

The announcement by GE Aviation on February 27 that its XA100 variable-cycle fighter engine design had completed—to the satisfaction of the US Air Force Research Laboratory (AFRL)—the detailed-design process under the US Air Force's Adaptive Engine Transition Program (AETP) means GE is cleared to manufacture all the parts required to build and test XA100 engines.

David Tweedie, GE Aviation's general manager for advanced combat engines, told AIR International that the detailed-design process involved GE passing "a staggered set of detailed-design reviews (DDRs) over the course of time. That activity was concentrated in 2018." GE completed the last of the detailed-design reviews before the end of last year, "so at this point there are no further customer DDRs planned as part of the baseline programme. Now we are pivoting to focus on getting the engine manufactured and tested. It's time for the engineers to put their pencils down, for parts to come in, and let's go get the data."

In completing the detailed design of the XA100, according to Tweedie, the company has moved on to a new phase of development from the primary technology-development effort in which it has been involved for the past 12 years to design and mature a variable-cycle fighter engine based on an adaptive-cycle fan design. Its XA100 design having been approved by the US Air Force, GE has now embarked on the final push to complete Phase 1 of the two-phase AETP programme. This push represents the final maturation

of adaptive-cycle fan engine development to the point where an XA100-sized engine can be placed quickly—and with very little technological and design risk—into volume production if required, said Tweedie.

This final push will involve GE Aviation manufacturing the parts needed for three complete XA100 engines that it will build and test by 2021, and GE testing the three engines fully and providing the resulting data to the AFRL. Also, highly importantly, throughout the process the company will be required to demonstrate to the satisfaction of the US Air Force Life Cycle Management Center (AFLCMC, which is overseeing the AETP programme) that GE can reliably manufacture the quantity and quality of parts needed for volume production of the XA100 should the US Air Force decide it requires that.

Along with Pratt & Whitney's XA101 variable-cycle engine, GE Aviation's XA100 is one of two adaptive-cycle fan engine designs competing for what may eventually be a decision by the US Air Force to order just one variable-cycle fighter-engine design into production based on the service's findings from AETP Phase 1. In 2016, the AFLCMC awarded each of the two companies a \$1 billion, five-year R&D contract under AETP Phase 1 so the US Air Force could choose a potential winner from the XA100 and XA101 and order it into production during the first half of the 2020s.

As finally became clear publicly in mid-2018, the US Air Force specifically had in mind a potential decision to re-engine the Lockheed F-35 from about 2025 onwards, partly as a

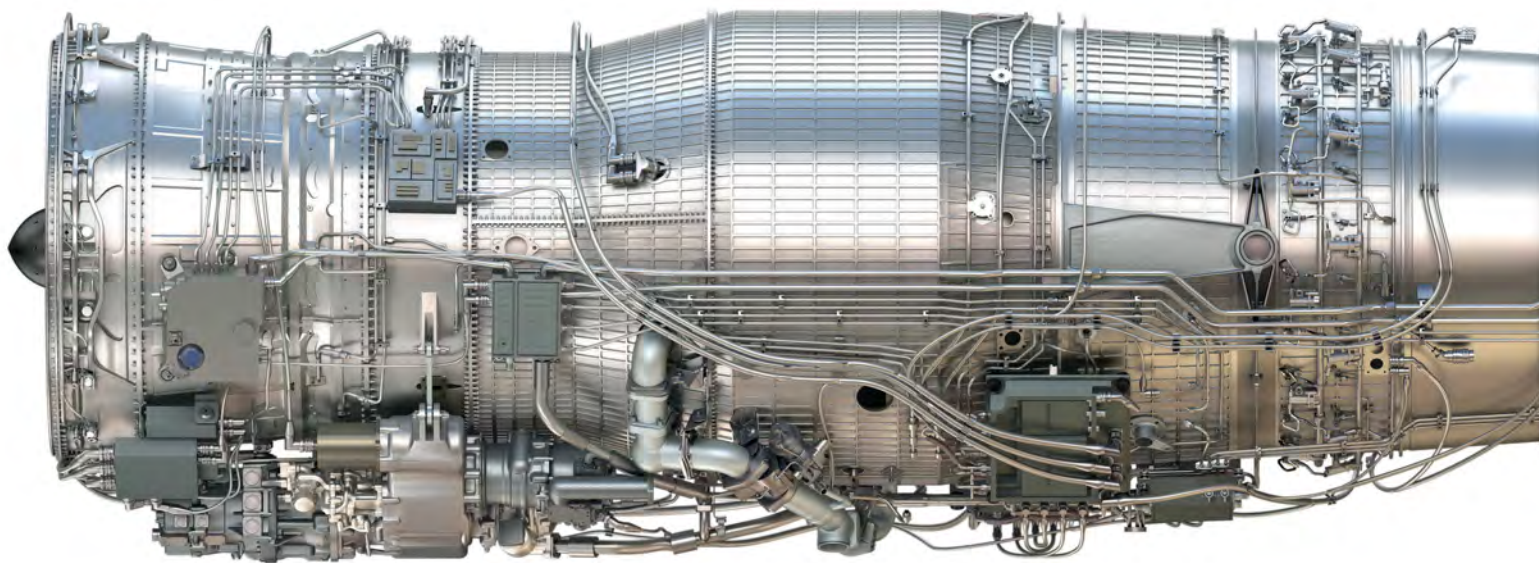
result of the known thermal-management challenges the F-35 has today in combination with its existing F135 engine. To that end, the AFLCMC specified that not only must the XA100 and XA101 fit the space within the F-35 that the F135 occupies today, but it also required the competitors' variable-cycle engines to demonstrate a 10% maximum-thrust increase over the F135, along with a 25% fuel-efficiency improvement and the capability to give the F-35 a 20% range increase.

Also specified, but not in a manner relayed publicly, is that the AETP Phase 1 competitors must provide the F-35 with substantially, perhaps very dramatically, improved thermal-management capabilities. Of necessity, those thermal-management capability improvements require that both AETP Phase 1 competitors work very closely with F-35 airframe manufacturer Lockheed Martin to integrate the airframe and its systems with the engine and its systems to an extremely high degree.

However, should either Pratt & Whitney's or GE Aviation's respective AETP Phase 1 engine design lose the AETP Phase 1 competition and not be ordered for volume production, the losing company may yet retain hope that its AETP R&D work may still end up in a production contract. This is because in 2018 the AFLC awarded each of the two companies a new \$437 million contract to pursue R&D work under a new Phase 2 of the AETP programme, which is aimed at reducing — "burning down", in the words of Tweedie's recently retired predecessor Dan McCormick — the technological risk associated with development and manufacturing of variable-

GE Aviation's future fighter engine

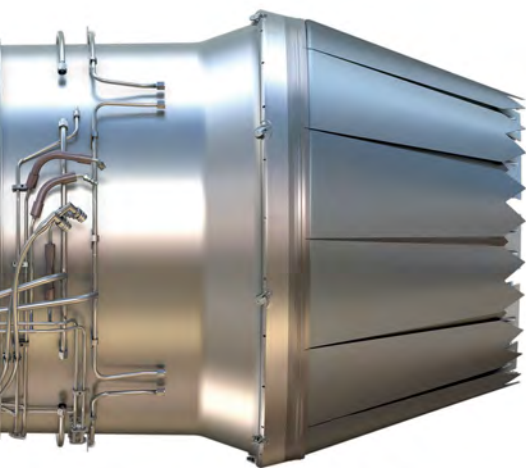
TECHNOLOGY XA100





GE Aviation's first fully adaptive-cycle fan engine in test. This engine was developed under the US Air Force's ADVENT research and development programme which ran between 2007 and 2012.

Completion by GE Aviation of the detailed design process for its adaptive-cycle fan engine signals a switch from technology development to ensuring manufacturing readiness, reports Chris Kjelgaard



GE Aviation's XA100 adaptive-cycle engine.

cycle engines sized in terms of thrust, weight and dimensions to power types or categories of future US Air Force combat aircraft other than the F-35.

So far the end date of AETP Phase 2 remains publicly unspecified; and Tweedie said the classified nature of the new R&D phase prevents him from indicating if it involves a preliminary design review and/or detailed design review. Nor is he prepared to discuss the potential timing, sequencing and details of any engine-module or full-engine testing programme that the AFLCMC may be requiring GE Aviation and P&W to perform under AETP Phase 2. All that is known definitely about the timing of the second phase of AETP is that it will run for an unspecified amount of time beyond the end of AETP Phase 1—but probably not more than a year or two beyond.

Completing phase 1

Any development programme for a modern military or commercial jet engine requires a complex, carefully timed staggering of the releases to parts suppliers of the detailed technical drawings for the hundreds of types of parts the engine-design contains. This is vital for allowing all the parts to be manufactured at the right time and in the right sequence to enable final assembly of test engines to take place, according to Tweedie. Release of the initial-design drawings for the longest-lead time parts comes first and the manufacturer continues to work on detailed design of long- and short-lead-time parts alike after those initial drawing releases.

For the XA100, "now, essentially, we're fully released," said Tweedie. "The engineers are putting the final [part] dimensions on drawings and [they] are clear to release all the drawings to the supply chain. We have released much of them and it's just a matter of releasing the drawings for the short-lead-time hardware."

By the 2000s, GE Aviation's long history of developing turbofan engines—Tweedie calls them "mixed-flow engines"—over nearly 60 years since it developed the CJ805-23 in 1960, the TF39 in 1968 and the F101 in 1970 eventually "told us we were pushing up against some empirical limits" in terms of the performance levels which can be obtained from a turbofan fighter engine, he said. However, GE's development of the first fully adaptive-cycle fan engine under the US Air Force's 2007-2012 ADVENT R&D programme persuaded it—and the US Air Force—that variable-cycle engines could create a paradigm shift in fighter-engine performance.

The company's subsequent learnings from the 2012-2016 Adaptive Engine Technology Development (AETD) and AETP programmes—both tendered and conducted with Pratt & Whitney in competition—told GE Aviation that by the detail-design stage of AETP Phase 1, "we liked our [adaptive-cycle fan] design the way it was", said Tweedie. Accordingly, throughout AETP Phase 1, GE Aviation has focused not only on fine-tuning its existing materials and aerodynamic design technologies in order to create a functioning and technologically low-risk XA100, but also in maturing its manufacturing technologies.



The US Air Force Life Cycle Management Center has specified that the GE Aviation XA100 and Pratt & Whitney XA101 must fit in the space within the F-35 currently occupied by the F135 turbofan engine.

Senior Airman Alexander Cook/US Air Force

"We have got the set of [required] technologies from ADVENT, AETD and AETP, but we still are going through some learning as we go through detailed manufacture," said Tweedie. This particularly applies to the manufacturing technologies involved in producing parts made of highly heat-resistant ceramic matrix composite materials and parts made using additive-manufacturing—popularly labelled "3D printing"—techniques. GE has made extensive use of both kinds of parts in the XA100 and the engine also incorporates parts made of polymer matrix composite materials, also made using advanced manufacturing techniques.

"Part of the learning is forcing yourself to make parts of sufficient quality to go in the engine," said Tweedie. From the US Air Force's point of view, the whole point of the AETP programme is to burn down manufacturing risk, which it and its industry partners describe systematically by means of a manufacturing readiness level (MRL) scale of defined technological and manufacturing capabilities. The scale's top step, MRL 6, is the fully continuing capability to sustain production at the fully required quality and at the fully required rate of any product or technology the US Air Force has ordered.

For the US Air Force, the whole point of the ADVENT, AETD and AETP R&D programmes has been to have a suitable engine — or

series of engines — fully available for its future combat aircraft when they are eventually built, said Tweedie. "We don't want to create [a situation where already-manufactured] aircraft have holes that need engines. Now that we understand the design system, when we commit to time, budget and performance, we can hit it with low risk," he said. "That includes the ability to manufacture in [the] quality, quantity and at a scale ... that is mature enough for us to have high confidence we can deliver quality hardware for these assets. By means of ADVENT, AETD and AETP, "we've gone from MRL 3 to 4 to 5 and now ... this is the final step, to go from MRL 5 to MRL 6, for many of the technologies."

Air Force thinking

Although the AETP R&D programme began in 2016 and specified an adaptive-cycle fan engine which was of the same dimensions as the F135 powering the F-35, the US Air Force and its two AETP contractors said at that time the specification merely served as a convenient reference point for GE Aviation and P&W to assist them in developing their respective AETP Phase 1 engines.

Indeed, each of the two contractors was allowed to inform the AFLCMC of its preference regarding the AETP engine's physical size and reportedly each asked to be able to develop an F-35-compatible engine.

Not until two years later did GE Aviation, in the person of then-GM advanced combat engines Dan McCormick, first confirm publicly—with the US Air Force's permission—that the AFLCMC had deliberately specified the AETP Phase 1 engine so that it could potentially serve as an F135 replacement.

Asked by AIR International why the US Air Force took this course, Tweedie said it had not wanted at the time to focus public attention specifically on a potential re-engining of the F-35 because the service had believed strongly for years—and had said publicly—that it believed variable-cycle engines would be fundamentally important for all of its future fighter aircraft. When the AETD programme began in 2012, the US Congress had asked about the purpose of the programme and even then the US Air Force indicated it thought adaptive-cycle engines represented the future for all of its fighter types, according to Tweedie.

Before the AETP programme began in 2016, the service had indicated the 10% thrust-increase requirement and the 25% fuel-efficiency improvement "would be foundational for the Air Force to have superiority against adversaries," Tweedie said. "Neither in words nor actions has the Air Force done or shown anything other than what it said then — this is the future for all our products."

The US Air Force has always had valid reasons for this belief, said Tweedie, adding that the most important one is illustrated by the concept of “technology S-curves”. When performance improvements generated as a result of the introduction of a major new technology are graphed against the time elapsed since the technology is first applied, the graph line usually exhibits a pronounced ‘S’ shape.

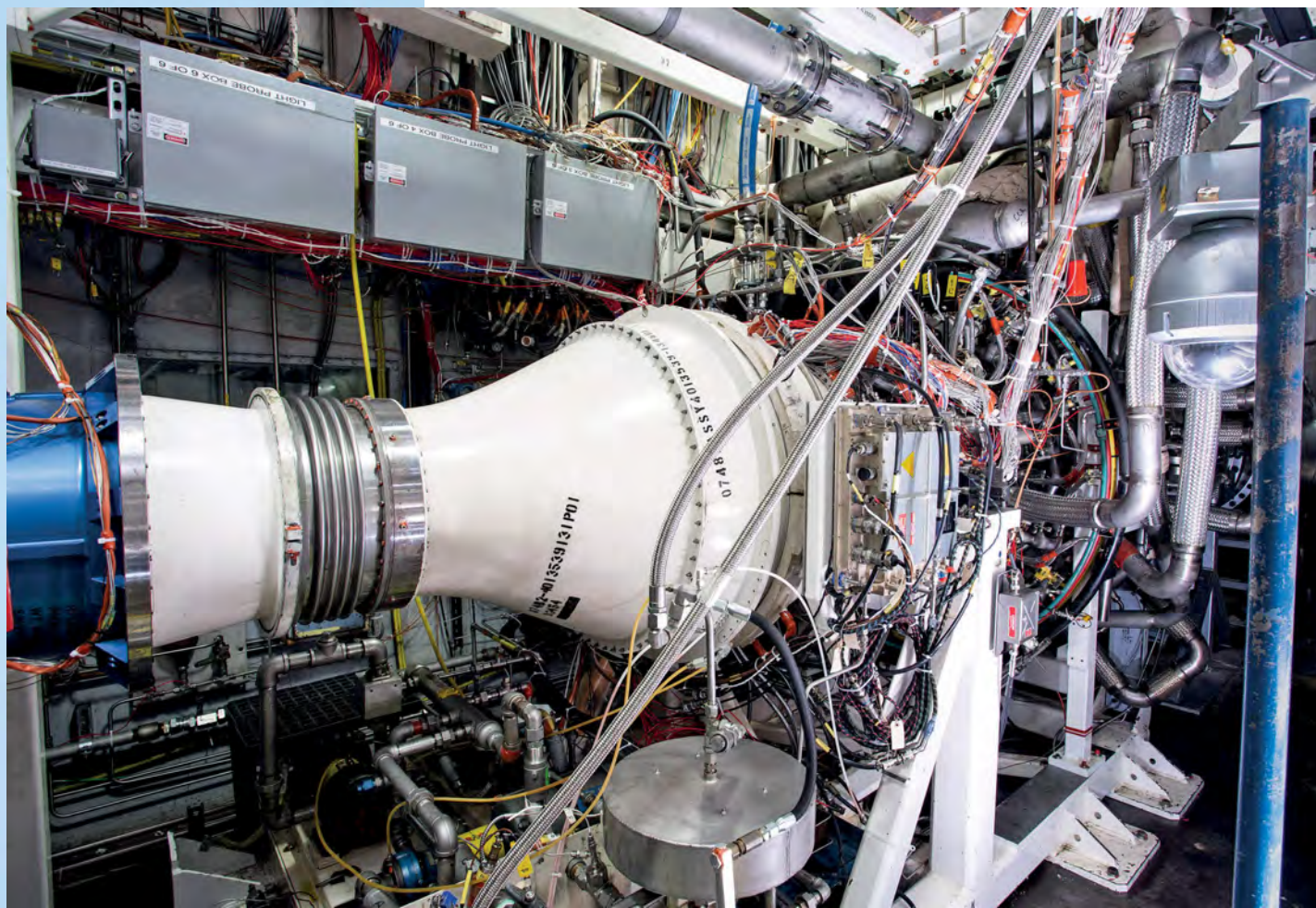
This ‘S’ shaped line occurs because, initially, the level of performance improvement is only gradual, as manufacturers begin to explore how the new technology can be improved and developed. At a certain inflection point, however, the manufacturers know enough about the new technology to be able to improve its performance dramatically in a relatively short period of time and this rapid improvement results in the graph line climbing steeply. But eventually, at a second inflection point, the technology becomes mature and manufacturers are no longer able to produce dramatic and rapid performance improvements by introducing further refinements to the technology. So the graph line flattens out again.

The respective development histories of turbojet and turbofan engines provide good examples of technology S-curves, according to Tweedie. After they were first introduced in the 1940s, turbojet engines initially offered only minor performance improvements, until a period of rapid improvement became possible in the 1950s and 1960s as a result of engine

aerodynamics being refined and new materials becoming available. However, by the end of the 1960s, major further improvements to the single-airstream turbojet engine architecture became impossible as the technology approached its theoretical efficiency limit.

At that point, the introduction of the mixed-flow turbofan engine—which produces two airstreams, core air and bypass air, rather than one—offered a major new avenue for technological and performance development for another four decades. As far as the US Air Force is concerned, the superb F135 engine represents nearly the apex point of turbofan technology. However, because it is by now very mature, turbofan technology is today pushing against its empirical limits, according to Tweedie—and it may not be capable of major further performance improvements.

In its place, variable-cycle engine technology, which employs at least three airstreams to enhance performance and efficiency throughout the flight envelope, represents the future for military high-performance engines, the US Air Force believes. “This is the foundation of a whole new family [of engines] that will mature over the coming decades,” until eventually it too matures to the point where further rapid performance improvement becomes extremely difficult, said Tweedie. “That thinking is what has driven a lot of this [variable-cycle engine R&D] and a lot of the [US] Air Force’s investment in this technology.” **AI**



GE Aviation's XA100 engine under test, as developed under the US Air Force's Adaptive Engine Transition Program.