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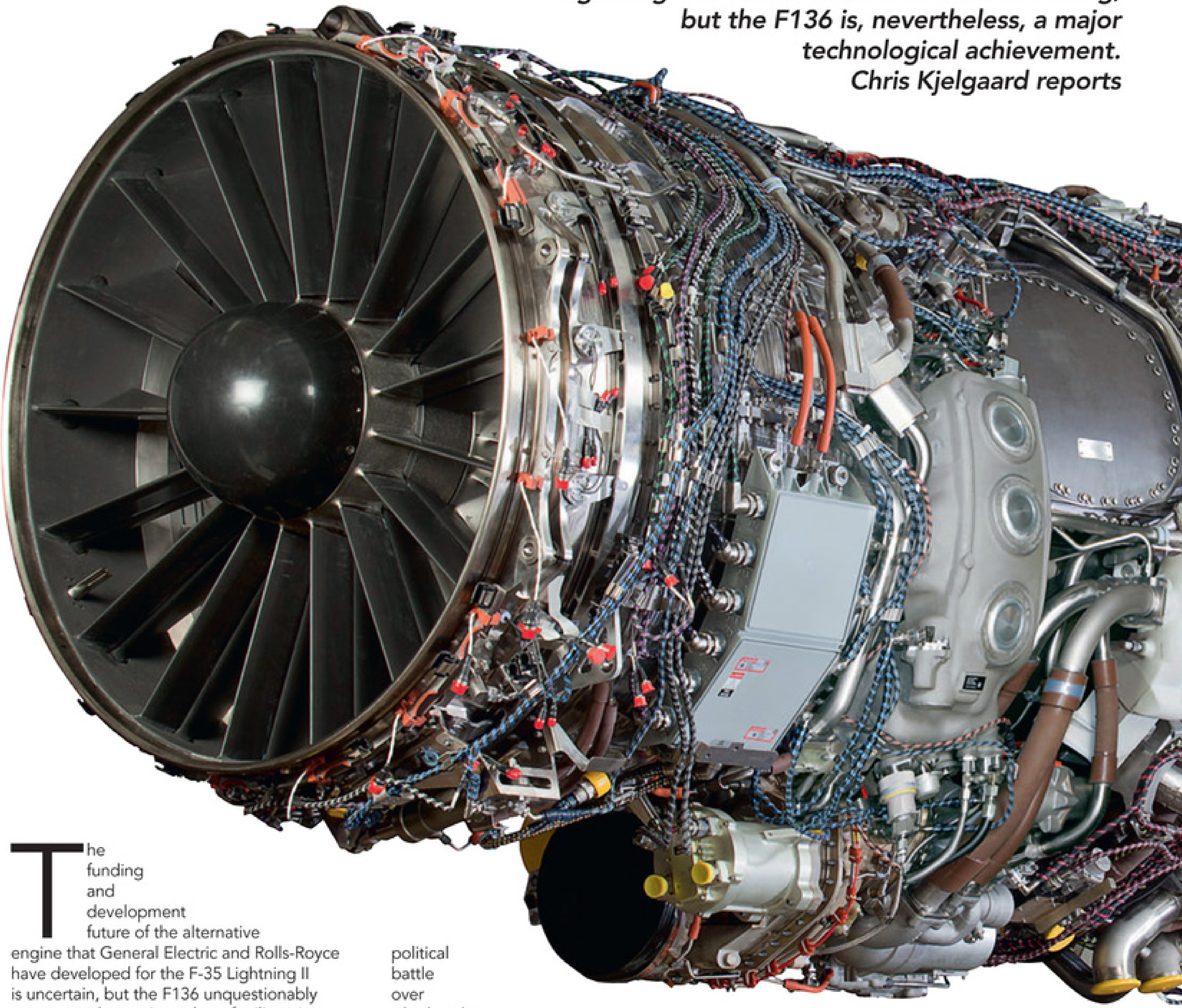
Its future as an alternative engine for the F-35 Lightning II is not assured at the time of writing, but the F136 is, nevertheless, a major technological achievement. Chris Kjelgaard reports



The funding and development future of the alternative engine that General Electric and Rolls-Royce have developed for the F-35 Lightning II is uncertain, but the F136 unquestionably represents the cutting edge of military jet-engine technology.

Despite a formal "termination order" on the F136 engine by the US Department of Defense in May, the GE/Rolls-Royce Fighter Engine Team offered to bear all costs for continued development of the competitive F136 fighter engine for the F-35 through September 30, 2012, the end of the US government's fiscal year 2012.

The unique offer requires no appropriated government funding in fiscal year 2012 and does not hinge upon any financial commitment from the government in 2013 or beyond. Under this agreement, the fighter engine team would be provided access to the engines, components, and testing facilities to continue development work. At press time, the GE/Rolls-Royce proposal is moving through the Congressional budgetary process, with formal resolution of the offer expected later this year.

So the F136 may yet power many F-35s: the political battle over whether the F-35 should have two engine choices or only a single engine type appears anything but over and the F136's chances of being officially designated as the F-35's alternate power plant may well be improved now that the engine's biggest detractor, Robert Gates, is leaving his post as US Secretary of Defense. But even if it doesn't, its technology is likely to see applications in other, future aircraft.

The partners had to wait until 2005 to receive a full-scale development contract (known as a system demonstration and development (SDD) contract) for the F136 and when it came it was for $2.4 billion, half the amount that Pratt & Whitney had been awarded for its F135 SDD contract in 2001. The SDD contract awarded to the GE Rolls-Royce Fighter Engine Team covered F136 development activities through till 2013. Prior to the contract award, the Fighter Engine Team had already successfully tested the F136's original core and conducted fan rig tests in 2000, after which the partners conducted their first full engine runs in 2004.

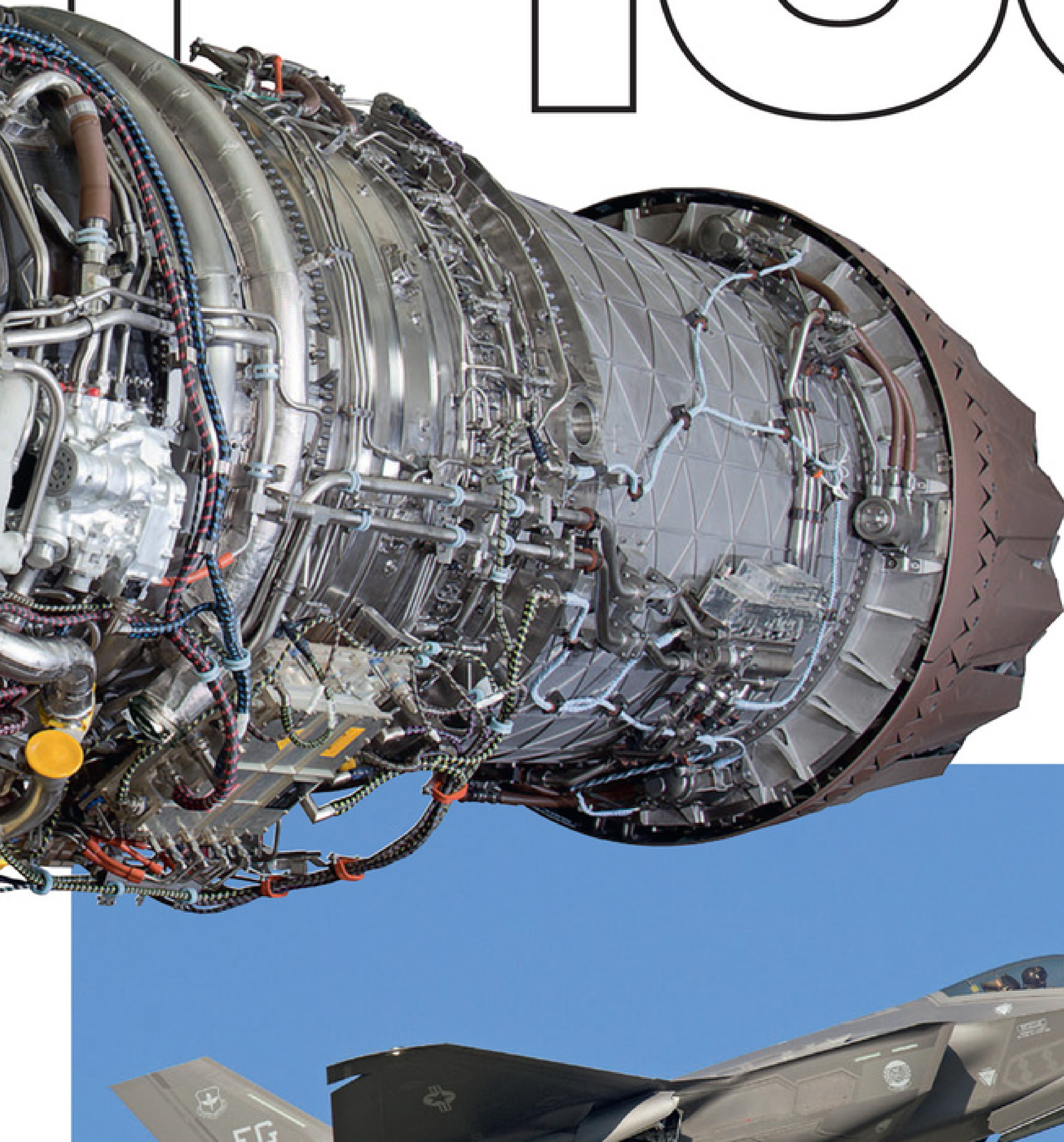
Although the GE/Rolls-Royce F136 did not receive the F136 SDD contract from the US Department of Defense until four years after the P&W F135 had received its SDD contract, and the F136's funding future has been in significant doubt throughout the F-35 programme, the engine benefited in several major ways from the SDD contract delay.

A Silver Lining in a Cloud

Primarily, the delay meant that the Fighter Engine Team was able, when finalizing the

F136

the F-35's Alternative Engine



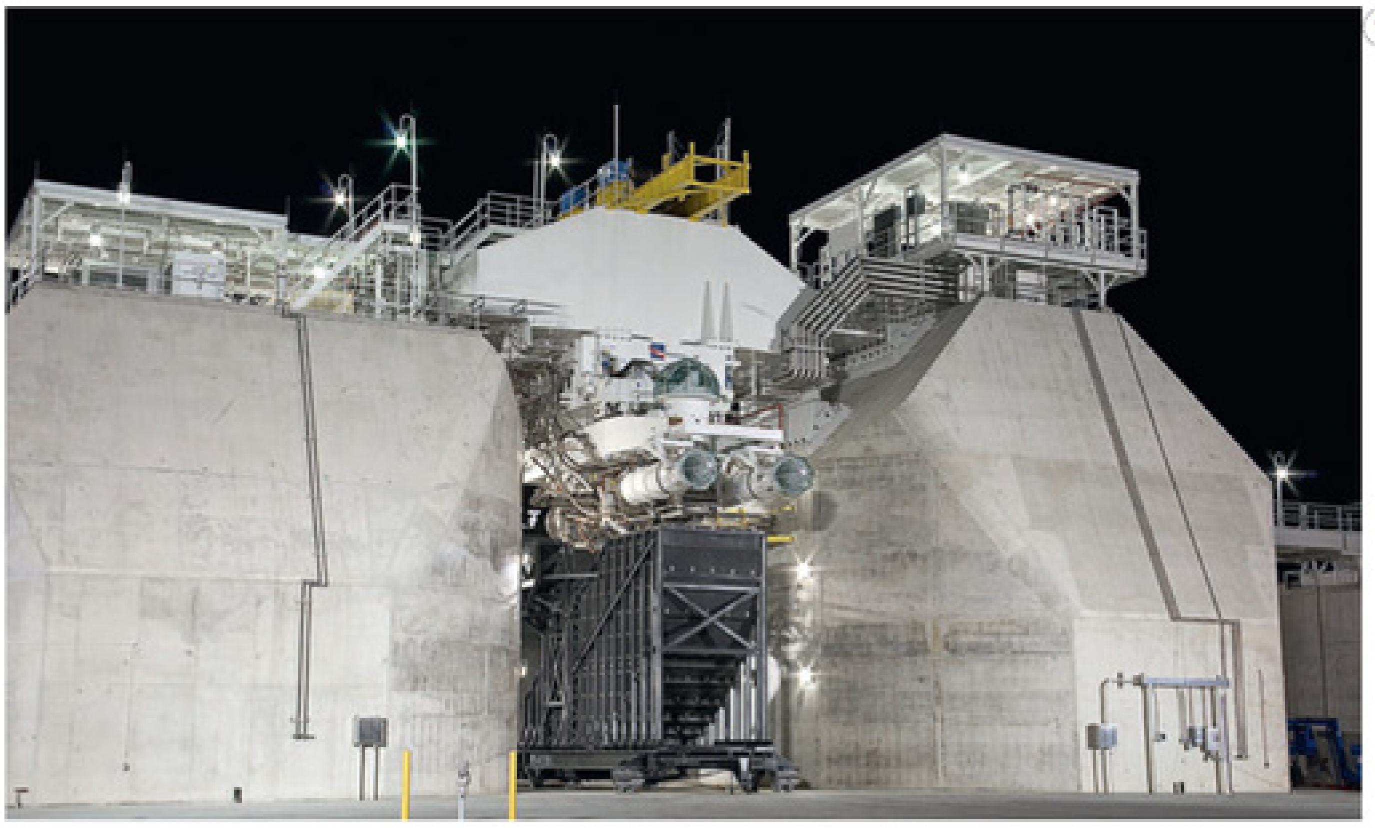
(1) **1** The GE Rolls-Royce Fighter Engine Team F136 has an overall diameter of 48 inches (1.219m). *All images General Electric unless noted* **2** Designed for the F-35, the F136 engine has not flown on an F-35. *Scott Fischer*

(2)

design of their powerplant, to take account of a substantial re-specification of the F-35 in 2005 and the consequent redesign of the aircraft's air intakes and engine inlet to provide more airflow to the engine. For the SDD phase, the F136's design featured both a scaled-up core and a larger fan compared with the pre-SDD engine.

"We assessed the engine architecture from the [original] demonstration programme and decided to increase the core airflow by 5% to 10% or more," remarks Dan McCormick, project manager for the F136. "The greater airflow through the engine was consistent with the redesigned inlet capability."

Now, the strategic move to increase the size of the F136's fan and of its core "is paying huge dividends", says Al DiLibero, President of the GE/Rolls-Royce Fighter Engine Team. "All testing is exceeding our design's intent on the fan and the core – and with more airflow in our design, we get more airflow and cooler [operating] temperatures."



Because the design of the F136 was finalised only after the F-35 itself was re-designed, a luxury the F135 did not have, the Fighter Engine Team has always claimed the F136 has a bigger core, a higher-flow fan and greater core airflow than the F135 and that it operates at cooler temperatures throughout the flight envelope. Not only does the engine's size imply that the F136 has considerable potential for thrust growth, according to the Fighter Engine Team, but it also means it has a substantial operating margin throughout the flight envelope.

This translates to the team claiming up to a 25% maintenance-cost advantage for their engine over its competitor – a statement which Fighter Engine Team spokesman Rick Kennedy notes the F-35 Joint Program Office has allowed to stand unaltered. Another advantage the team claims the SDD delay conferred on the F136 was that, since they actually began testing the core in the mid-1990s, and had "hundreds of hours" of core testing under their belts before the F136 got its $2.4 billion SDD contract in August 2005, "we had a lot more experience with the core than we normally would have had when we began SDD."

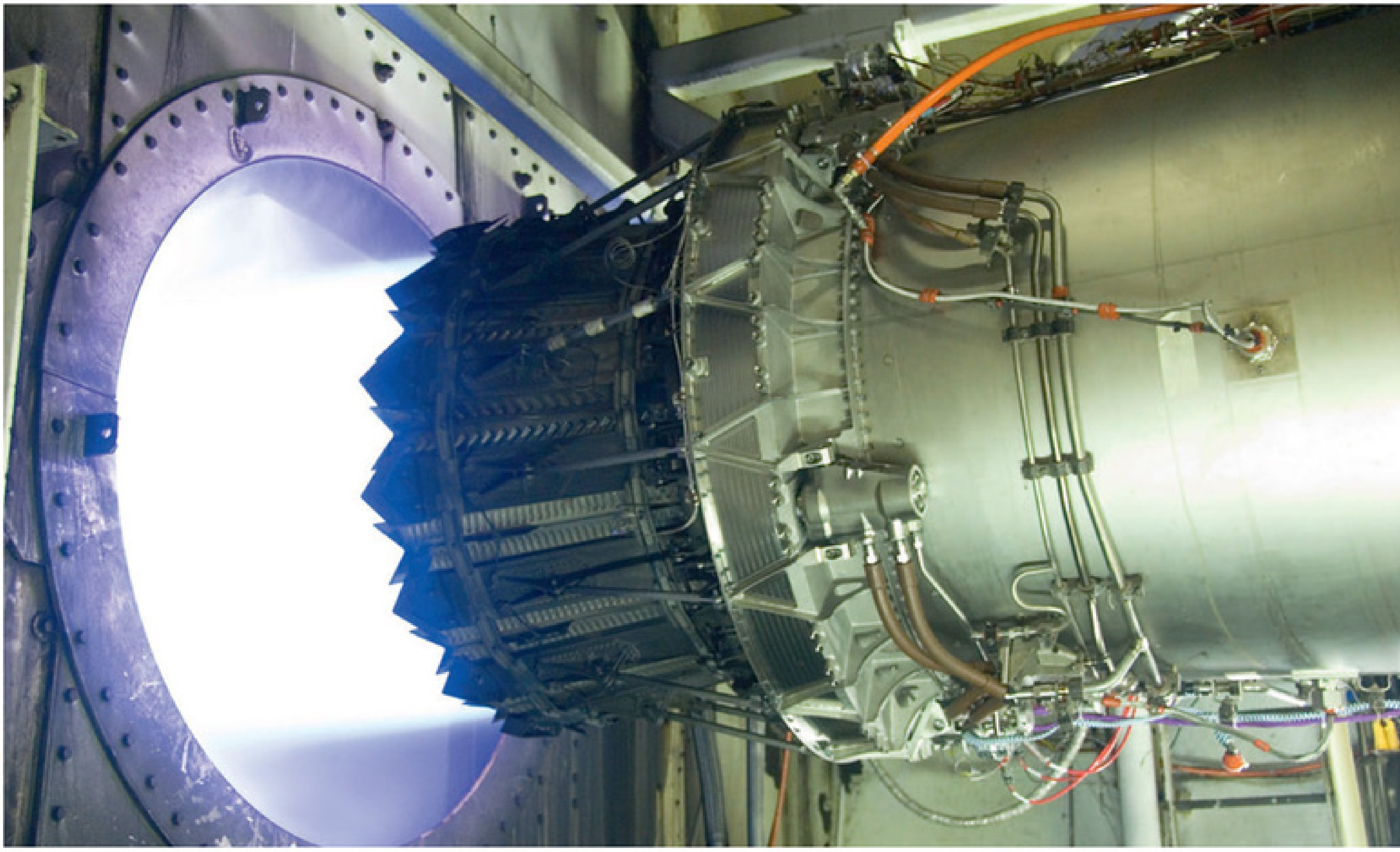
The Fighter Engine Team assembled to offer the F136 is a 60%/40% joint venture between GE and Rolls-Royce. Rolls-Royce designed and manufactures the engine's fan section, combustor and the second and third stages of its low-pressure turbine. GE is responsible for the compressor, high-pressure turbine, augmentor, structures and systems integration, and for making the engine's controls.

GE and Rolls-Royce have consistently maintained pricing pressure on the rival Pratt & Whitney F135, the engine of record for the F-35. Twice, in late 2009 and April 2010, the Fighter Engine Team offered the Pentagon low, fixed-price offers to produce F136s for low rate initial production (LRIP) batches of F-35s funded from US fiscal year 2012 onwards. The partners made their fixed-price offers on the LRIP 4 and LRIP 5 F-35 production batches, due to be manufactured some five years before the engine was officially available for delivery.

While the Pentagon didn't award the Fighter Engine Team the production contracts, the team's offers did have an effect on their competitor: Pratt & Whitney announced in March that it was reducing its F135 prices for those batches by 16% and was making its bid a fixed-price offer, instead of a cost-plus contract as had previously been the case.

The F136's Architecture and Design

The F136 has an overall diameter of 48in (1.219m), providing the same external dimensions as the F135, but since its design was finalised after the F-35's 2005 inlet redesign, its fan is optimally matched to the production F-35's air intakes. "As the airplane has evolved, our larger core and our fan paid



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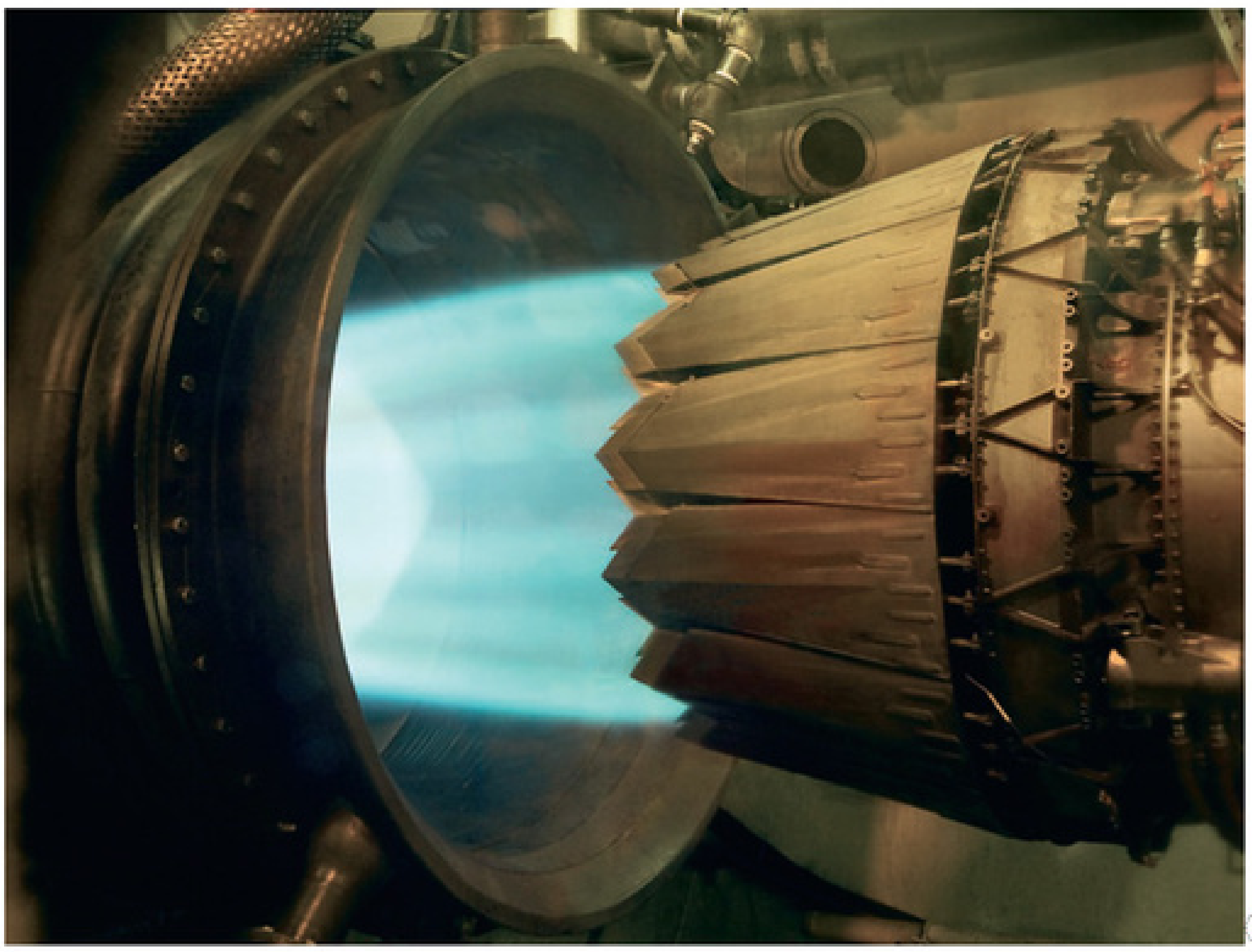

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1 Night time shot of GE's F136 engine testing facility at Peebles, Ohio. **2** F136 STOVL testing underway in February 2008 at GE's dedicated test facility at Peebles, Ohio. **3** F136 CTOL configuration testing underway in January 2008 at the Arnold Engineering Development Center in Tennessee. **4** The third F136 test engine hits full afterburner.

huge dividends," says Al DiLibero. "All testing is exceeding our design's intent on the fan and core."

While the F136 necessarily has to meet exactly the same installation requirements in the F-35 as the F135, and it must fit at all the same physical attachment and systems integration points inside the aircraft, the F136's architecture differs from that of the F135 in several important ways. Both engines have a three-stage fan, and both fan modules have all-blisk configurations, with the first stage featuring hollow titanium blades and the other two featuring solid titanium blades. The three fan stages are all bolted together to make up the fan unit.

However, where the F135 has a six-stage high-pressure compressor, the F136 has a five-stage HPC. Both engines' HPCs are all-blisk, but in the F136 two of the stages are married: they form one two-stage piece. Like the F135, the material from which the F136's HPC blisks are made changes from titanium to a nickel-based alloy for the stages nearer the combustor, where the core air has become highly compressed and much hotter than it is when first entering the compressor.

The F136's combustor features a diffuser and combustor case made from Lamilloy (the word probably is an abbreviation of "laminated alloy"). Patented decades ago by Allison Engine Company in Indianapolis, which was later acquired by Rolls-Royce, Lamilloy is a three-layer, diffusion-bonded sandwich of titanium sheets (or sheets of another metal) chemically etched so that each layer contains pillars of material and spaces between each pillar. Lamilloy also features pores in each layer of the sandwich. When the layers are bonded together, the pattern of pillars, spaces and pores creates a semi-porous material throughout which extensive airway passages run.

Bleed air from the compressor is forced through these airways in the Lamilloy diffuser and combustor case and is forced out of the material's surface pores. Not only does this effectively make the Lamilloy material "sweat" by means of transpiration of the relatively cool bleed air, helping the diffuser and combustor case stay cool enough to withstand the high temperatures inside the combustor, but it also creates a layer of insulating air between the hot air inside the combustor and the combustor wall. Lamilloy "takes significantly less cooling than legacy material and helps from an efficiency standpoint", says McCormick.

Like the F135, the F136 has a single HPT stage, but where the F135 has two LPT stages, the F136 has three. The F136 has counter-rotating high-pressure and low-pressure spools and McCormick says GE has been able to design the airflow transition between them so that the counter-rotation "eliminates what in legacy engines you'd call the Stage 1 low-pressure turbine nozzle". This reduces the engine's parts count, the amount of cooling air it needs to extract from the compressor, and the overall length of the engine. To achieve this elimination of a vane stage, the HPT stage and first LPT stage are "aerocoupled", which (among other things) means that they have had to be designed as one unit to produce the maximum efficiency benefit – the benefit deriving from the fact that the aerocoupled HPT provides for fewer static parts. As a result, while Rolls-Royce is responsible for producing stages two and three of the LPT, GE produces stage one, as well as the single HPT stage.

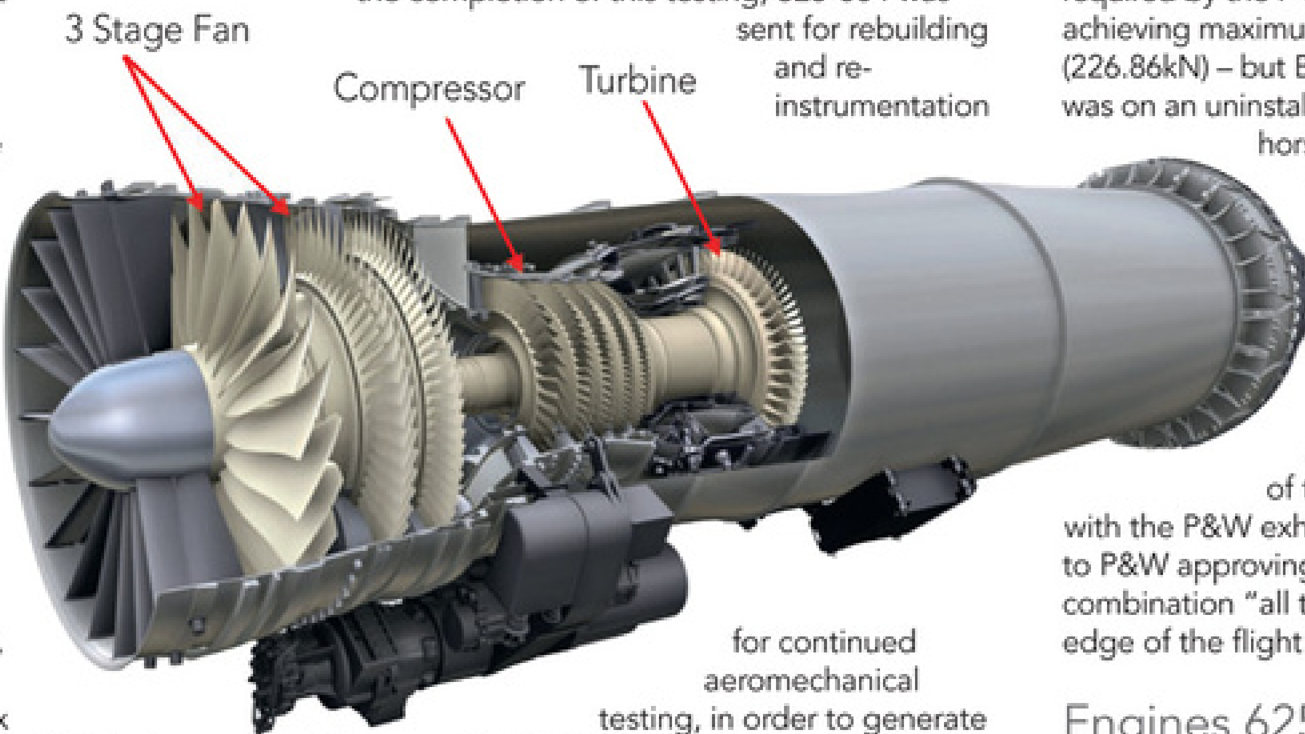
The rotors of LPT stages two and three straddle the turbine frame (with stage two in front of it and stage three behind). Affixed to the rear of the frame are the stage three vanes, which in the F136 are made from ceramic matrix composite (CMC) material. "This is the first time CMCs have been used in the hot section of an engine," says McCormick. "They are performing extremely well and we have had no durability issues whatsoever. We have literally shot [metal] balls through them and there has been no degradation."

After LPT stage three, air then exits the F136 into its augmentor, which features three fuel-injection zones – producing a smooth increase of power rather than distinct thrust bumps as the pilot applies more reheat – and a radial design with hubs positioned axially along the centre of the nozzle and spokes leading up towards the nozzle walls. "From a fuelling standpoint it's very similar to the F110 in the F-16 and the F414 in the F-18 – it's just sized and designed for the F136 application," says McCormick. The Fighter Engine Team has not said whether the F136 augmentor is stealthy but since the F-35 specification calls for the engine augmentor to be stealthed – and Pratt & Whitney's augmentor for the F135 is a stealth design – the presumption is that the design of the F136's afterburner unit incorporates stealth features.

F136 Ground-testing

DiLibero says that the Fighter Engine Team accumulated more than 900 hours of testing with six SDD-standard F136s in 2010 – more than 400 hours of it on engine 625-005, the second SDD-standard engine, which was sent to the US Air Force's Arnold Engineering Development Center (AEDC) in Tennessee for testing of its overall performance capabilities – and was "laser-focused" on meeting its target first-flight date this year to move towards CTOL initial service release (ISR), when the Pentagon issued its stop-work order on the F136. Like the F135, the F136 has sophisticated FADEC software and a real-time prognostic and health monitoring system to aid maintainability.

Engine 625-005 "has been the cornerstone of our overall performance capability" testing, says McCormick. The Fighter Engine Team has built eight engines for the F136 ground-test program, six of which had run by April. Engine 625-004 – tested at GE's facility at Cincinnati – was the first SDD-configured engine and was festooned with "several thousand pieces of instrumentation" to look at the aeromechanics of the finalized engine design's increased airflow and the design of its fan section. After the completion of this testing, 625-004 was sent for rebuilding and re-instrumentation for continued aeromechanical testing, in order to generate data for F136 flight-testing. That work was stopped due to the Pentagon's "stop-work" order.



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Powerplant number 625-005 went back to GE's Cincinnati facility in March after completing more than 400 hours of ground-testing at AEDC beginning in autumn 2010. Testing focused initially on controls development and then progressed to exploring performance throughout the flight envelope, including (ground-simulated) stall testing, performance testing and air starts. "The experience has been extremely good," says McCormick. "The engine has met or exceeded all [required] performance characteristics," including dry and wet thrust, operating temperatures and temperature margins, and airflow rate.

"We floated a 15% [thrust] margin at max afterburner as an installed assessment, and we generated a little over a 15% thrust margin," recalls McCormick. Performing an "installed assessment" mean the partners tested the engine for thrust while taking shaft horsepower from it via a drive shaft and while also extracting bleed air to power aircraft systems. The 15%-plus achieved thrust margin suggests the F136 recorded maximum thrust with afterburner of nearly 50,000lb (222.4 kN). Warren Boley, President of Pratt & Whitney Military Engines, has suggested that P&W's F135 has achieved a 20% margin over the 43,000lb (191.27kN) required by the F-35 specification – thus achieving maximum thrust of at least 51,000lb (226.86kN) – but Boley concedes the testing was on an uninstalled basis, without shaft horsepower and bleed air being extracted from the engine.

In the F-35 installation, the F136 uses the Pratt & Whitney exhaust system and a key element of testing of the second SDD-standard F136 at AEDC in 2010 was validation of the F136 and its augmentor with the P&W exhaust system. Testing led to P&W approving the F136-augmentor combination "all the way out to the right-hand edge of the flight envelope," says McCormick.

Engines 625-006 and 625-007

Engine 625-006, the third SDD-configured F136, first ran "very early" in 2010 and testing continued "for a couple of months", with the engine accumulating about 145 hours of test time. McCormick says the main objective of initial testing on 625-006 "was to validate augmentor work". GE and Rolls-Royce had not done any such testing in their pre-SDD phase, because they actually used the pre-SDD hardware to do augmentor testing in the SDD phase. "So we wanted to do risk reduction and get early experience with the SDD-configured engine."

After this testing, 625-006 was partially disassembled, refurbished and rebuilt as an engine configured for the F-35B short take-off/vertical landing (STOVL) requirement, complete with drive shaft, Rolls-Royce LiftFan, roll posts and the three-bearing swivel module behind the engine's exhaust nozzle. The engine is now hung on the test stand at GE's unique Site 7 STOVL facility at the company's Peebles plant

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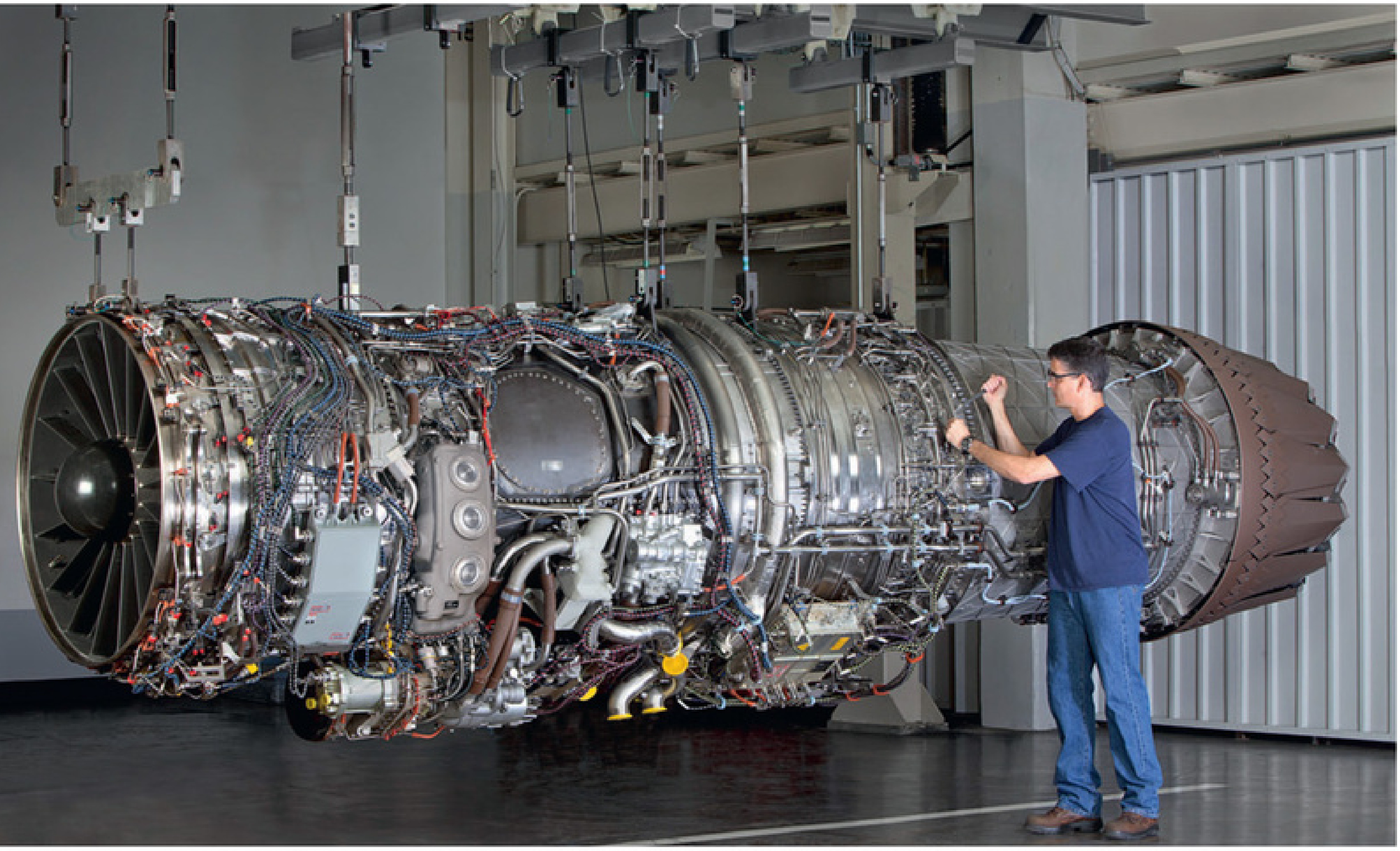

1 A cutaway image of the GE Rolls-Royce Fighter Engine Team F136. **2** The first F136 test engine at the GE facility at Evendale, Ohio.

east of Cincinnati. "It's ready to run as soon as we get funding," says McCormick.

Like the rival F135, any F136 installed in an F-35 will be controlled through BAE Systems FADEC (full authority digital engine control) computers attached to the engine casing. However, the Fighter Engine Team has developed its own FADEC software and engine performance and health monitoring (PHM) software. "We have a building-block approach to software – we started with the CTOL [conventional take-off and landing] version and last October we finished up the next version, incorporating the STOVL operation," says McCormick. "In addition to generating software to run the ground-test engines, we package it and give it to Lockheed Martin," which loads the software in rigs at its Fort Worth F-35 assembly plant. "So we're running our own software in the simulator and on their rigs – we have a lot of integration with Lockheed Martin."

Another F136 that has accumulated a lot of ground-test hours is 625-007, the fourth SDD-configured engine, which has run for more than 400 hours at GE's facility at Evendale, Ohio. Testing on 625-007 primarily focused on the stall margins for the fan unit and compressor, along with "overall controls work to make sure we have the right control cycles round the entire flight envelope", air starts and the engine's lubrication system. McCormick describes the testing carried out on 625-007 as "key testing" for the F136 programme.

Testing on 625-007 was completed in February before sending it to AEDC for final CTOL flight-clearance testing in preparation of the first flight of the F136. Before the Pentagon issued its Stop Work order on the F136, the first flight was planned for later this year. Engines 625-005 and 625-007, each of which had accumulated more than 400 hours of ground-testing before going into rebuild and which were the highest-time engines, had the same late-model release of the F136 FADEC and PHM software. Data collected from testing of this package was to be incorporated into the final software package for flight-test F136s and was also to be sent to Lockheed Martin for final flight-integration work on the F136.

Engines 625-008 to 625-010 and beyond

In a GE test cell, engine 625-008 suffered the only serious failure of any F136 to date when a combination of parts tolerances "not in the right direction" created a seal-clearance issue in the fan module, during testing at sea-level, static air-pressure conditions. "The parts were all manufactured to print, but there is a variation of tolerance allowed within parts and this stacked up" in an unsuitable way, according to McCormick. As a result, the seal clearance was "tighter than we understood it should be", and this caused the failure of a fan rotor arm. The fan stayed intact, so no blades or other fan fragments entered the engine core, but the failure of the rotor arm required Rolls-Royce to redesign the fan module so that, in future, normally allowable variations in tolerances cannot stack up to create an overall set of tolerances which can cause a failure.

Engine 625-009, which carried out only limited testing, has been in rebuild with a view to beginning 300 hours of endurance testing of the F136 – to gather data for the flight-clearance programme – if or when the funding issue is resolved. (Although GE said following the Pentagon's Stop Work order that it would continue to fund the F136 programme itself, the order specifically banned the Fighter Engine Team from continuing to ground- or flight-test the F136. As a result, the team will only be able to analyse data and perform design work until the order is rescinded.) Meanwhile, the Fighter Engine Team is "gathering hardware" for engine 625-010 and – when the funding environment allows – it will be used for endurance testing.

The last of the eight SDD-configured engines (for which some hardware was in process by April but which would not be built until late 2011) has been given a serial number well out-of-sequence with the preceding engines. This engine has been numbered 625-047, because it is the first engine built specifically to a configuration and quality standard for flight-clearance testing. The engine's serial number follows on from the 625-041-to-625-046 sequence which the Fighter Engine Team has allocated for the first six planned F136 flight-test engines, because GE and Rolls-Royce intend for 625-047 not only to be used for flight-clearance testing, but also to be available as a spare engine for the flight-test programme.