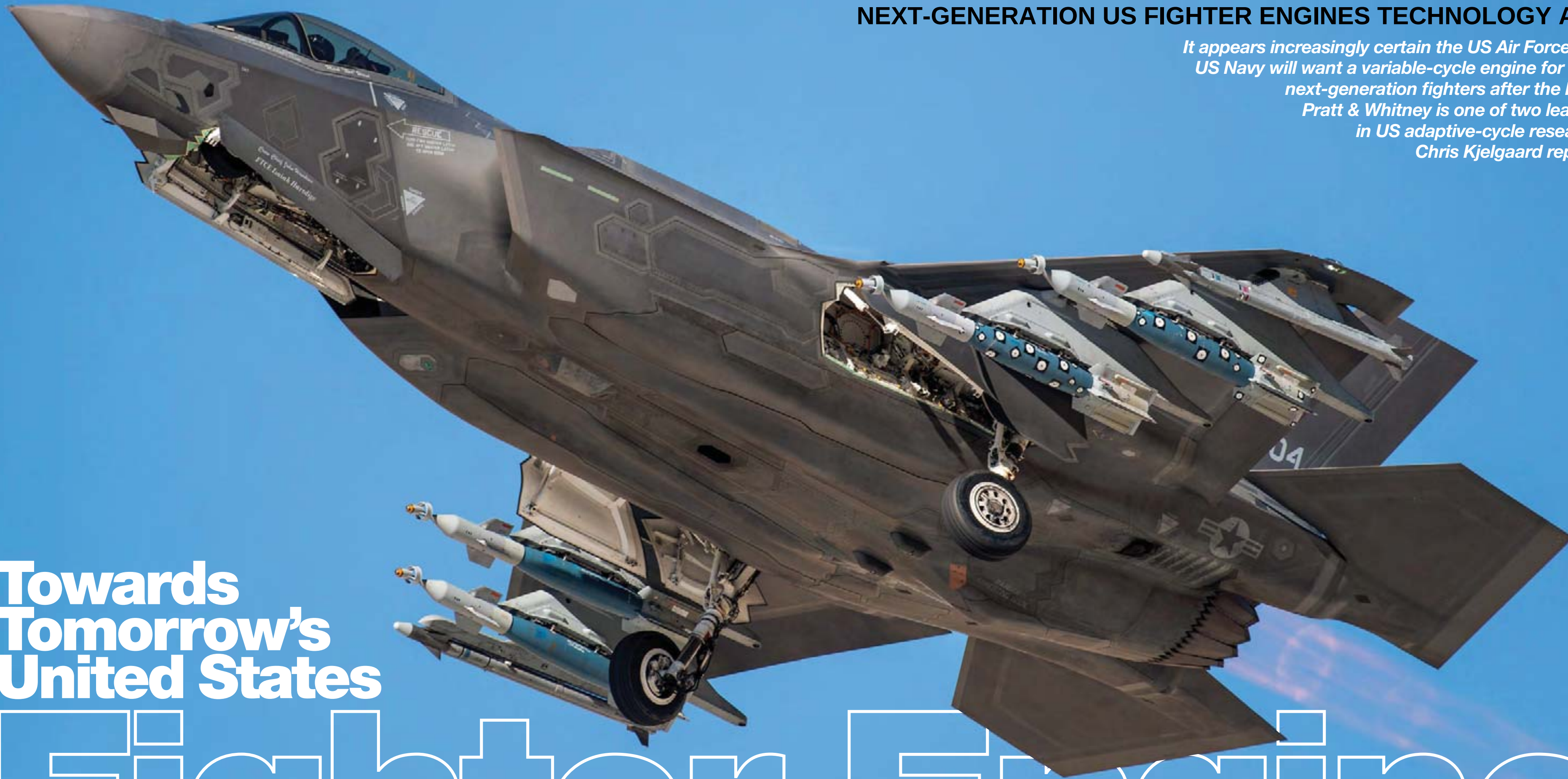
It appears increasingly certain the US Air Force and US Navy will want a variable-cycle engine for their next-generation fighters after the F-35. Pratt & Whitney is one of two leaders in US adaptive-cycle research. Chris Kjelgaard reports

Towards Tomorrow's United States Fighter Engine



Richard VanderMeulen

President Barack Obama's inclusion of a funding allocation for a four-year Adaptive Engine Transition Programme (AETP) in his Fiscal 2016 annual budget request to the US Congress has focused attention on the research efforts that both GE Aviation and Pratt & Whitney are conducting for the Air Force Research Laboratory (AFRL) on variable-cycle turbofan engines for next-generation fighters.

Should Congress approve President Obama's request, the four-year Adaptive Engine Technology Development (AETD) research projects on which the two US-based manufacturers have been working since 2012 (and which are due to end with demonstrations of their designs before the end of 2016) would undergo a quick transition into a full development effort.

Other than vetoing outright President Obama's AETP budget request, it's possible that Congress might choose only one of the two AETD designs under development to move towards volume production. That would depend on the Pentagon's view on which of the two manufacturers' designs holds most promise in terms of performance, reliability and cost.

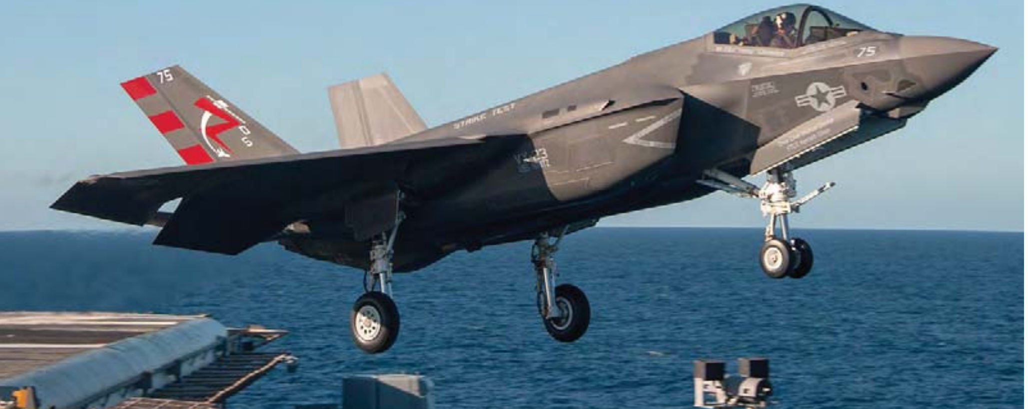
Congress could also choose to allow development of both AETD designs to proceed through the engineering, manufacturing and development phases of the AETP into full production. This would happen if Congress felt sales competition between the two manufacturers represented the best way to keep overall engine-purchasing costs down and offer flexibility in propulsion choices for future US fighters.

A potential AETP development effort for either P&W's or GE's AETD designs, or both, would be aimed particularly at developing and creating the conditions for volume production of adaptive-cycle engines. These would be designed specifically to power the sixth-generation aircraft beyond the F-35 meeting, respectively, the US Air Force's Next Generation Air Dominance (NGAD) and the US Navy's FA-XX project requirements.

Decision Time Nears

Jimmy Kenyon, Pratt & Whitney's Director of Advanced Programmes and Technologies told *AIR International*: "Unlike any other time in history, when F135 SDD [system development and demonstration] ends at the end of 2016, there will be no [new] US fighter engine in development." He said "the increased urgency of [the] NGAD [requirement] creates an opportunity" for Congress to act swiftly to ensure the US leads future fighter-engine design by approving the transition of today's AETD projects into AETP efforts, leading to full production of sixth-generation adaptive-cycle engines.

Kenyon declared that AETD/AETP is "integral" to that future-fighter engine effort: "If you take and mature it, it is timed pretty



well for when NGAD [development] would start in earnest. The other part of it is that [the adaptive-cycle engine] is a fundamental new technology and is a game-changer. I can inform and be informed by those requirements, so I can develop the right technology for the right application for the right time."

He added: "It is sort of linked to the Aerospace Innovation Initiative". This was announced by US Under Secretary of Defense for Acquisition, Technology and Logistics Frank Kendall on January 28. It is a funding strategy designed to protect the US industrial base from losing its global lead in military aerospace design and technology as a result of sequestration cuts.

The initiative, which would initially be led by the Defense Advanced Research Projects Agency but would also involve the air force and navy, would concentrate on developing prototypes for the next generation of US fighter aircraft – manned, unmanned or both.

Beyond the F-35

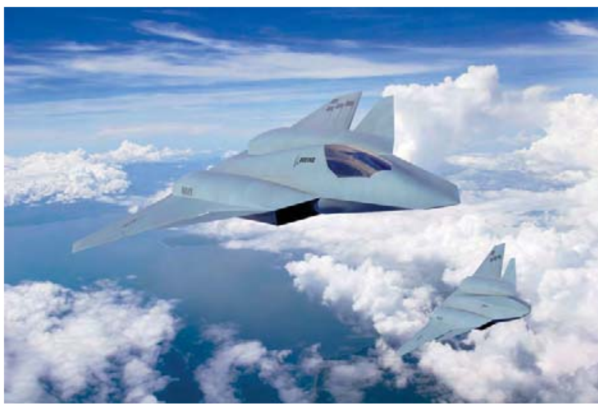
Within this supporting funding structure, any manufacturers selected to develop adaptive-cycle designs into one or more production-capable engines would be "taking technology and being influenced by those next-generation-of-aircraft needs", said Kenyon.

At present, P&W and GE Aviation "can only really use the F-35 as an example" of a current-production, advanced fighter to inform their future fighter-engine designs.

This is why, in the absence of an airframe-specific requirement from the AFRL other than that the manufacturers' AETD designs should provide 10% higher maximum thrust than the F135 but be 25% more fuel-efficient, both companies chose to base their AETD designs on the existing F-35 installation.

The F-35's existing F135 powerplant is the world's most powerful fighter engine, but its installation within the F-35 is a particularly complex tight squeeze due to the designed-by-committee constraints and requirements the F-35 airframe has had to satisfy.

Any adaptive-cycle engine that can fit into exactly the same dimensions as the F135 (or the F136, GE's alternative F-35 engine, which Congress killed off despite that engine's promise) will require exquisite skill in its design, major technological advances to provide its performance improvements, and superb engineering to pack its complexity into the F-35 airframe.



Contrastingly, "having an aircraft optimised [for a future engine developed in parallel with the airframe] would be sort of a holy grail," remarked Mark Buongiorno, Pratt & Whitney's Vice President of the F135 Engine Program: there wouldn't be anything like as many adaptive-cycle engine design constraints for a new airframe as there would be for one designed for the F-35.

The Need for Adaptive-Cycle Engines

But why are the USAF and US Navy so excited about adaptive-cycle engines? They see these propulsion systems as the only way technologically can develop turbofan engines that can meet the thrust, cooling, fuel-efficiency and electrical power-generation requirements – one megawatt or more, for directed-energy weapons and electronic countermeasure needs – that the sixth generation of USAF and US Navy fighters will demand.

Military operators would use the 25% fuel-efficiency improvement and 10% additional thrust (compared with the F135) the AFRL is demanding from the manufacturers' AETD designs in various different ways.

Although much of a typical mission consists of target-area ingress and egress in cruise configuration, in the target area itself the pilot may require high power from the aircraft. Here, the 10% thrust improvement would help ensure rapid acceleration and improved manoeuvring capability.

In a sixth-generation aircraft the 25% fuel-efficiency improvement would probably translate into a 30%-35% increase in range over today's fighters – a performance enhancement that could transform an air force's basing and force-allocation decisions. Meanwhile, for flight- and combat-training missions, pilots could upload far less fuel and still spend the same amount of time in the air.

Providing the Benefits

Instead of relying on the two streams of air – core air and bypass air – that current-generation military and civil turbofans use, tomorrow's fighter engines will also use a third stream of air passing outside the engine core and the main bypass duct to perform a variety of functions. To perform these functions, the third air stream will be capable of being modulated.

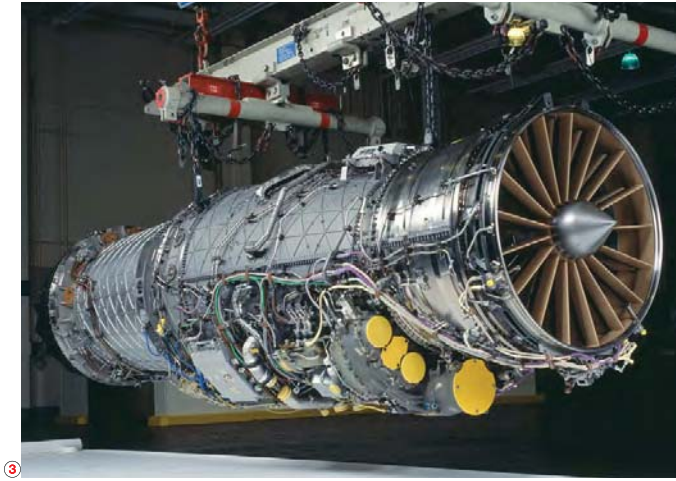
This modulation will be controlled by variable-geometry features within the fan section and the extra, annular duct through which the third stream will flow. The additional functions and variable-geometry features will flexibly modify the way the engine's fan section operates, creating what effectively will be a variety of different turbofan engine designs in one package.

The third stream will provide a way to offer a smooth transition from a low-pressure-fan, high-bypass turbofan at one end of the fuel-efficiency/power curve to a high-pressure-fan, low-bypass turbofan at the other. At the high-pressure-fan end of the curve, the adaptive-cycle engine will act like a pure turbojet – pushing almost all the air entering the engine inlet through into the core, to be combusted and exhausted, providing high power for take-off and acceleration.

At the low-pressure-fan end of the curve, the third stream will turn the adaptive-cycle engine into a high-bypass turbofan offering high fuel efficiency. This will provide the future fighter with increased range and longer loiter time and will reduce its overall fuel burn.

Transitions through intermediate stages of fan pressure and bypass ratio will offer a range of operating states, any one of which will be automatically selected during a given phase of flight or manoeuvre to provide the engine with an optimal ratio of core air to bypass air.

During supercruise, the duct carrying the third stream would be able to swallow and feed through the adaptive-cycle engine much or all of the inlet air that the core and bypass streams of today's two-stream fighter turbofans can't accept. In supercruise today this air gets pushed back out of the engine inlet, essentially being dumped overboard. This dumping creates a phenomenon known as spillage drag, which complicates and hampers a fighter's ability to supercruise easily and fuel-efficiently.



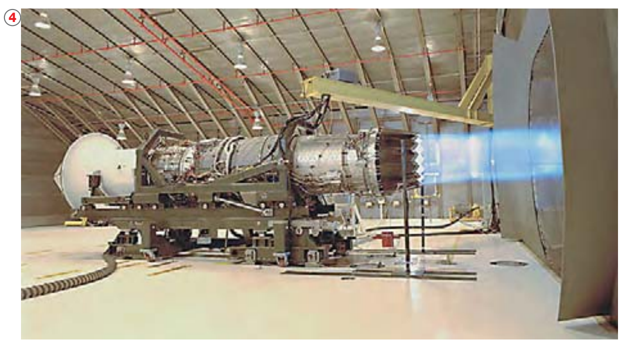
The third, adaptive stream of air will also increase greatly the extent of cooling the engine can offer the airframe, to make sure the aircraft's performance isn't constrained in any area of its flight envelope by the airframe retaining too much heat.

When this article was written in mid-April, the F-35 was known still to have an airframe heat-retention issue that prevented it from operating at sustained high subsonic speeds (within 20% of Mach 1) at low altitudes. While potentially solvable, this isn't a problem that F-35 pilots or operators of future NGAD fighters would want to have during a mission.

Additionally, the third stream will provide a way to increase the electrical power requirement available from the engine when such an increase is needed.

Kenyon also noted that, "it would be very good for the efficiency of the engine if you could manage adaptively the very high transient temperatures behind the augmentor". Yet another benefit is that the third stream will cool the hottest parts of the two-dimensional, non-axisymmetrical exhaust nozzles that future US fighters will use to mask their exhaust heat to improve their stealth qualities and missile-defence capabilities.

1 Based on the AFRL's requirements P&W's AETD design should provide 10% higher maximum thrust than the F135 but be 25% more fuel efficient. *Lockheed Martin* **2** P&W's AETD design would be aimed at an adaptive-cycle engine for the US Navy's sixth-generation F/A-XX. *Boeing* **3** Block 1 F135 improvements could be available for new-production examples and for retrofit into existing ones from as early as 2018. **4** P&W is working with the US Navy on the Fuel Burn Reduction programme, which has married the HPT technologies from the XTE68-LF1 with a series of improvements to the F135's six-stage, all-blisk compressor.



P&W's AETD Project

At the time of writing, Pratt & Whitney was about to enter a two-to-three week preliminary design review (PDR) of its design with AFRL engineers and scientists, a passing grade from which was necessary for the company to be able to proceed with its planned additional AETD developments and demonstrations. (GE Aviation completed its PDR in the first half of March, the AFRL approving of GE's AETD design work to date and allowing the manufacturer to proceed to its planned series of rig tests and demonstrations.)

While P&W doesn't intend to perform a compressor rig test of its AETD design, the company did have a "very successful first test of a three-stream, full-scale design in late 2013", according to Kenyon, primarily to verify P&W's tooling and design capabilities for the subsequent AETD research effort.

Assuming a successful completion of its PDR process, P&W will then manufacture hardware for the two big AETD tests it plans to conduct before the programme ends in the latter half of 2016. First will be a test of a full-scale "very high-efficiency core" that P&W has designed specifically for the AETD project. P&W's testing will culminate next year with a demonstration of a full-scale, three-stream fan module "in a real-engine environment", according to Kenyon.

P&W has ensured this demonstration will be authentic by purchasing internally one of its own F135 engines. The company will fit its three-stage, full-scale AETD fan on to the front of the core of this engine,

1 The F135 Block 1 upgrades rely partly on development work carried out by P&W in autumn 2013 for US Navy's XTE68-LF1 project to demonstrate higher operating temperatures in the F135's turbine.

which will retain the augmentor and exhaust nozzle. (GE's AETD strategy is different: it is conducting a rig test of a full-scale compressor but plans to test only a sub-scale version of its AETD fan design, before doing a full core test.)

Potential Future Developments

Although the AETD project seeks flexible variation of the fan pressure and bypass ratio of a turbofan fighter engine in order to alter its fuel efficiency, thrust, cooling and electrical power-generation capabilities, Kenyon sees no reason why future fighter engines shouldn't be made adaptive in other ways as well.

"There are ways of looking at taking the core and making it adaptive, as well as the fan," he said. "It's really pretty neat, when you look at it in that context. It's all about air management, and where do I want to put that air in the [compression-combustion-exhaust] cycle.

"Beyond AETD, can [adaptive design] change? Yes, if there's more funding. AETD opened up the [adaptive] world…[there could also be] an adaptive core, somewhere in five-ish years. If I know I have a propulsion system that needs to do a lot of stuff of a transient nature, that's a big deal. Adaptive capability] changes the performance of the core in a number of different ways."

Here Kenyon is talking about the US Navy's Variable Cycle Advanced Technology (VCAT) programme, in which P&W has been engaged as an industry partner since 2012. This nine-phase programme, still in an early stage of development, aims to create a suite of technologies which, Kenyon said, would be different from but in many ways complementary to the adaptive-fan technologies developed for AETD. Few details are available about VCAT, but it is concentrating on developing adaptive-cycle features for a future fighter-engine core.

Asked if marrying VCAT technologies with those from the AETD programme would produce fuel-burn and thrust-increase benefits beyond those produced by an adaptive-fan engine alone, Kenyon said an engine design incorporating AETD and VCAT adaptive features would offer "substantially greater" benefits.

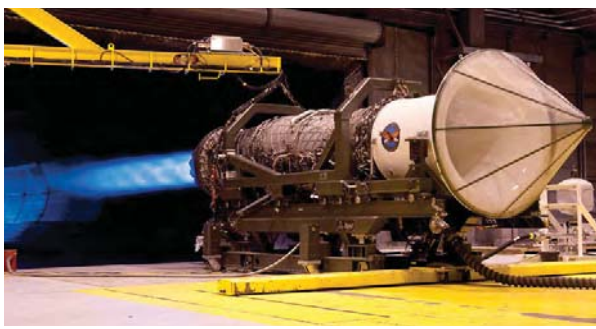
A Two-Pronged Approach

Kenyon and Buongiorno are sure the adaptive-cycle approach is the right one for the next generation of US fighter aircraft potentially entering production in the latter half of the 2020s or beyond. But they are by no means as sure it is necessary to re-engine the F-35 with a fully adaptive-cycle engine by the mid-2020s – a step for which some military strategists have argued, given the F-35's known heat-retention problem and likely future increases in operators' power-generation requirements.

As the manufacturer of the F135, P&W has a vested interest in ensuring that its engine continues to be the sole-choice powerplant for the F-35 throughout the aircraft's production life.

Nevertheless, Kenyon and Buongiorno said many of the benefits an adaptive-cycle engine could provide for the F-35 could instead be provided by a lower-risk, two-stage F135 development strategy that P&W is calling its F135 Block Upgrade Plan.

Under this new strategy, which the company revealed on April 2, P&W would create a development plan for the F135 – much as it did for its enormously successful F100 engine, which has been in service for 40 years this year but will remain in production at least until late 2016. Today's F100s are vastly different from early F100s in terms of their time-on-wing durability, their operational reliability and the maximum thrust they offer; P&W thinks F135 development will proceed similarly.



Kenyon believes there are many parallels between the F100 and the F135 programmes: just like the F100, thousands of F135s will be built and it will see service for decades with a wide variety of air arms throughout the world. Now the end of the F135 SDD initial-capability phase is in sight, it behoves P&W to address a long-term development plan for the F135.

The F135 Block Upgrade Plan

Under the F135 Block Upgrade Plan, a series of initial 'Block 1' improvements might potentially be available for new-production examples and for retrofit into existing ones from as early as 2018. Then a second series of AETD project-derived, more substantial 'Block 2' improvements could be put "into production in the very early 2020s", depending on "funding and the requirement pool", according to Kenyon.

Although Kenyon points out this plan is "not part of the F135 programme proper", he said "it is an opportunity looking ahead to demonstrate fuel-burn cost savings" to F-35 operators – and particularly to the US Navy, with which P&W is working to try to get the Block 1 F135 upgrades into production within the next few years.

The Block 1 upgrades rely partly on development work that P&W carried out for a demonstration in autumn 2013 for the navy's XTE68-LF1 project. This focused on demonstrating a capability for higher operating temperatures in the F135's turbine and introduced a variety of new technologies into the engine's high-pressure turbine (HPT) module.

These improvements, which Kenyon described as "advanced cooling technologies", included new casting technologies for metal-alloy parts; new, highly temperature-resistant HPT materials; new thermal barrier coatings for HPT blades and vanes; more temperature-resistant oils for lubricating and cooling; and a new main shaft bearing.

He said P&W's XTE68-LF1 demonstration in autumn 2013 was "tremendously successful" – so successful that it recorded "the hottest-ever temperature in a production engine".

P&W has parlayed this successful demonstration into another F135 development initiative on which it is working with the US Navy, called the Fuel Burn Reduction (FBR) programme. FBR has married the HPT technologies from the XTE68-LF1 demonstration with a series of improvements to the F135's six-stage, all-blisk compressor to produce an engine offering a fuel-burn reduction of "about 5% – and we've identified another couple of opportunities to give [another] 1%-2% of fuel-burn improvement", said Kenyon.

However, saying the XTE68-LF1 and FBR technologies would just reduce fuel burn only in production F135s would be inaccurate: the technologies would also offer other improvements. "The JPO (F-35 Joint Programme Office) and navy are both focused on [engine] life-cycle cost and they need to have the technology working reliably," said Kenyon.

An important feature of the XTE68-LF1 and FBR advanced cooling technologies is that "you need less air to do the cooling [in the HPT] and you can use it more to do other things, with the cooling capability already in the engine. We're using low-lying fruit to get better thermal management," he said.

"Right now I'm going to insert this nice cooling technology into my turbine because it helps with [life-cycle] cost [by making the engine more durable], but I could use it to generate more thrust" – perhaps up to 10% more, making the F135 capable of meeting any foreseeable F-35 thrust-growth requirement.

There is no doubt about this. During its original ground-testing effort for the F135, P&W ran an unimproved engine at thrust levels of up to 51,000lb in uninstalled configuration (ie without any accessory gearboxes or drives drawing power from the engine). This suggested that, even on an installed basis, the F135 had several thousand pounds of additional thrust available if necessary, if run at high temperatures.

Kenyon pointed out that, although the F-35 airframe has had heat-retention issues, "right now, there are no thermal restrictions with the engine". In-service F135s are operating within the specifications required by the JPO and presumably could be operated at a higher maximum temperature as long as the F-35 airframe could withstand and dump the additional heat burden.

F135 Block Upgrade Programme: Block 2

Pratt & Whitney's proposed Block 2 upgrades for the F135 would be more complex than those in Block 1. The manufacturer can see a potential path by which it could introduce into the F135 engine, for production from the early 2020s, some of the advanced technologies it has developed for the compressor and turbine in its high-pressure AETD core.

The F135 has the same dimensions as the AETD demonstrator upon which P&W is now working. But while that is a three-stream engine, at this juncture P&W does not view redesigning the F135 into a three-stream, adaptive-cycle engine – which may be theoretically possible.

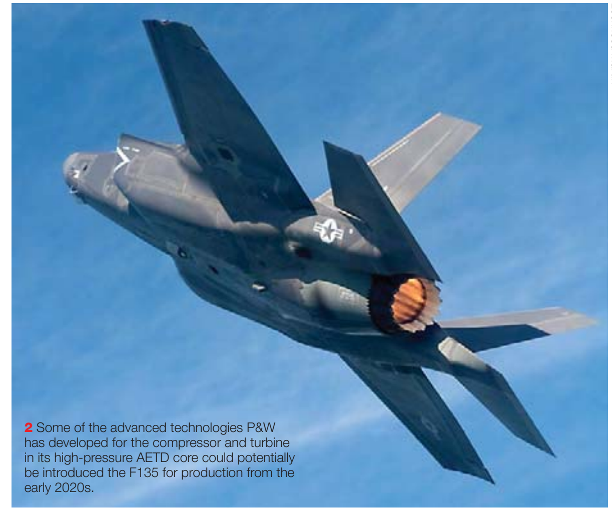
However, Kenyon said there is an "exciting opportunity we've identified, which is unique to Pratt & Whitney's position, to take some of the key technologies of the three-stream AETD architecture into the F135 to get lots of benefits".

This opportunity could rely on a potential evolution of the company's engine-control software for its AETD demonstrator.

Kenyon said: "For example, if you can modulate the [existing] bleed air using the three-stream control laws, rather than using an actual third stream of air," this could produce substantial benefits from an enhanced capability to use cooling air flexibly at different places in the engine's hot section. "The trade is really around the re-use of current learning," he said.

In addition to incorporating a series of AETD-derived hardware and software upgrades, as well as other cooling and design technologies, a future Block 2 upgrade of the F135 might also incorporate the improvements already provided under Block 1. P&W isn't sure yet of the scale of the fuel-burn reduction and thrust increase a Block 2 upgrade would offer, but they would certainly be more substantial than those provided in Block 1. It's possible Block 2 modifications could produce benefits even greater than the AFRL's AETD project targets of a 25% fuel-burn improvement and 10% thrust increase over today's F135 engine.

The future of adaptive-cycle engines for US fighters, and even the future development of the existing F135, relies greatly upon Congress approving President Obama's AETP budget request. If approval comes at all, it will likely come this year. Pratt & Whitney is now beginning to flesh out a two-pronged strategy to try to retain its dominant position in current-generation US fighters and win a prominent position on US next-generation fighters. It will hope Congressional approval for AETP is prompt and generous – and that the AFRL likes P&W's AETD design.



Lockheed Martin

2 Some of the advanced technologies P&W has developed for the compressor and turbine in its high-pressure AETD core could potentially be introduced the F135 for production from the early 2020s.