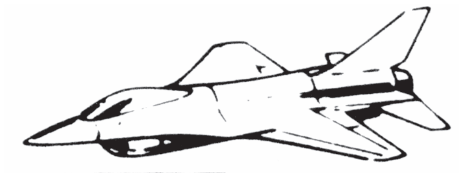
Model 401F-2 featured the sharpened LERX and retained the simple unswept wing of Model 401F-0. It was tested with both single and twin fins. While Model 401F-3 and 401F-4 reverted to twin fins, minor layout changes were tested, different strakes, wing shapes and minor



Wind tunnel tests of Model 401F (chin intake) and Model 401FS-2 (bifurcated side mounted wedge intakes) confirmed the superiority of the chin intake position, especially at high angles of attack. Note that the original oval pitot intake has been replaced by a 'smiling' shape. **Code One**



Model 401F-5 was the breakthrough design in development of the F-16. The engineers literally sawed Model 401F-4 and 785 models in half and mated the front half of Model 401F to the back end of Model 785 for the first tests. Miniature canards were tested, as shown here, for vortex control. **Code One**

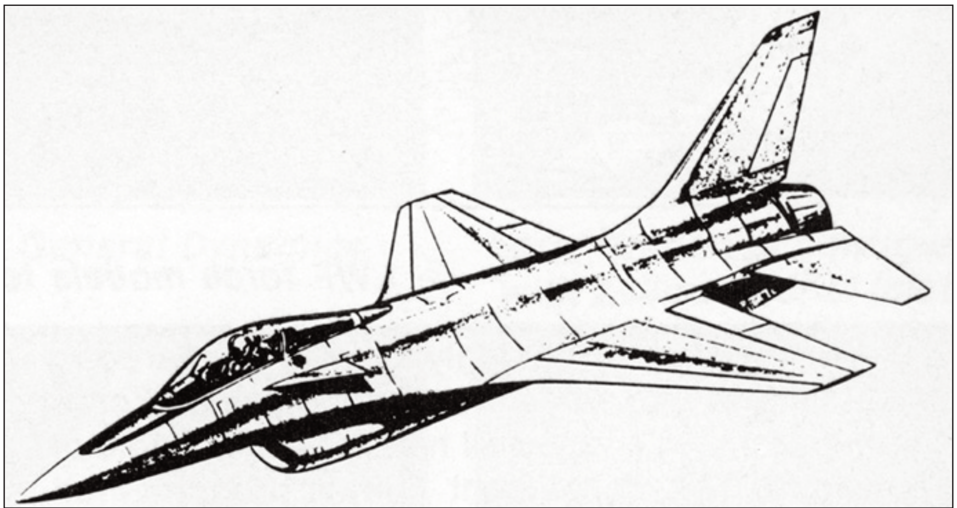


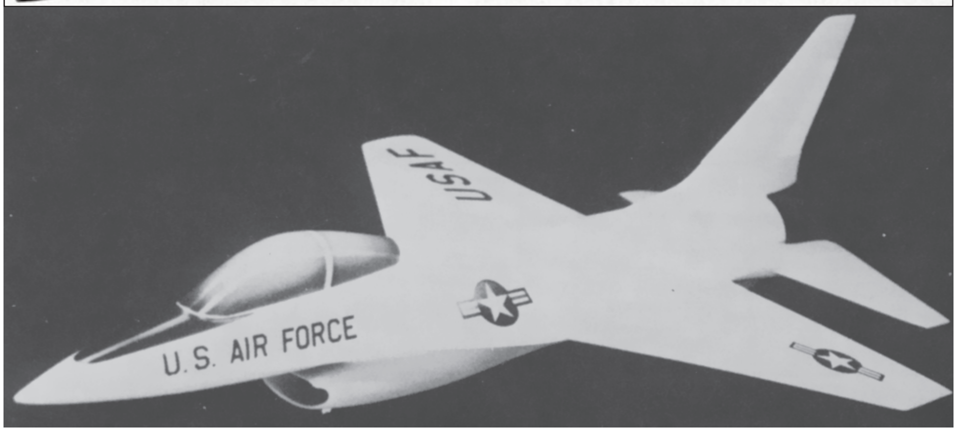
Above, right: *Model 401F-5A added tailboom shelves either side of the engine to mount the horizontal tails. Vortex generating strakes continued to be be tested alongside numerous LERX shapes but were eventually discarded.* **Code One, Jay Miller**

aerodynamic refinements to features like the inlet. The final choice between single and twin fins was made by two main factors. The strong vortices thrown from the leading edge strakes made positioning twin tails to avoid them difficult, something that would later cause the F-18 problems with vibration causing structural failure, while the single tail was out of the path of the LERX-generated vortices in most typical flight conditions. Additionally, a single fin required less area, which reduced weight and friction drag. Some reduction in fin authority at high angle of attack over the twin fins was accepted. The Eurofighter Typhoon designers made the exact same decision more than ten years later for largely the same reasons.

A key feature of the 401F design was the extensive use of wing-body blending. The thickened wing roots lowered structural weight and increased stiffness, and added additional volume which increased available internal volume for fuel and equipment. According to W.C Dietz of General Dynamics, the weight savings from wing-body blending on YF-16 was about 320lbs from a fuselage length reduction of 5.5ft over a non-blended design, plus 250lb reduction in wing structural weight due to thickened wing roots. Transonic drag was reduced due to lower wetted area and better area distribution.

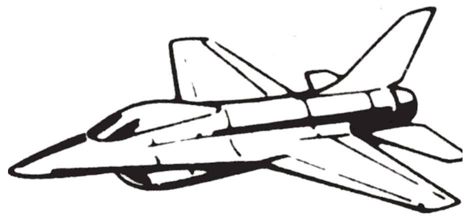
A key design decision on the F-16 was to use the extra volume to maximise the fuel fraction. The range of an aircraft is basically determined by the ratio of its fuel load to takeoff weight or fuel fraction.. Lightweight fighters in the past had often had lower fuel fractions which had led to the idea that lighter weight fighters were automatically longer legged. Boyd's analysis had shown that this wasn't true, providing the lightweight fighter had enough fuel. However, there were many items that would go into an aeroplane which didn't scale down well with aeroplane size,

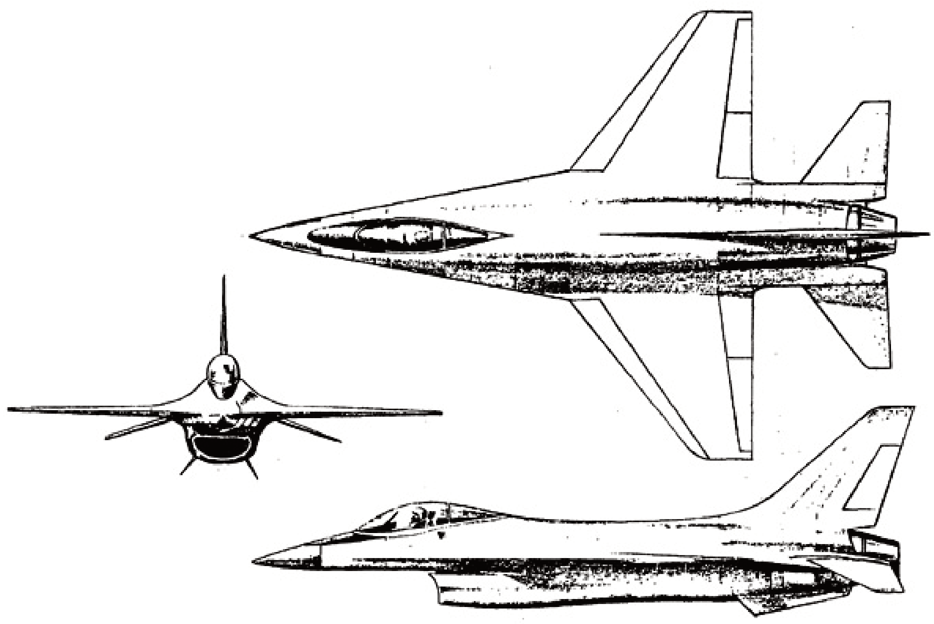




Right: *Model 401F-10 continued to refine the basic design.* **Code One**

Below: *Model 401F-10A looks increasingly like the final YF-16 design, though the LERX illustrated here is completely straight and the base of the vertical tail is curved, while the ventral fins are long and shallow. From the proposal to the final YF-16, the Mach 1.2 area ruling was improved by a number of minor tweaks.* **Code One**





like avionics. Hillaker said, “We were well aware that the avionics folks would be putting a bunch of gadgets in the airplane, which would increase weight and decrease performance. We stacked the deck. We made the airplane so dense that there wasn't room for all that stuff.”

The Model 401F-5 became the 401F-5A with the addition of shelves either side of the engine to carry the horizontal tails. Canard surfaces on the upper LERX surfaces were tested to help control the formation of vortices, but were removed.

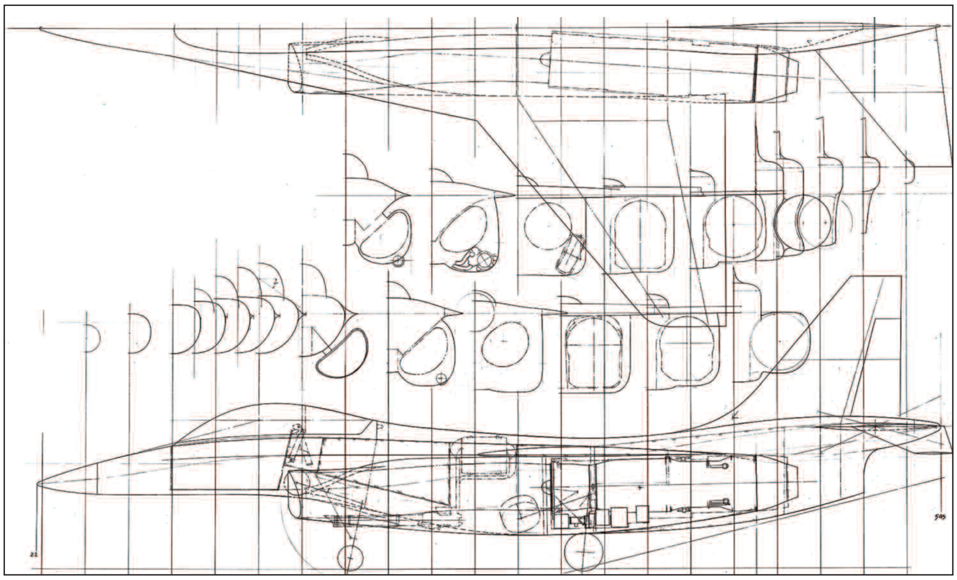
General Dynamics explored a number of alternative designs, two of which are illustrated here. The Model 503 was a twin engine design, and Model 773 was a canard delta, possibly influenced by work done by General Dynamics San Diego, who would use a similar layout with side intakes on their Model 200 V/STOL fighter.

The AIr Force Prototype Selection Board was formed in early 1971 to recommend commencement on several prototyping programs. By August 1971 the LWF was one of the selected programs for funding in FY1972, and work on the Model 401F increased significantly in tempo at that point. General Dynamics were ahead of the game on LWF due to their extensive work on Model 401F. Fighter Mafia member John Boyd was a member of the selection board and most likely was keeping Hillaker (and Begin at Northrop) appraised of the prospect of a LWF prototype program appearing soon.

The LWF RFP was finally released to industry in early January 1972, and responses were due on February 18. The LWF RFP was very short, 21 pages, and the required response was just 60 pages, 50 technical and 10 on program management, rather than the usual multi-volume,flatbed-sized proposals.

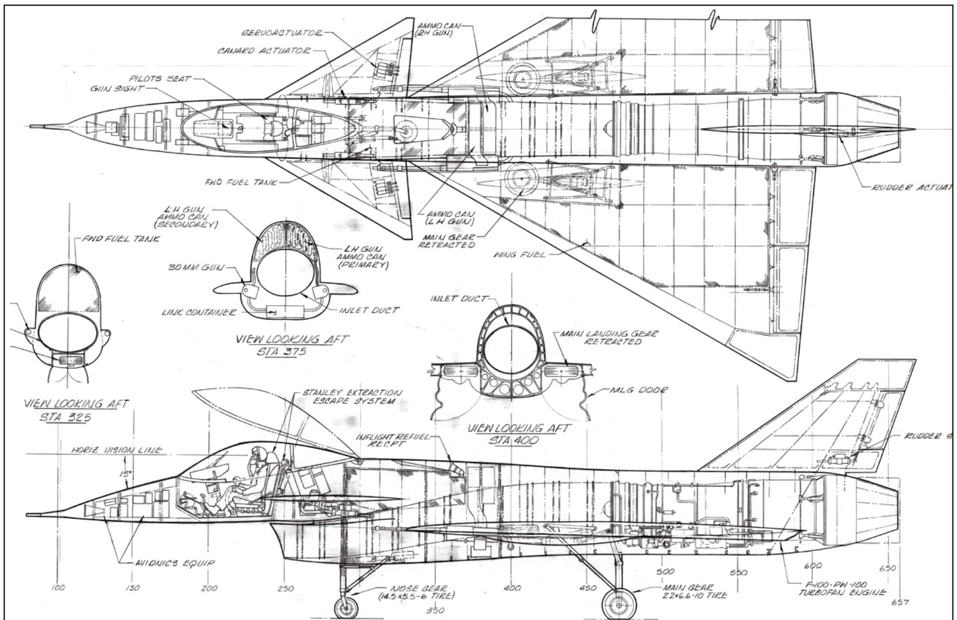
General Dynamics were able to build on the extensive body of work already put into the Model 401 to create a winning proposal. According to Harry Hillaker, “We were interested in what the US Air Force wanted, and we stayed flexible in the design to respond to their needs. We looked at a number of designs. We waited until the very last to choose the best one.”

Northrop in contrast had selected the basic layout for its P-600 proposal several years earlier with the P-530 ‘Cobra”



Above: *Model 503 (December 1971) was a design using twin engines to challenge the main designs. It gave the same performance but at a significant weight penalty.*

Below: *Model 772 (August 1971) was a canard delta quite similar to the contemporary General Dynamics (San Diego) Model 200 V/STOL fighter. Performance was inferior at subsonic and equal at supersonic speed, but with a weight penalty.* **Code One**



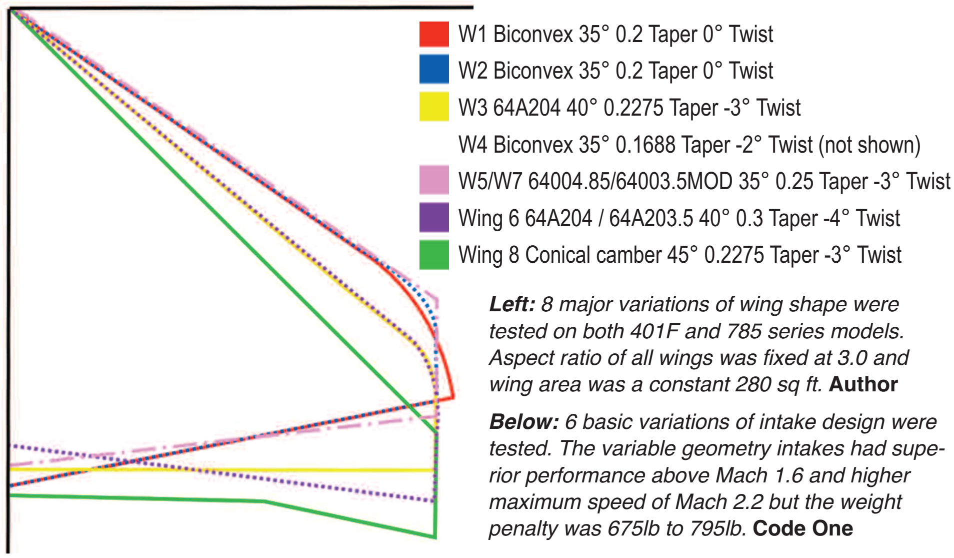
	Configurations Tested	Λ_{LE}	Wings: Fixed Camber	Wings: Variable Camber	Wings: Airfoil(s)	Inlets: Side	Inlets: Bottom	Vertical Tails: Twin	Vertical Tails: Single	Vortex Lift (Forebody Strakes)	Wind Tunnel Test Hours
Coventional Forebody	785	40°	✓		64A205 & 64A403.5		✓		✓	✓	48
		35°	✓		64004.9 & 64043.5		✓		✓		20
	786 (Twin Tail 785)	40°		✓	64A205 & 64A403.5		✓	✓		✓	48
Wing/Forebody Shaping	401F-0	35°		✓	4% BICONVEX		✓	✓		✓ (2) Strakes	187
		40°	✓		64A204		✓	✓			
	401F-2	40°		✓	64A204		✓ ✓	✓	✓	✓	91
		35°		✓	64004.9 & 64043.5			✓			
	401F-3 (Ferri Inlet)	40°		✓	64A204		✓	✓			20
	401F-4 (High Wing)	40°		✓	64A204		✓	✓	✓	✓ (3) Strakes	39
	401FS	40°		✓	64A204	✓		✓			29
	401F-5	40°		✓	64A204		✓	(3) Horiz Tail Positions	✓	✓	130
	401F-5A	40°		✓	64A204		✓		✓	✓	30
	401F-10	40°		✓	64A204		✓		✓	✓	30
	401F-10A	40°		✓	64A204		✓		✓	✓	32
	401F-16	40°		✓	64A204		✓	(2)	✓	✓	442
		45°	✓	✓	CONICAL CAMBER 64A(X)5.9/64A203						
	401F-16E	40° (Wing Moved Forward 14 inches)		✓	64A204		✓	(2)	✓	✓	126

Right: *this diagram shows the various configurations wind tunnel tested during the evolution of the F-16 configuration. 78 variations in total were tested, a total of 1272 hours windtunnel time.* **Code One**

and it lacked some of the advanced technologies of the Model 401, including the fly-by-wire control system and the unstable CCV design. The other LWF contenders included Boeing, where Jim Sandusky had worked on their Model 909-908 fighter which was rwas well-regarded by the selection board. The other contenders, Lockheed and Vought, offered a warmed-over F-104 Starfighter and a new design with some F-8 Crusader heritage respectively and neither were seriously considered responsive to the RFP.

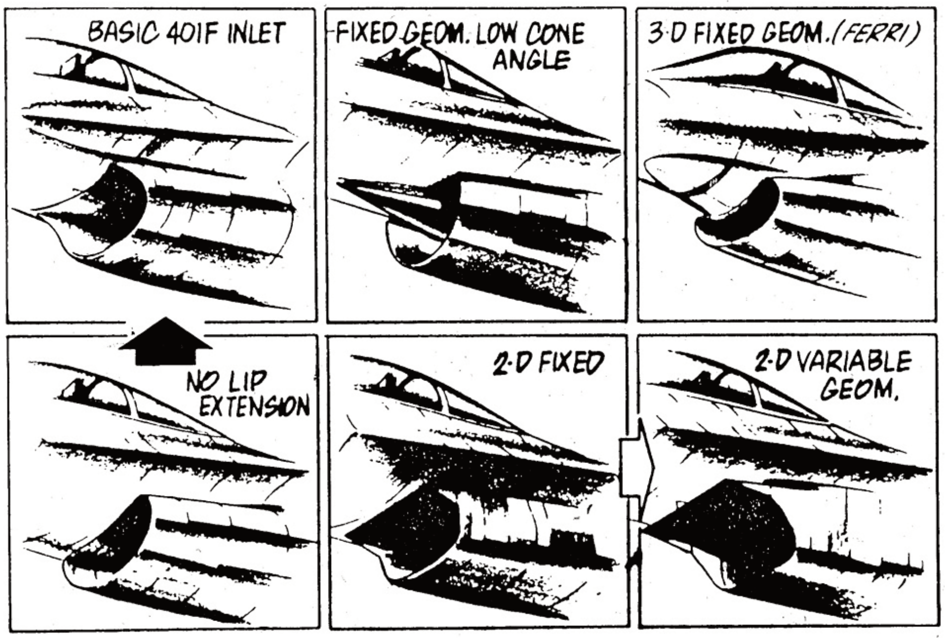
CCV was the riskiest element of the YF-16, though Harry Hillaker revealed that there was a contingency: the wing mount points were design such that if the instability proved a problem in testing, the wing could be moved to restore the design to a stable configuration, albeit at a performance penalty. However, using CCV gave the YF-16 an improvement in maximum lift of 4% at Mach 0.9 and 8% at Mach 1.2, which helped it achieve winning performsnce levels compared to the conventionally stable YF-17. YF-17 also suffered from excessive drag from its rear end; according to General Dynamics, designing a single engine rear end and exhaust was an order of magnitude easier than a twin engine configuration, and this had been taken into consideration in selecting a single engine layout for the YF-16. Perhaps the weakest area of performance for the YF-16 was high angle of attack performance. With some nasty departure characteristics, partly due to the single tail, the decision was made to enforce an AOA limit of about 25 degrees in the fly-by-wire flight control system. Within the these limits, manouvering the F-16 was entirely carefree. In contrast the YF-17 and later the F-18 had much more benign high angle of attack performance at slow speed. This wasn't however a selectable criteria.

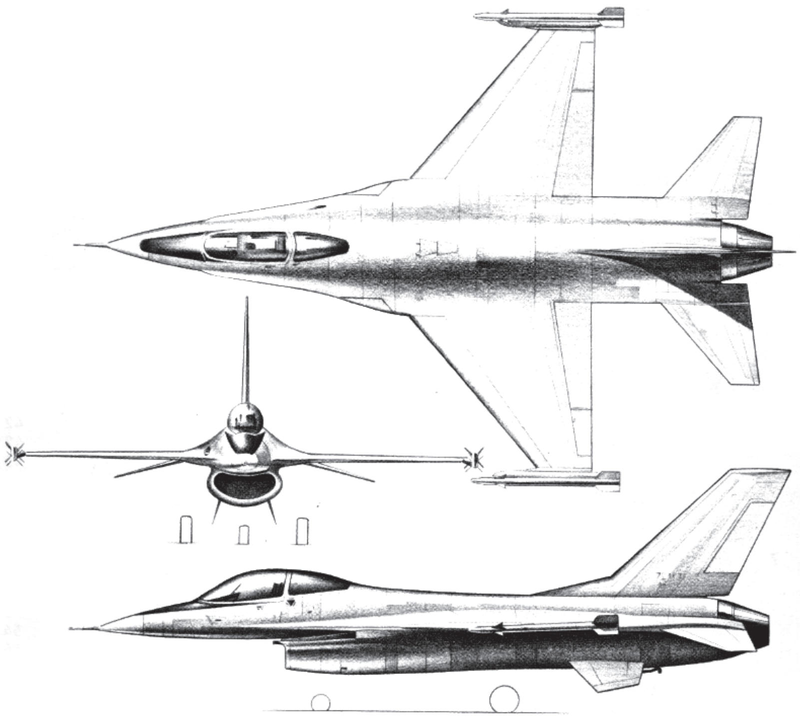
While the 'Fighter Mafia' had been instrumental in getting the YF-16 buii, it eventuallyt departed far from their vision of an austere day fighter, gaining a sophisticated radar and tasked with a primarily air-to-surface mission. Luckily, the F-16 program coincided with the invention of VLSI techniques which drastically decreased the size of computer chips and meant eww lighter weight digital avionics could be fitted into the small amount of space available within the airframe.



Left: 8 major variations of wing shape were tested on both 401F and 785 series models. Aspect ratio of all wings was fixed at 3.0 and wing area was a constant 280 sq ft. **Author**

Below: 6 basic variations of intake design were tested. The variable geometry intakes had superior performance above Mach 1.6 and higher maximum speed of Mach 2.2 but the weight penalty was 675lb to 795lb. **Code One**





Right: General Dynamics Model 401F-16 was close to the final YF-16 as built. This was the first configuration to be tested at low speeds; all previous testing was concentrated on Mach 0.8 to 1.2.
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