# F-35 Lightning II

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# Contents

Lockheed Martin



*Much has been written in the media and 'blogged' on websites about Lockheed Martin's F-35 II Joint Strike Fighter. And much of that coverage has been highly critical, even controversial; focussing on programme delays and budget overspends.*

*Highly important as those aspects are, coverage of that nature overlooks one point – the aircraft itself.*

*AIR International has been on the road, visiting production and flight test facilities around the world to compile this 48-page supplement.*

*Its intention is to explain how the aircraft and its major systems work, and how the F-35 handles in flight based on accounts from the test pilots who fly it.*

*The F-35 is undoubtedly unlike any fighter aircraft built to date, and is bristling with complex and revolutionary systems.*

*In April 2010, the flight test programme under way at three test sites appears to be gathering pace with a significant increase in the total number of flights scheduled and more systems under test.*

*Certainly the aircraft still has hurdles to overcome, but once clear of those, the F-35 Lightning II looks set to become the world's most advanced strike fighter.*

*Mark Ayton*
*EDITOR*

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*The two X-35 airframes proved the basic commonality of the three versions of the JSF. This is Article 301 during its time as the X-35B.* LOCKHEED MARTIN

In November 1994 the United States merged the Joint Advanced Strike Technology and Common Affordable Lightweight Fighter programmes to create the JSF programme. Low observable technology, powerful sensors, net-centric capabilities, internal weapons carriage, a high-thrust engine and manoeuvrability would enable the resultant aircraft to undertake both air-to-air and air-to-ground missions with a high degree of survivability. Equally important was affordability, allowing the US military to replace its existing inventory on a one-for-one basis.

A conventional take-off and landing (CTOL) version would replace most of the US Air Force's inventory of fighter-bombers, while a carrier variant (CV) would supplant the US Navy's F/A-18 Hornets at sea. The US Marine Corps would replace its AV-8B Harrier IIs with a short take-off and vertical landing (STOVL) variant of the JSF. Currently the US Air Force plans to acquire 1,763 examples, and the US Navy and Marine Corps 760, while exports are likely to raise production to more than 3,100 by 2035.

Industrial interest in JSF was high from the start given the numbers involved and most of the major players submitted proposals for a four-year weapons system concept demonstration (WSCD) phase, requests for which were released in December 1995. WSCD sought two competing teams to build two demonstrators and later modify one into the third variant to prove the commonality between the CTOL, STOVL and CV variants. In November 1996 Boeing was informed it would produce two X-32s, and Lockheed Martin two X-35s. Subsequently Northrop Grumman and British Aerospace joined Lockheed Martin's team.

## Demonstrators

The X-35A CTOL demonstrator (Article 301) first flew from Palmdale, California, on October 24, 2000, and was tested at Edwards AFB, California, until November 22, when it returned to Palmdale for installation of a lift fan during its conversion to become the X-35B STOVL demonstrator. It commenced hover pit trials in February 2001 and made its first vertical take-off and landing on June 23, 2001. The X-35C (Article 300) was the CV demonstrator and first flew on December 16, 2000.

After the US Department of Defense evaluated both the X-32 and X-35, on October 26, 2001, Lockheed Martin was selected to enter the system development and demonstration (SDD) phase, and the designations F-35A, F-35B and F-35C were allocated to production CTOL, STOVL and CV variants respectively. In addition to the baseline versions, an electronic attack variant of the F-35C – the 'EF-35B' – is required (but currently unfunded) by the Marines. In mid-2006 unmanned and optionally manned versions were proposed by Lockheed Martin.

To fund development, the US Department of Defense offered foreign nations involvement in the programme at different levels, depending on their financial contributions. Those at Level 1, funding 10% of the costs, and Level 2 (around 5%), could directly receive contracts related to the F-35, while Level 3 (1 to 2%) could look forward to contracts from Level 1/2 nations. Security Co-operation Participants (SCP) are entitled to data on the programme in exchange for approximately $50 million. The only Level 1 nation is the UK, with Italy and the Netherlands at Level 2, and Australia, Canada, Denmark, Norway and Turkey at Level 3. Israel and Singapore joined as SCP nations.

## Flight Testing

SDD was due to involve 15 (later reduced to 13) instrumented test aircraft and seven ground test airframes, two of each variant plus another for radar signature evaluation. In addition the co-operative avionics testbed (CAT-bird), a modified Boeing 737-300, would test the F-35's mission systems. Flight trials are undertaken by Lockheed Martin at Fort Worth, and by industry and service teams at Edwards AFB, California, and NAS Patuxent River, Maryland.

AA-1, the first F-35A rolled off the production line at Fort Worth, Texas, on February 19, 2006, and was formally unveiled on July 7 at a ceremony during which the aircraft was named the Lightning II. It completed its maiden flight on December 15, 2006. Weight reduction measures and other redesigns made AA-1 non-representative of the planned production standard, but were incorporated into the others produced for SDD.

The second to fly was the first F-35B (BF-01) on June 11, 2008, followed by BF-02 on

February 25, 2009. On November 14, 2009, the initial optimised F-35A (AF-01) was flown, while the first F-35C (CF-01) took off for its maiden flight on June 7, 2010, the eighth Lightning II to enter the test programme. BF-04 became the first equipped with the complete mission system, flying on April 7, 2010. By early March 2011 a total of eleven pre-production aircraft had flown, plus two F-35As from low rate initial production 1 (LRIP 1). The LRIP 1 aircraft (AF-06 07-0744 and AF-07 07-0745) joined the flight programme on February 25 and March 4 respectively, both carrying markings for the 33rd Fighter Wing at Eglin AFB, Florida, responsible for the training of service pilots and ground crews on the aircraft.

Early production aircraft were due to be delivered with Block 1 software, allowing them to employ Joint Direct Attack Munitions and AIM-120 AMRAAM missiles, but initial deliveries will use Block 0.5, originally intended only for training and test support activities. Block 2 will add further capability, while Block 3 will be the initial operating capability (IOC) standard.


*F-35A AF-01 was the first optimised example of the CTOL variant to fly in November 2009. Unlike the other two versions, the F-35A is equipped with an internal gun.* Lockheed Martin

# IGHTNING II
## The Story So Far

### The Joint Strike Fighter (JSF) programme has spawned what is intended to be the West's most capable strike fighter aircraft. David Willis reports

#### Challenges Ahead

While the JSF programme has come a long way, some significant hurdles remain. Delays caused by design alterations and inevitable problems discovered during flight testing will make it difficult for the aircraft to meet its IOC within the current timeframe. Initially the F-35B had an IOC of 2012, but development of this variant has proved more troublesome than the other two. In January 2011 it was put on a two-year 'probation' during which its engineering deficits will need to be overcome before its future is secured.

IOC for the F-35A and F-35C is set for 2013. This is before initial operational test and evaluation (IOT&E) is concluded in November 2015 – an unparalleled situation, brought about by the delays. IOT&E completion is 13 months behind the original schedule established in May 2008, and four years later than originally set out in 2001. Milestone C, which signals the end of LRIP and allows multiyear buys, cannot be declared until operational testing is completed. It is currently planned for 2016.

The biggest uncertainty, however, is the cost of the F-35. Original plans for an F-16-priced aircraft have long since been forgotten, with some analysts suggesting the actual cost is closer to that of the top-end F-22 Raptor. Export customers also have issues with technology transfer, including access to source codes, without which their ability to perform indigenous service upgrades would be severely curtailed.


*Development of the F-35B STOVL variant has been the most problematic and it has been placed on probation.* Lockheed Martin

# FLIGHT THE


*F-35A AA-1 took off on its initial test flight from Fort Worth, Texas at 12:44 local time on December 15, 2006 piloted by Jon Beesley. The aircraft was airborne for 35 minutes on its maiden flight during which it climbed to 15,000 feet allowing Beesley to perform a series of manoeuvres to test aircraft handling and the operation of the Pratt & Whitney F135 turbofan and subsystems.*

Lockheed Martin began initial flight testing of the F-35 in 2006 with aircraft AA-1, the first F-35A CTOL variant. The primary role of AA-1 was to prove the feasibility of major new systems integrated on the F-35 as part of a risk reduction effort.

Systems include the electro-hydro static actuator (see Electric Muscle), the electrical system and the integrated power pack: "All of which have new and unique things that no one has done before, so we had to reduce the risk on all of them," said Beesley.

Other systems flown on AA-1 as part of the risk reduction effort included the engine control system, the panoramic glass cockpit and the helmet mounted display. Speaking about the flight testing, Jon Beesley told *AIR International:* "We undertook aero strut testing, flew supersonic, opened the weapons bay doors during flight and flew the aircraft with a full internal combat weapons load, all of which were undertaken to discover problems and reduce the risk to the programme."

AA-1 also completed a series of cable engagements to verify the design of the tail hook before its retirement after 90 flights.

F-35s currently being used in the flight test programme for the system development and demonstration (SDD) phase were modified or built to a revised gross weight configuration. This design change followed the SWAT (STOVL Weight Attack Team) weight optimization effort launched by Lockheed Martin in February 2004.

This effort sought to reduce the gross weight of the original F-35B design by 3,000lb (1,360kg) and the changes that were made had beneficial effects to the aircraft in the conventional and STOVL modes of flight.

"We done a lot of ground testing in the STOVL mode with the lift fan engaged and spent several months on the instrumented hover pit to measure force and moments," said Beesley.

"We found that the force from the aeroplane was a bit better than we had thought, so a nice surprise. We also looked at the mechanical issues associated with controlling the aircraft in the STOVL mode. Making the aeroplane transform from conventional flight mode into STOVL mode is really incredible and requires a lot of complex mechanization.

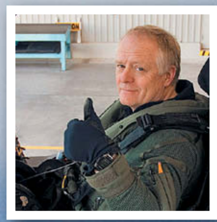
## Electric Muscle

One revolutionary system on the F-35 is the electro-hydrostatic actuator (EHA), which are used to power the flight controls. Jon Beesley is enthusiastic about the use of the EHA: "The F-16, Typhoon, even Raptor all have 'electric brains' and 'hydraulic muscle', but the F-35 has electric muscle. Nobody has really done that before. We flew AA-1 and learned how to improve on the original design that was incorporated into the other aeroplanes."

But the electric nature of the F-35 also includes the integrated power pack (IPP), a new type of system that removes the need to have an APU (auxiliary power unit, a turbine) as typically used by a legacy aircraft, to start the engine(s). Similarly the environmental control, pressurization and air conditioning systems on legacy jets are also powered by another

# Testing F-35

## Mark Ayton spoke with Jon Beesley, Lockheed Martin's Chief Test Pilot, before his retirement




turbine run on bleed air, and in the case of single engine aircraft like the F-16 a third turbine run on hydrazine is used as an emergency power unit. "On the F-35 we have the IPP and use it to start the aeroplane (like an APU) and switch it over to the environmental control system and then we can run it either off the engine and use bleed air as an air emergency generation system, or we start it in the air in the fuel mode and run it that way. Nobody has done that before, and quite honestly those three systems [APU, environmental control and emergency power] were the biggest problem in the first two or three years of flying the Raptor," said Beesley.

### STOVL Trials

BF-01 first flew its airworthiness flights in June 2008 a process that continued for longer than planned while modifications took place ahead of the hover pit testing in October.

Using flight test aides fitted on the aeroplane, Beesley and his test pilot colleagues were able to open the doors in various sequences primarily for structural reasons to determine the loads induced upon the doors in flight. As a result Beesley and his team found the aerodynamic effect was worse than originally thought. Lockheed Martin engineers adjusted the flight control laws applied to the aircraft to accommodate the aerodynamic differences encountered during the early flights. Flying the F-35B with the doors open provided data that allowed the engineers to study the changes and in the way the computer controls the aeroplane. This analysis led to a better understanding of the aerodynamic effect with the doors in the open position that allowed tighter flight control to be achieved.

The flights were all undertaken without the lift fan engaged; "Which is clearly the worst situation, with the upper lift fan door up, you get a tremendous amount of effect, which only turns beneficial when you start to flow a lot of air through the fan. Before that, the air has no place to go and tends to degrade aerodynamic performance," said Beesley.

### Pit Testing

In late March 2009, Lockheed Martin commenced hover pit testing using a purpose built facility at its Fort Worth plant. Jon Beesley explained: "It is a graded pit so there are no ground effects and the air exits at another place, so it is really a free airborne test.

"We chained the aircraft down on the load measurement system [a large equivalent of bathroom scales] and ran the aircraft all the way to full power with the thrust pointed at various angles to simulate all of the various facets of flying. The obvious ones are vertical lift, but we also simulated short take-off and short landing profiles.


Beesley and the test team also tested the rates at which the actuators worked and the response of the flight control surfaces. This was undertaken to determine whether controls were providing the equivalent performance to that used by the engineers in their analysis. Other tests studied the effectiveness of the roll-posts (see Powering the Lightning II) .

"We also placed plates over the pit to see the resultant effect on the ground and on the bottom of the aeroplane during vertical take-offs and landings. The thermal effects on the aeroplane certainly matched what the engineers had predicted," said Beesley.

Thrust was one of the primary reasons for the pit tests. According to Jon Beesley the engine demonstrated greater thrust than was expected and the aircraft handled very well throughout the test campaign.

## Handling Characteristics

When asked about the differences in handling characteristics between the F-35A and the F-35B Jon Beesley said that the two variants differed only slightly in the conventional mode applicable to each. In terms of manoeuvrability the two handle exactly the same because of the control laws applied to counter the different aerodynamic characteristics of each variant.

Aircraft AF-01 and BF-01 are closer in terms of handling than AA-1 and BF-01, which according to Lockheed Martin is caused by the differences in the landing gear. Pilots encountered a challenge with AA-1 on the early flights. The movement arm between the landing gear and the tail was too short causing the aircraft to rotate a little faster than it

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*JON BEESLEY, LOCKHEED MARTIN'S CHIEF TEST PILOT*


*Opposite Top:* *Flight sciences aircraft BF-02 is one of five F-35B STOVL variants assigned to the flight test programme.*
*Opposite Bottom:* *F-35A CTOL AF-01 on a test flight from Edwards AFB in California during June 2010.*
*Below:* *F-35B BF-01 commenced hover pit testing at Lockheed Martin's Fort Worth facility in May 2008 during which time the aircraft operated at 30% power and converted to STOVL mode. All doors and nozzles were exercised during testing.*

should to achieve the best take-off. As part of the SWAT effort, the landing gear was canted forward by 5 inches (125mm), which "makes a world of difference," said Beesley.

The F-35C CV variant has a bigger wing so the main handling difference is felt during take-off and landings, which are 15-20 knots (28-37km/h) slower because of its heavier weight, bigger stabilators and greater down force. Other differences are associated with, and specific to carrier operations.

But the design goals of all three variants remain the same: "We want an aeroplane that a pilot could [in theory] go from flying a CTOL in the morning to a STOVL in the afternoon and the CV in the evening and would be comfortable in all three because of similarity," said Beesley.

"We have gone to great lengths to make the aeroplane easy to perform STOVL

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operations. That is very hard to do, but the guys have done some really brilliant work capitalising on a concept developed on the VAAC Harrier at Boscombe Down called the unified control law, a technique that makes conversion to the F-35B and STOVL operations very straightforward." So much so that a pilot's primary focus during training will be on the tactical aspects of the mission as opposed to vertical landing technique.

## Performance of the Aircraft

According to the test pilots that spoke with *AIR International* the performance they first experienced in the F-35 was more than expected. "On my first flight in AA-1, I found myself climbing out with the gear down much steeper than I thought," said Beesley adding: "When I did supersonic testing carrying two 2,000lb bombs and two missiles, the aircraft had no trouble at all getting there [to supersonic flight] which is really quite an accomplishment, the F-16 chase aircraft was occasionally tapping the afterburner to keep up." He enthused about its performance, citing examples in which the aircraft performed very well flying at low level with the doors open, or at 450 knots (830km/h) at 10,000ft (3,048m) with the doors open, up to Mach 1.1, and to 500 knots (925km/h) at 10,000ft with the doors closed.

The F-35 is designed to perform a huge variety of missions with stealth: air-to-air, interdiction, and when the battlefield environment is permissive, close air support with munitions carried on external weapons stations. Performance-wise, an F-35 with a full internal-load of weapons is comparable to a fourth generation aircraft like an F-16 with no weapons at all.

And in terms of manoeuvrability the F-35 will be cleared to a 50° angle of attack, similar to the F/A-18 Hornet, with a full load of munitions (two 2,000lb precision-guided weapons or eight small diameter bombs) inside.

Most of the test flights are flown at 30,000-32,000ft (9,144-9,753m) but the aircraft has a 50,000ft (15,240m) ceiling and will be optimized for the block 20,000-40,000ft (6,096-12,192m).

## Challenge for the Fifth Generation

There are people who maintain that the F-35 is an unnecessary weapon system. When the author discussed this with Jon Beesley he shared his own view: "Lockheed Martin was asked to build a combat aircraft to address a very real need. Sometimes people conjecture, typically without much knowledge, that threats will evolve to negate the things that fifth generation aeroplanes bring.

Well, anything that will not work because of the physics involved, against a fifth generation aeroplane will be an order of magnitude more effective against a current generation aeroplane, and so that argument says that you should have probably done it sooner, and should do it more."

In terms of evolution the sensors on the F-35 will provide the pilot with answers rather than just data, which will allow him or her to do what is most important – think. And the answers presented by the fusion system can be shared across the network to enhance the situational awareness in the battlefield all from a stealthy aircraft.

# POWERING THE LIGHTNING II

**The F-35 Lightning IIs flying today feature the Pratt & Whitney F135, the most powerful production jet engine ever made for a fighter. Additionally, the F-35B incorporates the Rolls-Royce LiftSystem, which enables the aircraft to perform its unique STOVL-to-supersonic mission. Chris Kjelgaard reports**

In the convoluted development history of the F-35 Lightning II, no issues have drawn more public attention than those involving the aircraft's propulsion systems. These have been among the most contentious aspects of the F-35's development, from the long political battle over whether it is to have one engine type or two, to the threat of programme cancellation hanging over the STOVL F-35B.

But whatever political challenges the F-35 faces, the technological advances achieved by Pratt & Whitney in developing the F135 – the engine of record for the F-35 Lightning II – and by Rolls-Royce in developing the STOVL F-35B's extraordinary LiftSystem have been immense.

## The Pratt & Whitney F135

Chosen on October 26, 2001, by the US Department of Defense (DoD) for a $4 billion system development and demonstration (SDD) contract which decided the Pratt & Whitney F135 would be used for all F-35 development flight-testing, the F135 is a bigger-diameter, higher-airflow derivative of the company's F119 engine powering the F-22 Raptor. The F135 was chosen for the SDD contract because both Lockheed Martin and Boeing had selected it (in the form of augmented F119s) to power their respective X-35 and X-32 Joint Strike Fighter (JSF) demonstrators, Lockheed Martin winning the JSF contract with its X-35. The Pentagon also found attractive the fact that the F135 shared a high degree of commonality with the F119, two of which power each F-22 Raptor.

The F135 and F119 are both axial-flow engines (air goes through the core of the engine in a straight line) and they share a "highly common core", according to Ed O'Donnell, Business Development Director for Pratt & Whitney's F135 and F119 programmes. From front to back, these two-spool engines are "largely common through the compression system," says O'Donnell – noting, however, that the commonality is mainly in the firm of shared engine architecture rather than common part numbers. Part numbers for the F135 have been designated differently to those for similar parts in the F119 because the US services want to be able to allocate specific part numbers to specific programmes for inventory-management reasons.

Despite their similarities, there are some crucial differences between the F135 and the F119. One is that the F135 needs to be able to generate up to 43,000lb (191.27kN) of thrust 'wet' (with afterburner) for the single-engine F-35, whereas the F119 provides a lesser 35,000lb (155.7kN) of thrust with full afterburner. As a result the F135 has a larger inlet diameter (46 inches/1,168mm), larger fan diameter (50 inches/1,270mm) and larger overall engine diameter (51 inches/1,295mm) than does the F119, so it can achieve a higher airflow.

Like the F119, the F135 has a three-stage fan (in military-engine parlance, the fan is the entire low-pressure compressor assembly). Each fan stage comprises a one-piece integrally bladed rotor (or 'blisk', short for bladed disc) featuring a solid titanium hub with titanium blades welded on to it. The first fan stage has hollow titanium blades and each of the subsequent two stages has solid titanium blades. Aft of the third fan stage the accelerated airflow is split, 57% of it going through the fan duct as bypass air and the remaining 48% entering the core to be compressed, mixed with fuel, ignited and then exhausted as hot gas to turn the turbine stages and produce up to 28,000lb (124.55kn) of dry thrust before afterburner.

The F135 has a six-stage high-pressure compressor (HPC) and again each stage is comprises a blisk. Some of the initial HPC stages are made from titanium but because the airflow becomes hotter as it passes through each stage of compression, one or more later HPC stages are made from nickel-based alloy to be able to withstand the high air temperature. In conventional F-35 flight, air exiting the HPC into the combustor is at 28 times the pressure it was when entering the fan and it is at 29 times the pressure when the F-35B is in hover mode.

The engine's single annular combustor features removable liners and a series of fuel nozzles, all housed within a diffuser case. O'Donnell says the F135 combustor is "highly similar" to that in the F119, but features "some improvements to accommodate the appropriate temperature requirements" of the higher-power F135. Overall, the cores of the two engines – the region from HPC to combustor to HPT – are essentially the same size and since the F135 has to produce more dry power at full thrust than the F119 it is likely to run hotter than the F119.

While both the F119 and the F135 feature a single-stage high-pressure turbine (HPT), the F135 has a two-stage low-pressure turbine (LPT) where the F119 has a single-stage LPT. This is because, in the F-35B STOVL aircraft, the low-pressure spool to which the LPT is attached has to drive not only the fan stages but also the driveshaft powering the Rolls-Royce LiftFan located behind the cockpit and ahead of the engine.


*Raw power of the P&W F135-PW-100 engine seen on F-35A AF-02 during an afterburner test.* Lockheed Martin

The LiftFan (one of three major components of the Rolls-Royce LiftSystem, which provides the F-35B's hover capability) is not engaged while in normal forward flight and does not feature at all in the F-35A CTOL and F-35C CV conventional take-off and landing variants of the Lightning II. However, from the outset the specification for the F-35's engine called for "tri-variant compatibility": the engine powering an F-35A is identical to that powering an F-35B or an F-35C. Nevertheless, the engines are designated differently: the F-35A powerplant is the F135-PW-100; the engine for the F-35C is the F135-PW-400; and the F-35B engine is the F135-PW-600.

Since the F-35B powerplant needs an extra LPT stage to provide the power necessary to turn the driveshaft (which, through a clutch and gearbox, drives the LiftFan), F135s built to power other F-35 variants have the second LPT stage as well. "The engine was designed to support that severe STOVL requirement," says O'Donnell. For engines powering CTOL F-35As and F-35Cs, the additional turbine stage offers a substantial extra power margin, allowing for potential F-35 weight growth. Since the engine isn't heavily taxed in many CTOL missions, its maintainability is improved too.

The geometries of the cooling-air paths and airflows in the F135's hot section are different from those in the F119. Turbine-blade coating materials, used to prevent nickel-alloy turbine blades and vanes from melting in the several-thousand-degrees airflow coming from the combustor, may well have been updated too. P&W may be able to apply retroactively to production F119s the advances in cooling-path and coating technologies it devised for the F135.

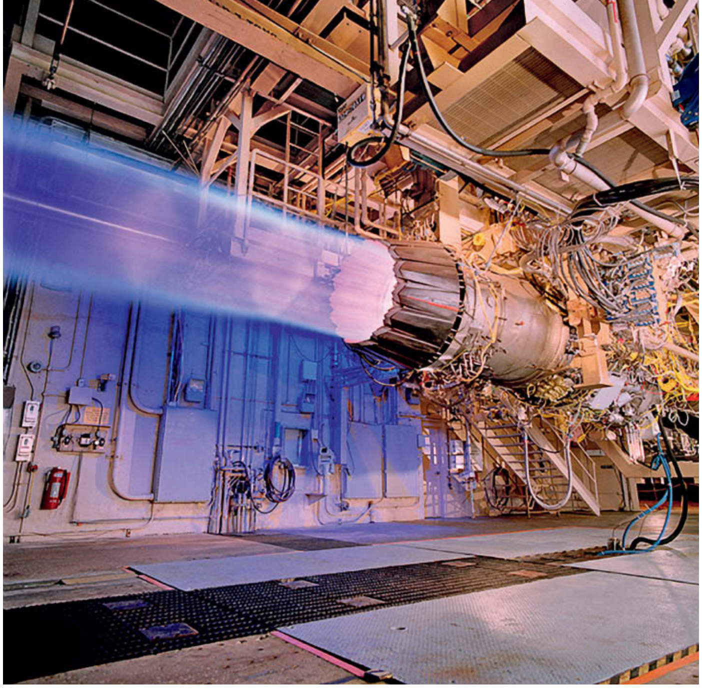
In both engines, cooling air is taken from the bypass airflow and by bleeding air away from the HPC stages to cool the HPT and LPT stages, probably by means of air channels etched into their blades and into the turbine casing, as is the case in commercial turbofans. "Even fifteen-hundred-degree air is cooling air if it's relative to hotter air," notes O'Donnell. "The [blade] metal melts at the temperatures we're operating at and a lot of the technology is in the cooling and coatings."

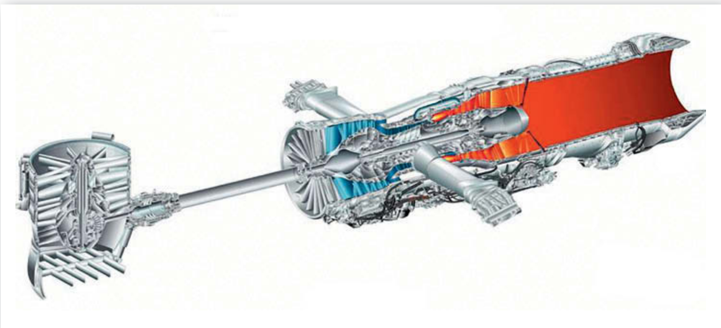
## Counter-rotating Spools, Ceramics and Augmentors

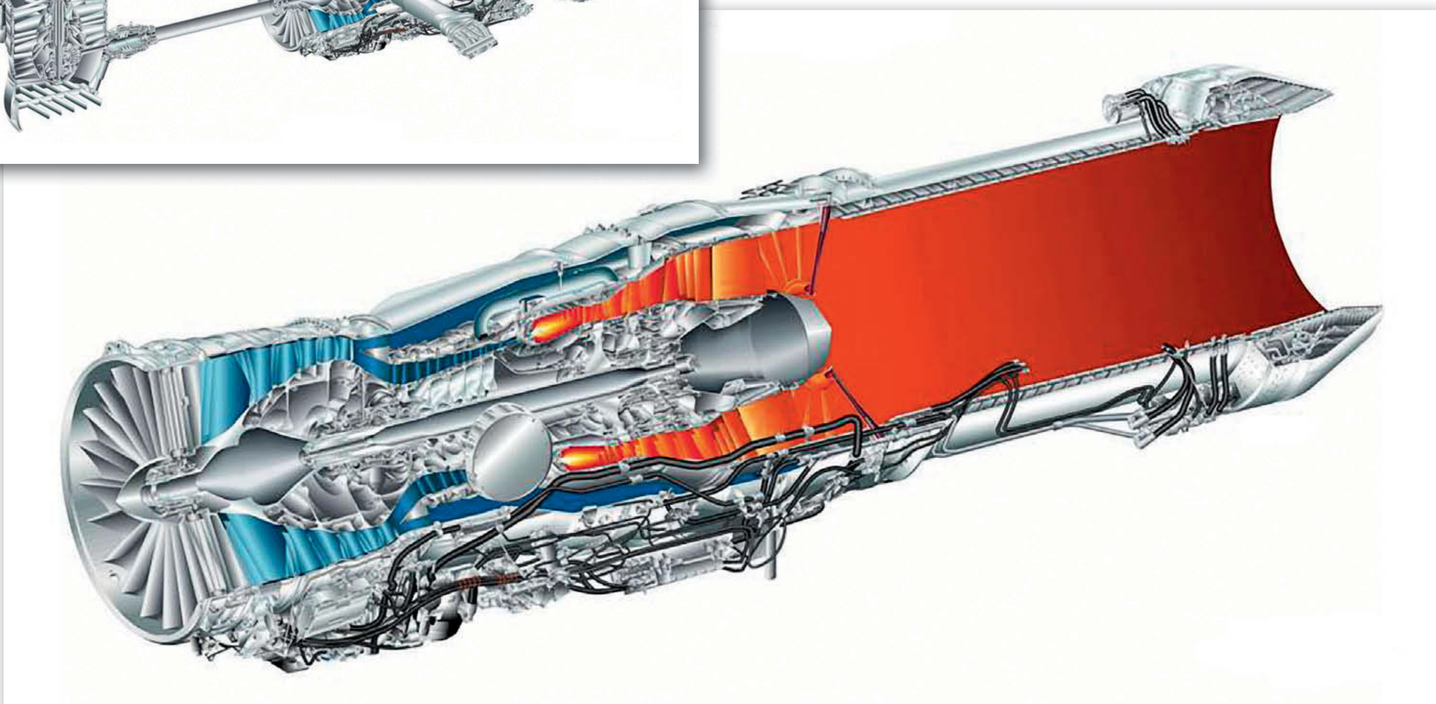
A potentially important feature of the F135 – but one which Pratt & Whitney doesn't talk about much – is that the engine's two spools are counter-rotating, like those in the F119. Since in some cases spool counter-rotation can be used to shape the direction of core airflow as it transitions between the HPT and LPT to improve the overall efficiency of the airflow through the engine, this might have allowed P&W to dispense with one or more rows of static stators and vanes in the F135. (Rows of stators and vanes, which are static blades found between many fan, compressor and turbine stages, act to condition and present the core airflow optimally to each subsequent rotating stage.) So P&W possibly has been able to reduce the parts count in the engine and make it somewhat lighter – but it declines to confirm this.

P&W also won't confirm the dry weight of the F135, but a source commenting on an aviation blog cites Warren Boley, President of Pratt & Whitney Military Engines, as saying the F135 weighs 1,500lb (680kg) more than the F119. This would put the F135's dry weight at around 5,400lb (2,450kg). However, the F135 may have a higher thrust-to-weight ratio than the F119 (the F119's overall pressure ratio is 26:1 compared with the F135's 28:1) and so the 5,400lb figure might be high. Boley has also suggested the F135 has an uninstalled wet-thrust capability of approximately 51,000lb (226.86kN). If this reads across to an installed basis – in which bleed air and shaft horsepower would be extracted to power aircraft systems – it should provide a comfortable operating margin over the 43,000lb (119.27kN) of wet thrust required by the spec.

The F135 uses ceramic matrix composites (CMCs) in its exhaust nozzle, primarily on the outside sections of the exhaust nozzle on the F135-PW-600 STOVL version of the engine. O'Donnell says that on the STOVL engine, also, some sections of the fan ducts – particularly







*Top: An F135-PW-100 engine undergoing a test run with full afterburner or augmented power generating up to 43,000lb of thrust.* Pratt & Whitney
*Opposite: This shot shows an F-35B STOVL F135-PW-600 engine undergoing a test run with full afterburner or augmented power.* Pratt & Whitney
*Below & left: Cutaway diagrams of the F135 engine. The diagram on the left also shows the LiftFan, gearbox, driveshaft, roll posts and roll ducts components of the Rolls-Royce LiftSystem.* Pratt & Whitney

at the bottom, “where all the accessories hang on to” – are made from organic matrix composites (OMCs), whereas the fan ducts for the F-35A and F-35C engines are made from titanium. Some of the inlet ducting in the aircraft is also made from OMC material.

According to O'Donnell, P&W has used OMCs in the F-35B to reduce weight by 40 to 50lb (18 to 22.5kg) so that the aircraft can carry a little extra weight – say, an additional 50lb of ordnance – and bring it back if required when the mission calls for the aircraft to land vertically. This “vertical lift bring-back” (VLBB) measurement is a critical performance requirement for the F-35B and while the aircraft as it stands today meets the current spec, the worry is that if the F-35B's maximum gross weight grows over the course of its operational career (as usually happens with military aircraft), its VLBB performance will need to improve.

Another key feature of the F135 is its augmentor, or afterburner system. While available details of the augmentor are sketchy, the F135 is known to employ multi-zone (probably three-zone) fuel injection aft of the afterburner's pilot light. These zones inject fuel independently, so that the afterburner does not act in an all-or-nothing way but instead provides a variable range of additional, smoothly transitioning wet thrust at the pilot's command. Also, like the F119 augmentor, the F135 augmentor is stealthy: The design of the two engines' augmentors places multi-zone fuel injection into curved vanes which eliminate conventional spray bars and flame holders and block the line of sight to the turbine when looking into the engine from behind.

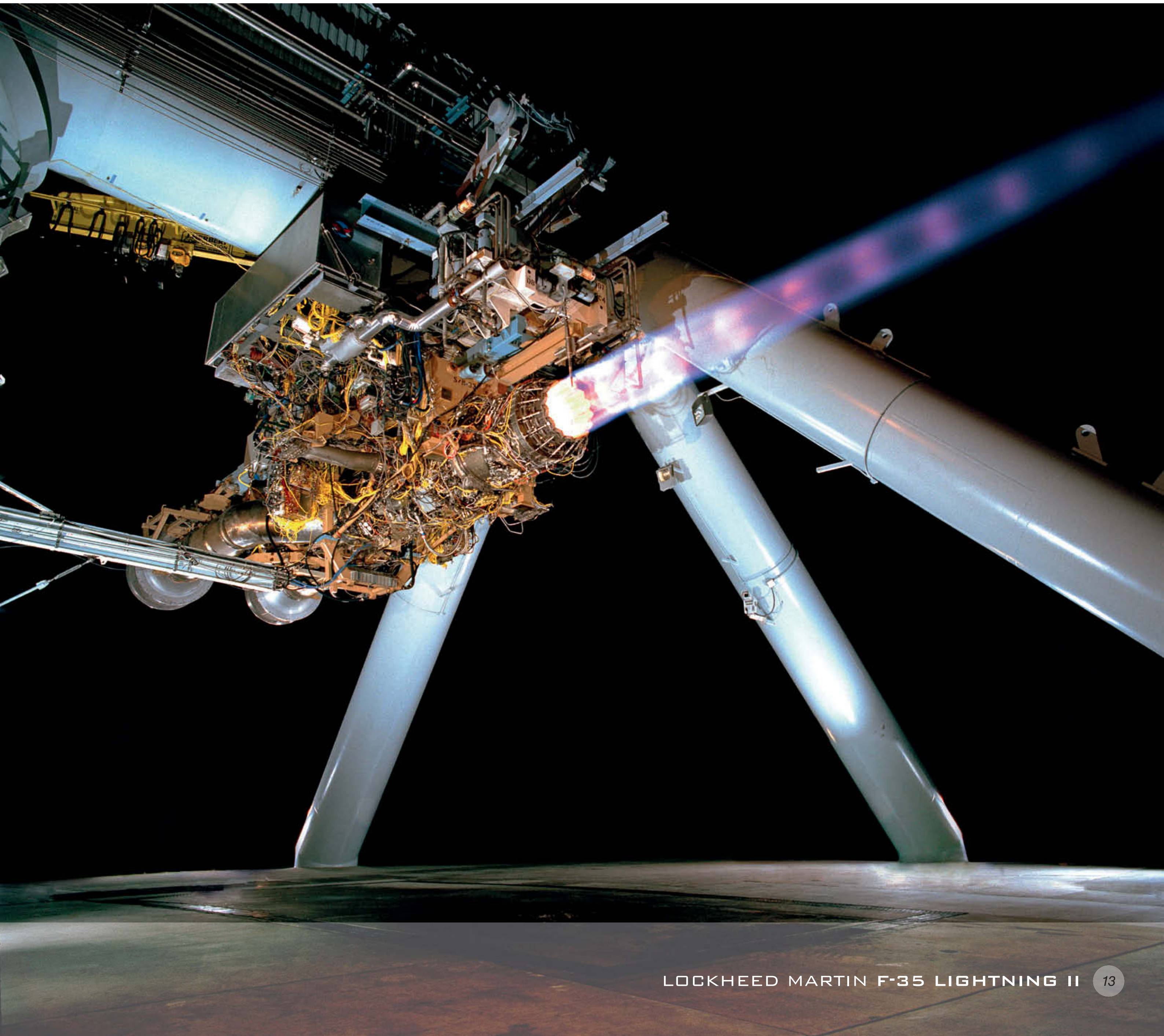
## Maintainability

From the outset the F135 has been designed for maintainability, building on the experience Pratt & Whitney gained with the F100 for the F-15 and F-16 and then with the F119 for the F-22. (When designing the F119, the company brought in US Air Force mechanics to help design its engine-mounted controls and accessories for maintainability). In the F135, all controls affixed to the casing are ‘single-deep’ – no control units are mounted on top of each other – and the nuts and bolts which attach them to the engine casing are encapsulated in the control assemblies themselves, so nuts and bolts stay with the control units when these are removed. This greatly minimizes the risks of nuts and bolts being lost and causing foreign-object debris (FOD) damage.

Similarly, all engine clamps and blocks stay on the engine casing when an F135 is removed for maintenance and the engine uses no safety wire, eliminating another potential source of FOD damage. All controls and accessories are mounted on the bottom of the engine, making it easier for mechanics to get to them; and these assemblies are modular so that, say, a mechanic could easily remove the electronics or valves or relays for an F135 fuel control unit as entire modules.

O'Donnell says the US Air Force has found the F119 to be “significantly more maintainable” than the earlier F100 – the F119 offers “major orders” of improvement of mean time between failures in terms of maintenance man-hours required – and says P&W expects operators to find the F135 even more easily maintainable and reliable than the F119. Another plus, he says, is that P&W can apply the design-for-maintainability improvements it has developed for the F135 to new F119 production batches as well.

The F135 engine also comes with a digital prognostic and health monitoring (PHM) system and an extensive sensor suite. By means of the sensors, the PHM system constantly monitors the engine's operating parameters and the condition of its components, and alerts aircraft mechanics if it finds anything abnormal. “So a lot less time is devoted to



troubleshooting," says O'Donnell. So seriously did P&W take the job of making the F135 highly maintainable that it tried to design the engine to require only a single hand tool, clamped to the engine when not in use, for all line-maintenance jobs. P&W couldn't quite achieve that ideal but did succeed to the point where only six hand tools are required.

## Production

Having obtained initial service release (ISR) certification from the DoD for the CTOL F135 in February 2010 and for the STOVL engine in December, Pratt & Whitney was delivering three production F135s a month by March. Brett Rhodes, P&W's Production Program Lead for the F135, says the company increased the rate to four a month in April as it completed deliveries under Phase 2 of low rate initial production (LRIP 2) and began delivering engines for aircraft in the LRIP 3 production batch. "That's a really big achievement – we're really into the production aspect of delivering production hardware," says Rhodes. "Lockheed Martin is going to be selling its first CTOL aircraft soon. We started propulsion deliveries a year ago – the engine always has to lead the airplane in the maturity of its development."

By late March, also, through sub-contractor Rolls-Royce, P&W had completed delivering F-35B variable area vane boxes all the way through LRIP 3 and into LRIP 4. (The variable area vane box [VAVB], which is a critical component in the F-35B's LiftSystem, actually forms part of the keel of the aircraft and so for any F-35B has to be delivered much earlier than the engine). Additionally, P&W has already delivered F135 inlet debris monitoring systems – the IDMS is a new system which detects debris anywhere in the inlet or engine and alerts the pilot and mechanics – for aircraft well into the LRIP 3 production batch.

Rhodes says that by March 25 P&W had delivered 12 CTOL engines – eight for installation in aircraft and four as spares – to Lockheed Martin at Fort Worth, as well as six STOVL engines. The company's target for 2011 is to deliver 40 production F135s, with production from April through December to be split evenly between CTOL and STOVL engines. LRIP 4 deliveries for the F135 itself begin in the fourth quarter and P&W has agreed a deal with the Pentagon to deliver each LRIP 4 engine for 16% less cost than engines under the LRIP 3 cost-plus contract.

At the time of writing, the F135 had flown in more than 740 F-35 flight tests and accumulated more than 1,200 flight hours – and a total of more than 21,000 hours of ground and flight testing. The F135 and Rolls-Royce LiftSystem had achieved 64 vertical landings by early April and the number should have climbed to well over 70 by this issue's publication date.

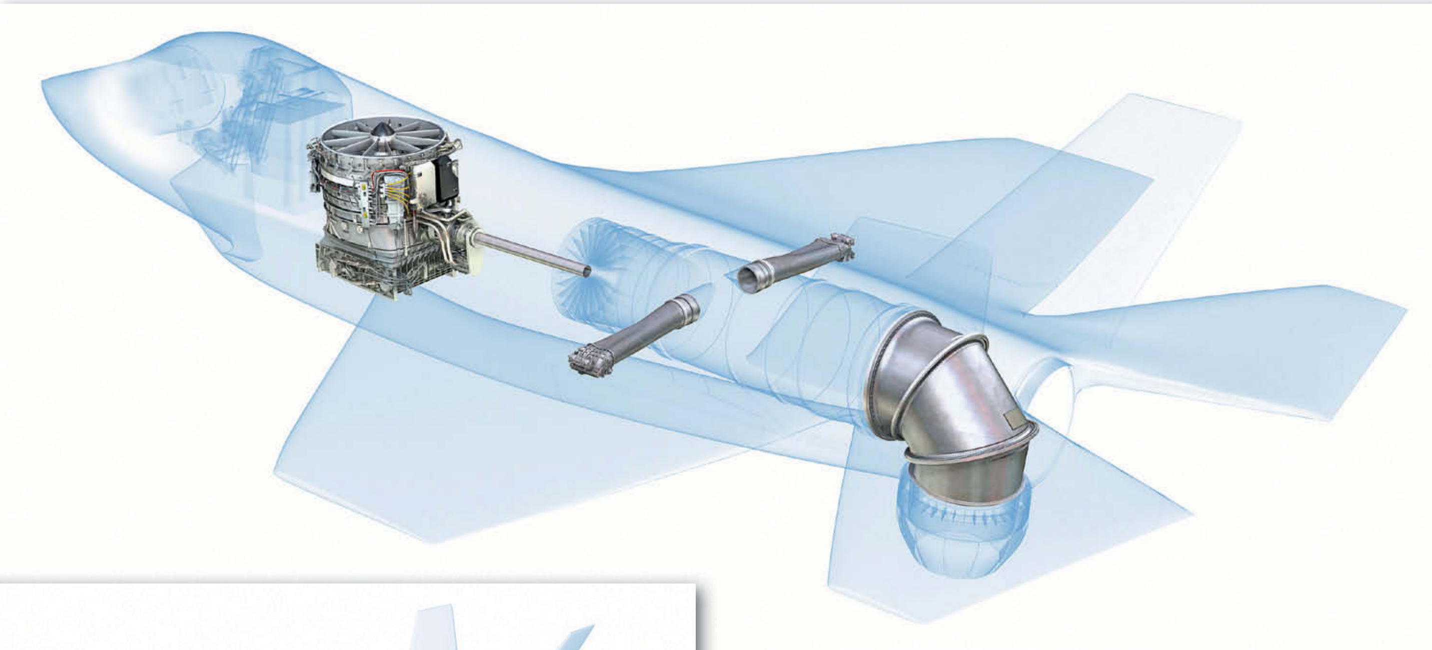
In the DoD's budget for fiscal 2012, P&W has obtained $1 billion for more engines, flight-test support out to October 2016 and component improvements, like those the Pentagon funds under its Component Improvement Program (CIP). The rival GE/Rolls-Royce Fighter Engine team has always said the F135 has durability issues because it essentially uses the core of the smaller F119 and accordingly runs hot. However, Boley describes the $400 million of what he calls "CIP-like" funding in the budget as being for "maintainability, sustainment and affordability" improvements in the mature F135 engine rather than to improve component durability. P&W would introduce such improvements in block upgrades, he says.

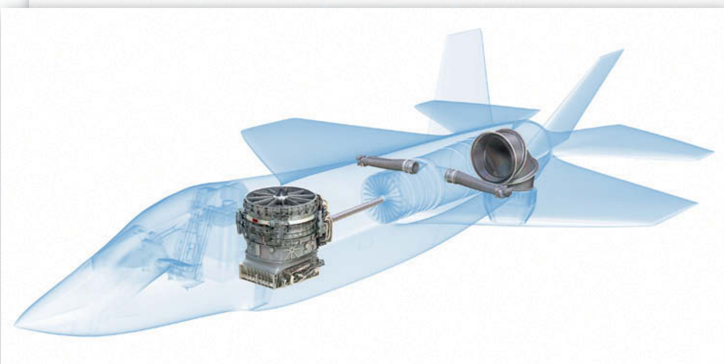
"At this point in the development cycle, it's really maintainability related and for affordability more than durability," says Boley. "We'd like to get these in as soon as possible to reduce costs & 'spend a dollar today and save a dollar tomorrow'. Durability improvements take much longer, because you need to design, test and incorporate them."

Boley says the F-35B's probationary period will not stop production of the F135-PW-600 STOVL engine after the LRIP 4 production phase, but it means F135 production won't be increased as originally planned. "Through Lot 4, we're producing at the same rate," as previously planned. "Lots 5, 6 and 7 are reduced because that's the probation." Previously, the F135 production plan called for equal numbers of STOVL and CTOL engines to be delivered in the LRIP 5 batch, but now CTOL production will overtake STOVL in LRIP 5.

"Net-net, there will be a reduced quantity" of F-35B engines, but "if it gets through the probation, there may be only a reduction of 10 to 12 units," says Boley. But while P&W will be increasing production to 50-to-80 F135s a year by 2013 or 2014, "We're not ramping yet to that 125 a year," originally envisaged for that period.

However, F-35 flight-testing has now been extended to October 2016 from 2013 and spare engines will be required for production F-35s as well. Boley says Pratt & Whitney has





*Above and Left: Major components of the Rolls-Royce LiftSystem from left to right: the LiftFan, gearbox, driveshaft, roll posts and roll ducts, and the three-bearing swivel module.* Rolls-Royce
*Top left: An F135-PW-100 engine undergoing a test run with augmented power.* Pratt & Whitney
*Top right: F-35B BF-01 in the hover at NAS Patuxent River, Maryland.* Lockheed Martin


proposed to the DoD that, "to keep some of the production rate up," it should be allowed to increase deliveries as much as possible towards the 125-a-year production plan by building more engines as spares than originally planned. "Now we have to do more, because we have to produce more flight-test engines. We need to fly longer."

### The Rolls-Royce LiftSystem

One of the most remarkable features of the F-35 programme is that when the STOVL F-35B is hovering, its propulsion system produces very nearly as much thrust without afterburner as the engine does in forward flight with its afterburner fully lit. The F-35B's engine has to produce 39,400lb (176kN) of vertical thrust without afterburner in hover mode, while in conventional flight it produces 28,000lb (124.55kN) of dry thrust and 43,000lb (191.27kN) with full afterburner.

The F135-powered F-35B relies on two systems to achieve the high level of vertical thrust. First is its full authority digital engine control (FADEC) unit – computers made by BAE Systems and attached to the engine, but running on Pratt & Whitney proprietary FADEC software. In hovering flight, the FADEC computers make the engine work harder, allowing it to increase dry thrust from 28,000lb to 39,400lb without using afterburner.

Second, the F-35B relies on the Rolls-Royce LiftSystem. This consists of several major components. First is the LiftFan, a horizontally mounted fan unit located behind the F-35's cockpit. The 50-inch diameter, 50-inch deep (50 inches equates to 1,270mm) LiftFan draws in cold air through an inlet on the top of the fuselage and accelerates it to produce vertical lift. The LiftFan inlet is covered by a large, Lockheed Martin-made door – nicknamed the '57 Chevy Hood' – hinged to the structure of the aircraft aft of the LiftFan inlet. The door is only opened when the F-35B is hovering, performing a short take-off or transitioning between horizontal and vertical flight.

> **"THE ENGINE WAS DESIGNED TO SUPPORT THE SEVERE STOVL REQUIREMENT."**

The LiftFan features two counter-rotating fans, one directly above the other. Each is a blisk, with the upper fan containing 24 hollow titanium blades and the lower fan containing 28 solid titanium blades, according to Gareth Jones, Rolls-Royce's Chief Engineer for the LiftSystem. Each fan is driven by a separate bevel gear system. (Bevel gears allow torque from a horizontal shaft to be transmitted through 90° to a vertical shaft by means of conical gears.)

Both bevel gears are contained in a common gearbox and are powered by a driveshaft which runs along the F-35B's longitudinal axis. The driveshaft is powered by the low-pressure spool of the F-35B's engine, which is located behind the LiftFan. (The LiftFan is located in front of the engine inlet and the driveshaft connecting the LiftFan and the engine runs through the inlet, under a fairing). On the engine, the driveshaft is connected to the fan hub for the engine's first fan stage, which is driven by the low-pressure spool.

Another major LiftSystem component is the clutch for the LiftFan gearbox. The driveshaft is always spinning when the engine is lit, but vertical lift from the LiftFan is not always required. When vertical lift is not required – for instance, in conventional flight – the clutch is disengaged. It only engages and locks when vertical thrust is commanded. Because of the significant amounts of friction generated and the high temperatures involved, the clutch plates are made from the same hard-wearing material as is used in the carbon brakes of large commercial aircraft such as the A380.

Below the LiftFan, the variable area vane box (VAVB) provides an exit path for the cool air driven downwards vertically by the LiftFan. Rolls-Royce produces the VAVB, which is made of aluminium and contains louvred vane doors. These can be angled all the way from 45° back, through fully vertical to 5° forward to provide variable directionality for the downward cool-air flow from the LiftFan, as commanded by the pilot through the aircraft's FADEC units.

When the F-35B is hovering, the driveshaft delivers 28,000 shaft horsepower to the LiftFan's clutch-and-bevel-gear system so that the LiftFan provides 20,000lb (124.55kN) of downward thrust as a column of cool air. (In the F-35B's hover mode the coupled F135-driveshaft arrangement acts exactly like a turboprop engine, except that most of its power output is used to drive air vertically rather than horizontally, so the F135 is actually the world's most powerful turboprop engine when installed in the F-35B.)

In hover mode another 15,700lb (69.84kN) of thrust exits the engine exhaust as hot gas and is directed downwards at the rear of the aircraft by the aircraft's three-bearing swivel module (3BSM). This remarkable piece of equipment consists of three articulated sections of nozzle casing, each of which is made from titanium. Each section is joined to the other sections by and driven by its own ring bearing. When the F-35B hovers, the FADEC commands the 3BSM – which can direct air through a 95-degree range from 5° forward to horizontally back – to swivel downwards to direct hot engine-exhaust air in the same direction as the direction of the cool air produced by the LiftFan near the front of the aircraft. The 3BSM can swivel fully from horizontal to vertical orientation in 2.5 seconds.

Jones says the ring bearing for the first 3BSM nozzle section is driven by its own actuator, while the bearings for the second and third sections are driven by a common actuator which acts directly on the ring bearing for the second nozzle section and drives the ring bearing for the third section through a travel gearbox. "These [two] sections can't articulate independently but do so through a fixed ratio, and they are set to oblique angles to each other," explains Jones. Both of the ring-bearing actuators for the 3BSM are powered by fueldraulics: some of the aircraft's fuel is pressurized to 3,500lb per square inch (2.46kg per square millimetre) to act as a hydraulic fluid to power the 3BSM actuators' servo-valves.

Other major components of the LiftSystem are the aircraft's two roll posts and the roll-post ducts which connect them to the engine. Jones says each roll-post duct is a "very


*Above: The F135 augmentor or afterburner system has ceramic matrix composites in the exhaust nozzle.* Paul Ridgway

*Left: This shot shows the F135's first fan stage blisk comprising a solid titanium hub and hollow blades.* Pratt & Whitney

complex part" whose shape changes from a circular shape at one end – where it connects to the engine – into a toroidal (a surface generated by rotating a closed plane curve about a coplanar line that does not intersect the curve) shape at the other end, where it attaches to the roll post. Each titanium roll-post duct is superplastically formed, diffusion-bonded and laser-welded.

According to Jones, the roll posts themselves are variable-area nozzles which are situated in the lower part of each inner wing section and act to provide roll control for the F-35B while it is in hover mode. In order to do this, the roll-post ducts direct bypass air from the engine to the roll posts, which drive the air out through the bottom of each wing. In the F-35B, 3,700lb (16.46kN) of thrust in the form of bypass air is directed out to the two roll posts while hovering.

Each roll-post assembly features a pair of flap-type doors in the bottom of the wing, controlled by the FADEC. Jones says these titanium doors are controlled by rotary actuators which allow fully variable opening, providing a degree of thrust variability and directionality so that the pilot can control roll while hovering. He says Lockheed Martin's original X-35 concept demonstrator featured doors between the engine casing and the roll-post ducts which could be closed when the aircraft was not hovering, but in production aircraft there are no such doors and bypass airflow is constantly sent to the ducts. The only way to control roll-post thrust is via the flap-doors in the bottom of the wing.

The demand for very high power during hover requires that the engine receive a high amount of airflow, so Lockheed Martin designed the F-35B with a pair of auxiliary air inlet (AAI) doors in the upper surface of the fuselage behind the big inlet door for the LiftFan. These AAIs provide additional inlet air for the F135 engine, not the LiftFan.

## Complexities

The complexity of the F-35B's propulsion system and the performance requirements demanded of the aircraft by the Pentagon has created issues that have become evident in flight-testing. These are among the issues which have delayed the F-35B, led it to running well over-budget and persuaded US Defense Secretary Gates to put the F-35B into a two-year probationary period. However, the three main issues affecting the LiftSystem are all well understood; and long-term fixes – none involving massive technological challenges – are in development.

Two issues involve parts getting too hot. LiftFan clutch plates have been found to rub together occasionally while the F-35B is in conventional flight and plates have been overheating. The plates are cooled by a fan forcing air over them in hover mode but not during conventional flight. The fix is to install a passive air-cooling circuit in the clutch for cooling during conventional flight and also to install a sensor to alert the pilot to climb up to 10,000ft (3,048m) if the clutch plates get too hot.

Roll-post actuators have also been burning out faster than anticipated, because of overheating through leakage of hot bypass air as roll-post nozzle seals age. Again, sensors have been installed and in the short term the actuators have been insulated. Jones says a permanent fix, redesign of the actuators to withstand hotter temperatures, uses proven technology and is well under way. Insulation of the actuators will not form part of the permanent fix.

The third LiftSystem issue is that build tolerances and engine thermal and pressure growth have caused the driveshaft for the LiftFan to expand and contract to a greater degree longitudinally during operation than Lockheed Martin's original design requirement intended. In development aircraft, clasp spacers are being used between the driveshaft and the engine's low-pressure spool to accommodate the extra expansion, but in production aircraft a bellows-type coupling will be affixed between the driveshaft and the engine fan hub.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# COCKPIT

## & Electronic Warfare Systems

**Davis Isby describes the ASQ-239 Electronic Warfare system used on the F-35 and Mark Ayton explains the cockpit and helmet-mounted display system**

## Cockpit

The F-35 cockpit is dominated by a 20 x 8 inch (500 x 200mm) panoramic cockpit display (PCD) incorporating touch screen control produced by L-3. The PCD is actually two 10 x 8 (250 x 200mm) displays side by side.

The top part of the 20 x 8 display is devoted to sub-system information such as engine and fuel gauges, stores management, flight controls, wheels, caution and warning systems, autopilot, auto throttle, navigation information, IFF, altitude and time data.

Tactical employment information is all displayed on the lower part of the screen and is split into four windows called portals 1, 2, 3 and 4, left to right.

The pilot can place anything anywhere and change the size of the portals. Most pilots fly with a tactical information display on one side and all of the sensors on the other. A hallmark of the F-35 is the fused picture presented on the display, which is very easy to interpret for the pilot.

Symbology at the bottom left of the display on an F-35B STOVL variant shows what the nozzle is doing.

There is no head-up display (HUD) in the F-35; everything that would normally be placed on the glass is displayed on the helmet-mounted display visor focused in on infinity.

On the right hand side of the cockpit is the side stick controller, which has a fair bit of movement and in the case of the F-35B STOVL variant so that the pilot can hover the aeroplane.

The throttle is on the left hand side and has a long linear throw rather than a rotary arc. This allows pilots of all physical sizes (from really small 104lb all the way up to 245lb) to fit and reach the controls, and sit comfortably in the aeroplane.

There are hardly any levers or switches in the cockpit, which minimizes the cockpit mass; only essentials are included such as the landing gear handle, emergency release, and engine start controls. All other control is through the touch screen or voice control.

In the centre of the console is the standby flight display, which has a separate inertial navigation system and runs on battery power alone. The left hand side of the main display is also battery powered. If the engine fails, leaving only battery power, the left side of the display and the standby display both stay alive, providing the pilot with sufficient data to fly the aeroplane safely – but nothing else. **Mark Ayton**

*Above: **Weighing less than 4 ½ lb (2kg) including the oxygen mask, the HMD comprises the flight helmet and display unit.** Lockheed Martin*

*Opposite: **The F-35 cockpit is dominated by two 10 x 8 inch displays side by side with touch screen control.** Lockheed Martin*

## Helmet Mounted Display System

The F-35 pilot uses the helmet-mounted display system (HMDS), which comprises a number of components. A display management computer that provides the interface from the aircraft and all of the tracker and display generation. The tracker system consists of the magnetic source installed in the cockpit and the sensor located on the helmet mounted display (HMD).

Weighing less than 4.5lb (2kg) including the oxygen mask, the HMD comprises the flight helmet and display unit, and provides the pilot with an 'out of the canopy display' to enhance situational awareness, targeting and tracking capability. The HMD also includes a day or night sensor to provide video for displaying and or recording. The HMD can present video source and symbology commanded by the aircraft's mission computer but fusion of multiple sensor sources is not a requirement or function implemented in the system. Seven high-speed links including fibre optics and MIL-STD-1394 interfaces provide video and controls.

The HMD is capable of supporting three modes of operation: day symbology only, day video and symbology, and night video and symbology. These allow the pilot to continue using the night capability into the dawn and dusk with the HMD day/night camera. Raw data and symbology commands are received by the HMD, most of which are determined by mission system software.

The HMD provides accurate head orientation and position data to the mission computer. Data fusion and the pilot-vehicle interface automatically display air and surface targets on the HMD generated by any of the F-35 sensors. In addition the HMD uses line of sight commands to queue the radar. The fusion system controls and decides by priority which air-to-air and air-to-ground targets are displayed on the HMD.

The APG-81 active electronically scanned array radar sends all contacts to the integrated core processor, which tasks them to the mission system for processing and displays the screen on the HMD. **Mark Ayton**

## ELECTRONIC WARFARE SYSTEM

*A fighter aircraft intended to enable control of both the air and of the electromagnetic spectrum, the F-35 Lightning II was designed from the outset with its own electronic warfare (EW) system. With BAE Systems at Nashua, New Hampshire as the team lead, but including the participation of leading EW specialists worldwide, including Northrop Grumman, the F-35's EW system is part of the basic design, alongside its avionics, communications, navigation and intelligence; and sensor systems.*

*While all the aircraft types that the F-35 will replace use EW systems, some highly capable against current threats, the F-35's EW system enables its effective integration with all the other onboard systems. Each of the F-35's systems is able to inform and operate with components of each other. This F-35 network can also link to larger multi-unit networks, other aircraft or terrestrial platforms via its built-in MADL (Multifunction Airborne Data Link), which allows the EW system to be networked either in attack or defence.*

*The internally mounted AN/ASQ-239 Barracuda EW system built by BAE Systems completed its flight testing in 2005 and was soon in low-rate initial production, with a unit cost estimated at $1.7 million. Weighing some 200lb (90kg), it was developed from the BAE Systems AN/ALR-94 EW suite fitted to the F-22 Raptor, using emerging technologies to produce greater capabilities with a goal of achieving twice the reliability at a quarter the cost.*

*The F-35 EW system provides radar warning (enhanced to provide analysis, identification and tracing of emitting radars) and multispectral countermeasures for self-defence against both radar and infrared guided threats. In addition to these capabilities, it is also capable of electronic surveillance, including geo-location of radars. This allows the F-35 to evade, jam, or attack them, either autonomously or as part of a networked effort. The enhanced capabilities of the ASQ-239 (and integration with the F-35's other systems) allow it to perform SIGINT (signals intelligence) electronic collection. The aircraft's stealth capabilities make it possible for an F-35 to undertake passive detection and SIGINT while operating closer to an emitter with less vulnerability. For the use of active deception jamming, the F-35's stealth design also allows false target generation and range-gate stealing with less use of power.*

*The EW system also sends and receives data and status and warning information from other onboard systems through the MADL data link.*

*The ASQ-239 has ten dedicated apertures, six on the wing leading edge, two on the trailing edge, and two on the horizontal stabilizer trailing edge. The system also has the potential to use the F-35's other apertures, most notably that associated with its APG-81 AESA (active electronically scanned array) radar. In addition to functioning with the radar, this array, transmitting only at high-power, could function as a stand-off jammer.*

*When used in receive only mode, the APG-81 provides enhanced SIGINT capability. The radar could also be used, following future upgrades, as an electronic attack weapon, burning out emitters with pure power or injecting hostile radars or command and control systems with computer inputs that would provide false targets, misleading information, or shut down an air defence system. Combining these capabilities and data links will give F-35s the potential to do more than defend themselves and jam or attack enemy emitters they locate.*

*Groups of F-35s could collect SIGINT from multiple directions, and then use the information gathered and analyzed to fire missiles, start jamming, or launch an electronic attack. Data links mean that F-35s can provide this information to other platforms in near real-time and have their actions coordinated 'off-board', where there will be more access to fused intelligence, greater situational awareness, and less chance of lethal information overload, than in the cockpit of an F-35.*

*The 513th Electronic Warfare Squadron part of the 53rd Electronic Warfare Group, formed in 2010 at Eglin AFB, Florida, is tasked with introducing the F-35's EW capabilities at an operational level. A joint squadron with personnel from all US services, the 513th is co-located with the 33rd Fighter Wing, the F-35 school house for pilot and crew chiefs.*

*Tactics, techniques and procedures (TTPs) to be used by the F-35 in electronic combat are being developed by the 513th. The unit will also provide and update the threat libraries and systems programming that will keep the F-35's systems responsive to changing threats. To do this, the 513th will operate a new $300 million reprogramming laboratory at Eglin, scheduled to open in mid-2011.* ***David Isby***

# ULTIMATE

*Above:* *US Air Force F-35A 07-0744/AF-06, the very first production aircraft is fitted with an APG-81 AESA radar, and is due to be delivered to Eglin AFB, Florida later this year.* Scott Fischer
*Opposite top:* *On June 22, 2010, F-35B STOVL BF-04 became the first mission systems aircraft to fly with an APG-81 radar fitted.* Lockheed Martin
*Opposite bottom:* *Once fitted to the fore body of an F-35, the array is fixed in position and looks much different than mechanical radars.* Lockheed Martin
*Below:* *The APG-81's array fitted to Northrop Grumman's BAC 1-11 test bed, showing the hundreds of T/R modules.* Lockheed Martin

Like other systems on the F-35, the APG-81 AESA (active electronically scanned array) radar is housed in a minimal amount of space, with its transmit-receive (T/R) module array packed into the aircraft's radome. Despite the constraints, Northrop Grumman's latest product line is bristling with capability and performance.

## System Components

Complex in design, the APG-81 radar has a variety of main components including the T/R modules, the beam steering computer, array driver, power supplies, inertial navigation systems, and an electronic warfare interface unit. There are about ten assemblies for the antenna and 15 for the receiver-exciter, wideband and narrowband waveform generators.

Built by Northrop Grumman, the RF support electronics comprise a receiver module, an exciter module and power supplies. Each module is shipped to Lockheed Martin's Fort Worth facility, where it is integrated into the aircraft.

"The front end of the radar comprises what we call the array, which has the T/R modules and the radiating element, and is bolted directly to the integrated forebody and positioned up front in the radome," said Dave Bouchard, Program Director for the APG-81.

The size of the APG-81 antenna or array is governed by the internal size of the radome and comprises many of hundreds of T/R modules.

Once installed into the aircraft, in theory, the radar's front end should not have to be removed or replaced. "The array is designed to last the 30-year life of the platform, with a meantime between critical failure (MTBCF) rate greater than 10,000 hours," Dave Bouchard asserted.

Items that drive the antenna, such as the power supply, are on the other side of the bulkhead (to the array) and their MTBCF rate is not as high. These components will eventually require maintenance and are easy to access without removing the radome.

Receiver-exciters are usually packed into one box but because of space restriction they are broken into two different boxes located behind the bulkhead and linked to the antenna with a very short cable.

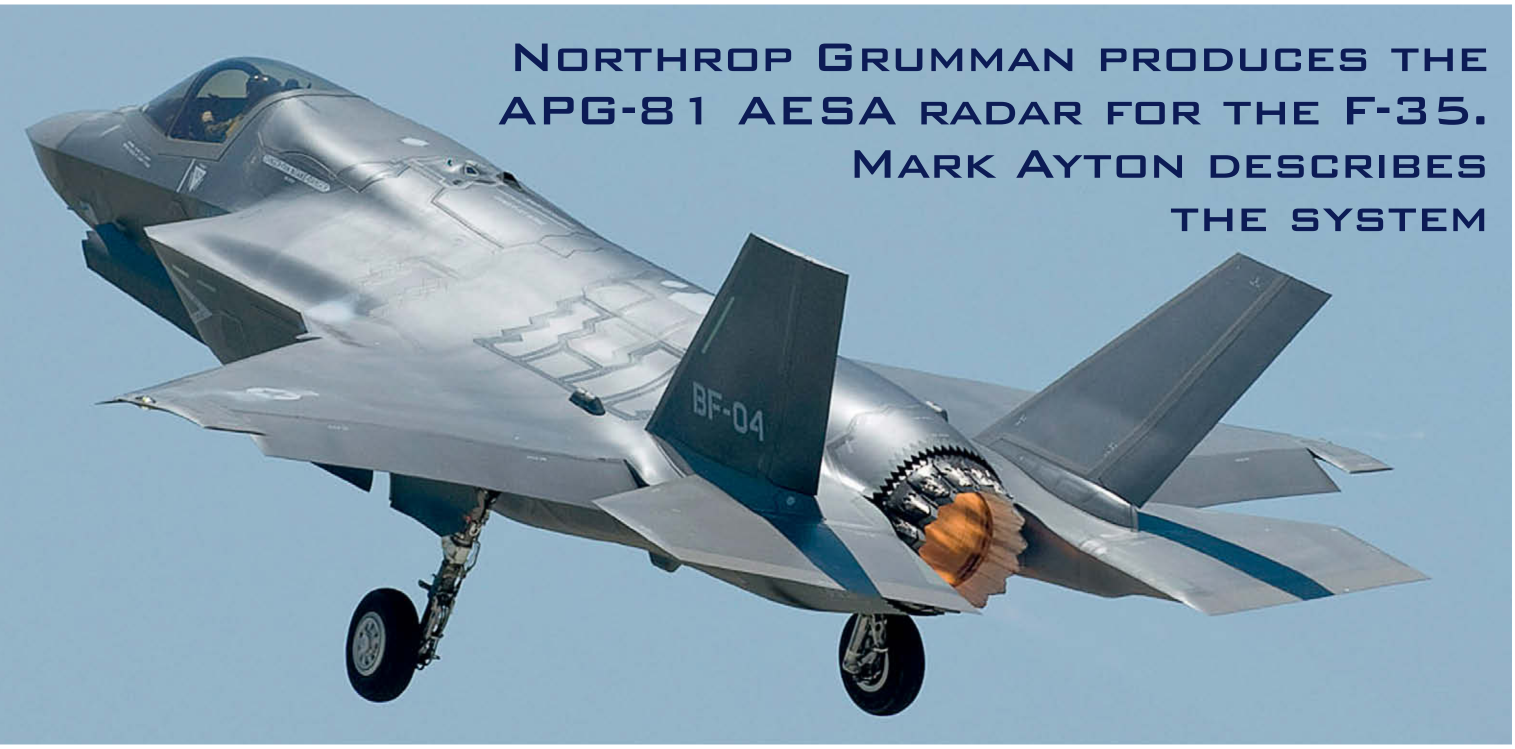
## Functionality

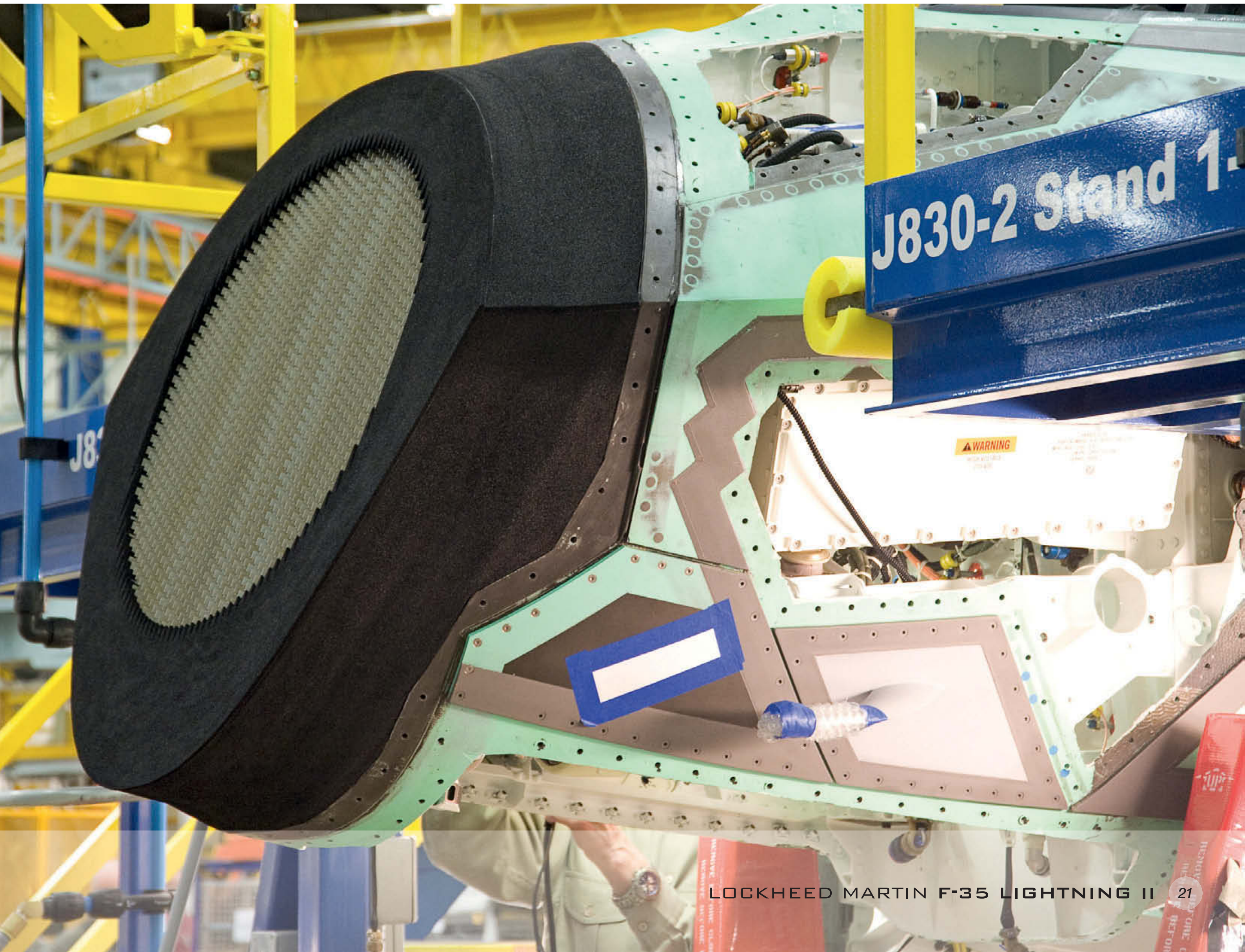
The APG-81 has an electronically steered array controlled by a steering computer with no mechanical motion. Designed as a multi-mode system, the APG-81 has 32 modes of operation which are common to all three F-35 variants; 12 air-to-air, 12 air-to-ground (including two maritime modes ship target track and sea search), four electronic warfare (electronic attack and electronic protection), two navigation, and two weather. Some of the modes are high resolution and are supported by the sophisticated signal processing available.

Although Northrop Grumman would not confirm as such, the APG-81 can operate in LPI (low probability of intercept) and LPD (low probability of detection) modes that are used to minimize the aircraft's signature to comply with its low observable (LO) requirements. The radar is optimised for agility, very low noise and high efficiency and fully supports the LO

# Detection

**Northrop Grumman produces the APG-81 AESA radar for the F-35. Mark Ayton describes the system**



nature of the aircraft. Northrop Grumman claims that it is capable of detecting very small targets and tracking at 'relevant tactical ranges'.

Sensor track information is sent into the aircraft's integrated core processor (ICP). Tasked by the ICP, the mission system then fuses radar data with that sent from the DAS, EOTS, EW or CNI to provide what Lockheed Martin describes as unparallel situational awareness. Operational flight program (OFP) software for both the APG-81 and DAS reside in the ICP, which allocates processing power to each system. "What really helps is having the ICP provide more memory and throughput that gives the timeline to execute targeting," said Dave Bouchard adding: "We send our radar and DAS information to the mission system and have an interface control that defines what messages are passed from radar and DAS to the fusion system."

Another interesting aspect of the APG-81 is the interface with the ASQ-239 electronic warfare (EW) system. On most legacy aircraft the radar and EW are confederated systems that work separately of each other. On the F-35, radar and EW functions work collaboratively, and in some modes they work independently of one another.

## Accuracy

Detection and tracking capability are two aspects in which the new APG-81 has set new performance criteria. But how does the system achieve the range accuracy required by the F-35 mission set. Dave Bouchard explained: "Range accuracy is achieved by multiple air-to-air waveforms that drive the dozen air-to-air radar modes. Range measurements are provided to the common filter, which uses algorithms to filter out drift or inaccuracies that arise over time, and thereby maintain track accuracy."

In terms of type, the APG-81 is a pulse-doppler radar system that runs multiple waveforms for air-to-air and air-to-ground, with what Northrop Grumman calls 'very robust electronic protection' (EP), which helps the system to achieve its accuracy requirements. EP is a series of techniques that help prevent the radar from being confused or jammed and ensures that information presented to the fusion system is very accurate.

DAS, CNI, EOTS and the APG-81 radar all provide track information and track updates to the fusion system that in turn controls the portrayal of targets and symbology on the panoramic cockpit display and the HMD (helmet-mounted display).

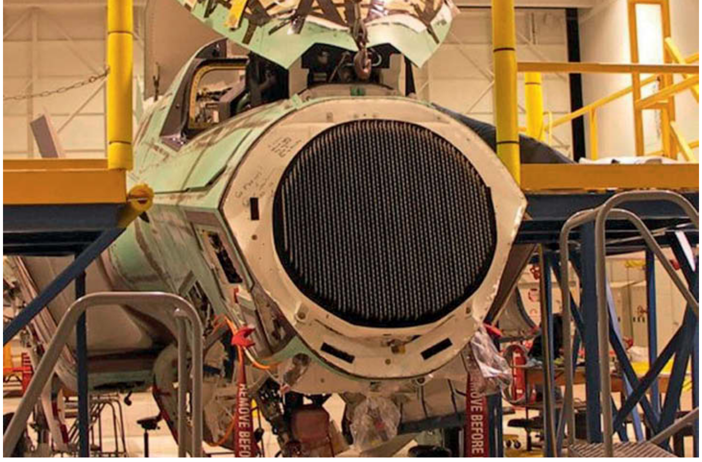
In terms of ground target identification and coordinate generation, Dave Bouchard claims that the APG-81 outperforms current AESA radars in two ways.

By processing synthetic aperture radar (SAR) data with multiple advanced algorithms, the system performs automatic target recognition (ATR) and automatic target cueing (ATC) on the SAR maps. "We can take a very high resolution ground map of a large area and use algorithms that pick out targets of opportunity that the pilot would be interested in," Bouchard advised.

Many radar systems have SAR capability with a set resolution such as 20ft, 10ft, 5ft (6m, 3m, 1.5m). In comparison the APG-81 has what Northrop Grumman calls 'Big SAR', which instantly generates a huge SAR map when commanded. The pilot can zoom in or out on a specific point for a higher fidelity image display without having to generate a new SAR map. The ATR and ATC work simultaneously on the entire area of the 'Big SAR' map, and greatly reduce pilot work load during the most demanding phases of air-to-ground operations.


Scott Fisher

*Top left: Different view of the APG-81's array fitted to Northrop Grumman's BAC 1-11 test bed.* Lockheed Martin
*Top right: The APG-81's array fitted to the fore body of F-35A CTOL AF-04 in a flight test shed at Lockheed Martin's Fort Worth facility.* Lockheed Martin



## Maintenance and Reliability

In support of the two-level maintenance system to be set in place for the APG-81, maintainers will use the APG-81's prognostic health monitoring system to check the status of the radar for flight line maintenance. Faults are presented on a display located inside a bay on the aircraft, indicating which line replaceable component (LRC) to change. This is a straightforward procedure requiring the maintainer to remove a cover, unplug the LRC, unfasten ten screws, remove the old LRC and replace with a new one, run a test and in theory the radar should be serviceable once again.

All other radar maintenance (the second level) will be undertaken either by Northrop Grumman or at the respective depot facility.

The radar's antenna, housed inside the radome, has a MTBF (mean time between failure) rating of 10,000 hours, though the APG-81 as a system is not rated at that level. Dave Bouchard explained: "One of the advantages of the system from a reliability standpoint is based on the T/R module array that allows graceful degradation, meaning you can afford to lose T/R modules and still maintain the performance."

A premise of the F-35 programme is that logistics will be performance based, so all suppliers have an incentive to build reliability into their products and a system that can achieve the short duration MTBR (mean time between repair) target.

## Proving Reliability

The F-35 radar gained a significant amount of radar design heritage from the APG-77 used by the F-22 and the APG-80 AESA system used by the Block 60 F-16, both of which have thousands of hours of field data and robust reliability requirements.

Using field history of the T/R module architecture used on the APG-77 and APG-80, and sophisticated predictive modelling, Northrop Grumman is performing operational and support modelling to help support its performance-based logistics programme.

Because no single APG-81 array has reached the equivalent MTBCF hours yet, modelling of this nature must be performed to mitigate this situation.

Lockheed Martin received the first APG-81 radar units from Northrop Grumman in 2005, the same year that the system flew on Northrop Grumman's BAC 1-11 test bed aircraft for the first time.

In 2009 the radar made its maiden flight fully integrated onboard Lockheed Martin's Boeing 737 CATbird, and flew for the first time in an F-35 (F-35B BF-04) in April 2010.

Since its first flight on the BAC 1-11, the radar has made 150 flights and accumulated 400 hours as part of a risk reduction effort.

"We are flying with the integrated core processor [linked in to the radar] and using PAO cooling [the APG-81 is cooled with Polyalphaolefin or PAO a coolant], to represent an environmental condition that will be encountered in an F-35," said the Program Director. According to Northrop Grumman, the radar system has demonstrated good stability and performance onboard the BAC 1-11 and also in Lockheed's integration lab and on the CATbird. "The reliability we have seen in the field to date, even though it's primarily in the lab and in test jets, supports what our modelling has predicted we will see from F-35," extolled Dave Bouchard.

## Future Upgrades

Northrop Grumman has already undertaken discussions with Lockheed Martin and the F-35 Joint Project Office on Block 4 – the first F-35 upgrade configuration. Dave Bouchard explained: "There is a roadmap for future upgrades. After initial operating capability in 2016 with Block 3, we can expect Block 4 in the 2018-2019 timeframe and a subsequent block every two years after that. Each upgrade, which will be software driven, will require integration with the fusion system. But any upgrades that require detailed hardware changes to the aircraft will be undertaken further into the future.

# TARGE
# REVOLU


**Mark Ayton details the F-35's revolutionary AAQ-40 Electro-Optical Targeting System**

# TING
# TION

With ample experience in building some of the world's most advanced targeting systems, scientists and engineers working for Lockheed Martin's Missiles and Fire Control in Orlando, Florida, were in a good position to take targeting capability even further when the requirements for the F-35 were received. The resulting AN/AAQ-40 electro-optical targeting system (EOTS) leverages on the experience gained from producing the LANTIRN targeting system ('the genesis of night, precision weapons employment'), the AN/AAQ-33 Sniper advanced targeting pod, and the AN/AAS-42 infrared search and track (IRST) system used on the F-14D Super Tomcat. "The EOTS is the first sensor to combine a targeting FLIR and IRST. Marrying the two capabilities into one sensor was the big technical challenge in developing the system," said Don Bolling, Lockheed Martin's Business Development Manager for EOTS.

## Multi-capable

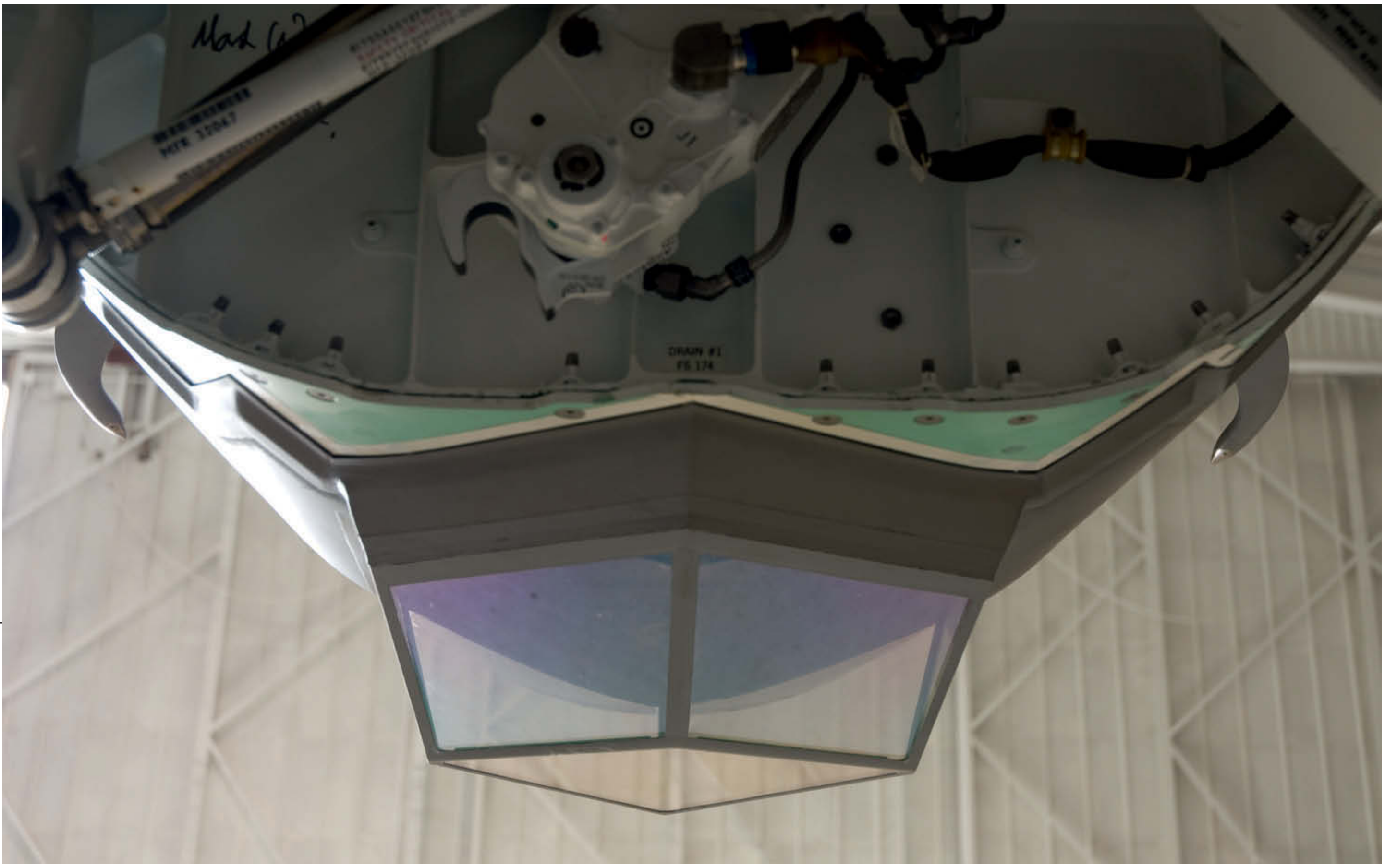
Principally viewed as an air-to-ground targeting pod, the EOTS was initially destined for every third F-35 produced. But the US Navy successfully argued for EOTS to be fitted to every F-35 built citing the capability as an absolute indispensible part of the sensor suite used throughout the mission spectrum. The EOTS provides laser designation, laser spot tracker for cooperative engagements, air-to-air and air-to-ground tracking FLIR, digital zoom, wide area IRST and generation of geo-coordinate to support GPS-guided weapons. All three variants of the F-35 are fitted with the EOTS.

Measuring (W x D x H) approximately 19.4 x 27.5 x 32.1 inches (493 x 698 x 815mm), the EOTS populates a box with a volume of less than $4ft^3$ and weighs 202lb (91kg). "There are DAS sensors on the left and the right of EOTS, and radar equipment above, the space constraints are very tight," said Bolling. By comparison a Sniper pod comprises a 7½ ft (2.3m) long tube weighing about 440lb (200kg). One reason for the difference in size between the Sniper pod and the EOTS is the cooling method used. Most conventional targeting pods such as Sniper are air-cooled requiring the necessary system to be carried on the back of the pod. The EOTS is a liquid-cooled system using PAO (polyalphaolefin) fed from the aircraft.

The EOTS is positioned within the F-35 lower forward fuselage between the radar and cockpit bulkheads. "When you think of the level of complexity in a targeting system, which are like telescopes with long straight optical paths, and see where the EOTS is positioned on the F-35, space is at a premium," said the EOTS boss.

Space is limited to such an extent that a standard targeting system with a straight optical path is physically impossible to house in the space available. The EOTS optical path is therefore folded via mirrors and prisms to refract the light off several different surfaces to direct it on to the focal plane array and fit within the space.

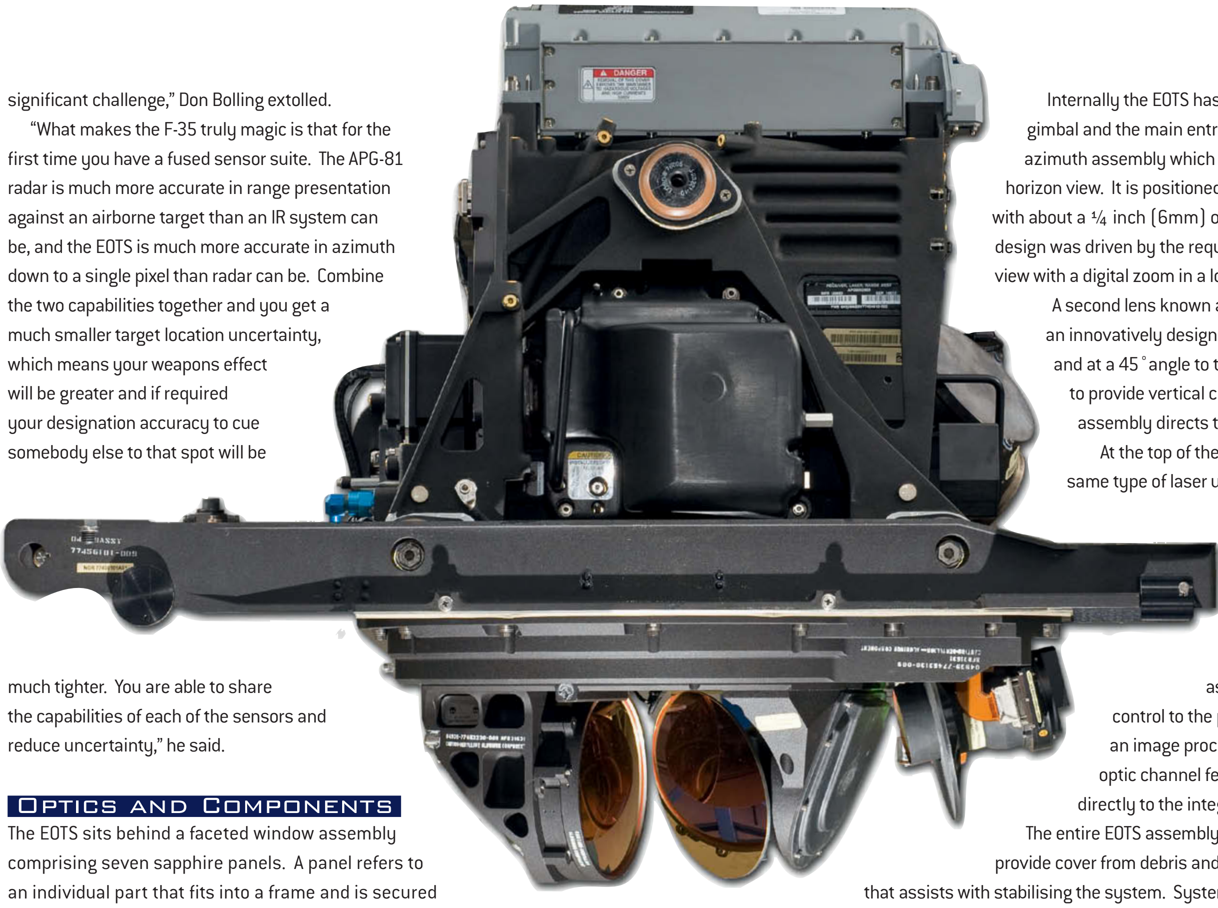
"We are effectively bending light at least four times from the point where it enters the window and is finally directed onto the focal plane array or the detector, which was a



*Above: The aft end of the faceted window assembly showing three of the seven sapphire panels.* Lockheed Martin
*Opposite: The EOTS faceted window assembly is clearly seen under the forward fuselage of F-35A 07-0744.* Scott Fischer

significant challenge," Don Bolling extolled.

"What makes the F-35 truly magic is that for the first time you have a fused sensor suite. The APG-81 radar is much more accurate in range presentation against an airborne target than an IR system can be, and the EOTS is much more accurate in azimuth down to a single pixel than radar can be. Combine the two capabilities together and you get a much smaller target location uncertainty, which means your weapons effect will be greater and if required your designation accuracy to cue somebody else to that spot will be much tighter. You are able to share the capabilities of each of the sensors and reduce uncertainty," he said.



## Optics and Components

The EOTS sits behind a faceted window assembly comprising seven sapphire panels. A panel refers to an individual part that fits into a frame and is secured in place to comprise the whole window assembly. Driven by the requirement to comply with the aircraft's radar signature, the EOTS window assembly is the first such design in existence. By comparison, Lockheed Martin's AAQ-33 Sniper pod has four smaller panels with a much shallower angle of incidence between the sensor and the window. Maintaining the required optical performance and complying with radar signature requirements presented a real challenge according to Bolling.

Internally the EOTS has unique designs for the gimbal and the main entry lens called the A-focal or azimuth assembly which provides the horizon-to-horizon view. It is positioned right up against the window with about a ¼ inch (6mm) of sway space. This intricate design was driven by the requirement for multiple fields of view with a digital zoom in a low-observable application.

A second lens known as the elevation assembly is an innovatively designed mirror that sits opposite and at a 45° angle to the main A-focal and rotates to provide vertical coverage. The elevation assembly directs the light into the optical path.

At the top of the system is the laser, the same type of laser used in the Sniper ATP but with a different output path. Just below the laser on top of the gimbal assembly are two circuit boards or electronic control assemblies. One provides control to the power servo and the other is an image processor mechanism. A fibre-optic channel feeds data from the sensor directly to the integrated core processor.

The entire EOTS assembly has a composite shroud to provide cover from debris and act as a structural element that assists with stabilising the system. System stabilisation is hugely important for holding a spot on the ground and very steady so a geo coordinate can be derived and fed to a GPS-guided weapon for targeting.

## Boresight

Each time the EOTS powers up, an automatic boresight aligns the laser and the FLIR. The boresight mechanism is a module fitted on the back of the gimbal. At power-up the sensor slews into the boresight module and aligns itself with the FLIR and the laser so

*Above:* ***The EOTS measures approximately 19.4 x 27.5 x 32.1 inches (493 x 698 x 815mm), weighs 202lb (91kg) and populates a box with a volume of less than 4ft³.*** *Lockheed Martin*
*Opposite Top:* ***This shot shows the A-focal and elevation assemblies of the EOTS.*** *Lockheed Martin*
*Opposite Bottom:* ***The colour of the sapphire panels is clearly shown in this side shot of the EOTS faceted window.*** *Lockheed Martin*
*Below:* ***Sabreliner 60 N11LX was leased by Lockheed Martin for flight testing of the AAQ-40 EOTS.*** *Lockheed Martin*

that they are pointing at the same spot. Having a single aperture means the FLIR and the laser all go through the same optical path.

"All of the sensors on the aircraft need to be boresighted to a spot in space so that when the pilot looks at the radar display he or she is looking at the same spot on the ground as the EO system whether it happens to be the DAS or EOTS," said Don Bolling.

"We are working on improvements that would ideally place a larger aperture system [a larger aperture behind the window] into the aeroplane for greater detection range whether that for the IRST functionality or for air-to-ground weapons employment," he said adding: "we have to remain within the volume of the window because that has signature implications but we have looked at getting larger apertures behind that window to increase our effective range."

## IR Search and Track

On stealth platforms like the F-35 the aircraft's signature must be carefully managed. With IRST the aircraft has a passive IR sensor that creates no emissions unless the laser is used. If the APG-81 radar detects something out at range, using IRST mode the pilot can feed the data to EOTS and passively track the contact with high fidelity while minimizing transmission of RF energy and the aircraft's signature.

The EOTS IRST uses a gimbal, an inertial measuring unit, and a fast steering mirror to provide precise stabilization. Passive in operation, the IRST has a wide area search capability comparable to the APG-81 radar with very high scan and slew rates because of the unique gimbal design.

Looking to future capabilities Don Bolling told *AIR International:* "We are looking at options where we might be able to apply the very fast IRST scan volume across the ground for an IR ground moving target indicator, which has some unique applications for the ISR role."

## Maintenance

The EOTS is a two-level maintenance system that enables maintainers to undertake maintenance on the flight line using the built-in test functionality, capable, according to Lockheed Martin, of isolating a single line replacement component (LRC). The EOTS can be dropped down from within its bay to allow maintainers access to replace any one of 15 different LRCs carried.

## Programme

Development of the EOTS sensor was completed at the end of September 2010 as part of the F-35 system development and demonstration phase. Much of the EOTS flight testing was completed on Sabreliner 60 N11LX leased by Lockheed Martin and flown from Goodyear, Arizona. Operated with a crew comprising pilot and co-pilot, and in the back end a sensor operator and a flight test director, the aircraft first flew with the sensor installed in May 2007.

In late May 2010, the EOTS undertook ground taxi tests followed by flight testing on Lockheed Martin's Boeing 737 CatBird test bed. Fitted with the DAS, the APG-81 radar, the ESM (electronic support measures) suite, the CNI suite, an F-35 cockpit and engineer test stations in the back, CatBird can test all sensor fusion and is set-up to exactly replicate what the pilot will see in the F-35. To provide transparency to the pilot sitting in the test cockpit onboard the CatBird during flight, the EOTS is installed behind a window in exactly the same way as on the F-35.

In March 2011, the EOTS commenced flying on F-35 mission systems aircraft at NAS Patuxent River, Maryland and Edwards AFB, California.

# WHEN ALL

## MARK AYTON OUTLINES THIS LIFE

British company Martin-Baker has developed the US16E ejection seat specifically for the Lockheed Martin F-35 Lightning II Joint Strike Fighter to the requirements laid down through the JSF Contract Specification (JCS). The company has been on the F-35 programme since its inception and to ensure a low-risk approach was followed, design of the US16E evolved from the proven Mk16 ejection seat range.

Many demanding requirements for the ejection seat were introduced in the system development and demonstration (SDD) phase of the F-35 programme. These requirements shaped the design of the US16E seat in a manner unlike other programmes in which MBA has participated. This led to the adoption of a fully integrated and full production standard design from inception.

### Requirements

Because the F-35 is destined to replace so many different aircraft types, affordability is crucial to ensure that the F-35 is deployed in sufficient quantities for all of the air arms due to operate the Lightning II. This requires a common ejection seat configuration for all three variants; the F-35A CTOL, F-35B STOVL and F-35C CV.

The F-35 requirement for crewmember accommodation has been expanded to include the widest nude population mass range (103 to 245lb/47 to 111kg) and the multivariate accommodation range (cases 1 through 8), as defined by the F-35 sub-set of the Civilian American and European Surface Anthropometry Resource (CAESAR) database. This requirement formally includes the female gender for the very first time.

Terrain clearance is defined as the height above ground that the ejectee first attains the safe descent rate of 24 feet per second (7.3 metres per second) while suspended under the parachute. The descent rate must be achieved across the wide accommodation range.

These requirements are based on the 'best-of-legacy' approach in which all ejection seat terrain clearance charts have been amalgamated and distilled from the US Seat inventory (Stencel SIIIS), MBA Navy Aircrew Common Ejection Seat (NACES) and Advanced Concept Ejection Seat (Douglas ACES II) into a common set of terrain clearance tables.

F-35 is the first programme to introduce neck injury criteria (NIC) because it combines three criteria: accommodation range, gender and the need for the pilot to wear a helmet-mounted display (HMD). The US16E seat is the only ejection seat that meets the NIC across the speed and accommodation ranges, including small females.

Ejection seat mass plays a critical part of the cockpit mass allocation, which was essential for the F-35B STOVL variant following the STOVL Weight Attack Team weight optimization effort launched by Lockheed Martin in February 2004. Design-to-mass is a fundamental principal of MBA seat design.

The STOVL aircraft propulsion configuration results in unique failure mode conditions, which the pilot is not able to react to quickly enough to eject manually. This resulted in the US16E seat interfacing with Lockheed Martin's auto-eject system which caters for low-altitude, low-speed and adverse pitch attitude escape conditions.

### Integrated Design

The F-35 ejection seat is customer specified and not government specified, which is the ideal circumstance for Lockheed Martin to entertain a fully integrated solution for


*MAIN IMAGE: This shot shows the launch trajectory taken by the US16E seat.* ALL IMAGES MARTIN-BAKER
*BELOW LEFT: The Martin-Baker US16E ejection seat is designed specifically for the F-35 Lightning II.*

# ELSE FAILS

## -SAVING US16E EJECTION SEAT

the F-35 cockpit, balancing the design requirements for accommodation, mass, life support, HMD requirements against the life-cycle cost targets.

A US16E ejection seat comprises six major assemblies: the guide rail, catapult, seat bucket, parachute and harness, and the seat survival kit. The guide rail assembly is mechanically attached onto the cockpit rear bulkhead and is able to rotate manually from 16.5° to 22°.

An air-vehicle interface disconnect unit (AIDU) which interfaces the electrical, ballistic, pneumatic services between the seat and the aircraft, is attached to the bottom of the guide rail.

The catapult is installed onto the rails and is the initial means by which the pilot is ejected from the cockpit. The catapult contains the neck protection device (NPD), which is an inflated system that supports the HMD during ejection thereby enabling the NIC requirements to be met.

A seat bucket, which mounts all the pilot controls, is connected to the catapult and a seat raising actuator raises and lowers the seat bucket over a range of 7.4 inches (188mm). For reasons of safety and operation, the HMD system is integrated onto the US16E seat. The catapult carries both the helmet transmitter unit (HTU) and seat position sensor (SPS), which are integral to determining HMD relative position in the cockpit.

Integrated within the seat bucket is a quick disconnect connector that carries all of the HMD signals to and from the aircraft. The US16E also carries a seat-mounted life support system. Integration onto the seat offers advantages from reach, maintenance, mass and cost perspectives.

The seat bucket houses the services connection package (SCP) which regulates breathing and anti-g supplies.

The catapult houses a 300L backup oxygen system (BOS) which can be removed or re-charged on the seat. Both the SCP and BOS are supplied by Honeywell Aerospace based in Yeovil, Somerset, UK.

A seat survival kit (SSK) contains all the survival aids, including a life raft and automatic inflation unit (ALIU). The SSK is installed into the seat bucket, on which the pilot sits. A fifth generation integrated harness is able to accommodate the wide range of pilot sizes and provides restraint during aircraft acceleration and ejection conditions.

The US16E seat meets the F-35 performance requirements by having a low acceleration catapult, the neck protection device which enables the neck injury criteria to be met, a drogue which is deployed early and downwind, and a larger main parachute, which is deployed early in the sequence and downwind.

### SUSTAINMENT

Legacy aircraft programmes have commonly used three levels of maintenance: maintenance tasks that take place daily on squadron to enable self sufficiency when deployed away on operation (without industry support known as organisational level (O-level); centralised maintenance tasks on base for several squadrons referred to as intermediate level (I-level); and deeper maintenance undertaken back at a depot or back with the manufacturer, known as depot level (D-level).

In order to minimise the in-service sustainment costs, Lockheed Martin has eliminated the need for I-level maintenance across the programme by transferring these tasks to either O- or D-level. The US16E seat modular design enables component removal and replacement at O-level, thereby supporting the sustainment philosophy.

# Spherical View

## Mark Ayton describes the Northrop Grumman AAQ-37 Distributed Aperture System for the F-35.

Lockheed Martin claims that the situational awareness provided to a pilot flying an F-35 Lightning II is unparalleled in comparison to that provided by other fighters on the market today. As the second fighter aircraft built in the fifth generation class, the F-35 is equipped with some very capable sensors including the extremely capable APG-81 AESA radar with 32 operating modes providing incredible performance according to its manufacturer Northrop Grumman. Also contributing to its superiority in situational awareness capabilities is the revolutionary AN/AAQ-37 Distributed Aperture System (DAS) also built by Northrop Grumman.

### Advanced Situational Awareness

The advanced features of the DAS include missile and aircraft detection, track, and warning for the F-35. DAS also gives a pilot 360° spherical day/night vision, with the capability of seeing through the floor of the aircraft. And because the DAS is a passive system, the pilot does not have to point a sensor in the direction of a target to gain a track. Comprising six infrared (IR) sensors (each housed in an aperture) located around the aircraft, Northrop Grumman classes the DAS as an integrated system and not a sensor or a series of sensors.

The six apertures each provide 95° field of regard and a total of 570° to ensure sufficient overlap in coverage around the aircraft.

One aperture is positioned on either side of the radome below the chine line (the right and left side apertures), one in front of canopy (upper forward), one in front of the refuelling receptacle (upper aft) and two on the under fuselage (the lower forward and lower aft) one pointing forward and one aft, but not straight down.

The six apertures are positioned so that no part of the aircraft blanks out its view. The system receives threat information from all directions and stitches it together to give a simultaneous three-dimensional spherical view, using that information to protect the aircraft.

### Functionality

If you consider how a traditional radar scan of less than 200° is displayed on the screen and then you might wonder how Northrop Grumman displays the entire 360° view generated by DAS? Phil Edwards, Business Development Manager for DAS explained:

"The sphere provides information on threats and feeds that information to the fusion system, which in turn displays the most relevant information into the HMD. Depending on which direction the pilot is working will dictate what frames or field of view from the sphere the pilot will be able to see in the HMD."

"While the imagery provided to the pilot in the HMD is the most tangible thing generated by the DAS and the one that people are most impressed by, in reality, the ability to simultaneously see different targets in all directions, feed information to the fusion system and provide warnings to the pilot, is the key advantage of the system." he added.

But providing images to the HMD is not the limit of the system's capability. The DAS also tracks airborne targets it


detects surface- and air-launched missiles, while providing passive protection of the aircraft. It performs different functions simultaneously but does not operate in different modes as requested or commanded by the pilot.

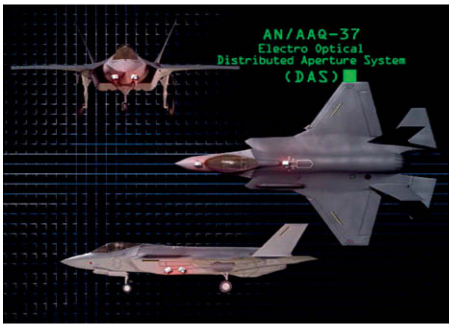
The six aperture sensors function in the infrared spectrum in all directions, run advanced exploitation algorithms to increase range, reduce false alarms, turn track information into useable data, feed it to the fusion system and add to the air picture displayed for the pilot.

Each of the six apertures is interlinked to the ICP, which runs the software algorithms that generate geo-registered threat reports and imagery. These are fed to the fusion computer which outputs data using two channels, one to the HMD and one to the panoramic cockpit display.

In the case of the HMD, whatever direction the pilot is looking, he will receive data from the sensor that supports his field of regard. With the panoramic cockpit display, the pilot can chose what he wants presented, which can be a permanent feed from one sensor or whichever sensor can view a given point on the ground, as two examples.

Because some (not all) of the six apertures are located close to hot components on the aircraft, they use an internal cryogenic coolant.

*Above left: This diagram shows a detected track and the DAS feed to the panoramic cockpit display.*
*Above right: Day (right) and night (left) imagery of a US Navy aircraft carrier as fed by the DAS to the helmet-mounted display.*
*Below: Approximate positions of the six infrared sensors on the aircraft are shown is this diagram.*




*Opposite top: This computer generated image shows the spherical coverage provided to the aircraft by the AAQ-37 DAS.*
*Below: One aperture is positioned on either side of the radome below the chine line, one in front of the canopy, one in front of the refuelling receptacle, two on the under fuselage.*
*All images Northrop Grumman*

Maintaining the DAS is straightforward because the sensor is laser-welted and permanently sealed and can only be removed and replaced on the flight line. For any kind of repair the sensor is sent back to the depot or Northrop Grumman.

## New Role

The DAS is designed to detect low intensity threats in a much cluttered background, and has the capability to detect threats such as ballistic missiles. In June 2010, Northrop Grumman collected data from a two-stage Falcon 9 ballistic missile launch from Cape Canaveral in Florida, to determine the applicability of the system to detect, track and potentially target missiles in the ballistic missile defence role. Northrop Grumman's BAC 1-11 test bed tracked the multi-stage rocket with the DAS for over 808 miles (1,300km) while airborne over the coast of North Carolina. According to Dave Bouchard, the processing power available enables the DAS to simultaneously track thousands of targets, far more than is possible with any current infrared system.

"DAS is an omni-directional infrared system that can simultaneously detect and track aircraft and missiles in every direction, with no practical limit on the number of targets it can track. DAS truly revolutionizes the way we think about situational awareness," said the Program Director.

# Complex A

Goodrich Corporation's landing gear business has introduced many technological breakthroughs in the aerospace industry making it one of the world's premier suppliers of landing gear. Goodrich pioneered the use of a gas-oil strut, introduced high-strength steel and advanced titanium alloys, unique fracture-resilient material for carrier operations and 'smart' health management systems.

Many of these technologies and others were adopted to meet the performance requirements of the F-35 Lightning II programme. The company received multiple design specifications to meet the aircraft's requirements for applied loads, stroke, landing gear length and operating environment.

From the inception of the design requirements through the design and testing phases, Goodrich integrated the design and performance requirements for the landing gear strut, sub-systems design, and test requirements, including rolling stock (wheels, tyres, and brakes), nose wheel steering, and electrical/hydraulic systems from the prime contractor Lockheed Martin. At the beginning of the F-35 programme, Lockheed Martin subcontracted various sub-systems to companies as

*Above: The CV nose gear staged shock strut carries a very complex mechanism to position the launch bar on to the catapult.* Key – Mark Ayton

*Opposite: Landing gears for the F-35C CV variant are unique and differ to the F-35A and F-35B systems to withstand the extreme high energy landings typical of naval aircraft operating from an aircraft carrier.* Lockheed Martin

core system integrators on the basis of capability, competency, resources and cost. Goodrich is the F-35 landing gear integrator across all three platforms for the same reasons today.

## Design Specific

Systems include specially-designed and developed non-metallic strut bearings to be used with titanium cylinders on the F-35B STOVL variant, a novel lightweight mechanism to shrink the F-35C CV variant main landing gears for stowage, and an internal fluid-level sensing capability.

When Goodrich started designing the F-35B STOVL landing gear, a standard cantilevered strut capable of being used with titanium cylinders did not exist. A typical cantilever strut has an upper bearing that slides under high pressure and at high velocity on the internal diameter of the cylinder. Titanium, the material selected for the F-35B strut cylinders, has a propensity to wear and transfer debris to another material, a condition known as galling, resulting in a degradation in service life.

The challenge Goodrich faced was to identify a strut-bearing material that was compatible with the titanium in a high load, high-speed sliding contact environment. Goodrich funded the development and testing of a specially-designed non-metallic bearing compatible with the titanium cylinders.

According to Bill Luce, F-35 Landing Gear Program Manager and Chief Engineer with Goodrich, the design team identified a non-metallic material that would withstand sliding contact with titanium permitting the cylinders to be made from that metal and reducing the overall weight of the landing gear.

Another main design consideration was the restricted space into which the main gear is retracted, which meant the Goodrich designers had to find a way of shortening the gear when it was being stowed. They therefore introduced an additional piston inside the shock strut positioned immediately below the upper bearing on the main piston. A small hydraulic system injects hydraulic fluid in between the extra piston and the lower bearing to stroke the main piston. Stroke refers to moving the piston up and down in the cylinder.

"We have a specific volume that we stroke in. Rather than directly connecting the chamber up to the aircraft's hydraulic system, we attach a transfer cylinder to the aircraft's high-pressure hydraulic system which is a relatively low flow rate system," said Bill Luce.

"We use the high pressure to stroke a piston with a mechanical disadvantage, to stroke a larger volume of fluid, at a lower pressure, into the shock strut chamber using the higher pressure fluid from the aircraft with a smaller volume. A series of locks and safety systems ensure that the gear remains shrunk during retraction."

All the landing gears used by the three F-35 variants are fitted with a system to detect levels of fluid inside each strut.

The original design concept for the F-35 landing gear system was to utilize a common structural geometry for both the F-35A CTOL and F-35B STOVL systems with a completely unique system for the F-35C CV. Different materials were to be used in the CTOL and STOVL systems in identically gauged structural components. The CTOL version was to be primarily made of 300M grade steel (a commonly used material in commercial landing gear) and the STOVL variant was to be made primarily of Aermet 100 (a grade for ship-based aircraft) and is the US Navy's choice for high strength steel.

Patented by Carpenter Steel, Aermet 100 has very high strength and slow crack propagation properties, so if a crack develops in the material, the crack will spread slowly with further load applications. By contrast 300M or 4340M grade steel has the same strength quality, but poor crack propagation. This gives more opportunities to discover cracks in the structure before a catastrophic failure occurs.

Each type of F-35 landing gear has a Goodrich-proprietary system integrated within the aircraft's maintenance system to help the maintainer assess the level of the gas and oil in each shock strut during servicing.

## Conventional and STOVL

Early in the development of the F-35 programme, Lockheed Martin made a significant change to the aircraft design which resulted in slightly different geometry requirements for the landing gear. The core design concept for CTOL remained the same, but a complete re-design for the STOVL variant was required allowing utilization of only a few common parts. STOVL-specific landing gear needed to be created to minimize its weight involving unique wheels, tyres and brakes.

For the F-35B STOVL variant, Goodrich is manufacturing the landing gear system

# nd Robust

Mark Ayton explains the highly complex landing gear systems used on the F-35

*This image & right: Nose and main gear retraction on F-35A AF-06 seen during take-off from Fort Worth. Retract actuators provide the force to retract the gear from the down position to the stowed position in the wheel well and vice versa.* Lockheed Martin

primarily from Aermet 100 steel, while the nose and main cylinders are made of a titanium alloy. Changing the cylinders from steel to titanium saved nearly 100lb (45kg) per aircraft. The grade of titanium alloy selected for the cylinders was chosen primarily for its strength and fracture toughness.

The CTOL and STOVL nose gears are conventional cantilever gas over oil struts. Each system has a retract actuator to generate the force to retract the gear from the down position to the stowed position in the wheel well and vice versa. Drag braces with locking linkage and locking actuator with backup springs, are fitted to react fore and aft ground loads.

All landing gear is subjected to vertical, drag and side loads and therefore has structural elements known as a drag and side braces. The tyres spin up as soon as they hit the ground causing a drag on the landing gear, which is countered by the brace to keep the gear structurally sound.

The drag brace attaches to a pivot pin on the strut and the aircraft so that as it is retracted it rolls around the strut centreline to minimize space take up in the cramped bay when retracted.

Steering is via a steer-by-wire system that utilizes a rotary hydraulic motor with integral control valve and feedback transducers.

An unusual feature of the nose struts is the long strut stroke required to create a sufficient angle of attack during takeoff roll. Both the CTOL and STOVL nose gear use a common nose wheel and tyre which were developed specifically for the F-35.

The main gears of the CTOL and STOVL variants are dual stage gas over oil cantilever struts containing a mix of hydraulic fluid (referred to as oil) for hydraulic damping, and Nitrogen gas (which forms what is known as a gas spring) to support the weight of the vehicle, provide a soft ride and extend the gear. Nitrogen is used because it limits the oxygen in the strut prohibiting corrosion. The gas migrates to the top of the strut and the oil stays at the bottom hence the term gas over oil.

Many of the struts used on F-35 have two chambers each containing gas at different pressures which produces a spring or staged air curve or staged shock strut. By having the two chambers the spring rate can be changed mid-stroke to react different loads on the strut. This helps to stabilise the aircraft for loading and unloading weapons. An F-35 strut has a relatively soft spring for the majority of the stroke from the fully extended position to the static position and a really stiff spring from the static to fully compressed position. If the aircraft is sat on a soft spring and its weight is changed the strut will be stroked but if the aircraft is on a stiff spring, the stroke will only marginally change.

Each main gear system has a retract actuator (that provides the force to retract the gear into the wheel well) linking the strut to a retract fitting, where the retract fitting is linked to the airframe.

Like the nose gear, each main gear has a drag brace with locking linkage and locking actuator with backup springs. The drag braces attach to a collar on the strut and a pivot pin in the aircraft so that during retraction, it rolls around the strut centreline to occupy a minimal space beside the strut when retracted.

**“AERMET 100 IS THE US NAVY’S CHOICE FOR HIGH**
**OF ITS HIGH FRACTURE TOUGHNESS WHICH ALLOWS**
**CRACK IN THE STRUCTURE TO BE FOUND PRIOR TO A**
***BILL LUCE, GOODRICH F-35 LANDING GEAR PROGRAM MANAGER***

*An F-35C CV aircraft undergoing landing gear extension and retraction testing at Fort Worth.* Goodrich

## Cats and Traps

Landing gears for the F-35C CV variant have to be able to withstand extreme high energy landings typical of naval aircraft operating from an aircraft carrier as well as the nose tow launch. Both the F-35C nose and main gears are made primarily of Aermet 100 steel.

The nose gear of the CV variant is a dual stage gas over oil cantilever strut with a staged air curve that provides a source of high energy, which helps the aircraft to achieve adequate angle of attack when released from the catapult during take-off from the aircraft carrier.

The CV nose gear carries a complex mechanism which positions the launch bar in readiness for various stages of operation during the launch of the aircraft off the carrier. The mechanism is driven by a power unit comprising a number of powerful springs and a small internal actuator.

There are two reasons for having a staged shock strut for the nose gear on the F-35C CV variant. One is to provide a stable platform for loading and unloading weapons and for engaging the catapult equipment. The second is to store energy gained from the compression of the strut under the high pressure effect of the catapult. When the catapult lets go of the launch bar, the energy is released, providing a rotation that helps achieve the angle of attack necessary to get off the deck.

Similarly when the aircraft hits the deck on landing the strut is compressed and energy is stored to help rotate the aeroplane and get it back off the deck if the arrestor cables are missed and a 'go-around' or 'bolter' is required. Bolter is the term used when the aircraft's tail hook misses the arrestor cables on the carrier deck forcing the pilot to go around for another landing.

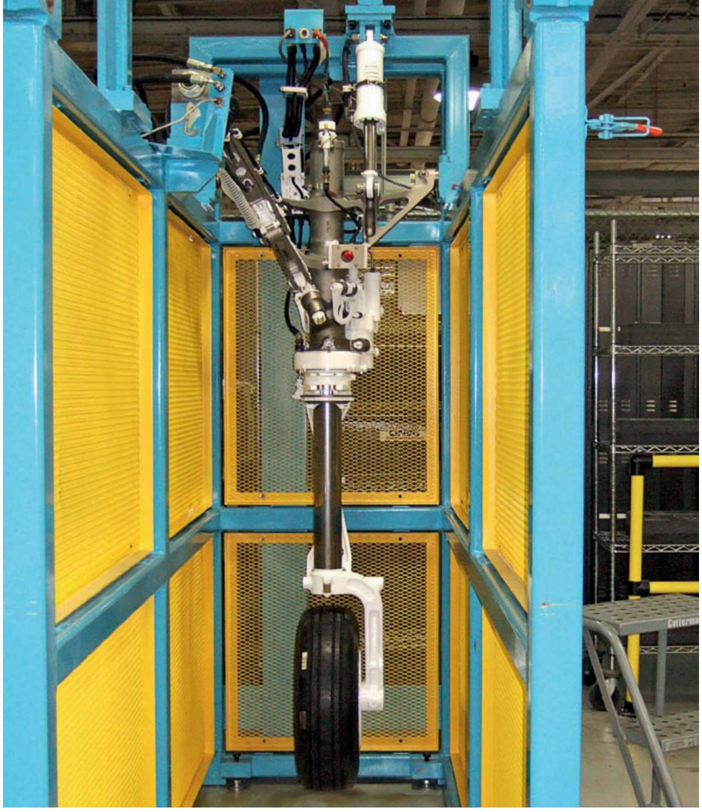
**STRENGTH STEEL BECAUSE THE OPPORTUNITY FOR A CATASTROPHIC FAILURE."**

The CV nose gear also has a locking drag brace and a launch bar that acts to transmit the high launch load from the catapult equipment to the airframe. A separate retract actuator provides the force to retract the gear into the wheel well. One end of the retract actuator is attached to the landing gear structure and the upper end to the airframe structure.

Fitted to the aft of the strut is a power unit housing an actuator that hydraulically lowers the launch bar to the deck to engage the catapult. When the launch bar hits the deck a second set of springs inside the power unit provide lighter power so that the launch bar can move up and down to engage the shuttle, without jamming or binding, or badly wearing the deck or the launch bar. Large powerful springs are able to pull the launch bar back up to an intermediate position when the hydraulic power is released.

The power unit also has a linkage that operates off the motion of the drag brace during retraction to position the launch bar in a stowed position (virtually parallel to the strut) when the gear is retracted. During the retraction process the launch bar moves upwards but also rotates around the strut to reduce the actual footprint within the stowage bay.

The torque arms that typically maintain alignment between the strut piston and the steering unit are on the aft of the strut as well, and have a fitting at the apex that engages the repeatable release holdback bar (RRHB) of the ship. This bar holds the aircraft back during engine runs and while the load builds during the start of a catapult sequence. Once the load reaches an adequate level, the RRHB releases the torque arm



*An F-35A CTOL nose gear in a test jig.* Goodrich

*Below: Main gears of the F-35B STOVL variant are dual stage gas over oil cantilever struts manufactured primarily from Aermet 100 steel.* Lockheed Martin

fitting, allowing the aircraft to be catapulted to flight. In comparison to the F-35A CTOL and the F-35B STOVL, the nose gear of the F-35C CV has a dual wheel/tyre arrangement to straddle the catapult equipment and to adequately react to the loads. Nose wheels are the same as those used on the other variants but the tyre was developed specifically for the F-35C.

Like the CTOL and STOVL variants, the CV main gear is a dual stage gas over oil cantilever strut with staged air curves that provide a stable platform for loading and unloading weapons and hold stored energy to assist in getting airborne in the case of a 'bolter' during carrier operations.

The main gears have a retract actuator between the strut and the airframe, providing the force to retract the gear into the wheel well. Each also has a drag brace with locking linkage and locking actuator with backup springs to react fore and aft ground loads. The F-35C's drag braces attach to a collar on the strut and a pivot pin in the aircraft that roll around the strut centreline during retraction to minimize the amount of space in the bay when retracted.

Featuring a long main strut the F-35C's main gear has a shrink mechanism to shorten the strut prior to retraction so it will fit within the available space. The Goodrich-proprietary shrink mechanism utilizes a novel transfer cylinder to convert high pressure and low flow aircraft hydraulics into a low pressure and high flow shock shrink hydraulics.

Unlike the nose gear, the CV main gear system utilizes the same main wheel and brake as the F-35A CTOL. All tyres used on the F-35C CV variant are significantly more robust than the CTOL and STOVL variants, because of the high energy landings on top of arrestor cables.

# LET

## Nigel Pittaway outlines the arsenal of weapons set to arm the F-35 Lightning II


As a stealthy design the Lockheed Martin F-35, like its F-22 predecessor, retains an edge over its opponents by carrying its weapons internally. Unlike the F-22, however, the F-35 has a wide range of air-to-air and air-to-ground missions to consider and with limited internal space, compromises have to be made.

### Load-Outs

In a 'first day of the war' configuration, all three variants of F-35 will have the initial Block 3 capability of carrying four Raytheon AIM-120C AMRAAMs (two in each weapons bay) for air-to-air missions, or two AMRAAMs (Advance Medium Range Air-to-Air Missiles) and two 1,000lb (454kg) GBU-32 JDAMs (Joint Direct Attack Munitions) for the air-to-ground scenario.

Lockheed Martin is currently redesigning the weapons bays and doors to allow the carriage of up to three AMRAAMs in each bay, thereby increasing air-to-air combat persistence by 50%.

Of course if stealth is not the primary concern, weapons can be carried externally (on low radar cross-section pylons), which increases load-out by approximately 18,000lb (8,164kg). By comparison the empty weight of a Block 15 F-16 is 16,285lb (7,387kg). The maximum air-to-air weapon load-out in this case is eight AMRAAM and two AIM-9X Sidewinders.

In its current form the AIM-9X cannot be carried internally because it needs to 'see' a heat source before launch, but Raytheon is developing a Block II variant, which will have 'lock on after launch' capability and a one-way forward data link added.

With each partner nation having its own requirements for weapons, the certification process will be quite a long one and the need for US services to reach initial operational capability first has driven the initial AIM-120 and JDAM weapon configuration.

# HAL Arsenal

Main Image: *F-35A 07-0744/'EG' is the first production standard aircraft that will eventually be assigned to the 58th Fighter Squadron at Eglin AFB, Florida for training. Once initial operating capability has been achieved this aircraft should be configured to Block 3 standard which will enable it to carry AIM-120 missiles and JDAM precision-guided bombs.* Scott Fischer

## Other Weapons

According to publicly released Lockheed Martin charts, other weapons currently required to be integrated into the weapons bays of the F-35A and F-35C variants include the 500lb (227kg) GBU-12 Paveway II laser-guided bombs, GBU-31 and GBU-38 JDAMs, CBU-103 and CBU-105 WCMDs (Wind Corrected Munitions Dispenser), Raytheon AGM-154A and AGM-154C JSOW (Joint Stand-Off Weapon) and MBDA Brimstone air-launched anti-tank missile.

Because the weapons bays of the F-35B are somewhat smaller, the list of internally-carried weapons is reduced and neither the 2,000lb (907kg) GBU-31 JDAM nor the AGM-154 JSOW munitions can be carried.

By contrast, the list of weapons that are slated for external carriage is extensive and includes the full range of JDAM and Paveway bombs and air-to-air missiles such as the aforementioned AMRAAM, AIM-9X and AIM-132 ASRAAM (Advanced Short Range

# FIFTH GENERATION WEAPONS

*Considerable media coverage has been given to the internal load-out capability of the F-35 Lightning II and the 'limited' number of bombs and weapons that the jet can carry. When the first F-35s enter service configured to Block 3 standard, the choice of weapons will initially be limited to a mix of AIM-120 AMRAAM missiles and JDAM precision-guided bombs. Later Block configurations will increase the number of different weapons available quite considerably. And when stealth capability is traded for more conventional missions, the F-35 becomes a bomb truck with an arsenal of new weapons, launchers and racks.*

## Lightning's Eleven

*Each F-35 variant has eleven weapon stations numbered 1 (the left side outer under wing pylon) to 11 (the right under wing pylon). These comprise air-to-air missile rails on stations 1 and 11, two inner stations under each wing; (2 and 3 on the left) and (9 and 10 on the right); the under fuselage centre line station (number 6) and those within the internal weapons bay (4 and 5 in the left side bay) and (7 and 8 in the right side bay). Within the two bays, stations 5 and 7 are positioned on each door (were ASRAAM will be carried) are dedicated to air-to-air missiles only. The stations are common to all variants.*

*Of the three Lightning II variants the F-35A CTOL is the only one equipped with an internal gun, the F-35B STOVL and F-35C CV require a gun pod.*

## Launchers and Racks

*The LAU-147/A missile launcher has been designed to eject-launch the AIM-120 AMRAAM missiles from the internal weapons bay stations 5 and 7 of the F-35A, F-35B and F-35C. It uses a high-pressure pneumatic system rated at 5,000psi to safely eject and separate the missiles.*

*A second external rail launcher, the LAU-148/A, will be used on the F-35 for external carriage and launch of a single AIM-9X Sidewinder or AIM-120 AMRAAM. The LAU-148/A is hard-mounted to the aircraft via either an external pylon station or an external missile adapter, and provides mechanical and electrical interface between the missile and aircraft.*

*Special bomb racks have also been produced for the F-35. The BRU-67/A has 14 inch (355mm) hooks and uses a high-pressure pneumatic system to safely eject and separate weapons and stores from stations 4 and 8. The BRU-67/A is only used in the weapons bay of the F-35B STOVL. A similar BRU-68/A bomb rack with 14 and 30 inch (355 and 762mm) hooks is used in the larger weapons bay of the F-35A CTOL and F-35C CV variants.*

## SDB and JDAM

*The 250lb-class (113kg) GBU-39/A Small Diameter Bomb (SDB increment I) is designed as a small autonomous, conventional air-to-ground precision glide weapon that is able to strike fixed and stationary re-locatable targets from a stand-off range. A GBU-39/A is fitted with a multi-purpose penetrating and blast fragmentation warhead. The SDB is coupled to the aircraft with a cockpit selectable electronic fuze and a proximity sensor to control the height at which the weapon bursts over its target.*

*As part of the Small Diameter Bomb increment II programme, the US Air Force has selected Raytheon's GBU-53/B air-launched, precision-strike stand-off weapon. The GBU-53/B incorporates a seeker that functions in three modes of operation: millimetre-wave radar, un-cooled imaging infrared, and semi-active laser. According to Raytheon, the GBU-53/B fully meets the load-out requirements for carriage in the internal weapon bays of all variants of the F-35. The GBU-31 Joint Direct Attack Munition (JDAM) is a 2,000lb-class (907kg) weapon fitted with a guidance set that converts an unguided bomb, typically the Mk84, BLU-117 or BLU-109, into a precision-guided munition. Similarly the GBU-32 JDAM guidance set converts unguided free-fall 1,000lb-class (454kg) bombs, typically the Mk82 or BLU-110.*

*A JDAM can be launched from very low to very high altitudes using different delivery trajectories, in a dive, toss and loft or in straight and level flight with an on-axis or off-axis delivery.*


*Above:* **Raytheon's GBU-53/B SDB II fully meets the load-out requirements for carriage in the internal weapon bays of all variants of the F-35.**

## Operational Requirements Document

*The F-35 operational requirements document (ORD) sets out the weapon specifications and lists what needs to be carried by the F-35. Within the ORD, the UK has a baseline set of weapons to be integrated on the F-35 that must be accommodated within the aircraft as part of the aircraft's development contract; these include ASRAAM, Brimstone and Storm Shadow. BAE Systems undertakes UK weapon integration work for the F-35 while Lockheed Martin is ultimately responsible for clearing each weapon for flight.*

Air-to-Air Missile).

Lockheed Martin's AGM-158 JASSM (Joint Air-to-Surface Stand off Missile) and the MBDA Storm Shadow air-launched cruise missiles are also slated for external carriage due to their size.

Israel has announced it will purchase F-35As under the Foreign Military Sales program, and may wish to integrate indigenous weapons on to the aircraft, but Lockheed Martin would not comment on the subject, beyond saying that any such work would be at the customer's cost.

Partner nations, such as Norway and Australia, have a requirement for an anti-shipping weapon. Work on this has been undertaken by Lockheed Martin and Norway's Kongsberg Gruppen to integrate a version of its surface-launched Naval Strike Missile, which retains most of its attributes but is designed to fit inside the F-35 weapons bays.

At the Australian International Airshow at Avalon in March 2011, Tom Burbage, Lockheed Martin's Executive Vice President and General Manager of F-35 Program Integration noted that the US Department of Defense is also interested in integrating a new anti-shipping weapon on the F-35. By the time the F-35 enters service the Boeing AGM-84 Harpoon will

*Far right:* **The F-35 has a total of 11 weapons stations, three under each wing, one on the under fuselage centreline and two in each of the two weapon bays.** *Lockheed Martin*

*Below middle top:* **Each of the F-35A CTOL and F-35C CV weapon bays can carry one 2,000lb (907kg) GBU-31 JDAM.** *SSgt Jessica Kochman/US Air Force*

*Below middle bottom:* **All three variants of the F-35 can carry a 1,000lb (454kg) GBU-32 inside each weapon bay.** *Boeing*

*Below:* **The UK has opted to buy the F-35C CV variant, which will eventually be able to employ ASRAAM, Meteor, Storm Shadow, SPEAR 2 Block 1 and SPEAR 3 missiles.** *Scott Fischer*

Above: **A fifth generation missile for a fifth generation aircraft – MBDA's beyond visual range, ramjet-powered Meteor is expected to be used by the UK's F-35s.** MBDA

## ASRAAM, Meteor, Storm Shadow and SPEAR

*The AIM-132 ASRAAM is a short-range missile with lock on before launch and lock on after launch target detection giving the F-35 a high off bore sight over the shoulder launch capability. In accordance with the SDD Block 3 configuration, the ASRAAM missile is identified for internal carriage on stations 5 and 7 and external carriage on station 1 and 11.*

*A contract between BAE Systems and Lockheed Martin is in place to integrate the ASRAAM onto the F-35 during the SDD phase, and some missile hardware is already at Lockheed Martin's Fort Worth facility. MBDA was not prepared to discuss missile carriage on a jet but understand that test articles of the AIM-120 AMRAAM and GBU-31 JDAM have been carried as part of the Block 1 configuration.*

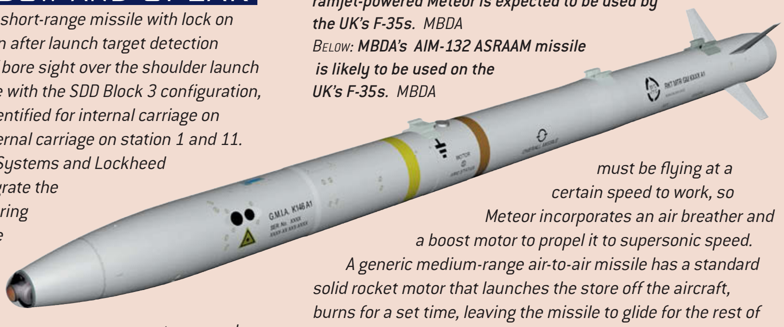
*The UK's beyond visual range air-to-air missile requirement for the F-35 is expected to be met by Meteor, a six nation programme between France, Germany, Italy, Spain, Sweden and the UK.*

*Built to the same size as AMRAAM, the Meteor uses a ramjet to achieve greater range and speed. A ramjet must be flying at a certain speed to work, so Meteor incorporates an air breather and a boost motor to propel it to supersonic speed.*

*A generic medium-range air-to-air missile has a standard solid rocket motor that launches the store off the aircraft, burns for a set time, leaving the missile to glide for the rest of the engagement. Meteor has a throttle that is controlled by the autopilot enabling the missile to maintain its speed throughout the engagement. This means from launch to striking the target, the Meteor's average speed is higher and sustained until impact. Flying with a terminal higher average speed means a Meteor missile is much harder for the target aircraft to out-manoeuvre.*

*A version of Meteor configured with a cropped fin (a reduced fin span) has been derived by MBDA so that the missile can fit inside the weapons bay. An integration study is currently in progress and should conclude mid-2011. The final part of the study will finalise how Meteor will fit on the aeroplane. A contract to cover integration will be the next step.*

*Meteor integration on the F-35 is based on carriage of four missiles in the weapons bay although under wing stations 2 and 3 (left side), 9 and 10 (right side) can also carry it if required.*



Below: **MBDA's AIM-132 ASRAAM missile is likely to be used on the UK's F-35s.** MBDA

Above: **One future air-to-surface missile within the UK's F-35 weapon road map is MBDA's SPEAR Capability 2 Block 1. The 50kg missile is an upgraded version of the Dual Mode Brimstone.** MBDA

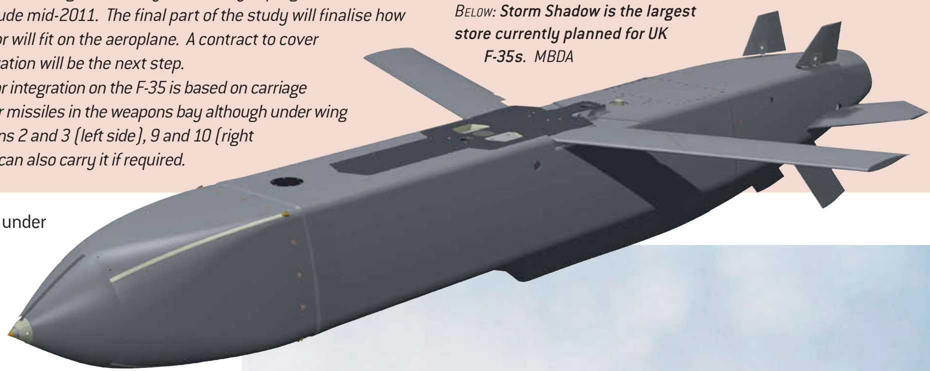
*A new air-to-surface missile, awkwardly referred to as SPEAR Capability 2 Block 1, is currently in a demonstration phase. This completely new weapon uses the front end of the existing Dual Mode Brimstone air-to-surface missile but has a new warhead, rocket motor and a more modular airframe. Weighing a total of 50kg (22lb), the flexible weapon which is suitable for a variety of target types, has a small pre-cursor warhead designed to punch through armour and explode within. Brimstone is identified for internal carriage on a yet-to-be-determined launcher and externally under the wing on a launcher carried on a pylon.*

*Storm Shadow, the UK's sovereign air-launched cruise missile, is likely to be the heaviest weapon that will be integrated on UK F-35s as part of the weapons 'road map'. No redesign will be required to integrate Storm Shadow on to an F-35, which will be carried on under wing stations 3 and 9. A contract for Storm Shadow integration would follow the weapon's inclusion on the Block plan and is likely to include carrier operations.*

*MBDA is also developing SPEAR 3, a new 220lb (100kg) class weapon with a multi-effects warhead and multi-mode seeker intended specifically for internal carriage on the F-35. Four weapons, all loaded on one rack with a powered release system, will be carried in each bay. In 2010 MBDA received an assessment phase contract to explore available technologies and devise a means of progressing to a demonstration phase.*

***Mark Ayton***

Below: **Storm Shadow is the largest store currently planned for UK F-35s.** MBDA



have been retired. He said that a Department of Defense study is under way to consider such a weapon but conceded that adapting the weapon to fit inside the weapons bay was a challenge.

Either way, customers will have to wait until a later Block of software has been developed before any such weapon can be integrated with the airframe.

Lastly, Burbage also revealed that the United Kingdom has asked Lockheed Martin, via a UK MoD-funded study, to look at the integration of the MBDA Meteor beyond visual range missile on to the F-35. MBDA has previously discussed a cropped-fin version of Meteor which it says should allow four missiles, two per bay, to be carried internally.

# BLUE SKY OPS

## Mark Ayton spoke with Peter Wilson, a former Royal Navy Sea Harrier pilot and now STOVL lead test pilot at NAS Patuxent River

*Above: F-35B BF-01 undertakes a vertical landing at NAS Patuxent River. All images Lockheed Martin*
*Left: Former Royal Navy Sea Harrier pilot, Peter Wilson is the STOVL Lead Test Pilot on the F-35 at NAS Patuxent River.*
*Opposite: Peter Wilson runs through cockpit checks in F-35B BF-03 at NAS Patuxent River on November 30, 2010. Paul Ridgway*

For the past five years teams of flight test engineers and test pilots have carefully followed well-established procedures to prepare and launch F-35 Lightning II strike fighters on flight test missions. F-35 flight testing continues at three sites – Edwards AFB, California, NAS Patuxent River in Maryland and from Lockheed Martin's massive production and test facility at Fort Worth in Texas, birthplace of the Joint Strike Fighter. Procedures involved with the F-35 are unique to the aircraft but have the same objective as any other aircraft and that is to prepare for each test flight. The test team based at NAS Patuxent River uses the term 'blue sky' to indicate that the aircraft is ready to go flying.

## Declaring Blue Sky

When preparing for any test sortie consideration must be given to what has been achieved and experienced during previous flights, and what the next steps will be.

Following a series of meetings between the pilot, engineers and specialists, test points for the next sortie are agreed based upon the requirements of the flight test programme. The team determines the complexity of each test point and what rehearsals are required by the pilot in the simulator. This is usually decided upon up to one week before the flight. Test points that are predicted to be difficult are then flown in the simulator, sometimes repeatedly, allowing the test pilot to refine his technique and give the team the opportunity to determine whether the results gained from the simulator meet the requirements for flight. It is very common for a test pilot to fly parts of a test mission in the simulator during the week leading up to the flight. The high fidelity of the simulator adds great value to the whole process.

In common with other flight test operations, all of the tests points required for an F-35 sortie are listed on a test card.

Engine start-up is highly automated, requiring just three switch selections, one each for the battery, integrated power pack and the engine. Only two selections are required for a hot start.

When the engine has started and is fully spooled up, the pilot must run a few brief checks specific to flight test procedures, which are undertaken before running the vehicle systems built in test (VS BIT). Initiated by a button in the cockpit, the system self-tests almost every function imaginable on the aircraft including the STOVL doors in the case of an F-35B. After 90 seconds, if there are no problems, the aircraft declares itself ready for flight.

The pilot then sets joker (return to base) and bingo (minimum) fuel states, turns on the helmet-mounted display, sets the brightness of the displays and is ready to taxi.

One thing that the pilot and test team always want to avoid is making a 'cold iron' call, which occurs when an onboard system indicates a problem requiring the entire process to be repeated with an engine restart. These were fairly common in the early days of flight testing but because of software and hardware upgrades integrated on the jet and maturity in the systems, cold iron cycles are now a rare event, according to those F-35 test pilots interviewed by *AIR International* at NAS Patuxent River.

## Pilot's View

The author was keen to hear what the F-35 is like to fly particularly at take-off which always shows dramatic acceleration. Peter Wilson explained: "The take-off itself is unremarkable, in afterburner the aeroplane accelerates dramatically, but it's comparable with legacy fighters, and very weight dependent."

Both the F-35A and the F-35C can carry more than 50% of their empty weight in fuel internally which gives an enormous variation of acceleration.

One very notable system on the F-35 is the side stick located on the right side of the

> **"WHEN I TELL YOU HOW EASY IT IS TO LAND, IN THE BACK OF MY MIND, I AM THINKING ISN'T THAT GOING TO BE GREAT FOR THE YOUNG PILOT WHO HAS WORKED HARD THROUGHOUT THE MISSION AND NEEDS TO GET HOME WHEN HE IS TIRED"**
> *PETER WILSON, F-35 STOVL LEAD TEST PILOT*

Ground crew follow mandatory procedures and engineering steps to prepare the aircraft, which typically takes a couple of hours to complete, before they refuel the aircraft to the desired fuel state and declare it as 'blue sky'.

At the same time, typically starting three hours before take-off, the flight test engineers, at least one representative from each of the 12 engineering disciplines that are in the control room during the mission, and the pilots (F-35 and chase planes) gather for the pre-flight briefing.

Lasting upwards of one hour, discussions take place between the pilot, the test conductor (one of the flight test engineers), the test director (with overall responsibility for the sortie) and the discipline engineers about predictions and expectations of the flight, reiterating to the pilot the points observed in the simulator.

The assembled team also runs through an entire drill to discuss how to deal with the 'emergency of the day'. This involves a system failure, which occurs during flight as selected by the pilot. It is a notional exercise staged to ensure everyone is well practised at the required procedures to get the aircraft back safely in one piece.

Test pilots assigned to the F-35 test force at Patuxent River are qualified to fly both the STOVL and CV variants and are usually allocated to the flight schedule 48 hours in advance of a sortie.

On the flight line, the pre-flight procedures required are somewhat different to those that will be involved for future operations and require a lot of people to support various systems during the start-up process. These include a team of four to manage the instrumentation system (the orange wire and sensors used to monitor behaviour and performance of the aircraft in flight test) common to all F-35 SDD aircraft, and a control engineer maintaining communication between the control room and ground team.

When the pilot arrives at the flight line the aircraft is in maintenance mode and its electrical systems are already powered up to provide instrumentation information to the control room. This enables displays and functions to be checked – the pilot can board the aircraft while these are under way but must wait until they are complete before helping the ground crew to power down the aircraft.

cockpit. The mechanics of the side stick are well balanced with just the right amount of movement (about 1½ inches or 38mm) according to Peter Wilson who said: "You first notice this when using the stick to rotate and bring the nose up to establish an attitude at which the aeroplane's going to climb away. The aeroplane feels absolutely rock solid, the handling feels precise."

A very distinct feature of the F-35 is noise both inside the cockpit and out. "From the cockpit it's not especially loud but it doesn't sound like any other aeroplane that I've flown," said the lead STOVL pilot.

The ride quality of the F-35 is also different, especially the precision with which the pilot can manoeuvre the aircraft using the side stick to put it exactly where he or she wants. "It's most noticeable when you're trying to do a tightly controlled formation task, like air refuelling. I've plugged into a tanker many times with a remarkably high success rate, higher than I would have had on the Harrier, and with a different technique. The pilot formates the air refuelling probe directly onto the basket of the tanker, sits behind it, and just plugs it when it's steady and level.

Coming in to land is also precise. "Even in a cross wind it's easy, the aeroplane points its nose in to wind very nicely and reduces side slip," said Peter Wilson.

Symbology in the helmet-mounted display allows the pilot to see the aircraft track, confirming that he or she is aligned with the runway even if the nose is not because of crosswind. The side stick is extremely precise for both flaring (the technique used to gradually reduce the descent rate) the aircraft and adjusting any drift, but even if he or she does not make any correction the aircraft will land and straighten itself up "beautifully" according to Peter Wilson. "It's the easiest aeroplane I've ever landed and really does look after you. When I tell you how easy it is to land, in the back of my mind, I am thinking 'isn't that going to be great for the young pilot who has worked hard throughout the mission and needs to get home when he is tired'," he added.

To date all conventional landings have been carried out manually with the stick. An automatic system on the throttle allows the pilot to select the APC (automatic power control) mode that controls the angle of attack flown on final approach during which the throttle moves up and down in response to the changes. At touchdown the throttle automatically goes to idle, the pilot applies the brakes to stop the aircraft and exits the runway. "Once on the ground, I do not have any flap levers to move or any flight controls to reposition, and if I want to get airborne again all I have to do is put the power up and initiate the rotation," said Peter Wilson.

The throttle commands thrust and not the rpm of the engine, so at idle the engine is providing 10% of the thrust available and when pushed forward to the mil stop it provides 100% of the available thrust or full mil power. The throttle gives a linear variation of the percentage of thrust available with its position, which makes it subtly different to use. One hundred percent thrust means just that, with no variation (which can be the case with a legacy aircraft), so the pilot knows when the engine is providing all of the power that it can.

## Landing Vertically

One of the most fascinating aspects of the whole programme is the way in which the F-35B achieves a vertical landing. When preparing to transition from conventional to STOVL mode the first thing the pilot must do is configure the aircraft to be able to fly at slow speed. This process is called conversion and from the pilot's perspective it starts when the aircraft is moving at 250kts (460km/h) or less at which point he or she simply presses a button.

"Seconds later, assuming all has gone well, you are in the mode that allows the aircraft to go to the hover," said Peter Wilson.

Nine external doors open in sequence taking about 8 seconds, after which the propulsion system (not to be confused with the engine) starts to spool up. The clutch engages to spool up the lift fan located behind the cockpit (which takes about 5-6 seconds) and the control laws change to make use of the propulsive effectors that have just been brought to life. The aircraft is now in STOVL mode and ready for a vertical landing. "You feel a little tingle in your back through the seat and it sounds like a very large mosquito buzzing behind your head," said Peter commenting on the lift fan.

The lift fan nozzle and main engine nozzle move independently as per the control laws of the aircraft (the aircraft is programmed to position the nozzles where the force is required). Peter Wilson says the varying pitch of the engine can be clearly heard from the cockpit as the thrust changes during low speed manoeuvring.

Commenting on the hover, Peter Wilson told *AIR International*: "It is absolutely astonishing, the aeroplane is rock solid in the hover, and holds its position extremely accurately without pilot input."

The aircraft can be accurately moved left to right, fore and aft, and up and down by 3ft

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(1m) at the preferred position of 100ft (33m) above the ground before descent. Control of the F-35B is governed by something called the unified control law, which was developed during research at Boscombe Down in the UK with the Vectored-thrust Aircraft Advanced Control (VAAC) Harrier in a project funded jointly by the UK and US as part of the Joint Strike Fighter programme.

And perhaps the real testament to the unified control law is the experience of pilots who had never before flown a STOVL aircraft. Having practised in the simulator, they have been able to step into an F-35B and complete a vertical landing with relative ease.

To descend from the hover and land, the pilot has to push on the side stick until he or she feels a stop, and hold it there until the aircraft detects the landing, at which point it returns the propulsion system back to idle and moves the nozzle to the correct position, allowing the pilot to taxi forward with nothing else to do. "The precision with which you can land is amazing – on the spot plus or minus 12 inches, every time consistently," said Wilson.

## Nine Hops

During STOVL testing in February 2010, Peter Wilson flew nine sorties from NAS Patuxent River in about four hours, all of which were less than 5 minutes in duration. Each sortie carried a relatively low fuel load allowing Peter to take off, and fly around for a brief period to ensure the fuel was at the right level in preparation for a landing

test. "The highlights on the day were the take-offs. I took off as slow as 50 knots [92km/h] with the STOVL mode engaged, accelerated out to the normal pattern speed of 150 knots [276km/h], turned downwind, and positioned ready for a vertical landing," he said.

Some of the vertical landings required extreme nose-down attitudes on the aircraft at various weights and phenomenal descent rates. Recounting the landings, Peter Wilson told *AIR International*: "I was trimming nose down to make the nose gear hit first rather than the main gear coming down as fast as I could, given the control law of the aeroplane. When the nose gear (underneath the pilot's seat) hits first at that sort of descent rate it gets your attention because it's a pretty heavy landing and a remarkable experience in the cockpit."

## F-35B Take-off Options

The F-35B STOVL variant has a range of take-off options using different modes to suit the basing. Take-offs from a ship, with either a flat deck or one with a ski jump, are also possible with a mode for each scenario. These are short take-off scenarios that can be achieved at speeds as low as 50kts with a deck or ground run of no more than a 200ft (60m). In the same mode, a take-off as fast as 150 knots is possible if the weight of the aircraft requires that speed. If the aircraft is light it can take off at a slow speed and faster when heavy.

Take-off at speeds as low as 5, 10, 15, 20kts (9, 18, 27 and 36km/h) are also possible, each of which is effectively a vertical take-off while moving forward. There are different ways of rotating the aircraft in STOVL mode, including the usual 'pull on the stick'. Other ways are by pressing a button or programming a ground distance required after which, the aircraft control law initiates the rotation and selects the ideal angle for climb-out.

F-35Bs BF-01 and BF-02 are the only B-models currently undertaking STOVL testing and therefore performing take-offs in STOVL mode. Peter Wilson commented: "We have found a remarkable similarity between BF-01 and BF-02 which gives us the confidence to move on and get more aeroplanes [BF-04 followed by BF-03] into STOVL mode very soon." At the time of closing for press in mid-April the first vertical take-off had not taken place.

## STOVL Road Map

Most of the STOVL flight test activity is now concentrated at NAS Patuxent River with the first four SDD F-35Bs – BF-01, BF-02, BF-03 and BF-04 –based there, the fifth aircraft BF-05 was due to be delivered during the spring of 2011. BF-01, BF-02 and BF-03 are flight sciences aircraft and are currently involved in flying qualities, loads and flutter testing. BF-04 and BF-05 are mission systems aircraft and are testing all of the sensors integrated on the F-35.

Perhaps the largest test event coming up in the final quarter of 2011 is the first sea trial to be undertaken onboard a Wasp-class amphibious assault ship. Summing up Peter Wilson said: "The test points required to go to the ship are clearly identified, most of them are complete, with a few more to complete very soon, which will be the final tick in the box to go to the ship.

"It is important for people to understand the reason that this aircraft exists is not as a science project set around take-off and landing, it exists to bring the most amazing range of sensors that have ever been put together on a single aeroplane, and deploy it to the battlefield reliably and repeatedly."

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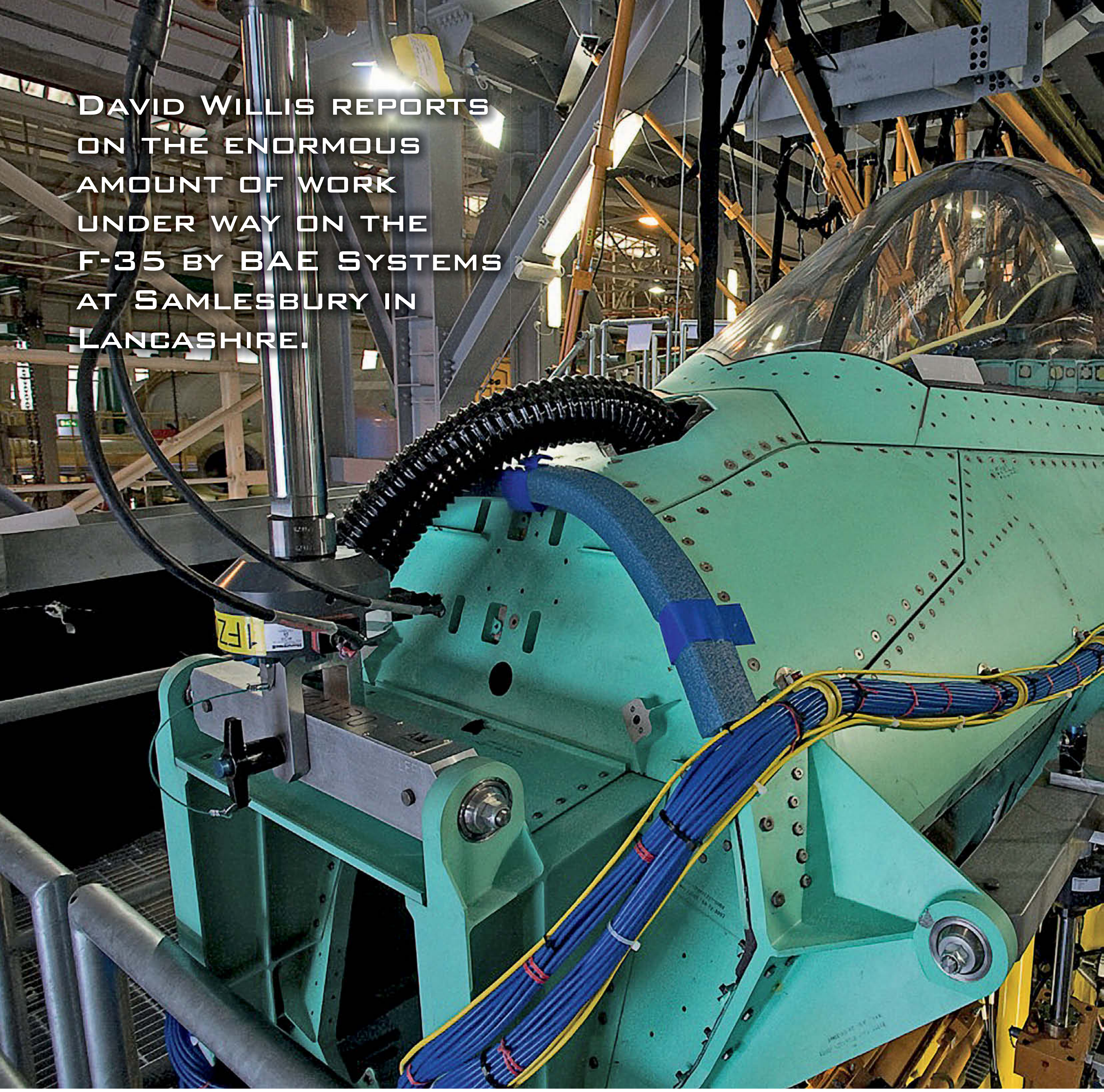
*Top: F-35C CF-01 sits on the ramp at NAS Patuxent River following a test flight on November 30, 2010. This shots shows the EOTS turret immediately forward of the landing gear bay and the configuration of the ladder bay.* Paul Ridgway
*Left: F-35C CF-01 is shown moments from touch down at NAS Patuxent River following a test flight on November 26, 2010.* Paul Ridgway
*Below: Peter Wilson was the first British pilot to fly F-35C CF-01.*

# David Willis reports on the enormous amount of work under way on the F-35 by BAE Systems at Samlesbury in Lancashire.

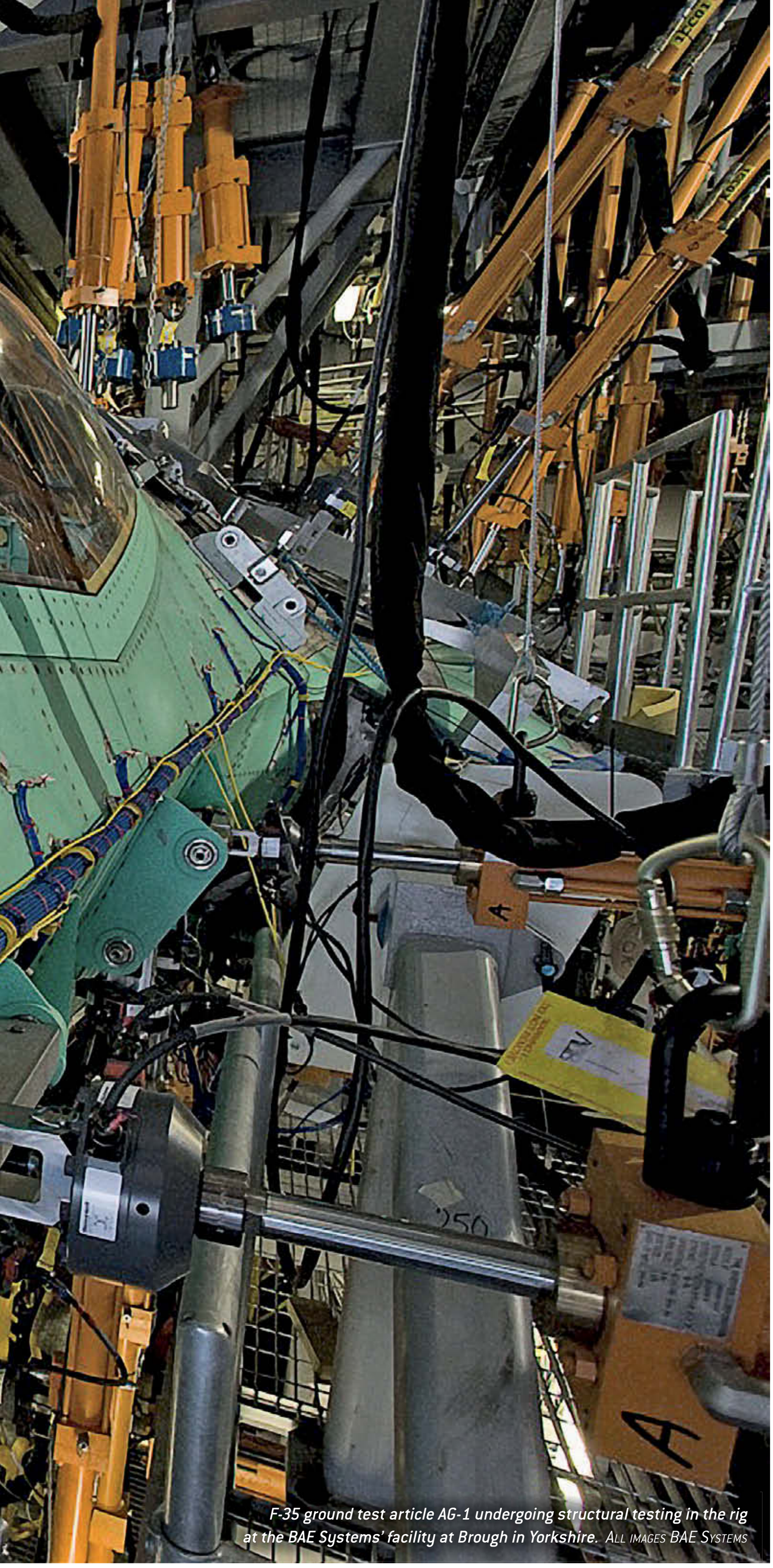


BAE Systems teamed with prime contractor Lockheed Martin, and fellow Team LM member Northrop Grumman, a couple of years before contract award for the JSF in October 2001. It brought its expertise in airframe design and manufacturing techniques to the team, allowing better control of the F-35 Lightning II's outer shape and meeting the challenge of keeping component costs down.

## Digital Thread

From contract award, Team LM used 'a digital thread' based on the CATIA 3D modelling software tool to create the F-35. According to Chris Garside, BAE System's Chief Engineer and Engineering Director for F-35, it is the foundation on which the programme is built. "The whole of the F-35 programme exists in a virtual environment, as there are no traditional paper drawings, no designers sat at drawing boards, no technical publications interpreted from paper-based drawings." In concert with the Metaphase Product Data Management System, CATIA allows BAE to develop the physical parts of the aircraft in a digital world. "When you start to generate a basic outline shape you can use that to drive computational three-dimensional dynamic models or manufacture wind tunnel models to validate some of the modelling data. It can be used to drive a basic manufacturing programme and, by using rapid prototyping techniques, produce components earlier than would otherwise have been possible, allowing us to compress the design cycle. The systems are also created virtually, so their routes in the aircraft can be modelled within CATIA, as can their behaviour. You can then take that data and build a simulation of the whole aircraft, so the pilot can jump in and 'fly' it very early...in the simulators at [Lockheed Martin's facility at] Fort Worth [Texas]. By doing that you start to understand certain characteristics of the aircraft and, if you need to, begin to design those out. It's not perfect when it comes to simulating how it will behave, or operate, but what it does is provide higher confidence in the product much earlier in its life cycle."

As flight hours are accumulated, the actual performance of the aircraft can be fed back to the digital thread to refine the model. "We managed to develop three variants of F-35 in quick succession because the digital thread gave us the foundation for understanding how the aircraft behaves and how it physically looked, and then we used the same information to lay out the factory," said Chris. "Using other [software] tools allows you to lay the factory out, model exactly how the product moves around it, how it works in the supply chain, identify where bottle necks will occur and optimise the flow line.



*F-35 ground test article AG-1 undergoing structural testing in the rig at the BAE Systems' facility at Brough in Yorkshire.* ALL IMAGES BAE SYSTEMS

# Made in the UK

By late March 2011, 48 aft fuselages had been produced at Samlesbury. "For airframes and systems, we have now designed, developed and delivered airframe components for all the SDD [System Development and Demonstration] aircraft, and are some way through deliveries on Lot 3," said Chris. Qualification of the components is currently at the Safety Flight Level, sufficient to fly within prescribed limits.

The British company also has responsibility for certain parts of the Autonomic Logistics Information System [ALIS], explained Chris, "which helps us manage aircraft through-life in terms of spares and repairs as it is progressively fielded by customers." ALIS is currently in use at Naval Air Station Patuxent River, Maryland to support the F-35B and F-35C test fleets on a trial basis and will be used at Eglin AFB, Florida when the aircraft is delivered to the 33rd Fighter Wing later this year.

While all aft fuselages will be built at Samlesbury, under the International Partner Plan other work has been contracted out to companies in other countries. "We have strategic offload, where we decide which parts we want to go where, and we are also obligated by the IP [International Participation] agreement to put a certain percentage of work, over that sourced from the UK, into International Partner countries. So, for example, in addition to putting certain components from Brough out to a local supply house, we put work out to Australia. Ultimately Australia will build vertical tails, and Canada and Germany will do the horizontal tails. Avcorp of Canada does the folding wing tips [for the F-35C] for us – we don't make those in house. It's not referred to as offset, its IP work and it has to be F-35 work that we put into those countries."

"The digital thread is not just there for the three partners, as some elements extend into the supply chain. For example, Martin Baker designed the ejector seat and created the CATIA model for it, which was then used to refine the design of the front fuselage. It allows rapid changes to be implemented and dissimulated. That same product data is then used to create the Joint Technical Documents [JTDs, technical publications] produced for the support phase of the programme, so the digital thread follows all the way through."

## Components

As part of the teaming contract, BAE Systems has 10% of the work by contract value, although it must achieve affordability targets to retain its share. It is responsible for the design, development, qualification and manufacture of the aft fuselage components, vertical and horizontal tails and the folding wing-tips used on the F-35C Carrier Variant (CV). It also has responsibility for the design, development and qualification of the fuel system, the life support system, development of the escape system and certain modules within the mission systems, as well as the prognostic health management (PHM) systems for the airframe structure and vehicle systems. Lockheed Martin has the task of integrating them with the airframe.

## Precision Manufacturing

Tolerances for components on the Lightning II are extremely high, down to 1/5000th of an inch in some cases. The low observable (LO) characteristics of the aircraft require that access panels fit exactly to reduce radar returns, while high tolerances are also required to ensure that internal parts fit together perfectly. Carbon access panels need to be interchangeable between aircraft, rather than replaceable (ie, identical, rather than built to fit). "In terms of how we produce the composite components, how we assemble them, and then how we assemble the modules in order to maintain overall alignment of the aircraft, we learnt a lot off Typhoon, put it on F-35 and shared that technology with Lockheed and Northrop. It basically reduces and helps maintain the LO characteristics over the life of the aircraft," said Chris.

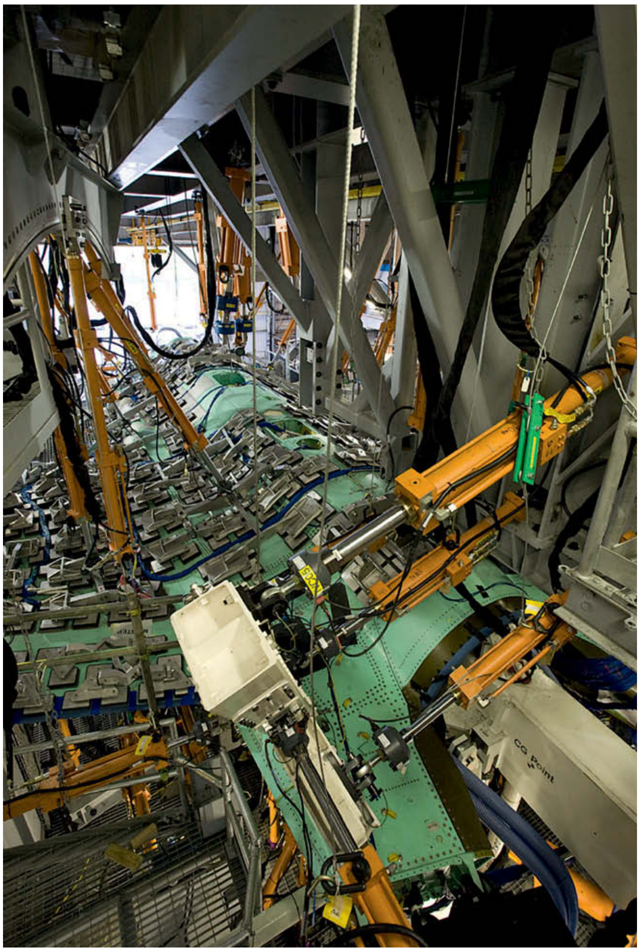
BAE has invested heavily in infrastructure at Samlesbury to produce F-35 components. Building 610 is a new 29,528 sq ft (9,000m$^2$) facility for the production of titanium components using highly automated flexible manufacturing systems (FMS). It became operational in late 2010 with half of the FMSs installed. The others are due to be installed later this year as production ramps up. Titanium is difficult to work, and much effort has gone into getting the maximum life out of each drill bit with a computerised management system to record usage.

Assembly of the aft fuselage and vertical and horizontal tail planes is undertaken in Building 430. Construction work is currently under way on the first phase of expansion of the building, with BAE due to get initial access to the additional space in July 2011 and full handover occurring in September. Assembly will start in the new section by late 2011/early 2012, adding approximately 200 workers to those already employed in Building 430. A third expansion is planned.

There are five work stations on the empennage line. The tails are currently built over 40 manufacturing days, with a set completed every eight days. The aft fuselage line currently has eight build stations, and a unit is produced over 64 manufacturing days with one coming off the line every eight manufacturing days. That is due to decrease to 24 and three days (for both the aft fuselage and empennage lines) following the opening of the extension to Building 430. The ultimate target is to roll one off the line every manufacturing

day. “Part of that will occur through the transition from a current station build to more of a pulse line build,” said Chris, “and those changes will be progressively introduced as we go forward, in terms of the number of units we have to build and the facilities that we actually bring on line to support that increased build rate.” Many more, smaller stations, with smaller stages of work, will be incorporated when production transitions to a pulse line. It is also important that the external supply chain can match the increased production targets. Once assembly is complete the units are air freighted to Fort Worth to take their place on the final assembly line.

Currently BAE bids for Low Rate Initial Production (LRIP) lots, which is a year's worth of production. Until development is completed the F-35 will continue to be procured via LRIP lots, nine of which are expected to be let before Milestone C is passed and multi-year purchases can be negotiated. “Each year we bid for an LRIP lot, and lead funding for the next lot as a separate contract. LRIP lots each have a defined number of aircraft in them, and a spares or sustainment content as well.” Bidding is currently under way for Lot 5, work on which will start in 12 to 18 months' time. Milestone C will be achieved after industry has qualified and demonstrated specified requirements and the US services have completed operational test and evaluation. It is expected around 2016.



*Above: AG-1 arrived at Brough on April 27, 2009, and was placed into a 365-ton test rig. This shot clearly shows some of the load actuators hooked up to the airframe.*
*Top Middle: Building 610 at the Salmesbury site is a new 29,528 sq ft (9,000m2) facility housing automated flexible manufacturing systems (FMS). This shot shows a component undergoing precision machining by an FMS.*
*Top right: Assembly of all F-35 aft fuselages, vertical and horizontal tail planes is undertaken in Building 430 at Salmesbury. This shot shows the left-hand vertical tail within the jig. This tail was eventually fitted to F-35B STOVL aircraft BF-01 now based at NAS Patuxent River in Maryland and part of the test force based there.*

## Sustainment

BAE Systems helps sustainment of the F-35 during the SDD phase of the programme. It is responsible for certain pieces of ground support equipment and preparation of technical publications (JTDs), along with Lockheed Martin and Northrop Grumman. “We have delivered all the ground support equipment and the joint technical data, and we also have produced elements of the software associated with ALIS,” said Chris, adding: “We're now building the team in the US to start to sustain aircraft when we build up the training squadron at Eglin AFB and start to stand up at other bases around the US. We are also working with Lockheed to define what sustainment solutions are implemented in the International Partner countries. Any issues that emerge from the customer operating the aircraft get logged on ALIS and routed through the operations centre in Fort Worth. The operations centre will then pass that question out to the appropriate engineering team so that, as we go forward into sustainment, we're starting to build up the people that we need to answer queries and help the customer actually support the aircraft.

“BAE Systems has the position of national support integrator for the UK in the F-35 programme. We have a similar position in Australia, as a support integrator. It's not a given right; we have to demonstrate to the Australian Ministry of Defence that we have the capability to support this aircraft affordably as part of Team LM. There is no suggestion that BAE is going to try and do its own thing in terms of supporting F-35 – it will always be as part of Team LM.”

## Brough

Static testing of the purpose-built airframes (two of each variant) is nearing completion. The F-35A Conventional Take-Off and Landing (CTOL) airframe, AG-1, was tested at BAE System's facility at Brough in East Yorkshire. It arrived there on April 27, 2009, was placed into a 365-ton test rig by July when load actuators were hooked up. Chris explained: “We built two of those rigs at Brough, one for the static testing and one for the durability test. During static testing a set of static loads are applied to the airframe, in a pre-defined set of combinations, which will confirm that, throughout the flight envelope, the structure will take the predicted loads. The durability test actually analyses how the airframe structure is going to behave at different altitude levels, so the techniques used to introduce loads differ. What we try to do is excite the structure to confirm that it's not going to fatigue or crack prematurely, so we can confirm an 8,000-hour crack-free life as required in the Structural Criteria Document.” Similar trials were completed on representative F-35B airframes at Lockheed Martin's premises at Fort Worth, Texas, while an F-35C is currently being tested there.

Experience testing Nimrod and Typhoon static airframes helped BAE develop the technologies used to gather data and share it in real time. “We basically ran through a series of load cases – monitored in real time simultaneously by Northrop Grumman, looking at the centre fuselage at Palmdale [California]; Lockheed Martin, wing and the front fuselage at Fort Worth; and BAE at Samlesbury, looking at the rear fuselage, vertical and horizontal tails. If any part of the test exceeded what was predicted in terms of response or loading characteristics, then it could be stopped.” Static testing of the CTOL airframe was completed quicker than anticipated, while durability tests continue. Both F-35A airframes will eventually be returned to Fort Worth where they will undergo teardown, during which the components and joints will be examined for damage.

## Carrier Integration

On behalf of Team LM, BAE Systems is responsible for integration of the F-35 with the UK's *Queen Elizabeth*-class Future Aircraft Carriers (CVF), which are due to be commissioned by the Royal Navy within the next decade. “Primarily it's ensuring that the carrier team is furnished with appropriate information associated with the aircraft – and what its environment is, which facilities it needs to ‘plug’ into on the deck and how certain operations will be performed. The other piece of work undertaken concerned the development of the Short Roll and Vertical Landing [SRVL] for the STOVL [Short Take-Off and Vertical Landing] variant. Instead of coming alongside the carrier, hovering, moving over the deck and landing vertically, as in the Harrier, SRVL involves landing with a component of forward velocity.” SRVL allows a higher landing weight as it utilises lift from the wing, so the F-35B can land back on the carrier heavier – removing the need to burn off additional fuel or, alternatively, jettison underwing stores. Development of SRVL was accomplished using the digital threads for the F-35B and the CVF, allowing pilots to ‘fly’ the approach in a simulator at Warton, Lancashire.

Following the decision to acquire the F-35C CV in last year's Strategic Defence and Security Review, BAE Systems is working with the Joint Carrier Aircraft (JCA) team within the Ministry of Defence to develop concepts of operations from the warships “long before we ever get to put an aircraft on a ship,” said Chris. “Design [of the F-35C] has been stable for some time, so things like landing velocities, maximum and minimum take-off weights, wingspan, spotting factors and deck choreography to optimise the use of the aircraft on the carrier were done some time ago. While nobody's starting from scratch, I would expect that what we will go through is a process of understanding.”