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# F-35 Air Vehicle Technology Overview

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**The Lockheed Martin F-35 Lightning II incorporates many significant technological enhancements derived from predecessor development programs. The X-35 concept demonstrator program incorporated some that were deemed critical to establish the technical credibility and readiness to enter the System Development and Demonstration (SDD) program. Key among them were the elements of the F-35B short takeoff and vertical landing propulsion system using the revolutionary shaft-driven LiftFan® system. However, due to X-35 schedule constraints and technical risks, the incorporation of some technologies was deferred to the SDD program. This paper provides insight into several of the key air vehicle and propulsion systems technologies selected for incorporation into the F-35. It describes the transition from several highly successful technology development projects to their incorporation into the production aircraft.**

## I. Introduction

THE F-35 Lightning II is a true 5th Generation trivariant, multiservice air system. It provides outstanding fighter class aerodynamic performance, supersonic speed, all-aspect stealth with weapons, and highly integrated and networked avionics. The F-35 aircraft features many technological enhancements in air vehicle and propulsion subsystems derived from predecessor programs. These include the Subsystems Integration Technology (SUIT) studies [1-7], Joint Advanced Strike Technology (JAST) program, Air Force Research Laboratory's (AFRL's) Advanced Compact Inlet Systems (ACIS) program, Vehicle Integration Technology Planning Studies (VITPS) studies [8, 9], More-Electric Aircraft (MEA) studies [10], and Joint Strike Fighter (JSF)/Integrated Subsystems Technology (J/IST) demonstration program [11-20]. Additionally, numerous independent research and development (IRAD) and contract research and development (CRAD) projects were completed that formed a part of the F-35 design basis [21-36]. Many of these technological enhancements were not incorporated into the X-35 demonstrator due to schedule constraints to complete the flyable demonstrator aircraft. They were also postponed due to the results of a technical risk assessment that made them undesirable candidates for the X-35. Instead, the full development and integration of these technologies were deferred for incorporation during the Engineering and Manufacturing Development (EMD) phase (later known as the System Development and Demonstration [SDD] program). This resulted in the final F-35 design configuration.

Enormous efforts from these less well-known predecessor projects produced many of the significant technical achievements that provided necessary technical maturity and risk reduction. This allowed Lockheed Martin to proceed with them confidently in the EMD proposal. The production F-35 incorporates a highly integrated air vehicle subsystems architecture that reduces overall aircraft size and takeoff gross weight. It does so by replacing the federated, individual subsystems used in other legacy aircraft. Low observable (LO) technologies are incorporated into the engine inlet and exhaust nozzle, and the F-35B short takeoff and vertical landing (STOVL) propulsion system, with its revolutionary integrated flight propulsion controls, provides unprecedented capabilities. The system represents a revolutionary step-increase in vertical lift, compared to predecessor aircraft. Its fault-tolerant controls are seamlessly integrated with the aircraft control laws, minimizing pilot workload across the entire flight envelope from hover to supersonic flight [36].

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The key air vehicle and propulsion systems technologies selected for incorporation are depicted in Fig. 1. This paper focuses on the evolutionary path followed to develop these technologies. The final F-35 aircraft subsystems [35], propulsion [36], and mission systems [37], as well as the SDD program, are discussed in greater detail in supporting publications. Each of the items featured in Fig. 1 represents a significant aircraft capability enhancement that added to the overall success of the F-35 configuration. Successes in the associated development programs for these led to their incorporation into the F-35 design baseline entering the SDD program.

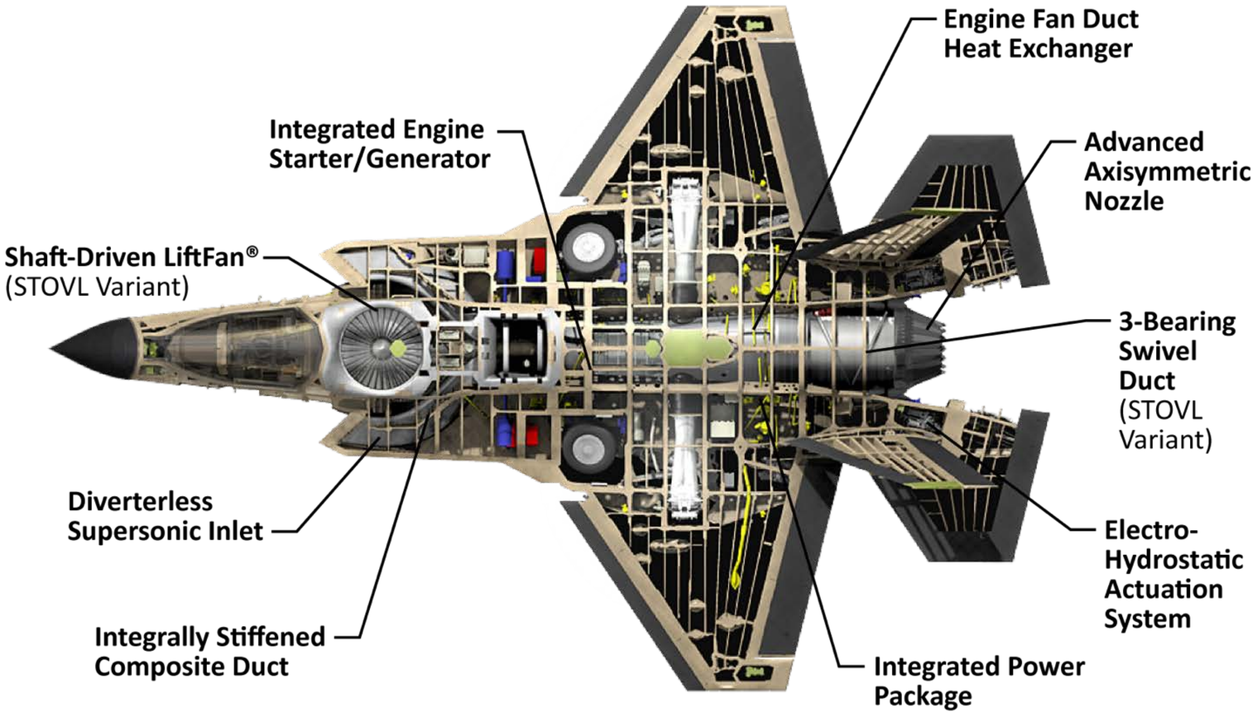


**Fig. 1 Advanced technologies selected for F-35 air vehicle and propulsion systems incorporation.**

The various development projects that evolved into the systems configurations used in the F-35 spanned the 1990s during the period preceding the winner of the JSF competition. Figure 2 provides key development milestones leading to the incorporation of selected technologies into the F-35 program.

The J/IST integrated subsystems development occurred in parallel with the Concept Development Program (CDP). Interestingly, in it the various JSF competitors cooperated in a collaborative environment, sharing all results and data. This allowed the risk reduction activities associated with the integrated vehicle systems to be pursued without the need to encumber the Concept Demonstrator Aircraft (CDA) aircraft schedule, and enabled the final results and lessons learned to be incorporated into the F-35 at the outset of the SDD program.

During the same period, numerous IRAD and CRAD studies evaluating potential propulsion innovations continued. As with the J/IST results, several of these were incorporated into the F-35 after the SDD contract award. Significant technical risks associated with the diverter-less supersonic inlet (DSI) and LO axisymmetric nozzle, and STOVL propulsion system configurations were retired in parallel with the CDA work, culminating in flight demonstrations showing the maturity and efficacy of the concepts. As an example, dual-redundancy features of the STOVL exhaust nozzle were developed in parallel with the CDA program and incorporated during SDD.

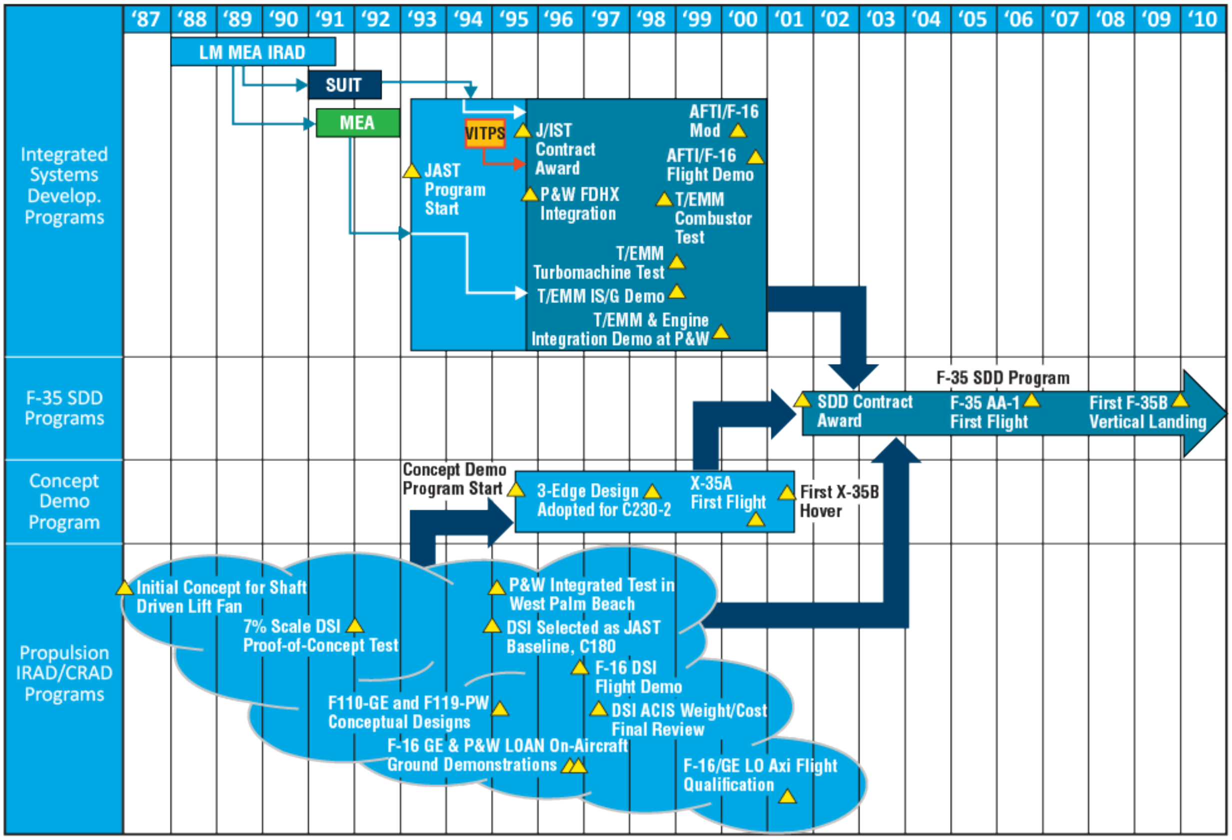


**Fig. 2 JSF program air vehicle and propulsion systems technology development roadmap.**

## II. Integrated Air Vehicle Subsystems

### A. Early Design Studies

Aircraft subsystems have traditionally been designed using a federated approach consisting of a number of independently designed subsystems. JSF-sponsored studies showed the potential for significant benefits from integrating these functions. This applied to three subsystems: flight controls and actuation systems, electrical and auxiliary power systems, and the environmental control system (ECS). Results from the studies showed that the effective integration of these three key subsystems could significantly improve aircraft performance and dramatically reduce the amount of equipment required. In doing so, it would provide improved affordability and warfighting benefits essential to F-35 program goals.

In conventional systems, electrical, hydraulic, pneumatic, and mechanical power are generated and distributed from the engines and auxiliary power system. The government-funded SUIT [1-7], MEA, and VITPS [8-9] studies showed the potential benefits of eliminating or shrinking the conventional centralized hydraulic system. They also showed the potential benefits of reducing engine bleed air extraction [1-7]. AFRL sponsored SUIT in the late 1980s and early 1990s to look into what could be gained from more efficient integrations of selected air vehicle subsystems [39]. The original SUIT concept was to replace single-function subsystem equipment with multifunctional hardware, potentially reducing volume and weight while increasing overall efficiency. Later, the objective of using the engine's fan air stream as a sink for waste heat from the subsystems was added. Concurrently, AFRL's propulsion laboratory was independently pursuing MEA technology, including electrically powered flight control actuation and robust electric power generation and distribution system concepts. As a result, MEA system and component technologies were undergoing development and testing through several separate and independent initiatives.

Between 1994 and 1995 the JAST program identified key technology building blocks to support the development of an advanced strike capability. The idea was to screen candidate technologies for their applicability based on their respective payoffs with regard to the four JSF program pillars: affordability, lethality, survivability, and supportability. At that time, three weapons systems contractors (WSCs) were actively competing to win JSF: Lockheed Martin, Boeing, and the McDonnell Douglas (later Boeing St. Louis)/Northrop Grumman/BAE Systems team. The candidate JSF configuration was expected to be a single-seat, single-engine strike aircraft, largely due to affordability considerations. Originally, the JSF platform focused on Air Force and Navy customers. However, during JAST the government concluded that the advanced STOVL (ASTOVL) concept development should be rolled into JAST/JSF. Thus, the STOVL jet was added to the JSF design space [39]. JAST initiated the VITPS studies [8-9]. All three WSCs concluded that SUIT and MEA technologies could be combined synergistically in a strike aircraft. Accordingly, they recommended that the SUIT/MEA combination be pursued under JAST. Each WSC advocated pursuing integrated subsystem technology, and from that advocacy the J/IST demonstration program was conceived.

### B. JSF Integrated Systems Technology Demonstration Program

The goals of the J/IST demonstration program were to set the stage for the JSF SDD program and sharpen the focus for the target JSF platform configuration. Ultimately, that configuration was shaped by the winning proposal for what would become be the largest acquisition program in Department of Defense history. The J/IST program was to be executed by all three WSCs competing for the JSF. Each WSC was supporting its own JSF proposal team while simultaneously being responsible to the other JSF WSCs for the technical results of the J/IST work.

The J/IST government team ensured that each participating WSC team was contractually accountable to and executing on behalf of the other WSCs. Each participant was treated by the government as customers for the technologies being demonstrated. This arrangement provided a level playing field using WSC input to make all key decisions within the scope and resources of the program. This fostered trust, a sense of fair play, and government responsiveness within the otherwise highly competitive JSF program environment. In turn, that collaborative environment enabled the results of each element of the studies to be capitalized by each competing contractor. Direct involvement of the three WSCs was fortuitous, as it compelled expanded involvement and cooperation beyond what otherwise might have been the case [39]. Each WSC benefitted from the combined J/IST demonstration results, as these provided information to be used in each WSC's preferred weapons system configuration aircraft proposals.

The focus of the J/IST demonstration program was to reduce the risks associated with subsystem integration technologies. This applied specifically to MEA technologies, including switched-reluctance (SR) starter/generators (S/Gs), electro-hydrostatic actuation system (EHAS) integration, and thermal/energy management module (T/EMM) integration through a series of maturation efforts. The work included developing and flight testing prototype versions of the SR S/G and electro-hydrostatic actuation (EHA) flight control actuators, successfully reducing the risks in these technologies from high to low for the SDD program. The work was divided into three main focus areas: one focusing on the electrical power and flight control actuation system (led by Lockheed Martin), one focusing on the development of T/EMM-related technologies (led by Boeing St. Louis), and one dedicated to independent benefit assessments (led by Boeing at its Seattle facility).

Figure 3 compares a conventional federated subsystems architecture to the F-35 integrated subsystems architectures. The integrated architectures reduced system parts count, which led to smaller, lighter, and lower-cost aircraft. Based on those conclusions and the configuration design developed for the SDD program, these systems were incorporated into the F-35 baseline.

The J/IST program was instrumental in reducing the risk of integrating these technologies prior to entering the JSF SDD program in 2001. The J/IST conclusions indicated an overall reduction in life-cycle costs (LCC) projected to be 2 to 3 percent, compared to the LCC of a similar legacy configuration [19]. The benefits of these integrated technologies are highlighted in Fig. 4.

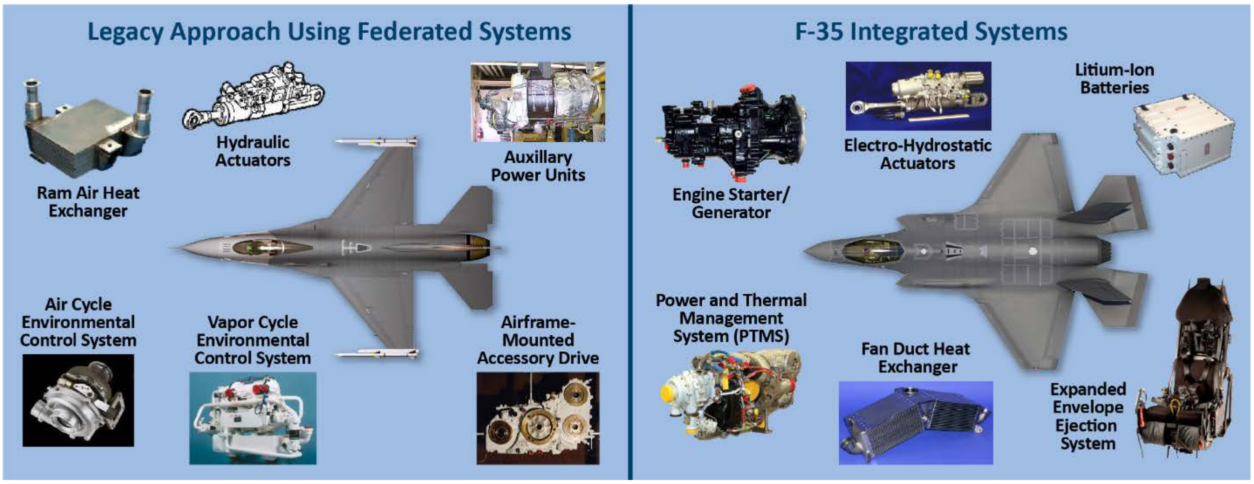


**Fig. 3 F-35 integrated vehicle systems.**

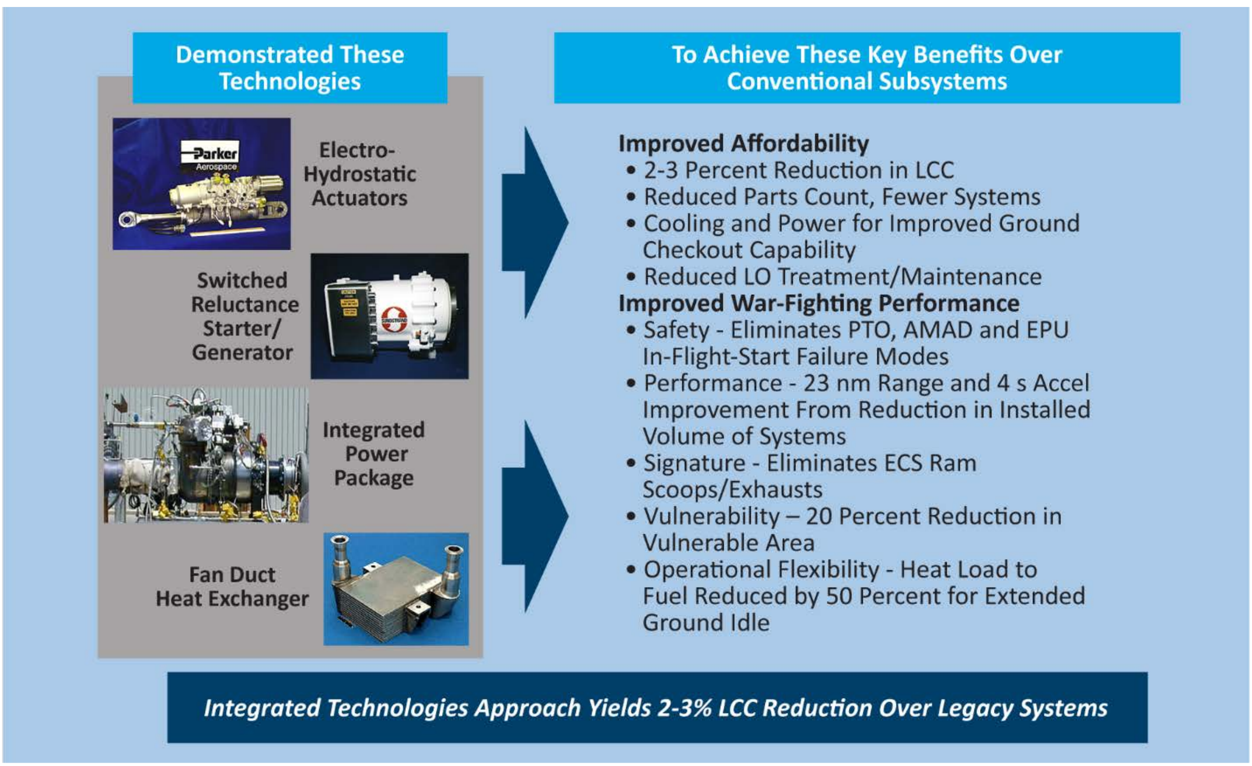


**Fig. 4 Benefits of integrated subsystems technologies.**

*1. J/IST Electrical Power System and Electro-Hydrostatic Actuation System*

The Lockheed Martin-led team achieved the following key accomplishments in the J/IST program:

1) Development and flight test of an SR, dual-channel S/G system to provide a fault-tolerant, redundant 270 VDC electrical power source for a single-engine fighter aircraft;
2) Development of a dual-redundant, flight-qualified electric actuation system;
3) Development of a flight-qualified 270 VDC battery system to provide uninterruptible electrical power to the flight-critical 270 VDC electrical power system (EPS);
4) Development of a flight-qualified emergency power system to provide a secondary power source;
5) Completion of specific technology demonstration tests on the S/G to verify operation under certain fault conditions;

6) Modification, integration, and flight test of the above technologies in a single-engine advanced flight technology integration (AFTI)/F-16 aircraft (Fig. 5); and
7) Validation of MEA technologies with an AFTI/F-16 demonstration for the F-35 subsystems suite.

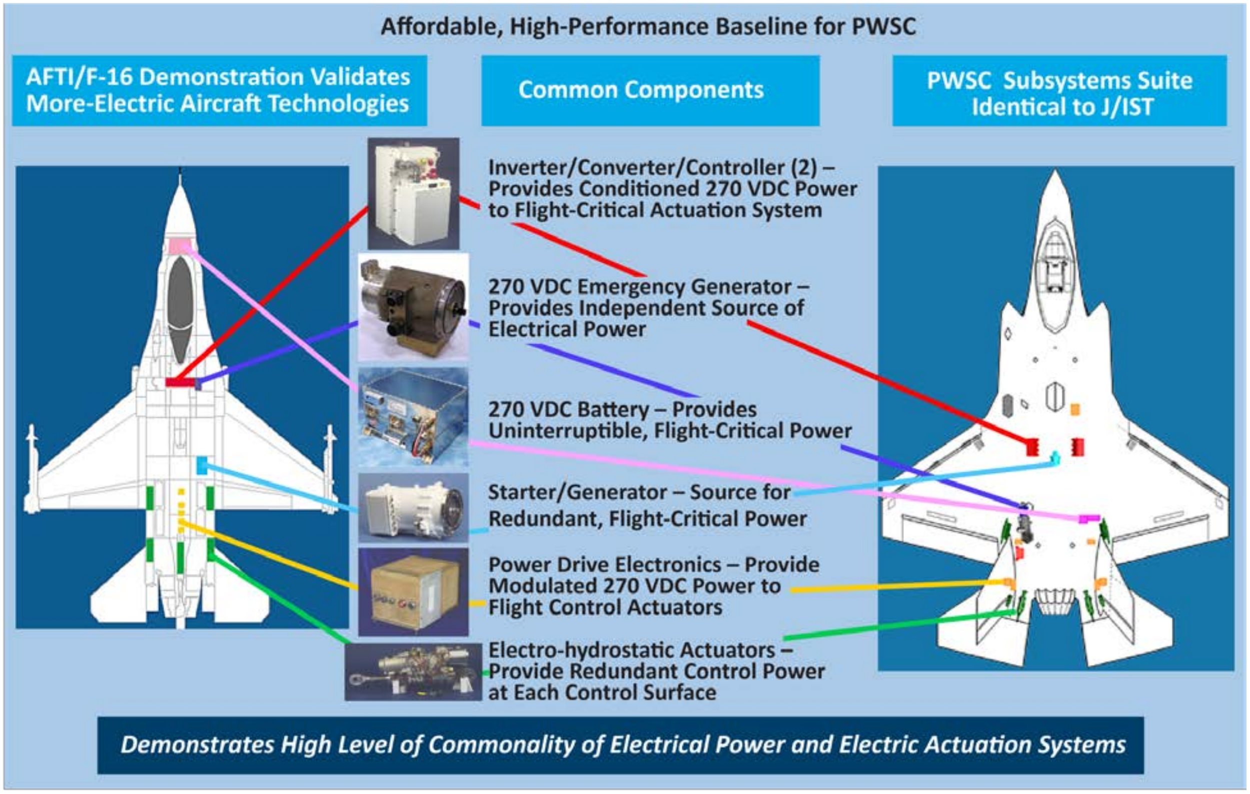


**Fig. 5 AFTI/F-16 J/IST aircraft MEA technologies and transition to F-35.**

### J/IST Electrical Power System

Immediately following J/IST contract award, Hamilton Sundstrand (now a UTC Aerospace Systems [UTAS] company) was selected to develop and qualify the SR generator system. UTAS was involved in the initial Air Force SR technology development and proposed using the same 250 kW 270 VDC generator design. However, UTAS rated it for 80 kW and packaged it for the F-16 application. The primary focus was on using an SR generator system, but the fault tolerance and redundancy of the 270 VDC power were emphasized as well. This included an emergency generator and a 270 VDC battery. The AFTI/F-16's EPS was modified significantly to support the J/IST program's MEA technologies. These consisted of one 270 VDC EHAS for the five primary flight control surfaces, two 270 VDC fuel pumps, one 270-to-28 VDC converter, and one 270 VDC-to-115 VAC inverter.

AFTI/F-16's pre-J/IST electrical system was a combination of an F-16 Block 15 production system and a digital flight control power system (production Block 40), receiving only 115 VAC and 28 VDC power. Therefore, to support the legacy F-16 equipment and MEA systems, the electrical system was modified to provide 270 VDC, 115 VAC, and 28 VDC power. During the initial program's design phase, it was determined that the MEA systems would consume the most power. Accordingly, the primary power type would be 270 VDC power. Also, since the EHAS is a flight-critical system, the 270 VDC system would be designed to be fault tolerant and provide limited uninterruptible power. For EPS integration, the primary challenges were:

1) SR S/G flight certification,
2) fault-tolerant power generation and distribution,
3) 270 VDC power system stability with multiple variable power loads,
4) 270 VDC fill-in battery operation, and
5) electromagnetic interference (EMI) and electromagnetic compatibility (EMC).

The following combination of components provided the baseline design for the J/IST engine S/G (ES/G) system. The inverter/converter/controller (ICC) for the ES/G system was taken from the UTAS LV100 SR S/G system. The power electronics converter and the SR generator were taken from the UTAS/General Electric Integrated High-Performance Turbine Engine Technology (IHPTET) research program. The ES/G system was required in two tests: the AFTI/F-16 flight test and a ground test. For the flight test it was used to demonstrate generation capability in an MEA application. For the ground test, it demonstrated motor, start, and generation capabilities. The ground test application included a demonstration of starting a Pratt & Whitney F119 engine and transitioning to generate mode. The ES/G system was designed to accommodate all applications. However, the ICC package design was driven by the AFTI/F-16 installation. Both the flight and ground demonstrations used nearly identical hardware, with minor changes made to adapt to their respective operating environments. The resultant J/IST MEA architecture is shown in Fig. 6.

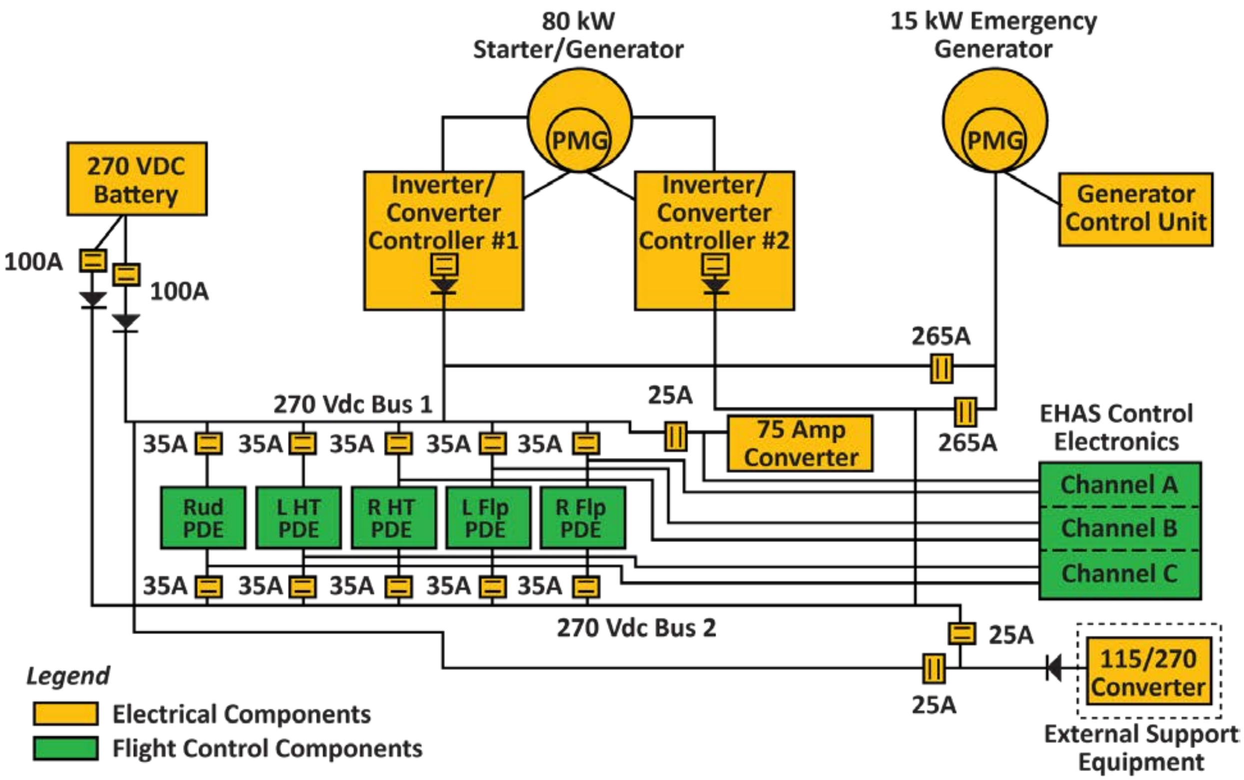


**Fig. 6 AFTI F-16 J/IST electrical power and actuation flight demonstration architecture.**

The ground demonstrations exercised all the capabilities of the ES/G system, specifically its engine motoring and starting, power generation, and fault tolerance. The T/EMM motor/generator system provided 270 VDC power to the ICCs for engine motoring and starting. The ES/G system was transitioned from start to generate to provide 270 VDC power to two primary motor buses. Modifications were made to the ES/G and ICCs from the AFTI/F-16 configuration to enable bidirectional power flow and increased speed range operation.

### J/IST Electrically Powered Flight Control System

Parker Aerospace was selected to provide the EHAS for the F-16. The company had previously developed prototype EHAs for various ground and flight test programs. Among them were the flight tests of an aileron actuator on the Lockheed Martin C-130 high-technology testbed. Previous electric actuation integration programs focused on single-surface operation or non-flight-critical control surfaces. Two examples are the F/A-18 Electrically Powered Actuation Development (EPAD) and F-15 Fly by Light Advanced Systems Hardware (FLASH) programs. By contrast, J/IST focused on integrating all primary flight control surfaces, with no hydromechanical backup system. This bold approach was essential to convincingly prove that the MEA concept supported the JSF technology transition criteria.

Lockheed Martin worked closely with Parker Aerospace to define the EHAS system-level requirements, integration test requirements, and software configuration management. The development and testing of the EHAS was the most challenging of the contracted tasks. The selection of the F-16 as the flight vehicle provided known air vehicle and system-level requirements, which made the development task easier. However, multiple hardware and software development challenges were encountered that provided valuable lessons learned for the SDD program.

The Lockheed Martin team conducted a detailed design of two EHASs: one to replace the F-16 flaperon and horizontal tail integrated servo-actuators (ISAs), and one to replace the F-16 rudder ISA (Fig. 7). The designs incorporated a common power electronics package for all five actuation systems. The Lockheed Martin team also provided an analog interface with the existing F-16 digital flight control computer (DFLCC). To do so, it developed and integrated a separate interface box that required no major flight control software or hardware changes to the DFLCC. This approach resulted in four major component designs: an F-16 flaperon/horizontal tail dual-tandem EHA, an F-16 rudder dual-tandem EHA, a common power drive electronics package, and an EHA interface controller electronics unit.

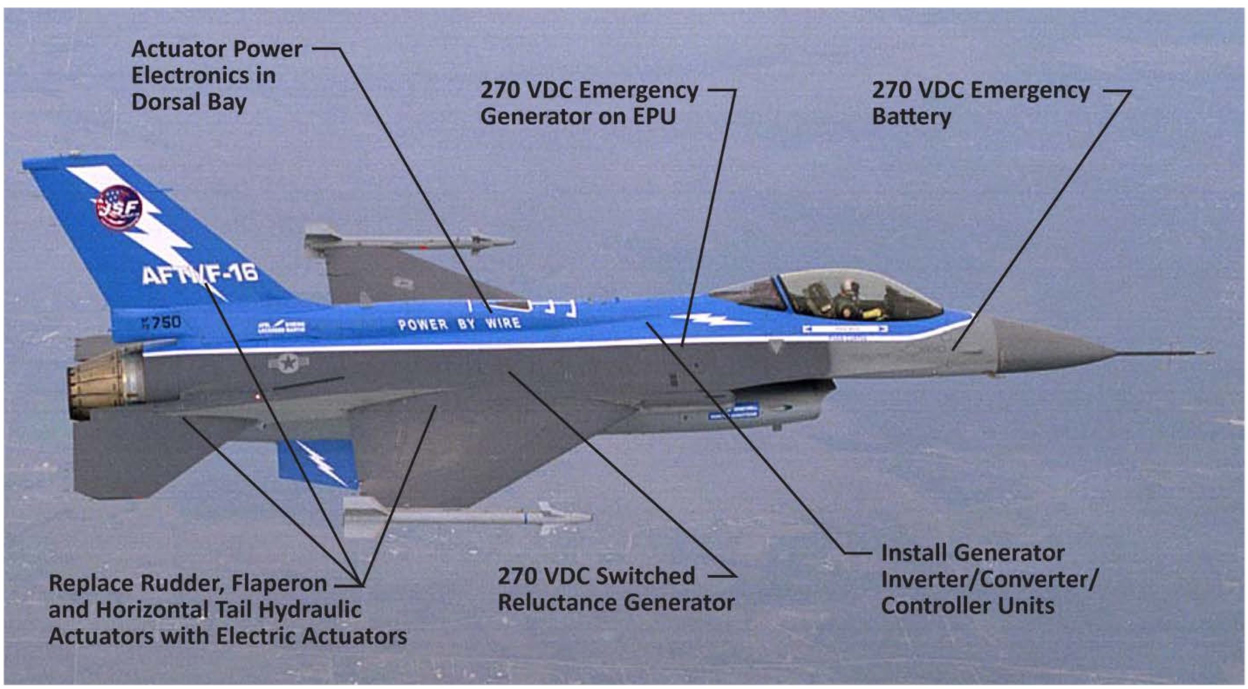


**Fig. 7 Key AFTI F-16 modifications.**

EHAS integration testing of all five actuators with electronics was successfully completed at Parker Aerospace's facility. The testing verified that the hardware and software met all design requirements. Further, it provided detailed visibility into the system's operation and added confidence in the EHAS software. It also reduced risk in the integration of the system into the AFTI/F-16 aircraft. The few technical issues discovered were resolved in the laboratory environment, avoiding the risks of discovery on aircraft. Throughout the on-aircraft flight control integration and test, minimal EHAS changes were required.

The power and actuation flight demonstration provided key technical proof to mature MEA technologies for the JSF EMD phase. This demonstration tested the external S/G, the 270 VDC power distribution system, and the EHAs in a realistic aircraft environment. It provided valuable integration and installation data for thermal environment, EMI/EMC, and supportability, among other areas. The AFTI/F-16 modifications were successfully demonstrated in the aircraft, with the key highlights including:

1) nine flights accomplished totaling 13 flight hours, performing realistic JSF-like mission profiles;
2) flight envelope including Mach 1.3 (600-knot engine limitation), up to 30,000 feet altitude (ferry); and
3) test pilots reporting no observable difference in handling qualities, compared to a baseline F-16.

For its achievements, the AFTI/F-16 flight demonstration won *Flight International* magazine's 2000 Aerospace Industry Award for Engineering, Maintenance and Modification, presented at the Paris Air Show in 2001 [40].

*2. J/IST Thermal/Energy Management Module*

Boeing St. Louis (formerly McDonnell Douglas) led an industry team responsible for the subsystem architectures and ground demonstrations of power and cooling integration, and electric actuation and power system integration [11]. Major participants in the team were Honeywell Aerospace (formerly AlliedSignal Aerospace Inc.), BAE Systems (formerly Astronics Corporation), Moog Inc., Northrop Grumman, and Pratt & Whitney. The team achieved the following key accomplishments in the J/IST program:

1) Development of an integrated T/EMM system:
    a. T/EMM turbomachine,
    b. high-temperature air/fuel heat exchanger,
    c. air/liquid heat exchanger,
    d. engine fan duct air-to-air heat exchanger,
    e. dual-mode recuperator heat exchanger,
    f. T/EMM integral S/G, and
    g. T/EMM controller and vehicle management computer interface.
2) Development of the T/EMM system controls and modes of operation;
3) Demonstration of integrating the power and cooling subsystems into a stand-alone integration environment; and
4) Demonstration of the integration of the T/EMM integrated subsystems with the engine.

The team selected a generic, JSF-like aircraft for assessing and defining the J/IST requirements. These included requirements for power, cooling, and actuation systems of the aircraft for ground, flight, and emergency operating conditions. The subsystem architecture that was developed resulted in the consensus architecture configuration depicted in Fig. 8. This architecture used the engine fan duct as a heat sink and integrated the functions traditionally performed by the ECS, auxiliary power unit (APU), and emergency power unit (EPU). The system was designed to support requirements for electrically powered flight control actuation and electric start of the main engine using T/EMM power to drive the ES/G.

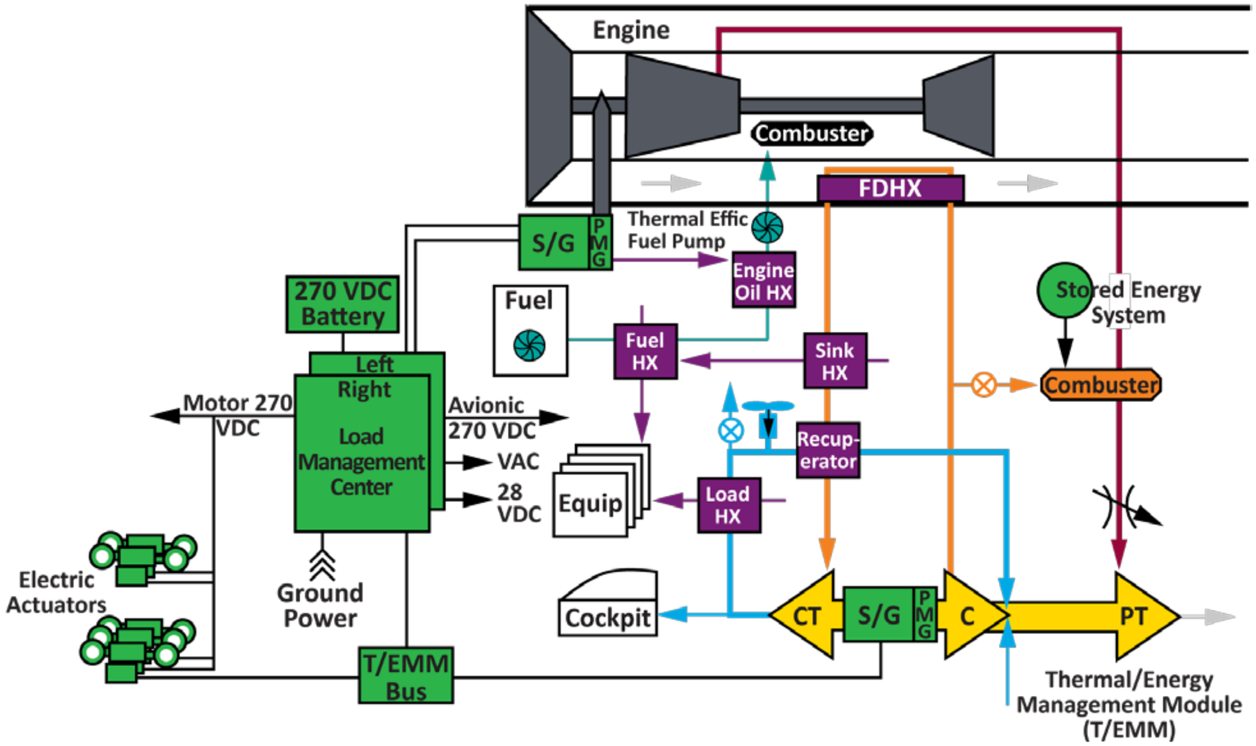


**Fig. 8 J/IST T/EMM architecture.**

### Thermal/Energy Management Module Requirements

The T/EMM system architecture was intended to perform all functions normally accomplished by a traditional aircraft ECS, auxiliary power system, and emergency power subsystems. The T/EMM was required to provide additional capabilities expected to be required in the F-35, including cooling high-powered electronics. This requirement drove the requirement in J/IST for a backup cooling capability to accommodate inflight failures and provide active cooling for Navy hangar deck maintenance. The operating requirements created a need to develop multiple modes of operation and reconfigure the system between these modes as required to perform the differing functions. Consequently, the following operating modes were developed and demonstrated in the J/IST effort:

1) Mode 1.0 – Electrically powered hangar deck cooling,
2) Mode 2.0 – Stand-alone T/EMM start,
3) Mode 3.0 – Cooling and electrical power for ground maintenance,
4) Mode 5.0 – Electrical power for main engine start,
5) Mode 6.0 – Engine bleed air-driven cooling and triplex electrical power (normal flight),
6) Mode 7.0 – Engine bleed air-driven cooling and emergency electrical power (failure of the ES/G),
7) Mode 8.0 – Emergency electrical power (failure of the ES/G),
8) Mode 9.0 – Stand-alone emergency electrical power – stored air (engine failure at high altitude),
9) Mode 10.0 – Stand-alone emergency cooling and electrical power – ambient air (engine failure at low altitude),
10) Mode 11.0 – Shutdown, and
11) Mode 12.0 – Emergency cooling – fuel heat sink (not demonstrated in J/IST).

### Thermal/Energy Management Module Turbomachine and Component Development

The design and development of a full-scale T/EMM turbomachine was accomplished by Honeywell Aerospace in Phoenix, Arizona. The turbomachine configuration incorporated a power turbine, compressor, SR integral S/G (IS/G) rotor, and cooling turbine on a single spool that operated at speeds up to 60,950 rpm (Fig. 9). The compressor and power turbine were mounted on a single shaft, and the IS/G and cooling turbine were mounted on a separate single shaft. The two shafts were connected by a floating quill shaft, resulting in a design that provided sufficient margin from high-speed shaft bending modes. This split allowed each section to be developed and tested independently. The power turbine used a variable geometry stator with movable vanes that allowed for performance optimization at the various operating conditions. The turbomachine included a canister type combustor developed specifically for the T/EMM that featured three distinct modes (tri-mode combustor) and was subsequently patented by Honeywell.

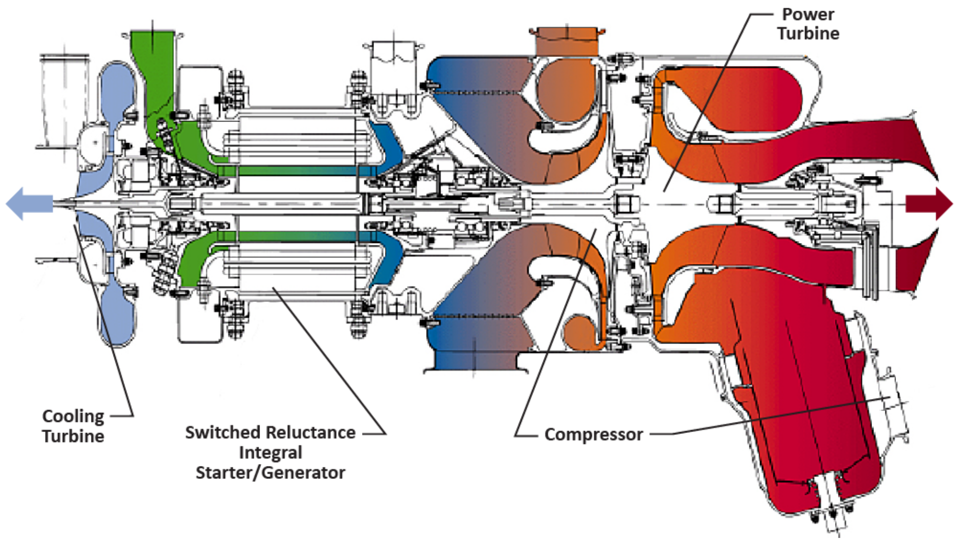


**Fig. 9 T/EMM turbomachine cross-section.**

Additional components making up the T/EMM configuration requiring significant development were the SR I/SG configuration, T/EMM controller, and various other heat exchangers, valves, and related components.

In parallel with the Honeywell T/EMM development projects, Pratt & Whitney integrated the Honeywell-designed fan duct heat exchangers into a modified F119 engine. This was another key success supporting the claim that the T/EMM concept was viable and supported the JSF technology transition criteria.

### T/EMM System Demonstrations

Several significant demonstrations were accomplished in support of the J/IST team effort. Figure 10 summarizes the major demonstrations, building up from the component level to successively higher levels of integration. One of the three most significant demonstrations was the integration of the power and cooling subsystems into a stand-alone integration environment. Another of the three was the electrical integration of T/EMM and ES/G, high-power EHA integration testing, and EMI testing. The third was the demonstration of the integration of the T/EMM integrated subsystems with the engine.

The stand-alone integration demonstration began in the summer of 1999 at Honeywell in Torrance, California. The demonstration, which simulated a mission profile, included ground maintenance operation with 25 kW of electrical power and 12 kW of cooling. It also included normal-engine-bleed air-driven operation during taxi, takeoff, acceleration, climb, cruise, loiter, descent, and landing. In addition, it showed emergency operations that simulated the loss of the engine and ES/G failure. The results demonstrated the capability to perform all the required modes and successfully reconfigure between modes as required. Post-test comparisons of test data with the dynamic model confirmed the model's ability to predict results. The comparisons also reinforced the value of the virtual modeling effort prior to commencing hardware operations.

The electrical power management integration of T/EMM and ES/G was conducted at Northrop Grumman's facility in El Segundo, California. The testing demonstrated that the IS/G-integrated EPS could provide the needed capability to power the ES/G using IS/G power to start the F119 engine. The testing also showed that the system could provide the necessary emergency power requirements, and that its generators could handle the dynamic loads imposed by the high-power EHAs.

The final engine integration demonstration was performed in 2000 at Pratt & Whitney's facility in West Palm Beach, Florida. It brought Honeywell's T/EMM system, Northrop Grumman's EPS, and Hamilton Sundstrand's (UTAS') ES/G together with a modified Pratt & Whitney F119 engine. With this combination, it validated the integrated subsystems concept. The Hamilton Sundstrand (UTAS) ES/G was connected to the engine using a speed-increaser gearbox. The Honeywell T/EMM system was connected to the engine with low-pressure drop plumbing. The demonstration included testing using a simulated mission profile incorporating operations in all ground, flight, and emergency modes. Mission segments included taxi, climb, cruise, loiter, descent, dash, and combat. The demonstration validated the integrated subsystems concept by operating the system successfully in all required conditions. It showed that the T/EMM could be successfully driven by engine bleed air, and it demonstrated the successful integration of engine and airframe systems. It also demonstrated electrical engine starting and motoring and showed that the required emergency power could be provided within 50 milliseconds without using a battery. The maximum starting torque of 131 lb/ft using electric power furnished from the T/EMM was also shown.

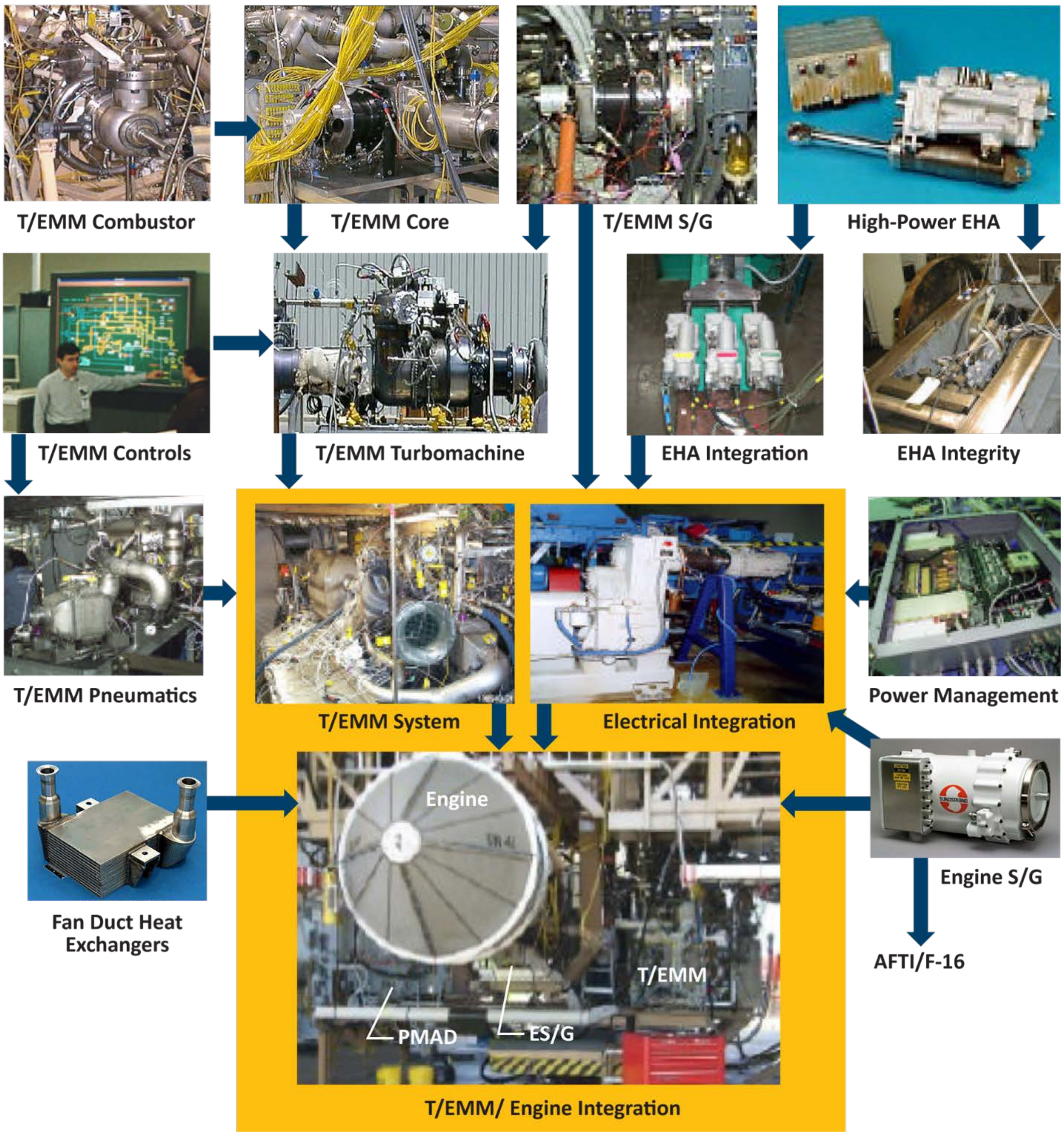


**Fig. 10  Key T/EMM-related J/IST demonstrations.**

## C. Transition to the F-35 Program

J/IST was one of the largest and most successful subsystems technology demonstration programs ever accomplished. Every major element of the J/IST architecture was transitioned to the F-35's design [39]. The program was composed of a series of cascading development and demonstration projects of increasing complexity. Each demonstration built upon a prior one to gradually reduce component, subsystem, and air vehicle-level risks. These efforts showed the various technology elements in the most appropriate environment, considering the desired risk reduction, available resources, and perceived potential. The two final J/IST demonstrations were the most significant. One was a comprehensive ground demonstration of the engine and relevant (associated) subsystems. The other was a flight test of an F-16 with all primary flight control surfaces powered electrically.

The F-35 employs the key elements derived from J/IST, including the EHAS and EPS architectures. It also incorporated numerous elements from the T/EMM architecture and equipment. The Pratt & Whitney F135 engine uses integral fan duct heat exchangers and additional bleed manifolds to support the power and thermal management system (PTMS) configuration. The F-35 EPS features the Hamilton Sundstrand (UTAS) ES/G and General Electric 270 VDC and 28 VDC lithium-ion batteries. The flight control system (FCS) features Moog/Parker Aerospace EHAS hardware.

The resultant F-35 PTMS uses many of the control modes and requirements developed in J/IST. The components used in the system derive directly from the J/IST configuration. Many lessons learned in J/IST were applied to the design, development, and test of the turbomachine and its subcomponent systems, the heat exchanger arrangements, the valve designs, and other system aspects.

The F-35 turbomachine was redesigned to eliminate the variable area nozzle and replace the SR generator with a permanent magnet generator. The F-35 PTMS has a robust, highly reliable electrical power and cooling system, providing an electrically driven engine start system and supporting inflight emergencies. The F-35 aircraft subsystems enable stand-alone ground maintenance power and cooling for all systems maintenance and checkout operations. The single-stage power turbine was replaced with a two-stage radial/axial configuration, and the variable area power turbine nozzle was eliminated. The SR generator was replaced by a permanent magnet generator configuration. Numerous design lessons learned were incorporated into the lubrication system, sump sizing, rotor element design and clearances, system controls, and operation. As a result of J/IST, Honeywell developed significant improvements for the modeling and simulation techniques applied when developing the SDD program. The F-35 PTMS heat exchanger configuration used a thermal cycle similar to that in the J/IST system. However, significant optimization in the packaging was made by Honeywell. This resulted in a highly integrated compact heat exchanger configuration with multiple cores in a single assembly that proved essential to meeting the installation design requirements. F-35 design requirements also permitted the elimination of the stored-energy system and avoided the need to integrate the T/EMM turbomachine exhaust into the main engine exhaust. The requirements also mitigated other complexities discovered during J/IST.

### *1. F-35 Flight Control Actuation System*

The F-35 FCS uses the EHAS to power its primary and secondary flight control surfaces. This is a departure from predecessor legacy combat aircraft powered by hydraulics. The conventional system design was reliable and had a mature design concept, but it added substantial weight and volume and drove the hydraulics system's sizing and redundancy. The SUIT and MEA studies showed that the more-electric architecture promised significant improvements [4]. The F-35 flight control actuation system provides control to position both of the primary and secondary flight control surfaces. The FCS architectures are largely common for all three F-35 variants for the primary control of horizontal tails, flaperons, rudders, and leading edge flaps. However, the F-35A and F-35C variants also incorporate horizontal tail centering actuators, and the F-35C variant also incorporates conventional hydraulically powered ailerons. The architecture of the F-35 flight control actuation system derived from the MEA studies and J/IST demonstration program. Integrating the flight control actuation system with the power and cooling systems was key to the overall success of the F-35 flight control development. Additional discussion of this can be found Ref. [35].

### *2. F-35 Electrical Power System*

The F-35 EPS provides the generation, distribution, control, and protection of electrical power for various equipment. Its key power management functions for the air vehicle include primary flight control power, power to numerous aircraft systems, main engine starting, emergency power control and distribution, and power for ground maintenance functions. Key system elements include a single ES/G, two ICCs, 28 VDC and 270 VDC batteries, and the additional elements required to provide the uninterruptable power sources required for safety of flight. The EPS provides 270 VDC, 28 VDC, and 115 VAC power. The architecture of the F-35 EPS was derived from the MEA studies and J/IST demonstration program. Integrating the main engine starting function and flight control power sources matured risk reduction activities during the F-35 development program. One major change made during the

SDD program was the replacement of the original SR machine ES/G with a synchronous generator to accommodate a broader power generation capability. The F-35 EPS design and development is further explored in Ref. [35].

*3. F-35 Power and Thermal Management System*

The F-35 PTMS, sometimes referred to as the Integrated Power Package (IPP), integrates the conventional functions of the ECS, emergency power system, engine starting system, and auxiliary power systems into a single, highly integrated system. The system features two primary modes of operation: stand-alone combusted-mode operation and bleed-driven operation when the F135 engine is running. The primary power and cooling enables stand-alone ground maintenance with no required external power and cooling carts. The PTMS also provides primary power for on-ground engine starting, followed by seamless reconfiguration into bleed-driven operation to support flight operations. The PTMS likewise supports inflight emergencies and automatically reconfigures into combusted-mode operation to support flight control, emergency electrical power, and inflight engine-start assist power.

The PTMS provides 270 VDC and 28 VDC electrical power, as well as forced-air cooling for flight-essential systems. It also provides liquid cooling for aircraft avionics systems and pressurization for the cockpit, fuel system, and other aircraft systems. During flight, waste heat generated by onboard systems is rejected overboard via engine-mounted heat exchangers embedded within the F135 engine fan air duct. This eliminates the weight and volume penalties associated with conventional ram air heat-sink systems.

The system incorporates many elements of the architectures developed in the J/IST demonstration program and MEA studies. However, substantial additional system design maturation was accomplished during F-35 development. Several of the concepts studied in J/IST were not adopted because they were not needed to meet the program requirements. Among these were a stored-energy backup system and an integrated T/EMM exhaust system integrated with the main engine exhaust [35]. The resultant configuration provides improvements in aircraft range due to reduced bleed air consumption and improved thermal management. The integrated PTMS eliminates the need for the separate aircraft-mounted accessory drive gearbox, air turbine starter, EPU, APU, and ECSs employed in legacy aircraft. The fan duct heat exchanger configuration avoids the increased weight and drag penalties and LO impacts associated with a dedicated ram air circuit.

## III. Propulsion Technologies

### A. Overview

The conventional F-35 propulsion system features critical propulsion/airframe integration technologies that began with technology development programs. These technologies were used in large-scale demonstrations, incorporated onto the X-35 demonstrator, and transitioned to the production F-35 program. Key propulsion features (Fig. 11) include a DSI and LO axisymmetric nozzle configuration (LO Axi) common among all variants. The F-35B STOVL variant includes a three-bearing swivel module (3BSM) that integrates the LO Axi configuration with thrust vectoring, providing vertical lift. The lift is augmented by a shaft-driven lift fan system providing additional vertical lift. The DSI design is characterized by a detailed, shaped compression surface and forward swept cowl, with twin inlet apertures feeding a bifurcated, serpentine duct. The design eliminates the need for boundary-layer diverter or bleed-system inlet subsystems, reducing cost and weight. The LO Axi configuration minimizes radar reflections by using serrated trailing edges, a serrated interface with the airframe, and tight gap and seam control. It also has specialized high-temperature coatings on internal and external surfaces to provide an excellent balance of signature, weight, and performance requirements.

The F-35B STOVL propulsion system utilizes the same main engine turbomachinery as the conventional takeoff and landing (CTOL)/carrier variant (CV) configurations with the addition of a shaft-driven lift fan, a roll control system, and an auxiliary inlet. The 3BSM adds thrust vectoring to the LO Axi nozzle. This permits engine exhaust to either pass straight through for forward propulsion in conventional flight or be deflected downward to provide aft vertical lift. The 3BSM can move through 95 degrees of motion seamlessly with no change in engine operation. The nozzle also provides yaw control during hover and transitions to hover. Additionally, the F-35B STOVL variant incorporates Rolls-Royce's shaft-driven LiftFan® system. In lift mode, horsepower is extracted from the F135 engine's low-pressure turbine via a drive shaft, clutch, and gearbox, and is used to drive the LiftFan. The exhaust is discharged through a thrust vectoring nozzle on the underside of the aircraft to provide balanced lift with the 3BSM. Engine fan air ducted to outboard roll nozzles provides roll control.

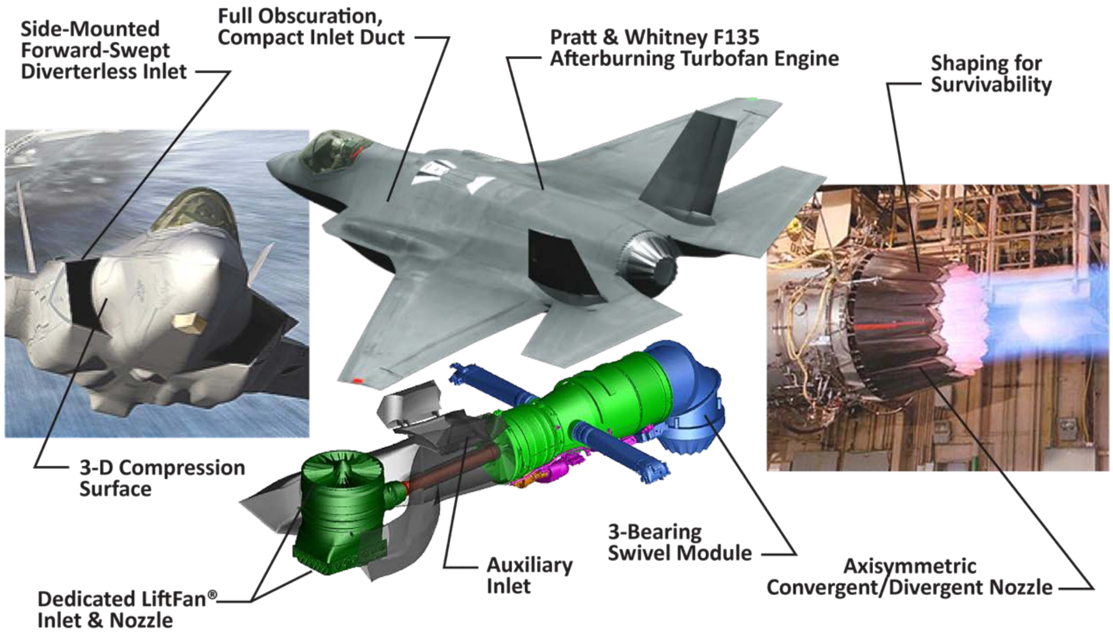


**Fig. 11 F-35 advanced propulsion system technologies.**

### B. F-35 Diverter-less Supersonic Inlet

The F-35's primary engine air induction system features a DSI design conceived and matured through several technology programs and then transitioned to the JSF program. The DSI is characterized by a 3-D compression surface and forward-swept cowl (Fig. 12). These features enable high aerodynamic perforce, boundary layer diversion, and inlet stability without using a boundary layer diverter or bleed system. Eliminating these inlet subsystems reduces cost and weight compared to prior state-of-the-art designs. While many different configurations were explored in the technology programs, the F-35's DSI is embodied in twin, side-mounted inlets that feed a compact bifurcated duct. A detailed history of the DSI concept can be found in Ref. [21] and Ref. [22].

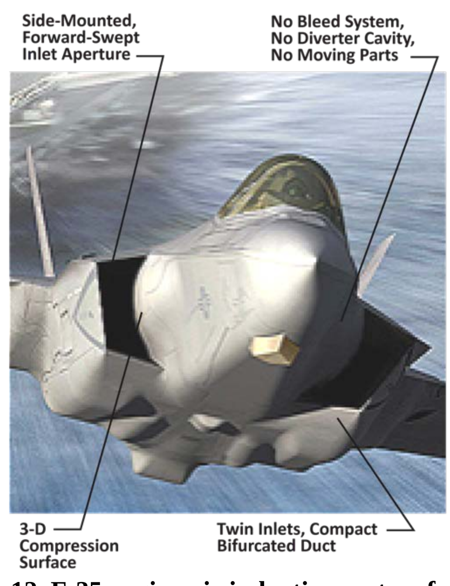


**Fig. 12 F-35 engine air induction system features.**

#### *1. Background*

Tactical aircraft have always posed a formidable challenge for engine inlet designers, and the incorporation of modern affordability and survivability requirements have made the challenge more difficult [23, 24]. The inlet must provide the engine with high-quality (high pressure, low distortion) airflow over a wide range of speeds, altitudes, and maneuver conditions. At the same time, it has to accommodate the full range of engine airflow from idle to maximum afterburning power. The inlet designer must also consider the constraints imposed by configuration features, such as nose landing gear, weapon bays, equipment bays and access panels, and forebody shaping.

In addition to these general considerations, two key aerodynamic requirements are at the forefront in the design of any supersonic inlet system. The first requirement is for flow compression. The inlet system must reduce the airstream's speed while increasing its static pressure as airflow approaches the engine. For combat aircraft, this is usually done with a series of external shockwaves and internal flow area expansion. As freestream speeds approach Mach 2, elaborate compression schemes, including movable compression ramps, were historically used to reduce losses and enable high inlet efficiency.

The second key issue is boundary layer control (BLC). This is the means by which the inlet system will account for a layer of low-energy air that forms on the surface of the fuselage and compression surfaces. This must be managed at both subsonic and supersonic speeds. The boundary layer can create chaos when disturbed by shockwaves created during flow compression. Shockwave/boundary layer interaction can lead to severe airflow distortion at the engine face, which may subsequently lead to engine stall. Several methods can be used for BLC. The inlet can be physically isolated from the fuselage by a boundary layer diverter, a feature found on most of today's combat aircraft. Another primary technique is boundary layer bleed. Bleed systems may be fully fixed or involve mechanical variation, such as movable exit louvers, to optimize performance. Many of today's tactical aircraft use a combination of bleed systems, diverters, and compression ramps.

Variable compression and bleed systems can provide the aerodynamic functionality required for a high-performance inlet. However, such features also introduce mechanical and structural complexity, weight, and cost into the system [24].

*2. Diverter-less Supersonic Inlet Conceptual Development*

In the early 1990s Lockheed Martin began an IRAD project to develop a Mach 2 class combat aircraft inlet concept. The concept would embody traditional aero-performance levels and advanced survivability features. Further, it would improve affordability (reduced cost and weight) compared to state-of-the-art design concepts. To meet these goals, the concept would need to incorporate flow compression and BLC functionality, advanced shaping, high structural efficiency, and minimal or no moving parts. These studies were conducted primarily with computational fluid dynamics (CFD) tools augmented with small-scale wind tunnel testing.

The DSI emerged as the preferred concept early in the IRAD program. It is distinguished by two main physical features: a fixed, 3-D compression surface (bump) and an edge-aligned, forward-swept cowl. The bump compression surface derives from the flow field produced by a reference axisymmetric body in supersonic flow. The reference body (virtual cone) may be a simple cone, a double or isentropic cone, or any of these bodies at incidence angle to the oncoming stream. In the latter case, the flow field is 3-D, not axisymmetric. A set of CFD particle traces are released along a locus of points representing the intersection of the shock field and aircraft surface. As the particles travel into the shock field, they are deflected away from the virtual cone by internal flow field pressure gradients. A 3-D contour is then defined by a surface faired through the particle traces. When introduced into an identical supersonic flow field, this contour produces a shock structure identical to that of the virtual cone. The bump surface not only achieves flow compression but also creates a span-wise static pressure gradient that assists with boundary layer diversion (Fig. 13).

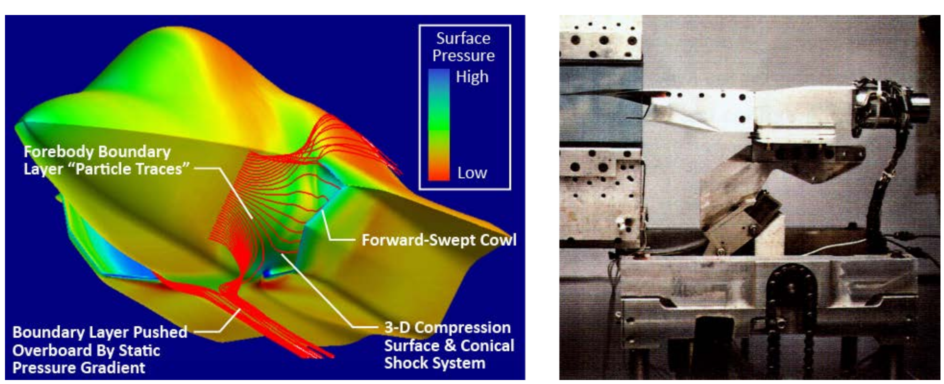


**Fig. 13 CFD simulation of DSI supersonic boundary layer diversion.**

The second physical feature distinguishing the DSI is a forward-swept cowl. *Forward swept* denotes that the cowl structure is cantilevered from the aircraft and closes against the forebody at its aft-most points. This geometry enables low-pressure boundary layer air to be spilled out the side of the inlet as mass flow ratio is decreased. Many CFD studies showed the effects of combining a bump compression surface and forward-swept cowl. The studies demonstrated that the combination could provide the aerodynamic functionality of traditional inlets without a boundary layer diverter or bleed system.

Small-scale testing of isolated inlet aperture models (Fig. 13) was conducted throughout the conceptual development program to augment CFD studies. Whereas CFD was best at providing detailed flow physics at a few specific operating conditions, testing produced key operating data at a broad range of conditions. These tests were used to evaluate inlet pressure recovery, distortion, and shockwave instability (buzz) boundaries for the key bump design parameters.

*3. Integrated Aircraft Design and Validation*

Having verified the basic DSI principles, the focus shifted to integrating the inlet into a realistic aircraft configuration and assessing air vehicle system-level impacts. These activities were accomplished with synergistic studies on the JAST and AFRL ACIS programs. JAST studies investigated the best way to integrate the unique DSI features. As with the eventual F-35 configuration, the JAST aircraft featured twin, side-mounted inlet apertures with a bifurcated duct and single engine. On ACIS, Lockheed Martin performed three tasks that helped to build the overall knowledge base. We analyzed the benefits, cost, weight, and maintainability of the DSI versus a reference system. We also assessed the performances of different subsonic diffuser concepts integrated with the DSI. In addition, we performed a large-scale wind tunnel validation of a forebody/inlet/duct configuration, shown in Fig. 14.

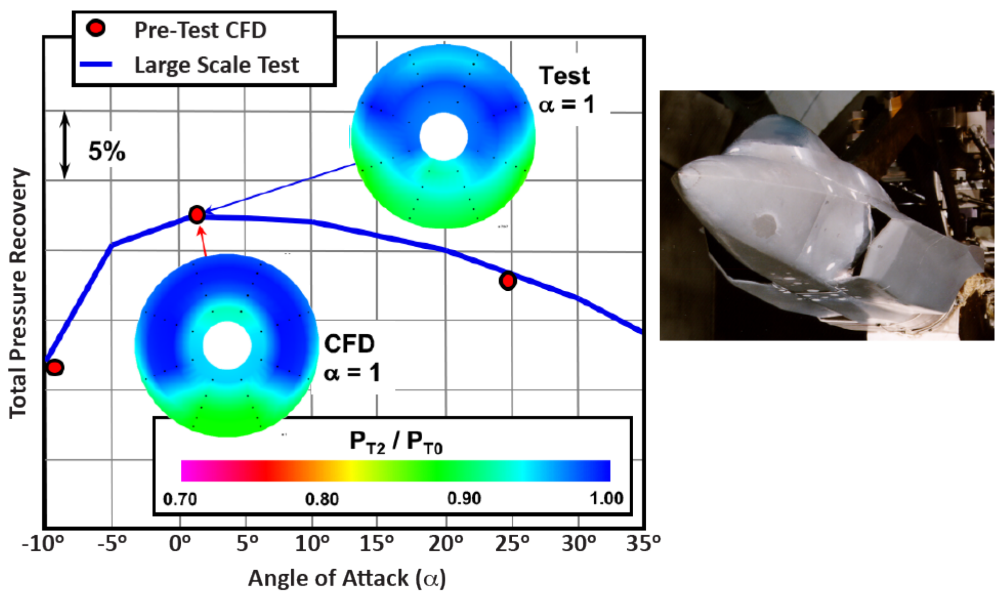


**Fig. 14 Large-scale wind tunnel testing validation of CFD design methodology and CFD test model (inset).**

System-level trade studies were performed to quantify the weight, cost, and benefits of the DSI, compared to more conventional inlets (e.g., F-22 and F/A-18E/F caret inlet systems). In these studies, a 30-percent inlet weight reduction was estimated for the DSI, relative to the reference caret inlet. The largest contributing factor was the elimination of the bleed and bypass systems. Studies performed by other ACIS contractors [25] indicated similar savings for diverter-less/bleed-less systems.

The ACIS subsonic diffuser study evaluated the DSI with both straight and serpentine diffusers and different flow area curves. Results from this task provided guidelines on how to best shape the diffuser, given the rather unique incoming flow field from the DSI.

A 0.125-scale inlet/forebody model of the ACIS configuration was tested at subsonic, transonic, and supersonic conditions in two test entries. A wind tunnel test was conducted at the NASA Langley Research Center 16-Foot Transonic Tunnel. Another was conducted at the Lockheed Martin High Speed Wind Tunnel, which is a 4-by-4-foot tri-sonic blow-down wind tunnel. Test data were obtained over a wide range of angle-of-attack and angle-of-sideslip conditions at speeds up to Mach 2. Test results indicated that the integrated inlet configuration satisfied typical goals of high pressure recovery, manageable distortion, and good supersonic stability. Pressure recovery for the DSI with a serpentine duct was shown to be comparable to that of the F-16 modular common inlet duct recovery. This was at static conditions and speeds ranging from Mach 0.6 to 1.2. At supersonic speeds, the DSI's recovery was shown to exceed F-16 recovery.

The development of the DSI was based on CFD. As such, it was necessary to verify the accuracy of CFD to predict the complex inlet flow fields associated with integrated forebody, aperture, and duct geometries. In general, excellent agreement between the CFD and test data was noted (Fig. 14).

*4. Diverter-less Supersonic Inlet Flight Demonstration Program*

The next step in the development of the DSI was to conduct a flight demonstration on a relevant combat aircraft platform. A Block 30 F-16 powered by an F110-GE-129 engine was selected for this demonstration due to its modular inlet construction and consequently low cost of modification. One objective of this effort was to demonstrate engine/inlet compatibility throughout the combat aircraft envelope. Another was to demonstrate stable inlet operation up to Mach 1.8. Although integration in the F-16 chin location dictated an inlet design different from the twin, side-mounted ACIS/JAST design, the aerodynamic design principles were identical.

Prior to the flight test, an inlet wind tunnel model was fabricated and tested at one of the Arnold Engineering Development Complex propulsion wind tunnels in November 1995. Wind tunnel test results verified CFD-predicted inlet performance and demonstrated engine/inlet compatibility. Inlet lines were frozen based solely on CFD results, and flight hardware fabrication had begun prior to any wind tunnel test verification of the CFD-based design. The flight test program consisted of 12 flights flown in nine days in December 1996. The flight tests covered the entire F-16 flight envelope and achieved a maximum speed of Mach 2 (Fig. 15). With this flight demonstration, the viability of the DSI as a Mach 2 class, diverter-less, bleed-less, highly survivable inlet concept was proven.


**Fig. 15 DSI technology was matured through rigorous F-16 flight demonstration.**

*5. Transition to the JSF Program*

Risk had been significantly reduced through IRAD efforts, ongoing work and the flight demonstrations on ACIS, and extensive program trade studies. As such, the DSI system was selected as the baseline inlet for Lockheed Martin's JAST program in early 1995, replacing the previous F-22-like inlet. Configuration refinement continued through the lines freeze on the X-35 concept demonstrator aircraft. Because of the sophisticated yet simple DSI design, it was possible to support this milestone with only a single additional up-and-away inlet wind tunnel entry.

### C. Low Observable Axisymmetric Nozzle

Before the development of the F-35 low observable axisymmetric nozzle (LOAN), signature demands typically drove nozzles to fixed, structurally integrated affairs (e.g., F-117). They had to have very high aspect ratio designs (e.g., F-117) or highly capable but heavy two-dimensional systems (e.g., F-22), as illustrated in Image 1. Departing from what was then the state of the art, industry and CRAD efforts developed multiple nozzle configurations to create a LOAN for the F-35. The F135 engine with a LOAN balanced the requirements of LO and efficient aeromechanical performance. This resulted in a lightweight configuration with reduced radar cross-section.

**Image 1  A spectrum of fighter aircraft nozzle designs.**

*1. Background*

The F-16's and F-15's exhaust systems are examples of what was used in classic 4th Generation tactical supersonic aircraft. These systems are axisymmetric for low weight and structural efficiency, with variable geometry to maintain stable and efficient engine operation. Specifically, afterburning requires a large increase in the minimum nozzle flow area (throat area) to retain engine stability. This is particularly necessary when fuel is being dumped into the exhaust and the resultant flow density decreases. These convergent/divergent nozzles are composed of overlapping flaps and seals. The exit area and throat area mechanically linked and scheduled with a power setting for efficient flow expansion. Externally, overlapping flaps provide a fairing between the air vehicle aft body and nozzle exit for reduced drag. However, the nozzles were not generally considered capable of meeting LO requirements.

The subsonic F-117 stealth fighter and B-2 bomber exemplify how exhaust system designs can be dominated by LO features. This effect results in nontraditional exhaust systems that are driven by air vehicle shaping. The F-117 incorporated an airframe-mounted, structurally integrated, fixed exhaust system with planform-aligned edges. The exhaust system transitions from axisymmetric to a high-aspect two-dimensional design and forgoes the variability needed to accommodate afterburning. Although these highly integrated designs can reduce drag, they are less aerodynamically and structurally efficient than axisymmetric designs.

IRAD and CRAD investments were critical to positioning the industry to develop world-class solutions targeted at major program innovations. Well before the JSF X-planes were contracted, multiple vertical lift and exhaust system configurations were developed and matured. These were then available on call to meet the evolving needs of both new and existing aircraft designs. Some of the nozzle technologies explored were conformal fully fixed aperture nozzles, fixed aperture nozzles, and LOANs.

Complexly shaped, fixed-geometry nozzles were matured for reduced drag and signature. These designs allowed flexibility to implement full line-of-sight obscuration. With few moving parts, they allowed for a great diversity of LO and thermally tolerant materials.

Innovations in convergent section mechanical manipulation and shaping were explored as well. These were intended to reduce leakage, weight, and structural integration penalties while enabling the nozzle exit to remain motionless. Throat skewing and inducing shocks in the divergent section were assessed for thrust vectoring potential. Variable cycle engines were evaluated to reduce the need for large-scale nozzle throat area control, even during augmentation.

During this period the notion that axisymmetric nozzles were not amenable to LO (or even thrust vectoring) was being challenged. A new generation of LO nozzles emerged that was characterized by shaping features to minimize radar reflections. Namely, they used a serrated trailing edge, serrated interface with the airframe, and interleaved external seals to complement the external flaps. They retained tight control of gaps and seals and had specialized high-temperature coatings on internal and external surfaces. In the years leading up to the X-35, various LOAN configurations were developed, ground tested, and flight tested on F-16s. Testing was done in concert with both Pratt & Whitney F100 and General Electric F110 engines. These versions incorporated a nod to an ejector feature that introduced nacelle bay airflow near the nozzle throat to cool divergent flaps. This improved divergent seal durability and reduced the infrared signature.

*2. Low Observable Axisymmetric Nozzle Rapid Prototype Evaluation*

In the early 1990s, engineers at Lockheed Martin used CFD and an astatic thrust measurement facility to perform rapid prototype evaluation and 3-D printing. This allowed for a rapid assessment of nozzle aerodynamic performance (Image 2). The facility had a flow-through six-component balance housed within an altitude (pressure reduction) chamber. Varying ambient backpressure allowed continuous, low-load testing with very high nozzle pressure ratios with minimal variation in mass flow and minimal model loads. This also allowed the balance to operate within an optimum band of its calibrated mass flow and force measurement range. It had excellent overall accuracy and repeatability and reduced the variation in the Reynolds number. Multiple airflows could be independently controlled and metered via a bank of critical-flow venturis.

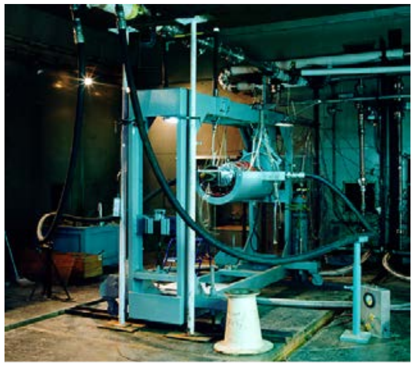

**Image 2 Lockheed Martin rapid nozzle prototyping capability in Fort Worth, Texas.**

*3. Aircraft Aerodynamic Integration*

Intentional aft body and nozzle integration is critical to balance drag and weight, which are driven by aft body and nozzle boattail angles. Finding the optimum length and external shape is important to net propulsion performance. Additionally, the aft body is typically not axisymmetric, and integrating an axisymmetric exhaust may result in large aft body boattail angles and base regions. This would introduce drag, effectively stealing from the net thrust of the propulsion system. This is evident in most twin-engine configurations in which a base or dead region is normally found between two closely spaced nozzles. In certain circumstances, the low local pressure endemic to these base regions can serve as an exit for secondary flow systems. For example, base regions at the root of the F-16 horizontal and vertical tail surfaces are used to promote nacelle ventilation.

*4. Ground and Flight Testing*

The LOAN configuration developed by Pratt & Whitney was developed under a precursor to the JSF contract to evaluate advanced, affordable technologies applicable to the F-35. Ground testing was completed in 1996 (Image 3). A Lockheed Martin/Pratt & Whitney team modified an Air Force F-16 and F100-PW-200 engine with a bailed LOAN from the F-35 Joint Program Office. This was used for the ground test in a two-day rapid prototype operation. During tests from idle to maximum afterburner, infrared images, nozzle temperatures, and nacelle inlet pressures and airflow velocities were measured. The Pratt & Whitney LOAN configuration significantly reduced radar cross-section and infrared signature emissions from the engine, as well as maintenance costs. The result was a low-cost nozzle system that reduced the chance of radar and infrared detection and applied to both retrofit and new-production aircraft.

The solution developed by General Electric was designated the LO Axi Nozzle, demonstrated by Lockheed Martin on an Air National Guard F-16C (Image 3). Dramatic temperature reductions provided by the LO Axi Nozzle were expected to greatly improve F-16 exhaust system durability. F-16 flight certification was conducted at Edwards Air Force Base in the summer of 2001. That system was offered as an F-16 upgrade option, reinforcing the vibrancy of the F-16 platform.


**Image 3 General Electric LO Axi Nozzle (left) and
Pratt & Whitney LOAN (right) ground and flight testing on the F-16.**

These F-16 LO nozzle configurations included an ejector feature to address thermal degradation of nozzle divergent section seals and flaps. That remains a top driver of maintenance on modern jet engines. The ejector provided effective film cooling to reduce nozzle temperatures and improve component life using engine nacelle bay bypass air. These techniques were expected to double or quadruple nozzle divergent flap life, resulting in significant maintenance cost savings.

*5. Radio Frequency Testing*

For the F-35, the ability to see before being seen provided a fulcrum upon which to balance sensor/radar capability and LO technologies; strengths in one area provided flexibility in the other. The strength of emerging technologies in the radar and sensor suites opened up options for using the LO nozzle. This was comparable to the manner in which the development of high off-boresight missiles reduced the appetite for thrust vectoring and nose pointing.

Radar testing was employed for the JSF program to evaluate the unique shape and special coatings evident in the Pratt & Whitney LOAN. The configuration achieved stealth through a combination of technologies, including geometric shaping, advanced cooling, and special coatings on internal and external surfaces. One major radio frequency model (Image 4) developed under IRAD was suitable for integrating inlets, nozzles, apertures, edges, and other subsystems. It was designed for installation on the 30,000-pound rotator at the Meridian Antenna Test Range in Meridian, Texas.

**Image 4 Radio frequency test fixture with the F-35 LO nozzle at the
Pratt & Whitney facility in West Palm Beach.**

*6. Transition to the JSF Program*

For the F-35, the Pratt & Whitney F135 engine and LOAN balanced the requirements of LO and efficient aeromechanical performance. It offered a lightweight (especially for the F-35B STOVL variant), low-cost configuration. The F-35A and F-35C variants use the same nozzle configuration. A shorter version was readily configured for compatibility with the F-35B STOVL 3BSM to meet ground clearance needs while landing vertically. Since the engine exhaust system is the primary contributor to aft sector infrared signature, engine and nozzle design needed to incorporate effective methods to reduce infrared emissions. This was accomplished using reduced radar cross-section-compatible techniques, including hiding, shaping, and temperature control. The F-35 exhaust system employs a cooled turbine face blocker, effectively eliminating the temptation to employ more impacting techniques like a serpentine exhaust duct. The F135 exhaust system does use a cooled nozzle to significantly reduce the aft sector infrared signature. With these techniques, the cooled blocker and nozzle tail-on infrared signature is significantly less than the signature of an uncooled exhaust system.

### D. F-35B STOVL Lift System

*1. Background*

For more than 50 years, fighter aircraft designers have vigorously pursued the speed and range of a conventional jet while achieving the basing flexibility of vertical takeoff and landing (VTOL). Numerous STOVL concepts have been developed over the decades, all with compromises that limited the effectiveness of the aircraft. The F-35B STOVL lift system successfully achieved a breakthrough that redefines the relationship between conventional thrust and vertical propulsive lift. Moreover, it achieves that with major increases in performance, efficiency, and safety. This elegant integration results in a relatively simple engine-driven LiftFan. It has an enabling engine powerful enough to achieve a lift-to-thrust ratio of approximately 1.5-to-1 (Fig. 16) – a significant increase over direct lift designs. The shaft-driven LiftFan provides high levels of thrust augmentation with a cool, low-pressure footprint, sufficient control power, and efficient packaging in the airframe design. Since the main engine is primarily optimized for conventional flight, the propulsion system performance is not compromised for its vertical lift capability. The LiftFan augments vertical flight similarly to the way an afterburner augments high-speed performance [31]. The lift fan provides an additional ingenious benefit: the (relatively cool) thrust exhaust protects the main engine inlet and forward portions of the aircraft from hot gas re-ingestion or damage.

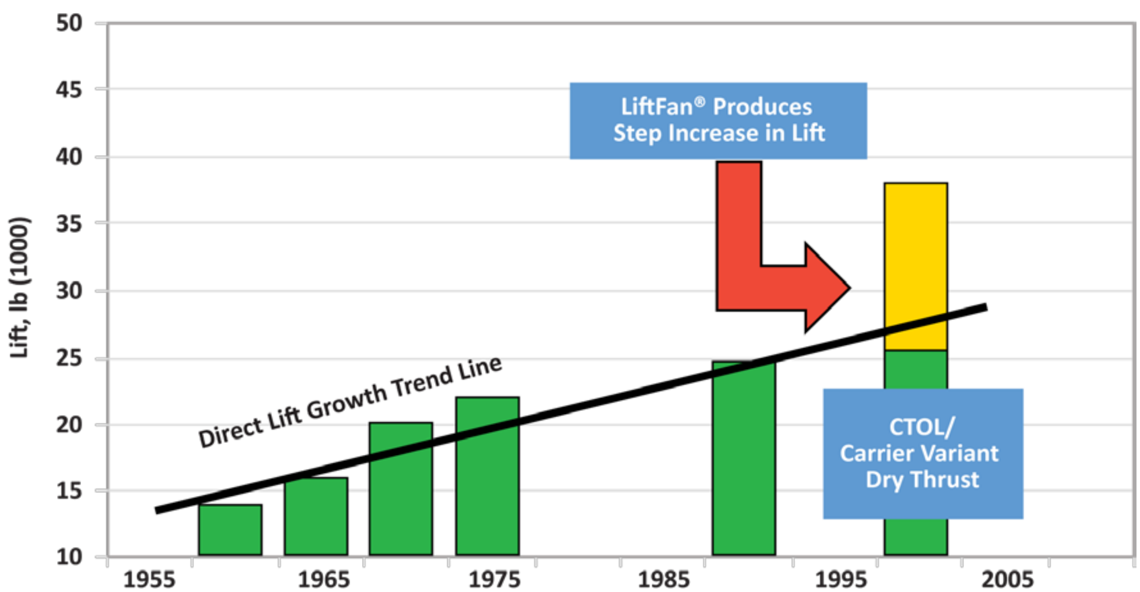


**Fig. 16 Revolutionary step increase in vertical lift.**

In addition to achieving powerful lift thrust, a STOVL aircraft must achieve sufficient control power in each axis to successfully transition through the wingborne, semi-jetborne, and jetborne flight phases. The F-35B STOVL lift system accomplishes this through several key components (Fig. 17):

1) LiftFan clutch and driveshaft: to selectively transfer power from the main engine to the LiftFan;
2) Variable area vane box nozzle (VAVBN): to control the LiftFan exit area and fore-aft thrust vectoring;
3) Roll post nozzles: to redirect main engine fan air through under-wing nozzles for roll control; and
4) 3BSM: to vector the main engine nozzle fore-aft and laterally for yaw control.

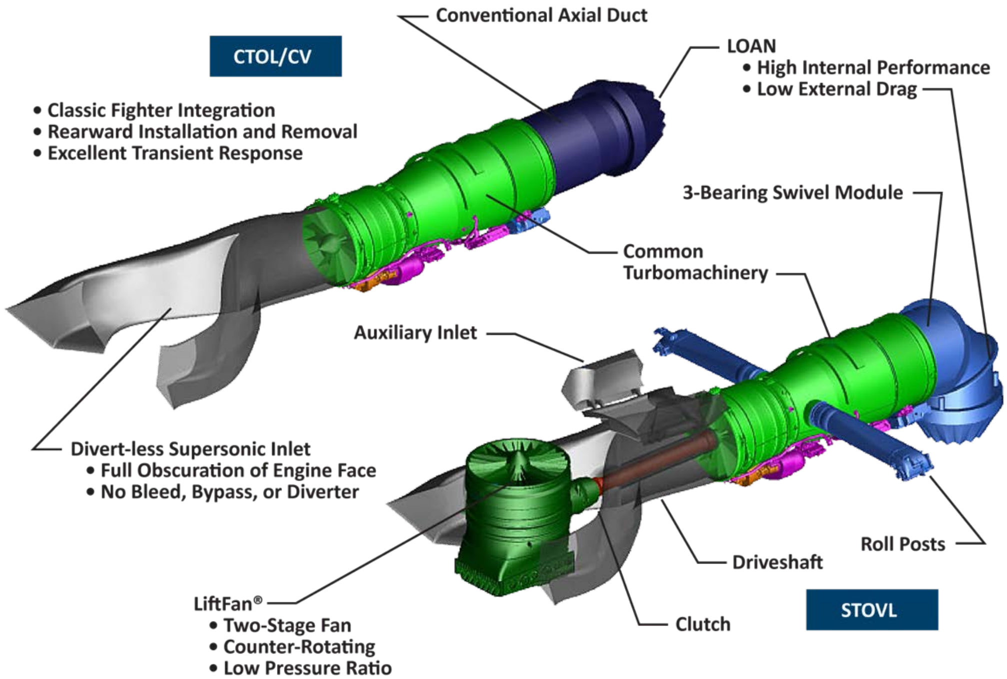


**Fig. 17 Comparison of F-35 conventional and F-35B STOVL lift systems.**

*2. LiftFan Development*

The F-35 LiftFan system is the overarching characteristic of the F-35B STOVL variant. It underwent years of technology development and maturation by Lockheed Martin and F-35 propulsion contractors Pratt & Whitney and Rolls-Royce. Initial work began in the late 1980s with STOVL JSF studies sponsored by the Defense Advanced Research Projects Agency. Lockheed Martin, General Dynamics, Boeing St. Louis (then McDonnell Douglas), and Boeing all developed concepts with different technologies for generating vertical lift [34]. These studies led to the ASTOVL competition that Lockheed Martin won with the shaft-driven LiftFan propulsive concept. This effort eventually evolved into the JSF concept demonstration phase resulting in the X-35B flight demonstration.

Rolls-Royce's LiftFan is a novel, counter-rotating concept with a bladed disk (blisk), two sets of stationary vanes, and a set of variable inlet guide vanes (VIGVs). The VIGVs provide the thrust variation from maximum to idle necessary for the VTOL application. The gearbox distributes 29,000 horsepower to the LiftFan rotor stages. The load capacity and envelope characteristics were key to providing an industry-first 30-1 horsepower-to-weight ratio. The previous norm (in earlier aircraft) was a ratio of no more than 15-to-1, which was then doubled.

The gearbox is integral to the LiftFan unit and employs counter-rotating output shafts to simplify geometry and reduce gear and bearing loads. VIGVs on the first fan stage provide thrust modulation. Lubrication for the LiftFan bearings and gearbox is provided by the LiftFan lubrication system, which is independent from the main engine lubrication system. The Rolls-Royce LiftFan is designed to operate throughout the entire speed range of the main engine.

One of the key challenges in transitioning the concept development to production was in the LiftFan's aeromechanical rotor modes. These caused operating restrictions (time at certain LiftFan speeds) on the X-35B. The spatial pressure distortions in the inlet flow field excited resonance modes in the LiftFan turbomachinery, becoming a high-cycle fatigue or aeromechanics concern. This was addressed in the F-35B by redesigning the upper LiftFan door configuration to reduce flow angularity and distortion. It was also addressed by redesigning the LiftFan rotor (hollow blades, blisk) that attenuated the modal responses.

*3. LiftFan Clutch Development*

Shaft/clutching functionality was achieved with both hardware and software functionality. Pioneering shaft, clutch, and gearbox designs permitted the development of a lightweight, high-speed (8000 rpm) drive train. A unique closed-loop clutching system provides precise control resulting in smooth, reliable power transmission to the LiftFan. This innovative clutch design, leveraging aircraft brake technology, produced a dry clutch plate arrangement. This achieved the required rapid engagement performance time, while providing durability that exceeded program requirements. The clutch is mounted to the LiftFan, with the input directly coupled through the main drive shaft and couplings to the main engine low-pressure rotor shaft. The clutch consists of a pack of dry disk plates. When driven together by aircraft-powered hydraulic actuation, the pack couples the main engine low-pressure rotor via the drive shaft to the LiftFan. Lubrication for the clutch bearings is provided by the LiftFan's lubrication system. The driveshaft couplings can flex to take up misalignment between the main engine and the clutch.

The LiftFan clutch allows the engagement and disengagement of the LiftFan from the main engine. It achieves this through two devices, each providing a torque path from input to output. During engagement, speed synchronization and acceleration of the fan rotors at low power is achieved by applying pressure to a pack of five carbon-carbon plates, operating dry. Subsequent engagement of a locking spline is required for high power transmission. Engaging the splined lock requires synchronizing the clutch input and output shaft speeds within a few rpm. An indexing mechanism insures against a failure to engage due to mating splines contacting end to end. During disengagement, the clutch plate pack unloads the splines to enable them to be retracted.

One of the key challenges experienced during the X-35 development was obtaining smooth clutch engagement with minimal transition time. Early clutch control design encountered a chatter phenomenon as the clutch plates came in contact. Through innovative closed-loop control modes, a combination of clutch clamping force and longitudinal position feedback solved the chatter problem, permitting smooth and precise engagements. Continued maturation during the F-35 program intended to complete the conversion in the minimum time (operational flexibility) and obtain a full-life clutch (minimized maintenance interval). The F-35 clutch can complete an engagement cycle within nine seconds from command to engage. With improved clutch plate material, the system will accommodate more than 1500 engagements.

*4. Variable Area Vane Box Nozzle Development*

Prior to the F-35 development phase, the X-35 LiftFan nozzle vectoring was accomplished via a three-hooded telescoping nozzle. Although very precise in directing the LiftFan thrust vector, it was heavy, required a lot of volume, and was difficult to integrate into the aircraft signature. This prompted the pursuit of a more compact design through a series of parallel vanes that could be hidden behind lower fuselage doors. The development of the F-35 VAVBN capitalized on five years of prior efforts by Rolls-Royce on vane box nozzles. These had been developed for earlier lift engine concepts that were considered in the JAST program [35]. It was tested in a 27-percent-scale demonstration (Image 5).

**Image 5 Twenty-seven-percent-scale F-35B STOVL VAVBN test, with (inset) VAVBN closeup.**

Many nozzle design variables were studied that included duct geometry, the number, spacing, and profiles of the movable vanes. Additional design parameters that influenced nozzle integration with the LiftFan included the gearbox profile, the location of six support struts, and the size and location of the vane actuator mechanism. Studies were also conducted to evaluate the tradeoffs of performance, vane actuation, and airframe integration. From these it became apparent that the vane box configuration with six highly cambered vanes with a low thickness-to-chord ratio was most promising. In addition to supporting flow path pressure, vane aerodynamics, and actuation loads, the nozzle box is designed to contribute to the airframe structural stiffness. The nozzle vane box is airframe-mounted, with the vane box sidewalls serving as aircraft structure keel members.

The VAVBN (Image 6) provides directional control of the LiftFan thrust vector and an additional effector to the VIGVs for turndown. *Turndown* refers to the commanded position of the lift fan inlet guide vanes used to control lift fan thrust. Three VAVBN vanes are driven by dual-tandem, linear, hydraulic actuators. Drive is transferred to the other three vanes through bar linkages. With this system, nozzle thrust may be directed in an arc of 41.75-104 degrees (fore/aft aircraft coordinate system), at a rate of 40 degrees per second. Independent control of the three VAVBN actuators provides the capability to vary the nozzle throat area independent of the vector angle. VIGV and VAVBN area variation are both used to control LiftFan performance, manage the LiftFan stall margin, and minimize thrust-thrust split coupling effects. Thrust split is defined as the ratio of main engine thrust over lift fan thrust, typically used to represent the propulsion system pitching moment applied to the aircraft.

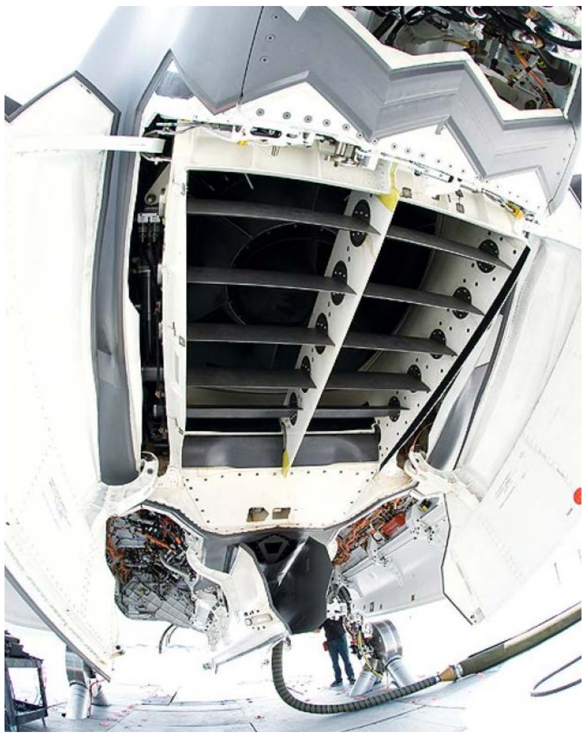

**Image 6  F-35 VAVBN as seen from below.**

*5. Roll Post Nozzle Development*

The F-35B STOVL lift system uses roll nozzles in each wing to provide roll control in powered-lift operation. The roll nozzle controls thrust by varying the nozzle area using two hinged flaps. Unlike the reaction control systems on legacy vertical and/or short takeoff and landing (V/STOL) aircraft, the F-35 roll posts produce about 10 percent of the vertical thrust through redirected engine fan air. The port and starboard side roll post systems are part-number common and interchangeable, providing improved maintenance flexibility. Actuation for the nozzle flaps is provided by a twin-motor, hydraulic, rotary actuator. External, hydraulically actuated aircraft doors on the underside of the wing are opened in powered-lift operation to provide an exit aperture for roll post thrust.

A key challenge in transitioning to the F-35B was providing adequate roll control authority and rate for store asymmetries and fuel imbalance. The roll post nozzles were positioned as far outboard as the internal wing structure would allow to maximize the moment arm. Main engine fan air to the roll posts was increased to the extent possible while maintaining adequate flow to cool the exhaust liner. Architectural changes in full-authority digital engine control were made to minimize the time delay from roll moment command to roll nozzle actuator response.

*6. 3BSM Development*

The original design for the primary nozzle on the ASTOVL was a two-dimensional single expansion ramp nozzle. In this design, one nozzle flap is longer than the other. The nozzle vectors the primary thrust by deflecting the upper flap through at least 90 degrees. To control the nozzle exit area in hover, the lower flap was designed as a sliding panel that would retract as needed to adjust the backpressure on the engine. This was a critical control needed to make the shaft-driven LiftFan turbine work.

As Lockheed Martin began construction and tests of the nozzle, the shortcomings of the design became more apparent. The abilities to turn the flow through 90 degrees under high loads and control the nozzle exit area would have resulted in a very heavy design. This resulted in the pursuit of a lighter design that traced its roots to an early 1970s nozzle design from the proposed Convair Model 200 V/STOL fighter aircraft concept. A three-bearing swivel nozzle was developed by Pratt & Whitney and became part of the Convair Model 200 design that never continued into development. Following joint studies by Pratt & Whitney and Lockheed Martin, the 3BSM concept was integrated into the X-35B design and shown to be lighter. It also provided a very efficient means for turning the aft thrust post with minimal losses [36].

The F-35B 3BSM consists of a STOVL LOAN and a three-bearing swivel mechanism. The mechanism can deflect the exhaust flow through 95 degrees in the pitch axis and ±12.25 degrees in the yaw axis as a function of pitch angle. The 3BSM can vector up to 23,900 pounds of thrust at the maximum rearward thrust split. The 3BSM forward (No. 1) bearing is powered by twin fueldraulic actuator motors through a gearbox and drive train. The middle (No. 2) bearing is likewise powered by a twin fueldraulic actuator motor and gearbox/drive train system. A transfer gearbox links the middle and aft (No. 3) bearings with an efficient, compact, epicycle gear train. The twin actuator motors on the No. 1 and Nos. 2 and 3 bearings, respectively, are designed with a fail-degraded capability (full torque, half rate). This is one of the key differences between this design and that of the X-35B. In the X-35B, the Nos. 2 and 3 bearings were braked following a first failure, with no ability to continue vectoring the aft thrust post. This did not satisfy operational requirements requiring an ability to perform a shipboard vertical landing following a first failure. The dual redundancy on the fueldraulic motors enabled that fault tolerance on the F-35B.

*7. Technology Demonstration Program and Transition to the JSF Program*

The X-35B STOVL lift system completed more than 1200 hours of ground testing, culminating in the successful concept flight demonstration in August 2001. The aircraft accomplished this impressive performance under demanding hot, high-desert conditions and substantiated the robust performance capabilities of the shaft-driven LiftFan concept. Particularly impressive were the precise aircraft dynamics enabled by the responsive and accurate control of the STOVL lift system. Thirty-nine flights were conducted on the X-35B, including 22 hovers, 17 vertical takeoffs, 18 short takeoffs, 57 STOVL mode transitions, 27 vertical landings, 116 conversions (95 ground, 21 inflight), 63 clutch engagements, and 21.5 flight hours. This performance far surpassed the vertical operation goals and demonstrated sufficient maturity to proceed to production aircraft development.

The transition to a production F-35B principally centered on evaluating the STOVL lift system design changes and demonstrating a full-life propulsion system. More insights into the transition and full system development for the production F-35 system can be found in Ref. [38].

## IV. Conclusion

The F-35 combines numerous technologies that have significantly advanced the state of the art in combat aircraft. This is particularly pronounced in the areas of integrated air vehicle subsystems and propulsion systems. The resultant aircraft provides exceptional performance with unparalleled capabilities, enabled by the air vehicle and propulsion systems.

The integrated air vehicle subsystems architecture selected for incorporation was based on a continuum of progressively refined development projects. Each of these further refined the concepts and validated the approach. The SUIT and MEA studies from the early 1990s gave the JSF contractor teams confidence in the concepts. The J/IST studies then provided the final proof of the viability of the designs. They also validated the conclusion that the overall air vehicle takeoff gross weight and cost could be reduced by 2 to 3 percent. The T/EMM system development project in J/IST contributed to the development of the turbomachine, fan duct heat exchangers, and other key elements used in the current F-35 PTMS. Without these elements, the chosen configuration might have been deemed too risky to pursue in the SDD program. Likewise, without the great successes of these development programs, many elements of the F-35's integrated systems, EHAS, and EPS would likely have been substituted with more conventional federated configurations. In such an instance, the benefits of the integrated systems might never have been realized. Instead, the resultant systems incorporated into the F-35 have been proven to provide excellent technical performance and reliability. They also provide a backbone for future systems growth through the expected long life of the F-35 program.

The F-35 propulsion systems incorporating the numerous technology upgrades have driven an unprecedented capability in performance. This has enabled the aircraft's unique performance capabilities, particularly in the F-35B STOVL variant. The final F-35 configuration incorporated a DSI, LO axisymmetric engine thrust nozzle, and unique STOVL propulsion system integrating the LiftFan and three-bearing swivel nozzle. These systems enabled the development of the F-35 variants, each providing exceptional performance and serving as the basis for long-term growth and capability improvements.

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