Genesis of the F-35 Joint Strike Fighter

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DOI: 10.2514/1.42903

Functional analysis has been used to design a common aircraft to replace the U.S. Air Force F-16s, Navy and Marine Corps F/A-18s, and Marine AV-8s. The technical and program challenges involved in developing a common aircraft for all three services were met by designing three highly common, but not identical, variants of the same aircraft. The key elements of this commonality are an innovative propulsion system that can be switched from a turbofan cycle for conventional flight to a turboshaft cycle for vertical takeoff and landing and a basic structural arrangement that can accommodate the substitution of stronger parts in the Naval variant to absorb the greater takeoff and landing loads of carrier operations.

Introduction

THE Wright Brothers Lectures commemorate Wilbur and Orville Wright's success in developing the first practical airplane. But in solving the problems of manned flight, they also demonstrated the value of their approach to problem-solving. The key elements of their approach were a skeptical study of the relevant literature, to identify errors as well as valid data; innovative thinking, which led to the idea that an airplane can be controlled with wing warping; constructive debate, to work the flaws out of their ideas; systematic testing, progressing from wind tunnels to kites to gliders to airplanes; and teamwork, including the contributions of their mechanic Charles Taylor, who actually implemented many of their ideas. Lockheed Martin used a similar approach in developing the Joint Strike Fighter (JSF), and so the subject of this paper seems appropriate for a lecture commemorating their accomplishments, and it is an honor to have been invited to present it.

The U.S. Air Force F-16 Falcon, U.S. Marine Corps AV-8B Harrier, and U.S. Navy F/A-18 Hornet, shown in Fig. 1, are fourth-generation strike fighters. They will all need to be replaced with new aircraft at about the same time, beginning in the next decade. Before the end of the Cold War, each of the services had begun programs to develop fifth-generation replacement aircraft. Fifth-generation successor aircraft will incorporate stealth, operate in a net-centric environment, and have greater range. However, it soon became apparent that there would not be enough money in the reduced defense budget to fund three separate replacement aircraft programs. A common replacement aircraft was an attractive solution that appealed to some in government and industry.

However, the idea that multiple service and mission requirements could be incorporated into a single aircraft design was initially greeted with considerable skepticism, largely because the joint Tactical Fighter Experimental (TFX) program of the 1960s had not succeeded as a joint program. The TFX program was intended to save several billions of dollars in life cycle costs by using a common airframe and engines to meet both the Navy's fleet air defense requirement and the Air Force's requirement for a long-range fighter bomber. The Navy withdrew from the TFX program when the aircraft became too heavy for carrier operations. The Air Force was left with an F-111 too small to be an effective bomber and not maneuverable enough to be a competitive fighter.

In addition, developing a supersonic, vertical takeoff and landing (VTOL) fighter was considered a significant technical challenge by itself. The stages in the evolution of VTOL aircraft are illustrated in Fig. 2. The first attempts to build a vertical takeoff and landing fighter were the tailsitters of the 1950s, including the XFV-1, the XFY-1, and the X-13. Because the thrust-to-weight ratio of fighter aircraft was already close to 1, designers thought that it would be a simple matter of standing a fighter on its tail and increasing the thrust a little to

Fig. 1 Fourth-generation strike fighter aircraft.

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Presented as Paper 1650 at the 47th Aerospace Sciences Meeting, Orlando, FL, 5–8 January 2009; received 23 December 2008; accepted for publication 2 July 2009.

Fig. 2 Evolution of VTOL aircraft.

develop a VTOL aircraft. However, tailsitter aircraft had limited range/payload performance due to the weight limits imposed by vertical takeoff and no ability to increase lift off weight with a short ground roll when there was a runway available. In addition, tailsitters were difficult for pilots to land because they had minimal control power in hover, and the pilot could not see over his shoulder to determine how high he was above the ground, or how fast he was descending.

Therefore, the second generation of VTOL aircraft, including the Mirage III-V and XV-4, were designed with lift engines installed vertically in the fuselage, so that the aircraft could take off and land in a conventional horizontal attitude. This enabled the pilot to see the ground and judge his sink rate. However, the lift engines took up too much space in the fuselage and were dead weight during cruise, whereas the cruise engines were dead weight during hover. As a result, the range/payload performance of these aircraft was also unsatisfactory. In addition, the hot exhaust gases of the lift engines damaged the airframe and caused ground erosion, and reingestion of these hot gases caused the lift engines to stall and lose lift.

The third generation of VTOL aircraft, such as the VJ-101, used swiveling lift/cruise engines that were rotated from a vertical position for hover to a horizontal position for cruise. However, these aircraft were difficult to transition from hover to cruise flight, or back, and they also suffered from hot-gas ingestion and ground-erosion problems. Further, because the engines had to be sized for hover, they were larger than optimal for cruise. The resulting inefficiencies reduced range/payload performance.

In the latest and most successful generation of VTOL aircraft, the thrust of the cruise engine is simply vectored down. The AV-8 uses thrust vectoring of a single lift/cruise engine with a high bypass ratio having enough thrust for vertical landing. In routine operations, it is flown from any available runway as a short takeoff and vertical landing aircraft. With a short takeoff run, the AV-8 has range/payload performance comparable with other lightweight fighters. However, the fan diameter is too large to enable the aircraft to achieve supersonic speeds. The VAK 191 and Yak 38 were hybrid concepts that vectored the thrust of the cruise engine, but also incorporated lift engines to increase thrust for hover. In these aircraft, the engines also took up internal volume and created hot-gas ingestion and ground-erosion problems.

Although the short takeoff and vertical landing (STOVL) AV-8 and Yak-38 were operational aircraft, they were not capable of supersonic speeds. The fundamental problem was that a propulsion system that provided enough thrust for hover was too large and required too much fuel to enable the design of a slender supersonic airframe. During the 1970s, in the decade before the start of the Joint Strike Fighter program, both the VAK 191 and XFV-12A supersonic demonstrator aircraft were unsuccessful, and neither became operational. To summarize, the development of VTOL fighter aircraft proceeded along a path to simplification: first the aircraft were tilted, then the engines were tilted, then the engines were vectored, until it was finally recognized that the only thing that had to be vectored was the thrust.

The purpose of this paper is to describe how the technical and program challenges involved in the creation of the F-35 Joint Strike Fighter were met. It will show how multiple service and mission requirements were incorporated into a single aircraft design. Analysis, design, ground-test, and experimental flight-test information will be presented. The first section of this paper describes the conceptual design of the original STOVL Strike Fighter for the Marines. Its development into the Air Force and Marine Common Strike Fighter will be discussed in the next section. The addition of the Navy and overseas partners to create the International Joint Strike Fighter will be described in the section after that. The last section summarizes the current status of the program and plans for the production and deployment of the F-35 Lightning II aircraft.

Marine STOVL Strike Fighter

In 1980, the Navy completed the Sea Based Air Master Study [1] on the future of Naval aviation. An essential conclusion was that an all-STOVL Naval air force designed around then-current technologies would cost more than an equivalent conventional carrier-based force. Given this result, the Navy began the construction of two new nuclear aircraft carriers. NASA took on the challenge of developing technologies for reducing the cost of supersonic STOVL aircraft and began the Advanced Short Take Off and Vertical Landing (ASTOVL) program. Between 1980 and 1987, NASA funded studies at all of the major aircraft companies to devise innovative concepts for a supersonic successor to the AV-8B Harrier, and the British Ministry of Defence conducted similar studies in the United Kingdom. Lockheed's ASTOVL concept was based on the tandem fan engine advocated by Rolls-Royce [2,3].

The tandem fan engine would have been created by lengthening a cruise engine to move the first stage of the engine fan forward. In the STOVL cycle, the first stage of the engine fan was to have been converted to a lift fan by diverting its exhaust flow to nozzles at the front of the aircraft. An auxiliary inlet would be opened to provide air to the engine core. By moving some of the cruise thrust forward in the vertical mode, this innovative engine concept enabled designers to balance the airplane while hovering. However, diverting the flow of the front fan from the engine core meant the loss of its supercharging effect on the core flow. Therefore, the tandem fan engine produced slightly less thrust in the vertical cycle than in the cruise cycle, despite the increased mass flow. As a result, the tandem fan engine had to be sized for the hover thrust requirement. This made it somewhat oversized for cruise, which increased fuel consumption. Also, the lift fan did not develop sufficient thrust to balance the thrust from the cruise nozzle, and so the engine had to be moved forward over the center of gravity of the aircraft. This concentration of wing, fuel, payload, and engine volume at the center of gravity made it difficult to design an aircraft that was slender enough to achieve supersonic speeds.

When these airframe studies were completed in the summer of 1986, a U.S./U.K. government review panel concluded that none of the proposed concepts offered a clear advantage in cost or performance. However, the panel did identify four propulsion concepts, including the tandem fan, which seemed promising. They recommended developing technologies that would improve the performance of these four concepts, and this work continued until 1991.

Invention of the Dual-Cycle Propulsion System

At the same time, NASA was also working with the Lockheed Skunk Works to study the installation of lift engines in the F-117, to identify the technologies needed to build a stealthy STOVL Strike Fighter (SSF). In the fall of 1986, the Defense Advanced Research Projects Agency (DARPA) expanded the scope of the NASA studies when it awarded the Skunk Works a nine-month-long exploratory study contract to see if a supersonic stealthy SSF could be developed for the Marines. This aircraft would have to perform the air superiority missions of the F/A-18 as well as the close air support missions of the AV-8. This combination of supersonic and vertical performance requirements meant that the engine must not only provide enough vertical thrust for short takeoffs and vertical landings, but must also be small enough that it would not increase supersonic drag. The propulsion system would be the key component in the development of this new strike fighter.

Ideally, a VTOL aircraft has a thrust-to-weight ratio of about 1.2 to provide thrust margins for vertical acceleration and control. A conventional F/A-18 has a usual takeoff weight of around 37,000 lb and dry thrust of 22,000 lb, giving a thrust-to-weight ratio of only 0.60 in dry power, increasing to just 0.95 in afterburner. A VTOL F/A-18 would require about 44,000 lb of dry thrust ($1.2 \times 37,000$ lb). Comparing a conventional F/A-18 with a VTOL F/A-18 illustrates the basic problem: there is not enough thrust, and it is all at the back. A VTOL F/A-18 requires an additional 22,000 lb of dry thrust ahead of the center of gravity for balance and to provide the necessary thrust margin. The problem became devising a way to double the engine thrust and move half of it to the front of the airplane. Posing the problem this way turned out to be the key to the solution.

Skunk Works engineers tried a number of brainstorming techniques, but the one that proved most useful was the method of forced associations. This is a technique for inventing something new by generating arbitrary combinations of existing mechanisms. The technique required making a list of all the ways to extract power from the hot high-pressure exhaust gases at the back of the engine (for example, turbines, scoops, heat pipes, magnetohydrodynamics, etc.), making another list of all of the ways to transfer power from one point in the aircraft to another (gas ducts, driveshafts, chain drives, superconducting wires, energy beams, etc.), and making a third list of all the ways to use power to generate thrust (fans, pulse jets, explosions, piezoelectric pumps, etc.). The procedure is to arbitrarily pick one mechanism from each list and figure out how they might be made to work together to solve the problem. This technique led to the invention of some truly innovative concepts: for example, using the energy of the exhaust gas to pump a gas laser, then beaming the energy forward, and then using it to explode the air in a pulse jet engine.

But none of these concepts were really practical. It became apparent that the best way to extract power from hot high-pressure exhaust gas is with a turbine, the best way to get the power forward in an aircraft is with a driveshaft (it is light and does not increase the cross-sectional area of the fuselage), and the best way to produce vertical thrust is with a fan (increasing mass flow is the best way to increase thrust per horsepower).

Therefore, the best solution to the problem of producing thrust ahead of the center of gravity would be to add another turbine stage to extract power from the exhaust gases. It would have to be variable-pitch, so that it could be feathered during cruise. Another driveshaft could be run from the added turbine stage through the engine to a lift fan: Rolls-Royce was already building three spool engines. The lift fan provides one lift post. Vectoring the cruise nozzle down would create another lift post. Shifting power between the lift fan and cruise nozzle would provide control in pitch. Similarly, engine bypass air could be ducted off to nozzles in the wings and thrust could be shifted from one wing to the other to provide roll control.

But ducting off the bypass air would effectively increase the nozzle exit area for the core flow and lower the back pressure on the turbine section. That would increase the power produced by the turbine [4], so that it would be necessary to close the cruise nozzle down to keep the engine from over speeding. On the other hand, if the lift fan was connected to the turbine at the same time that the bypass air was diverted to the wings, the lift fan would absorb the extra turbine power and keep the engine from speeding up. Then varying the nozzle area would shift power back and forth for pitch control.

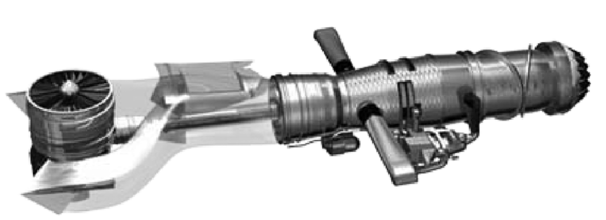

Fig. 3 Shaft-driven lift fan propulsion system.

When the lift fan was disengaged for cruise, the bypass flow would be returned to the cruise nozzle. This would match the nozzle area to the cruise power requirement again. In fact, it would not be necessary to add another turbine stage. The existing turbine would move off its design operating point to provide shaft power for hover and back to its design operating point for cruise. The existing driveshaft for the engine fan could just be lengthened to power the lift fan.

Because the lift fan is not connected to the engine during cruise flight, the engine operates like a conventional mixed-flow turbofan engine during cruise. For STOVL operations, the lift fan is connected to the cruise engine by engaging a clutch on the driveshaft. The cruise engine nozzle is simultaneously opened, increasing the pressure drop across the engine's turbine section. This causes it to extract additional shaft power, which is used to drive the lift fan. The engine then operates in hover like a separate-flow turbofan with a higher bypass ratio. This dual-cycle operation is the novel feature of the engine in the F-35 [5].

To summarize, the solution was to extract some of the energy from the engine exhaust jet by changing the operating point of the turbine, move it forward with a shaft, and turn it into additional thrust by adding it to a larger mass flow of air with a fan. The lift fan is attached to a driveshaft extending from the front of the cruise engine, as shown in Fig. 3, and bypass air for the roll jets is tapped off from behind the cruise engine fan. Thinking about how to extract power from the back of the airplane and transfer it to the front resulted in a flash of insight that produced the dual-cycle-engine concept as the solution for the STOVL Strike Fighter.

Principle of Operation

To appreciate how this dual-cycle engine turns jet thrust into additional shaft power, it is necessary to consider the changes in the static pressure of the air as it flows through the engine. The variation of total energy (top) and static pressure (middle) through an engine are shown in Fig. 4. The pressure rises through the compressor (2–3), remains constant through the combustor (3–4), and then drops through the turbine section (4–5) and nozzle (5–6), in two steps. As the pressure drops through the turbine section, the flow accelerates. The resulting thrust of the jets from the turbine nozzles spins the turbine disk that powers the driveshaft.

At every engine speed, the static pressure at the inlet to the turbine section is equal to the pressure rise across the compressor. The pressure drop across the turbine (P_4–P_5) plus the pressure drop across the exhaust nozzle (P_5–P_6) must therefore equal the pressure rise across the compressor ($P_3 - P_2$). The distribution of the pressure drops is controlled by the engine exhaust nozzle. Increasing the exhaust nozzle exit area reduces the pressure drop across the exhaust nozzle (P_5–P_6), and so the pressure drop across the turbine nozzles (P_4–P_5) must increase to compensate.

For example, increasing the nozzle exit area so that $A_6 = A_5$, as sketched in Fig. 4, causes the static pressure at the turbine exit, P_5, to drop to atmospheric pressure, P_6. The entire pressure drop then

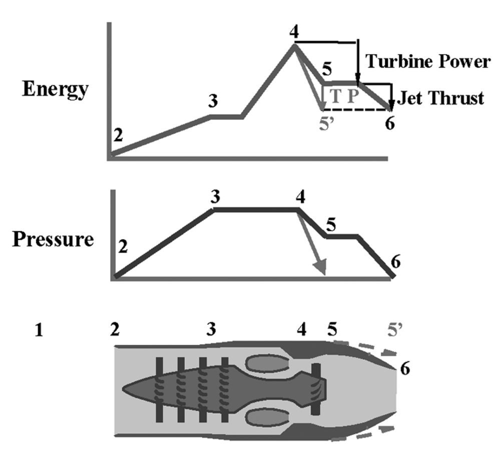

Fig. 4 Variation of pressure through a turbojet.

occurs across the turbine nozzles, increasing the thrust of the jets from the turbine nozzles and producing more shaft horsepower, while reducing the thrust of the exhaust flow. In general, the effect of opening the exhaust nozzle is to decrease its thrust while increasing the thrust of the turbine nozzles.

The power produced by the turbine section of a turbojet engine is given by the equation

$$\text{turbine power} = \dot{m} c_p T_{04}[1 - (P_5/P_4)^{(g-1)/g}] \tag{1}$$

where $\dot{m}$ is the mass flow through the turbine, c_p is the specific heat at constant pressure per unit mass of air, g is the gas constant, T_{04} is the stagnation temperature of the gas entering the turbine section, and P_5/P_4 is the pressure ratio across the turbine section. The usual method of increasing turbine power is by increasing the fuel flow, which increases T_{04}. The additional power of the turbine accelerates the engine until the power absorbed by the compressor matches the power produced by the turbine and the engine speed stabilizes. Because the rotational speed of the engine has increased, the engine pumps more air and produces more thrust.

The performance map of the turbine section in a typical modern fighter engine is shown in Fig. 5. The locus of steady-state matching conditions defines the engine operating line, which is the diagonal running from the bottom left to the top right in the figure. The engine and compressor are designed so that the turbine power and compressor power match near the point of maximum efficiency at every speed. However, at maximum thrust, the turbine inlet temperature T_{04} is already at the material limit of the turbine section. As a result, the gas temperature cannot be increased to provide the power to drive the lift fan. Instead, during VTOL operation, the additional power to drive the lift fan is obtained by increasing the pressure drop across the turbine section, P_4–P_5. The additional power is shown by the two points in Fig. 5.

The lower point is on the conventional operating line, and the upper point is obtained when the pressure drop across the turbine is increased. In this case, nearly 30,000 hp can be extracted before the turbine section reaches its stall limit. There is enough residual power in the exhaust flow to generate significant thrust from the cruise nozzle during hover. Engaging the clutch while increasing the nozzle area transfers the additional power to the lift fan, so that the speed of the engine does not increase.

Analytical Estimates

The horsepower needed to drive a lift fan can be estimated using basic momentum-energy considerations: horsepower hp is the product of thrust T and velocity V:

$$\text{hp} = TV \tag{2}$$

and thrust is the product of mass flow and velocity. If the duct of the lift fan is assumed to be cylindrical, so that the exit area of the duct equals the fan area, then thrust equals

$$T = \rho V^2 A \tag{3}$$

where ρ is the air density and A is the fan area.

Solving this thrust equation for velocity and substituting in Eq. (2) yields horsepower as a function of thrust for cylindrical ducted fans:

$$\text{hp} = (T^3/\rho A)^{1/2} \tag{4}$$

As previously noted, the lift fan must develop approximately 22,000 lb of thrust to balance an aircraft the size of an F/A-18. If the lift fan has the same 4 ft diameter as the cruise engine, then approximately 30,000 shp will be required, according to Eq. (4). To the accuracy of this analysis, there is sufficient power available from the engine to drive the lift fan.

This power must be transmitted by the driveshaft. The horsepower transmitted by a driveshaft is equal to the product of torque and rotational velocity. Therefore, for a given horsepower transmitted, the necessary torque decreases as the rotational velocity of the shaft increases. The shaft must be sized to transmit this torque. The torsion formula for hollow round shafts gives, for the diameter of the shaft,

$$d = [16 \times \text{shp}/\pi\omega\sigma(1 - f^4)]^{1/3} \tag{5}$$

where ω is the rotational speed of the shaft, σ is the maximum unit shear stress of the driveshaft material, and f is the fraction of the shaft diameter that is hollow. This formula gives the stress due to torsion only; it neglects other loads, such as those due to bending and vibration. Figure 6 shows how the diameter of a 0.05 thin-walled aluminum shaft transmitting 30,000 hp varies with engine rpm due to the torsion loads. The high rotational speeds typical of jet engines, more than 10,000 rpm, make it possible to transmit large amounts of power with an aluminum shaft just a few inches in diameter.

The size of the clutch depends on both the rotational kinetic energy of the fan, $I\omega^2/2$, and the period of engagement, t. The horsepower that must be absorbed by the clutch during engagement decreases as the time for engagement is increased according to the relation

$$\text{hp} = I\omega^2/2t \tag{6}$$

The knee of this curve is near 10 s at low engine speeds.

The jet pressure ratio can also be estimated from the thrust equation. Because the static pressure in the lift jet returns to ambient pressure behind the fan, then

$$\tfrac{1}{2}\rho V^2 = P_{\text{total}} - P_{\text{atmospheric}} \tag{7}$$

This equation can be solved for the fan pressure ratio $\text{PR} = P_{\text{total}}/P_{\text{atmospheric}}$ and yields

$$\text{PR} = 1 + \tfrac{1}{2}\rho V^2/P_{\text{atmospheric}} \tag{8}$$

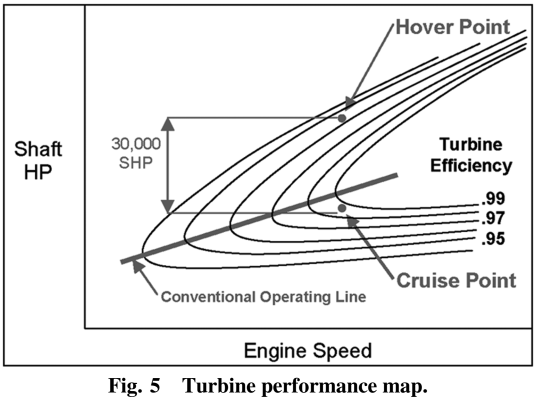

Fig. 5 Turbine performance map.

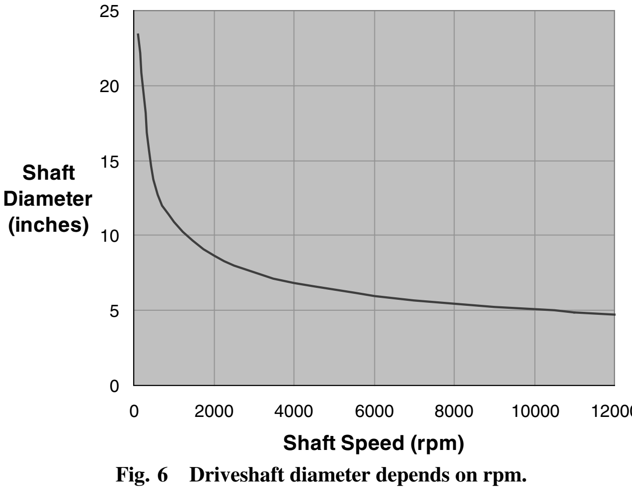

Fig. 6 Driveshaft diameter depends on rpm.

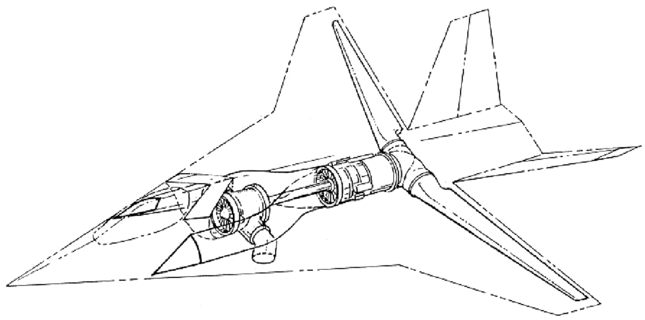

Fig. 7 Original sketch of the JSF propulsion system.

where $P_{\text{atmospheric}}$ is the ambient atmospheric pressure. Solving the thrust equation for the dynamic pressure at the fan face gives, for the dynamic pressure,

$$1/2\rho V^2 = T/2A \quad (9)$$

Therefore, for a 4 ft lift fan developing 22,000 lb of thrust, the pressure ratio is approximately 1.4, which is about the same as the pressure ratio of the lift jets of the AV-8 Harrier.

This first-order analysis suggested that it might be possible to almost double the thrust of an existing F-119 engine with a dual-cycle shaft-driven lift fan the same diameter as the engine. Such a variable-cycle propulsion system would provide high levels of thrust augmentation in the STOVL mode, with a cool low-pressure footprint, ample control power, and minimal effect on the design of the airframe. By placing the lift fan in line with the cruise engine, the bypass ratio would be increased without increasing the engine diameter. And because the cruise engine can be optimized for conventional flight, its performance is not penalized for its STOVL capability.

DARPA Conceptual Design Contract Awards

To illustrate the installation of such a propulsion system in a supersonic SSF, an airframe resembling an F-117 without facets was sketched for DARPA. The airframe was not faceted because computational speeds had increased in the decade since the F-117 was designed, so that it was now possible to analyze smooth contours. In this original sketch, shown in Fig. 7, the axis of the lift fan was aligned with the axis of the cruise engine, and rotating nozzles such as those on the Harrier were used to vector the fan thrust. The core thrust of the supercruising engine was vectored over a jet flap [6].

DARPA was interested in pursuing the concept further. In January 1988, it awarded the Skunk Works a follow-on contract to develop the conceptual design of an aircraft incorporating this dual-cycle propulsion system; McDonnell Douglas and General Dynamics were given similar contracts to design stealthy versions of their ASTOVL aircraft concepts. These were not major programs; only a couple of dozen people at each of the participating companies worked on these contracts.

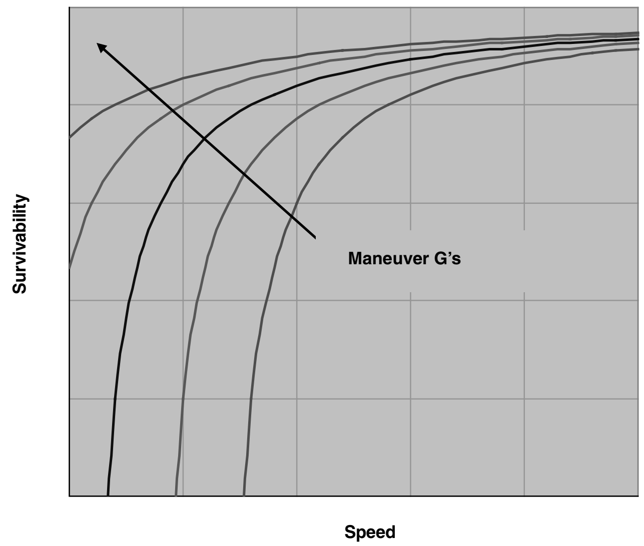

Fig. 9 Achieving survivability with speed and maneuver.

There were three design missions: Close Air Support, Combat Air Patrol, and Deck Launched Intercept. However, there were no specified speed, maneuver, signature, or other requirements. The only explicit requirement was that the empty weight of the aircraft be less than 24,000 lb, which is about 5% more than the empty weight of an F/A-18C. In other words, the weight of the STOVL equipment was to be about the same as the typical weight increment for the navalization of a conventional aircraft.

This use of weight as an independent variable was a novel program management tool used by DARPA to control the cost of the SSF. In the past, the Pentagon would release a set of specific performance requirements. The airframe contractors would then design the lightest and therefore most affordable airplane that would meet all of these requirements. Figure 8 is a typical carpet plot showing the effect of speed and maneuverability on weight. In this case, weight is the dependent variable; it depends on the specified $M = 1.5$ speed and the specified 7.5 g maneuver. Of course, weight also depends on signature, range, payload, etc., which are other dimensions of the carpet plot.

However, there are often several ways to meet a top-level mission requirement. For example, the same level of combat survivability can be achieved with different combinations of aircraft speed and maneuverability, as illustrated schematically in Fig. 9. Specifying a 24,000 lb empty weight limit, shown in Fig. 10, was intended to enable the designers to propose the most effective combination of speed, maneuver, signature, etc., for an aircraft of specified cost, without having to get government approval to change requirements.

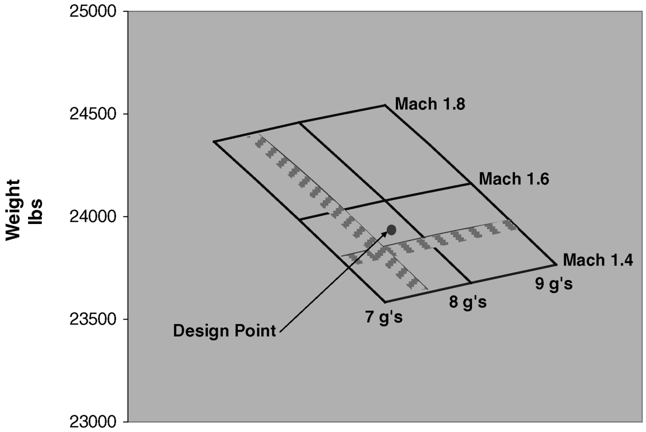

Fig. 8 Weight as a dependent variable.

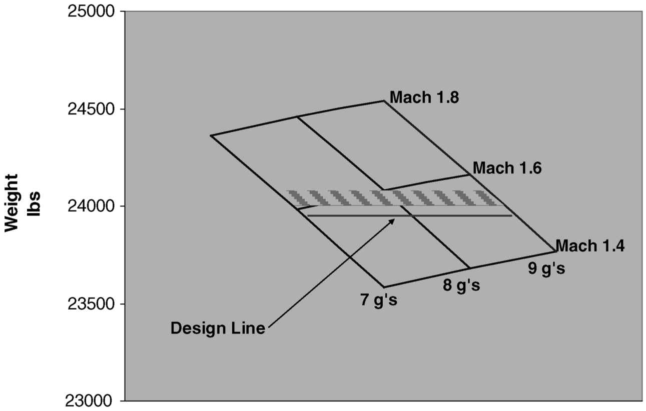

Fig. 10 Weight as an independent variable.

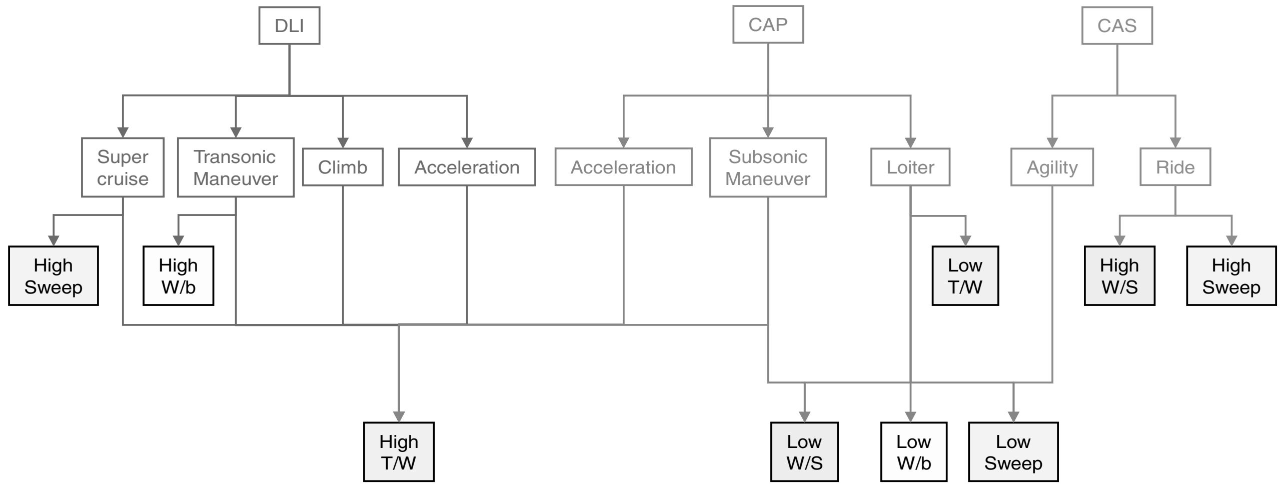

Fig. 11 Functional analysis was used to flow requirements down to the aircraft design.

This was a new way of designing an aircraft and it required a different approach to trade studies.

Skunk Works engineers used functional analysis to systematically analyze the conflicting performance requirements of the design missions and then used constraint analysis and tactical air combat simulations to devise the most cost-effective combination of aircraft capabilities. Functional analysis is a technique for deriving aircraft design features from mission requirements. Each of the required missions is subdivided into mission segments. Then each mission segment is decomposed into functions that the aircraft must perform to accomplish that segment. Finally, each function is analyzed to determine the specific design features needed to perform the function. This flowchart is often called a Willoughby template [7]. A simplified version of this analysis is shown in Fig. 11. It highlights the conflicting requirements for wing loading, thrust loading, span loading, and sweep.

Constraint analysis was used to select compromise values for these design parameters. Figure 12 shows the sensitivity of the design point to varying the speed and maneuver constraints that drove the design. The design point is above the speed and sustained maneuver constraint lines and to the left of the instantaneous maneuver constraint lines. The design point was selected by balancing the cost of improving performance against the cost of increasing combat losses if performance was not improved.

The cost savings obtained by improving all of the performance parameters fell on curves of diminishing returns, similar to those in Fig. 9, which meant that 80% of the optimum performance could be obtained for 20% of what the optimum cost. In other words, the last 20% of performance drove 80% of the costs. Therefore, the initial design point was selected at the knee of the curve, at the 80/20 point, which was judged to give the best value. This resulted in an aircraft with about the same performance as an F-18C, but which was more survivable because it was stealthier and capable of extended supersonic cruise. However, it was necessary to project a 15% weight savings through the use of composites to achieve the required weight of 24,000 lb.

Although the aircraft in the initial sketch shown to DARPA resembled an F-117, highly swept wings produce an unstable pitch up, even at moderate angles of attack, and were quickly abandoned. The initial design of the STOVL Strike Fighter had a delta/canard planform, as shown in Fig. 13. The active canard was moved like a weather vane during subsonic cruise and maneuver, so that it provided no lift and little drag, but it was adjusted to provide lift for trimming the nose-down moments that were produced when the flaps were deflected and when the center of lift moved aft at supersonic speeds. The active canard has less trim drag than a horizontal tail [8]. The desired performance required an afterburning engine. Because the jet flap nozzles could not accommodate an afterburner, the jet flap was similarly abandoned. The aircraft carried two long-range AIM 120 missiles and two short-range AIM 9 missiles in internal weapons bays. Models of the aircraft were tested in the wind tunnel and on the radar range to verify the predictions of both the aerodynamic forces and the radar cross section.

Paul Shumpert, the Skunk Works' lead propulsion engineer, used the software engine simulator provided by Pratt and Whitney (P&W) to show that dual-cycle operation of the Advanced Tactical Fighter engine was feasible and that sufficient power could be extracted to drive the lift fan. Both Pratt and Whitney and General Electric (GE)

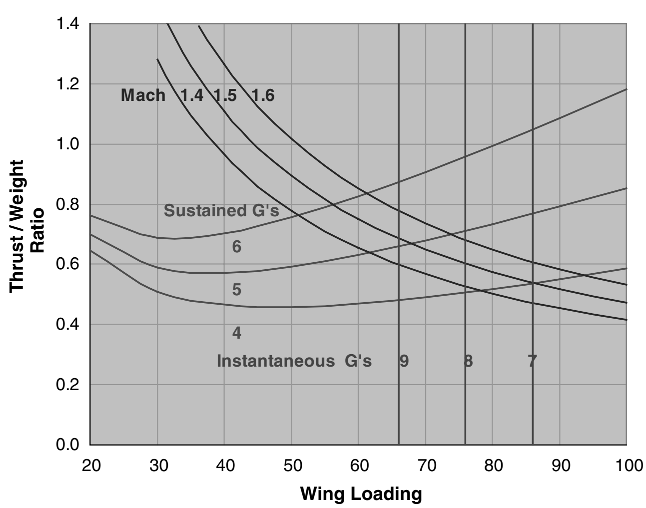

Fig. 12 Constraints that determined the design point.

Fig. 13 First STOVL Strike Fighter design iteration.

then worked with Skunk Works engineers to optimize their Advanced Tactical Fighter engine cycles to power a lift fan. The lift fan was installed with its axis vertical, because this maximized hover thrust. The Allison Engine Company designed an innovative lift fan with two counter-rotating fan stages. This configuration directs half of the power to each stage of the fan system, which reduces the gear loads in half. With this system, the power through each gear set is similar to that used in current heavy-lift helicopters.

Allison also designed a similarly innovative two-stage clutch to connect the lift fan to its driveshaft. A multidisk friction clutch is used to reduce the shock of engagement by slipping while the lift fan is accelerated from rest to the engine speed. Once the speed of the lift fan matches the engine speed, a mechanical lockup is engaged. This transmits the full power required for short takeoff or vertical landing.

However, because the dual-cycle propulsion system concept was new and unproven, Skunk Works engineers also designed a variant of this aircraft with a gas-driven lift fan, as a fallback option. In the gas-driven variant, some of the engine exhaust gases were ducted forward, around the engine, and used to spin a turbine that drove the lift fan, something like a turbocharger. This variant did not develop as much vertical lift, required more internal volume for the gas ducts, and was therefore heavier and slower than the shaft-driven variant. However, it appeared that it would be a satisfactory supersonic successor to the Harrier and it might be less expensive to develop than the shaft-driven system because it did not require modifying the cruise engine.

DARPA Naval Study Contract Awards

In the fall of 1989, DARPA arranged for all three contractors to present their concepts to the Naval Air Systems Command (NAVAIR). All three subsequently received follow-on contracts to refine their designs and investigate the feasibility of using stealth in the Naval environment. These studies were completed by the end of 1990. After reviewing the results, the Marines expressed interest in conducting a technology maturation effort that would enable them to choose between the shaft-driven and gas-driven variants of the lift fan system. This prompted the Skunk Works to apply for a patent on the shaft-driven lift fan and dual-cycle engine concept. The patent was awarded three years later [9].

However, in December 1990, then Defense Secretary Cheney canceled the Marine's V-22 program for the second time. The Marines explained that they were a small service and could only support one aircraft development program at a time, and they had to focus on the V-22. A few weeks later, in January 1991, Cheney terminated the troubled A-12 program for default, and the Secretary of the Navy directed NAVAIR to begin work on the A/F-X, a new stealth aircraft intended to replace the A-6. Most members of the Lockheed SSF design team were then reassigned to the A/F-X program.

Common Affordable Lightweight Fighter

During 1991, DARPA and the Skunk Works continued to brief the Pentagon and the staffs of the U.S. Congressional budget committees to secure funding for the SSF technology maturation and risk-reduction effort. This led Gerry Cann, the Assistant Secretary of the Navy for Research, Development, and Acquisition, to task the Naval Research Advisory Committee (NRAC) in early 1992 with assessing the feasibility and desirability of developing a STOVL Strike Fighter.

Beginnings of Jointness

In April 1992, Brig. Gen. George Muellner, who was then Deputy Chief of Staff for Requirements at Air Combat Command, visited the Skunk Works to review recent developments. The STOVL Strike Fighter was put on the agenda. However, the Air Force was not likely to be interested in a STOVL aircraft, because it had less need for such capabilities than the Navy and it had similar concerns about the increased cost. In fact, the Air Force had begun thinking about a conventional takeoff and landing (CTOL) MultiRole Fighter (MRF) to replace the F-16, although this program had no funding. Therefore, it was decided to brief Gen. Muellner on a stealthy conventional takeoff and landing strike fighter, instead. One of the secrets of the Skunk Works is that it was not necessary to deal with miles of red tape and endless approval chains to make this decision. Ben Rich described this Skunk Works management philosophy in his 1988 Wright Brothers Lecture [10].

The conventional variant was quickly created by simply removing the lift fan and vectoring nozzle from the SSF and substituting a fuel tank and a more conventional cruise nozzle. This reduced the empty weight of the aircraft by about 15%, while improving its range and reducing its cost. The weight of the fuel tank and one-half of a tank of fuel turned out to be about the same as the weight of the lift fan. As a result, both variants had the same midmission maneuver performance. The canard was to be used for trim at other points in the mission, as the fuel was burned. These aircraft are shown in Fig. 14.

At the end of the presentation on the conventional aircraft, Gen. Muellner was briefed on the Marine STOVL variant and it was suggested that developing a Common Strike Fighter might be an affordable way for both services to get the aircraft they wanted. Because the Navy, Marines, and Air Force had all flown the F-4 Phantom II, a joint program had previously been successful, despite the F-111 experience. It seemed to me that if we built it, they would come, to paraphrase the movies. General Muellner requested follow-on briefings by the Skunk Works to his staff at Langley Air Force Base. Then he met privately with DARPA and the Marines in the Pentagon. DARPA then arranged briefings for Gen. McPeak, the Air Force Chief of Staff; Adm. Dunleavy, the Assistant Chief of Naval Operations for Air Warfare; and the Office of the Secretary of Defense (OSD), who then advanced the idea to the service secretaries. In the summer of 1992, the NRAC endorsed the feasibility of the SSF and recommended that the Navy work with the Air Force to support the development of designs and technologies for highly common Air Force and Marine MultiRole Strike Fighters.

With the support of OSD and the Pentagon, Congress appropriated \$65 million for DARPA to begin a joint STOVL/CTOL Strike Fighter program. DARPA released a Request for Proposal (RFP) to

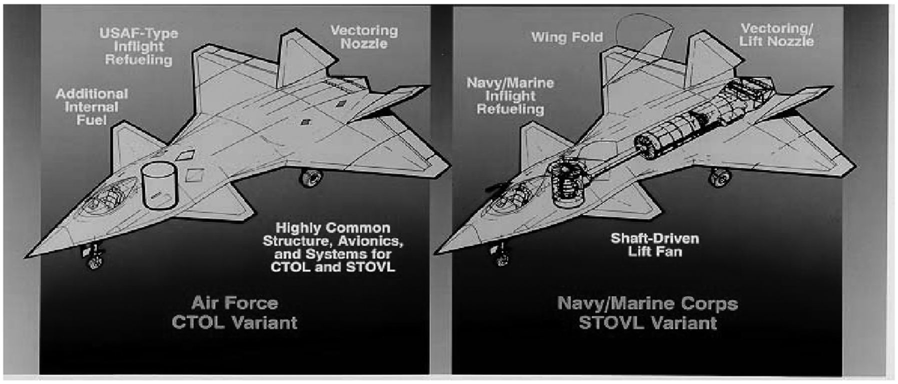

Fig. 14 Conventional and STOVL Strike Fighter variants.

industry in August 1992 for conducting critical technology demonstrations of shaft-driven and gas-driven lift fan systems and for the conceptual design of what was called the Common Affordable Lightweight Fighter (CALF). The RFP requested proposals for other novel lift systems as well. Because this was the first public disclosure of the DARPA program, some consider this RFP to be the start of the JSF program.

DARPA Technology Demonstration and Maturation Contracts

General Electric's proposal to the Skunk Works for demonstrating the dual-cycle propulsion system was $5 million less than P&W's proposal, and all the other aircraft companies gave subcontracts to GE. However, the Skunk Works chose P&W because the Air Force had selected the P&W engine over the GE engine for the F-22 program and it would be the only engine available when our demonstrator aircraft would need an engine. In exchange, P&W agreed to work exclusively with the Skunk Works on the development of the dual-cycle shaft-driven lift fan concept. Since the shaft-driven lift fan concept had been invented under DARPA contract, the system was actually available to any American aircraft company for government programs and McDonnell Douglas proposed that they perform an "apples to apples" comparison of both the shaft-driven and gas-driven lift fan systems for $60 million. However, in March 1993 the Skunk Works was awarded a $33 million contract to mature technologies for a shaft-driven lift fan and McDonnell Douglas received a $28 million contract for a gas-driven lift fan.

A year later, in March 1994, the U.S. Congress appropriated an additional $6 million to study designs based on a lift/cruise engine concept, which was considered to have less risk because it had been shown to be successful in the AV-8 Harrier. The Boeing Company agreed to match that amount with its own funds and received a DARPA contract to design a lift/cruise engine concept. The following year, the U.S. Congress appropriated an additional $10 million for the lift/cruise concept, which was again matched by Boeing.

All three contractors were required to design both operational and demonstrator aircraft and to perform large-scale powered-model demonstrations to reduce risk. These tests were intended to validate the propulsion concepts, to show that hot-gas ingestion would not be a problem, and to demonstrate that there was sufficient control power for transition from hover to cruise. Large models were used due to uncertainties about scaling the temperature and turbulence effects of the lift jets from small models. The Skunk Works created a new SSF baseline. This was nominally the same as the original SSF design, a delta canard configuration with a vertical lift fan and internal weapons bays. However, the aerodynamic performance estimates were supported by data from the F-22 program [11]. The principal differences from the F-22 configuration were that the SSF design had a single engine and a canard.

The addition of four new ground-attack missions from the MRF program changed the design emphasis from a fighter with some strike capability to a strike aircraft with some air-to-air defensive capability. The development of stealth and long-range air-to-air missiles had changed the nature of air combat, and so the emphasis was on achieving a first-look, first-kill capability and reducing the need to dogfight at close range. For these reasons, the two AIM 9 missiles were removed and the aircraft was designed to carry two 2000 lb bombs in the internal weapons bays, in addition to the two AIM 120 missiles. This increased the aircraft's frontal area and wave drag. The Air Force variant was derived, as before, by removing the lift fan and thrust-vectoring nozzles and substituting a fuel tank and conventional cruise nozzle. These aircraft are shown in Fig. 15.

Although analysis and computer simulation had shown that it was theoretically possible to extract enough energy from the exhaust of the F-119 engine to drive the lift fan, there were practical concerns regarding the operation of such a dual-cycle propulsion system. In particular, there were concerns about the thrust losses associated with the large swirl angles induced in the engine exhaust flow when the turbine operating point was changed. There were other questions about the ability of the engine controls to rapidly transfer thrust back and forth for pitch control by synchronizing the operation of the lift fan with the changes in engine nozzle area. And there were also questions about the weight and reliability of the driveshaft, clutch, and gearbox that powered the lift fan.

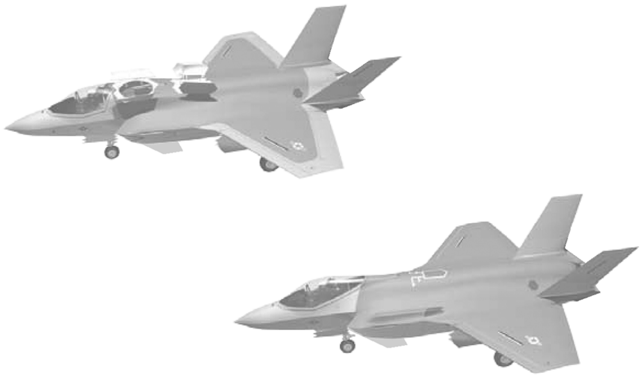

Fig. 15 Revised STOVL and conventional Strike Fighter variants.

The demonstrator propulsion system was built and tested to address these concerns and prove the feasibility of the dual-cycle engine and drive system. The demonstrator engine and lift fan were constructed, like a hot rod, with components from existing engines. The first-stage fan and inlet guide vanes from the Pratt & Whitney YF119 engine were used for the lift fan. This fan ran at the same power level as one stage of the production lift fan, so that the loading on the drive gears was the same as in the production gearbox. The demonstrator engine was assembled by joining the fan and core of the relatively-low-bypass-ratio P&W F100-PW-220 engine to the turbine section from the higher-bypass-ratio F100-PW-229 engine. This bigger turbine could provide enough power to drive the lift fan as well as the engine fan. Two holes were cut in the engine case so that the bypass air could be diverted to the pair of roll control jets, and the engine fan rotor was modified so that the driveshaft could be attached. A variable-area thrust-deflecting nozzle was mounted at the rear of the engine, and the digital engine control software was modified to run in both cruise and STOVL cycles.

In December 1994, the assembled lift fan, gearbox, and driveshaft were demonstrated at the Allison facility in Indianapolis, Indiana. The power transmission losses in the gear set were measured, and operation of the lubrication and oil cooling system in the vertical position were demonstrated. The distortion limits of the fan were established and the ability of the inlet guide vanes to modulate the fan thrust was shown. The success of these demonstrations showed the feasibility of building a flight-weight lift fan and gearbox for the required power levels.

The lift fan was then shipped to the P&W facility in West Palm Beach, Florida. During February 1995, it was connected to the demonstrator engine and operated in both cruise and STOVL cycles, which demonstrated that an engine turbine could be switched from providing jet thrust to providing shaft power to run the lift fan. The ability to rapidly transfer thrust back and forth from the cruise engine to the lift fan to provide pitch control was also shown.

When these tests were complete, the propulsion system was installed in a full-size airframe model made of fiberglass and steel. This model is shown in Fig. 16. This model was mounted in the outdoor hover test facility at the NASA Ames Research Center. The jet-induced downloads out of ground effect were measured to be less than 3% of the jet thrust, and the jet fountain and lift improvement devices were shown to be successful in limiting the induced downloads to less than 7% at wheel height. These are very low numbers. No hot-gas ingestion was detected over a wide range of pitch and roll angles while the aircraft model was suspended 1 ft off the ground.

The transition characteristics of the model were then measured in the NASA 80×120 ft wind tunnel. Drag polars obtained for a range of flap angles and tunnel speeds were used to show that the aircraft could take off and land on a Wasp-class assault carrier with a 20 kt wind over the deck without using a catapult or arresting gear and that it would have a wide corridor for transition from hover to wingborne

Fig. 16 Large-scale wind-tunnel model.

flight. Measurements also showed that there was sufficient control power for acceleration and deceleration during transition and for yaw control in crosswinds up to 20 kt. This technology maturation program [12,13] demonstrated the feasibility of the dual-cycle lift fan propulsion system and reduced risk to Technology Readiness Level 5.

Joint Advanced Strike Technology Program

In February 1993, at the same time that the first CALF contracts were awarded, the U.S. Department of Defense began a Bottom Up Review (BUR) of American military forces and modernization plans. One of the main objectives was the rationalization of the five tactical aircraft development programs then going on: the Air Force F-22 and MRF programs, the Navy F/A-18E/F and A/F-X programs, and the DARPA CALF program. The Air Force and Navy made a joint presentation to the BUR task force in which they suggested developing a highly common MultiRole Fighter based on the SSF, called the Joint Attack Fighter. The Naval variant was envisioned as a conventional carrier-based aircraft. However, Marine Col. Durham at OSD [14] and Air Force Lt. Gen. Croker at Air Combat Command [15] argued that the Naval variant should be the STOVL aircraft being developed by DARPA.

The results of the bottom-up review were announced in September 1993. It was decided to cancel the MRF and A/F-X programs and to develop technologies for a Joint Attack Fighter that would replace the AV-8, F-16, and F-18 when they were retired beginning in 2010. This effort was called the Joint Advanced Strike Technology program. General Muellner was appointed the JAST director in December 1993. The first JAST concept-exploration contracts were awarded in May 1994, more than a year into the DARPA program. The JAST studies did not initially include a Marine STOVL variant, pending the results of the DARPA demonstrations that were expected about October 1995 [16].

However, in October 1994, the U.S. Congress directed that the DARPA program (and, specifically, the STOVL variant for the Marines) be the focus of the JAST program. Thereafter, all the contractors worked on developing Air Force, Navy, and STOVL Marine variants of a single aircraft, although not all of the JAST contractors had CALF contracts. Figure 17 is a timeline showing the various programs that were integrated into the Joint Strike Fighter program. The dashed lines identify programs that never actually awarded any study contracts to industry. A more complete history covering the period up to 1994 is presented in [17].

The primary requirement for the Naval variant was the ability to take off and land on a carrier in 300 ft or less with a 20 kt wind over the deck. Lockheed Martin considered three alternative approaches. The first alternative was for the Navy to operate the same STOVL aircraft being developed for the Marines; this was certainly the easiest solution, but this aircraft would have less range/payload performance than a conventional Naval aircraft.

The second alternative was to remove the lift fan and adapt the roll control jets to blow the wing flaps. This would increase the wing lift, reducing the aircraft takeoff and landing speeds and enabling it to use the carrier catapult and arresting gear. However, the blown flaps on the F-4 Phantom had proved difficult to maintain and Lockheed Martin did not feel the Navy would favor this approach. Instead, it was decided to increase the wing area by enlarging the flaps and slats and adding a wingtip extension. The increased lift of the larger wing also reduced the takeoff and landing speeds and enabled use of the catapult and arresting gear. An additional benefit of the larger wing is that it gives the Naval variant greater range than either the Marine or Air Force variants, both by reducing the induced drag and by providing additional volume for fuel.

Because the carrier arresting system imposes greater loads on the landing gear and airframe than a conventional landing, the landing gear of the Naval variant was redesigned for a 25 fps vertical velocity, rather than 10 fps used for the conventional and STOVL variants. Similarly, the nose gear was redesigned for catapult launches. The additional airframe loads were handled through the use of cousin parts, which are stronger parts that replace conventional parts without

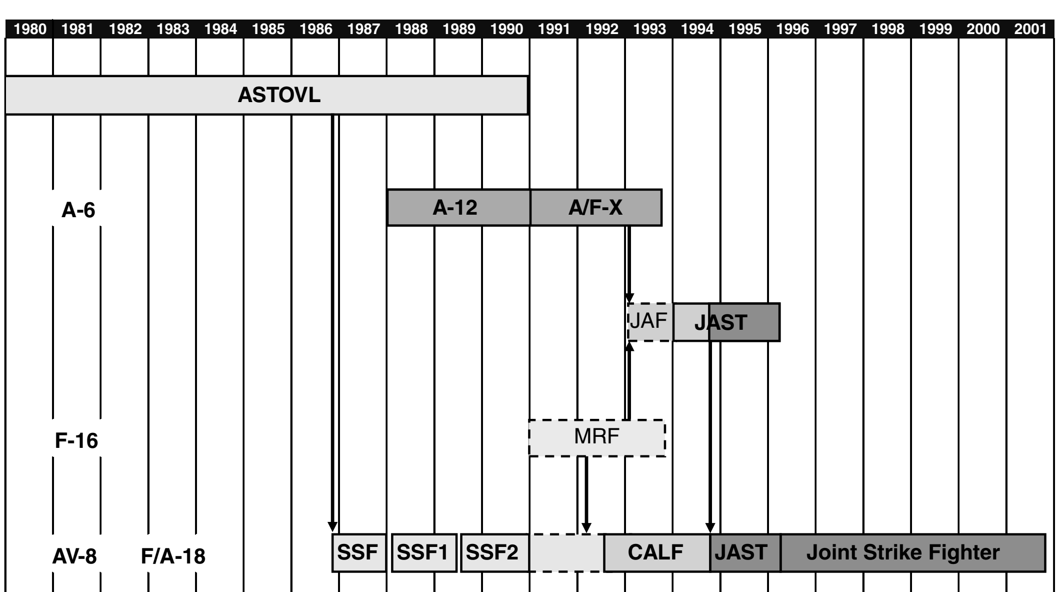

Fig. 17 Timelines of the programs that were integrated into the JSF program (JAF denotes the Joint Attack Fighter).

changing the basic structural arrangement. For example, on the Air Force and Marine variants, the bulkhead that takes the main landing gear load is made of aluminum and is approximately $\frac{1}{2}$ in. thick. The same bulkhead on the Naval variant is made of titanium and is about $\frac{3}{4}$ in. thick. This technique was adapted from the F-16 production line, in which cousin parts were used to create variants of the same basic airframe for different customers who preferred different subsystems.

Because the shaft-driven lift fan propulsion concept was new and therefore considered the riskiest of the alternative propulsion systems, it was decided to reduce the perceived risk of our aircraft design by replacing the canard with a more conventional aft tail. This was easily done, as one of the advantages of the lift fan concept was the ability to rebalance the aircraft with relatively small changes in the size and location of the fan. The three JAST variants are shown in Fig. 18.

In May 1995, Lockheed Martin gave the Yak Aircraft Corporation a contract to provide an independent assessment of our STOVL propulsion system and airframe concept and also to provide lessons learned from their STOVL aircraft development programs. They were provided with copies of everything regarding the competing CALF concepts that had been published in the open literature, including a copy of the U.S. patent [9] on the Lockheed dual-cycle propulsion system. Drawing on their own experience developing STOVL aircraft, Yak engineers provided us with predictions of the STOVL performance, including ground effects, of all three competing aircraft concepts. They also provided a risk assessment of each concept. In addition, they provided useful design and performance information for the lift systems of the Yak STOVL aircraft. Their final report was very complimentary of our design and gave us confidence that it was the right concept.

At the end of this phase of the program, all three contractors had designed demonstrator and production aircraft. The Lockheed Martin and McDonnell Douglas designs were very similar conventional wing/body/tail configurations, whereas Boeing had a tailless delta configuration. Lockheed Martin had demonstrated the dual-cycle shaft-driven lift fan concept at large scale in hover and transition. Boeing had tested their large-scale lift/cruise model in hover only. After testing the gas-driven lift fan propulsion system, McDonnell Douglas approached Lockheed Martin for permission to work with Pratt & Whitney on a shaft-driven lift fan system of their own, but were turned down. They switched to a lift engine concept; however, they did not perform a large-scale demonstration of this system. At this point, Lockheed Martin had become the low-risk alternative.

Joint Strike Fighter Program

In September 1995, not long after he was sworn in as Deputy Secretary of Defense, John White was briefed by his staff on the shortfall in tactical aviation that was forecast to begin about 2010 and on the JAST program created to address the problem. After the briefing, he directed Undersecretary of Defense for Acquisition and Technology Paul Kaminski to create a plan for developing a new joint aircraft from the JAST program. At a meeting with all the service

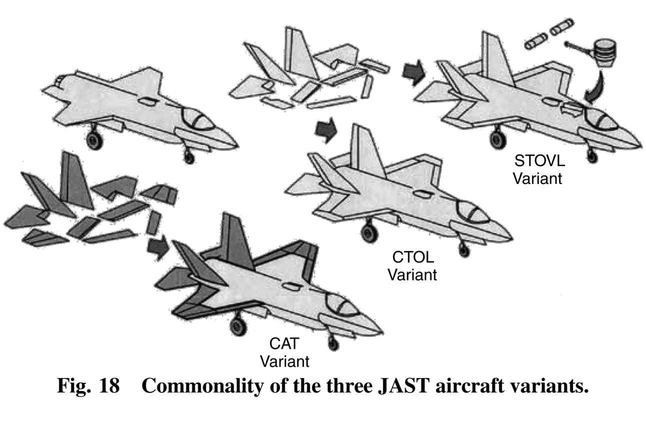

Fig. 18 Commonality of the three JAST aircraft variants.

secretaries in February 1996, John White approved the plan to develop a Joint Strike Fighter. A month later, before the tests of the large-scale aircraft models were completed, the JAST program office released an RFP to industry for the design and flight test of the demonstrator aircraft. The proposals were submitted in June of that year. The contractors were to propose their own demonstration test objectives. Lockheed Martin proposed three principle objectives: first, to demonstrate that it is possible to build highly common CTOL, STOVL, and Naval variants of a Joint Strike Fighter; second, to demonstrate STOVL performance and supersonic speed on the same flight, as this had never been done before; and third, to demonstrate the handling qualities and carrier suitability of the Naval variant, because Lockheed Martin had never built a Naval fighter before.

The Skunk Works proposal was to build two aircraft. One would be devoted to STOVL testing, because this had always been perceived as the greatest challenge. The other would be first flown as the Air Force variant and then be modified by replacing the wing flaps and slats to become the Naval variant. Both aircraft would be built with the Naval structure. To reduce the cost of the demonstration, available components were used for subsystems that were not critical to the test objectives. For example, these aircraft used the nose gear from the F-15 and modified main landing gear from the A-6. The increased weight of these off-the-shelf components was offset by not including mission avionics and weapons bays on the demonstrator aircraft.

Concept Demonstrator Contract Awards

In May of 1996, Undersecretary of Defense for Acquisition and Technology Paul Kaminski changed the program to an acquisition category 1D program and renamed it the Joint Strike Fighter program, reflecting the greater scope and cost of the next phase of development and making it clear to U.S. Congress that JSF was an aircraft development program. In November 1996, Boeing and Lockheed Martin were selected to build concept demonstrator aircraft. The Marines did not select the McDonnell Douglas lift engine concept based on concerns regarding the logistics of maintaining two different engines in the same aircraft and reports about the Russian experience with the Yak-38 and Yak-141. McDonnell Douglas subsequently merged into Boeing, and BAE Systems and Northrop Grumman, which had been teamed with McDonnell Douglas, joined the Lockheed Martin team.

Because the planforms of both the Lockheed Martin and the Boeing aircraft were relatively conventional, and the F-22 had demonstrated that unfaceted fighter airframes could have reduced signatures, the competition was between the STOVL propulsion system concepts. Thrust being the product of mass flow and velocity, Lockheed Martin's approach to achieving the necessary high thrust-to-weight ratio was to use a large mass flow of air at low velocity, whereas Boeing's approach was to use a smaller mass flow of air at a higher velocity. The mass flow of the lift fan system was approximately 2.5 times greater than in Boeing's lift/cruise system, and the lift jet velocity was more than one-third lower.

The need to reduce fabrication costs of the demonstrator aircraft and the success of the STOVL wind-tunnel tests at NASA Ames enabled Lockheed Martin to change its commonality demonstration. It was decided to devote one aircraft to the demonstration of carrier handling qualities, and the other aircraft would first be flown as the Air Force variant and then be converted to the STOVL variant by removing the fuel tank and installing the lift fan. The X-35A conventional variant was the first to fly. Its first flight was on 24 October 2000 from the Lockheed plant in Palmdale, California, to Edwards Air Force Base, a distance of just over 20 miles. It averaged a flight a day for the next 30 days, demonstrating fighterlike maneuver performance and supersonic speed. It met or exceeded all of its flight-test objectives.

The test program achieved such high productivity because the airplane had been approved for air-to-air refueling on the basis of qualification in a flight simulator. This was another first, because some new aircraft have taken more than a year of flight tests to be approved for aerial refueling. Boeing was not able to use air-to-air refueling during its flight-test program. In a very unusual step at this early stage in an aircraft development program, this aircraft was flown by American and British military test pilots in addition to the Lockheed Martin and BAE Systems test pilots.

During December and January, the conventional X-35A was converted into the STOVL X-35B by installing the lift fan and thrust-vectoring nozzle. During the spring of 2001, the aircraft was tethered to a deflector grid that diverted the lift jets to minimize ground effects. The operation of the propulsion system (engine, lift fan, nozzles, and reaction control system) was checked and measured. On 23 June 2001, the aircraft was untethered and BAE Systems test pilot Simon Hargreaves advanced the throttles to take weight off the wheels to check the response of the control system in this case. The airplane rose straight up to a height of 20 ft, under complete control, before Hargreaves settled it back to the grid. This flight is shown in Fig. 19.

Over the next month, the aircraft made 38 flights from the runway at Edwards Air Force Base during which the STOVL and transition performance were validated. Then, on 20 July 2001, the X-35B, flown by Marine Maj. Art Tomassetti, became the first aircraft in history to make a short takeoff, fly supersonically, hover, and land vertically. Boeing's X-32 aircraft were not able to demonstrate this Mission X. Lockheed Martin pilot Tom Morgenfeld ferried the aircraft back to Palmdale on the aircraft's final flight on 6 August 2001. The aircraft was refueled six times in the air and the flight lasted 3.5 h, ending with six touch-and-go landings.

The second aircraft, configured as the X-35C Naval variant, made its first flight on 16 December 2001. Lockheed Martin pilot Joe Sweeney ferried it to Edwards Air Force Base. During 33 h of flight-testing at Edwards Air Force Base, it successfully demonstrated the use of a side-stick controller in simulated carrier approaches. In February 2001, the X-35C was flown from Edwards Air Force Base in California to the Patuxent River Naval Air Station in Maryland, becoming the first X-Plane in history to make a coast to coast flight across the United States. Another 33 h of flight-testing were completed at Patuxent River. The X-35C also achieved supersonic speeds and accomplished more than 250 field carrier landing practice demonstrations. These showed the carrier suitability of the Naval variant.

Flight-testing of the three X-35 variants reduced the risk of the JSF airframe and propulsion systems to Technology Readiness Level 6. The X-35A/B is in the permanent collection of the Smithsonian Institution and was placed on display at the Udvar-Hazy Center. The X-35C is on display at the Naval Air Museum in Patuxent River.

F-35 Lightning II Program

In November 2000, the JSF Program Office requested proposals from both teams for the manufacture and test of 22 developmental aircraft: 8 ground-test aircraft and 14 flight-test aircraft. The proposals were submitted in February 2001, six months before the end of flight-testing. On 26 October 2001, the JSF Program Office announced that Lockheed Martin had won the competition. Boeing

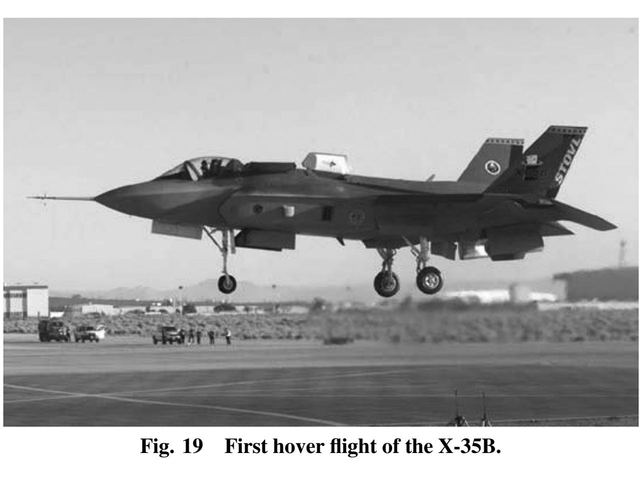

Fig. 19 First hover flight of the X-35B.

and the Pentagon credited the performance of the lift fan propulsion system with the win, and the Lockheed Martin JSF team was subsequently awarded the 2001 Collier Trophy for the development and demonstration of the lift fan propulsion system.

The developmental aircraft have a strong resemblance to the demonstrator aircraft. The planform of the airframe is the same, and the layout of the engine, lift fan, and nozzles is also retained. However, the prototypes incorporate mission equipment, including weapons bays, mission avionics, and low-observable coatings. Off-the-shelf subsystems used in the demonstrators have been replaced with new designs to reduce weight. Similarly, the ram air cooling systems used on the demonstrator aircraft were replaced by liquid cooling systems, such as those on the F-22. The wing span of the F-35A/B was increased slightly to improve maneuver and range performance. The rudder and horizontal tails were also enlarged to increase control power. The weapons bay doors on the STOVL variant were designed to open during vertical landing to capture the fountain created by the lift jets and counter suckdown in ground effect. Because this benefit had been demonstrated on the large-scale model at NASA Ames, weapons bay doors had not been included on the demonstrator aircraft. The lift fan inlet and nozzle were also changed.

The cockpit of the prototype aircraft is considerably more advanced than in the demonstrators. The controllers in the X-35B were similar to those in the Harrier, with a control stick, throttle, and a separate nozzle lever. In the F-35B, nozzle vectoring is controlled automatically by the stick commands. There is also a voice command system for noncritical functions, such as controlling radio frequency. The cockpit instrumentation in the X-35 included a head-up display (HUD) and two small color displays from a C-130 on the instrument panel. The cockpit of the F-35 includes a virtual HUD projected onto the visor of the pilot's helmet and a single large instrument display panel that the pilot can divide into several different screens.

The 24,000 lb weight limit and Weight as an Independent Variable were not used for the design of the production aircraft. As a result, the desire to improve performance and to reduce manufacturing costs began to add weight to the airframe. For example, a gun was added and the maneuver limit was raised from 7.5 to 9 g; the wing structure was redesigned to include pylons for external weapons, and the number of wing attach points was reduced to simplify assembly; the airframe structure was redesigned to accommodate subsystems and facilitate access, etc. By January 2004, weight had increased by more than 3000 lb. To get the weight back out, a design stand-down was declared on 7 April 2004 and the entire team shifted their emphasis to weight reduction. Lockheed Martin offered a $100 bonus to employees for every weight-saving idea and awarded $500 for every pound removed. More than 2000 ideas were submitted on the first day and more than 2700 lb were removed from the airframe by the end of the year. Lockheed Martin awarded more than $1.35 million to its employees for their weight-saving ideas.

On 19 February 2006, the first Air Force F-35A was rolled out at the Lockheed Martin plant in Fort Worth, Texas. After a series of ground vibration tests, it was unveiled in a public ceremony on 7 July 2006, when the Air Force announced that it would be called the Lightning II. The first flight of the F-35A was on 15 December 2006. The first STOVL F-35B was unveiled a year later, on 18 December 2007, and made its first flight on 11 June 2008. It will be flown using conventional takeoffs and landings through the end of 2008 and is scheduled to make short takeoffs, then hover, and finally make vertical landings during 2009. In addition to the two aircraft currently in flight test, one is in ground test, five more flight-test aircraft are in final assembly, and another 14 are in various stages of completion on the production line. The first aircraft are expected to become operational with the U.S. Marine Corps in 2012, with the U.S. Air Force in 2013, with the British Royal Navy and Air Force in 2014, and with the U.S. Navy in 2015.

Conclusions

The Joint Strike Fighter will achieve significant savings in aircraft production and life cycle costs by providing a common aircraft to replace the Air Force F-16s, Navy and Marine F/A-18s, and Marine AV-8s. All of the JSF variants have essentially the same airframe, engine, avionics, and subsystems. By spreading the development and support costs of these components over a larger number of aircraft, each variant becomes more affordable. In addition, the Air Force and Naval variants will provide greater stealth and range than the aircraft they will replace, and the Marine variant will combine the supersonic performance of the F/A-18C with the short takeoff and vertical landing performance of the AV-8B.

The technical challenges involved in designing a single aircraft for all three services were met by designing three highly common, but not identical, variants of the same aircraft. The STOVL variant, which was designed first, incorporates a shaft-driven lift fan in a bay between the inlet ducts and a thrust-vectoring cruise nozzle. The airframe was designed to Air Force specifications, so that the conventional takeoff and landing variant was developed by removing the lift fan and vectoring nozzles from the STOVL variant and substituting a fuel tank and a conventional cruise nozzle. The Naval variant was similarly developed from the conventional variant by increasing the wing area, designing stronger landing gear, and using stronger cousin parts to handle the larger airframe loads associated with carrier takeoffs and landings. Both the STOVL and Naval variants are about 15% heavier than the conventional variant.

The program challenges were met by having a credible technical solution and by creating a Joint Program Office, staffed by members of all three services. The positions of Acquisition Executive and Program Manager were rotated between the services. This program office developed a joint operational requirements document, which freed the airframe contractors from the need to satisfy multiple customers or mediate between them.

The three F-35 variants will initially replace at least 13 types of aircraft for 11 nations, making the Lightning II the most cost-effective fighter program in history. Lockheed Martin is developing the F-35 with its principal industrial partners, Northrop Grumman and BAE Systems. Two interchangeable engines are under development: the Pratt & Whitney F135, which powered the first aircraft, and the GE Rolls-Royce F136.

The success of the Wright Brothers in building the first practical airplane was due to their approach to solving the problems of manned flight. The key elements of their approach were teamwork, constructive debate, innovative thinking, systematic testing, and a skeptical study of the relevant literature. Lockheed Martin's success in developing the Joint Strike Fighter is further evidence of the value of the Wright Brothers' approach.

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