Appendix D

MODERN TACTICAL JET ENGINES

Ever since the Wright brothers redesigned their piston engine to reach a usable power-to-weight ratio for their Wright Flyer, aircraft propulsion systems have been a critical element in aircraft design and performance. U.S. military and civilian customers have placed high priorities on flight safety, engine performance, reliability, and life-cycle costs. The design and maintenance of safe, affordable, and reliable high-performance engines require the integration of many technical disciplines including aerodynamics, thermodynamics, fluid mechanics, solid mechanics, materials, fuels, combustion, heat transfer, and controls. The resulting jet engines are complex devices, which stress the limits of U.S. capabilities in each of these technical disciplines.

Pushing the state-of-the-art in integrated technologies leads to discoveries of new technical challenges both within these technological areas and at the points these technologies intersect. Because the application of new or refined jet engine technologies has been fairly continuous, so has the flow of new technical and support challenges. This situation is compounded for front-line fighter engines by the expansion of the flight envelopes for successive fighters. As we discussed in Appendix A, engine manufacturers, in cooperation with their customers, conduct rigorous development and testing programs, including AMT, to solve as many technical problems as possible before the engines are fielded. However, some problems are not manifested until the engine is stressed in actual combat or rigorous training environments, and sometimes not until engines have been operated for thousands of hours.

Technological advances are normally incorporated in one of three ways: new technologies are integrated into existing engine designs through component modifications[1] to correct specific problems, numerous technologies are integrated into a mature engine to create a derivative engine design, or an entirely new engine is developed. The extent of redesign to develop derivative engines varies. For example, the F110-PW-129 has approximately 80 percent parts commonality with its predecessor, the F110-PW-100, while the F100-PW-229 has approximately 20 percent to 30 percent parts commonality with the F100-PW-200 (Kandebo, 1998c, p. 22). In most cases, derivatives of existing engines typically introduce fewer unforeseen technical challenges than entirely new engines.

We next briefly describe several tactical aircraft engines that either are currently in the Air Force's inventory or could be in the near future. Not included are engines for transport and training aircraft, expendable missiles, unmanned aerial vehicles, and auxiliary power units (APUs).[2] These other engines and APUs will also continue to integrate new technologies, with emphasis on the performance, reliability, and affordability factors that are most important to their applications. The Air Force's *Engine Handbook* (1998) contains summary specifications for a large variety of Air Force engines.

EXISTING AIR FORCE TACTICAL AIRCRAFT ENGINES

F100-PW-220

This P&W engine is a low-bypass-ratio, mixed-flow, afterburning turbofan used to power Air Force F-15 and F-16 aircraft, having passed military qualification testing in 1985. Under takeoff conditions, this engine can produce 23,770 pounds of thrust with the afterburner lit ("wet") and 14,590 pounds of thrust with the afterburner turned off ("dry") (*The Engine Handbook*, 1998, p. 24).

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[1] The Department of Defense conducts component modification through what it calls the Component Improvement Program.

[2] APUs are essentially small turboshaft engines, which are used to provide electrical power or pressurized air. They are either mounted in ground-power carts or are integrated into some aircraft.

F100-PW-229

This is a low-bypass-ratio, mixed-flow, afterburning turbofan used to power Air Force F-15E and F-16C/D aircraft. This growth derivative of the F100-PW-220 was qualified in 1989. Under takeoff conditions this engine can produce 28,500 pounds of thrust wet and 17,000 pounds dry (*The Engine Handbook,* 1998, p. 25).

F100-PW-232

This is a growth version of the F100-PW-229. The F100-PW-232 is not currently in the Air Force inventory but could be used in U.S. Air Force or foreign F-15E and F-16C/D aircraft. Existing F100-PW-229 engines can be modified to this configuration by using kits that are available from Pratt & Whitney.

The primary enhancement over the F100-PW-229 is a redesigned fan. This fan provides up to 10 percent higher airflow through improved aerodynamics, and does so at a higher efficiency (Kandebo, 1996a and 1998b). This new fan can increase the thrust of the engine or can extend the engine's hot section design inspection interval from 4,300 total accumulated cycles (TACs) to 6,000 TACs by lowering the maximum turbine inlet temperature by approximately 120^{o}F while maintaining the F100-PW-229's maximum thrust level. In addition, the second and third stages of the new fan are integrally bladed, meaning that each stage's rotating blades and rotor (disk) are a single piece. These one-piece bladed disks (blisks) reduce the engine's part count, reduce weight and aerodynamic losses, and eliminate each rotor blade's traditional dovetail attachment roots, thereby precluding the common problem of cracks forming in the blade's root. The fan's first-stage blades are attached to their disk in a conventional manner "to allow easy field replacement" of blades due to FOD or bird strike (Colaguori, 1998). In addition, the fan's rotor blades have lower aspect ratios (the blades' radial length divided by axial length) than the corresponding F110-PW-229 fan blades, making them sturdier and, therefore, less susceptible to damage from bird strike or FOD.

F110-GE-100

This GE engine is a low-bypass-ratio, mixed-flow, afterburning turbofan used to power Air Force F-16 aircraft and was qualified as a military engine in 1985. Under takeoff conditions, this engine can produce 28,620 pounds of thrust wet and 18,330 pounds of thrust dry (*The Engine Handbook,* 1998, p. 32).

F110-GE-129

This is a low-bypass-ratio, mixed-flow, afterburning turbofan used to power Air Force F-16C/D aircraft and has also been qualified for the F-15E (Kandebo, 1998b). This growth derivative of the F110-GE-100 was qualified in 1989. Under takeoff conditions, this engine can produce 28,737 pounds of thrust wet and 17,155 pounds of thrust dry (*The Engine Handbook,* 1998, p. 33).

F110-GE-132

Also known as the F110-GE-129 Enhanced Fighter Engine, this growth version of the F110-GE-129 is not currently in the Air Force inventory but could be used in U.S. Air Force or foreign F-15E and F-16C/D aircraft. Existing F110-GE-129 engines can be modified to this configuration using kits available from GE. As in the corresponding P&W engine (F100-PW-232), GE's F110–GE-132 has a more efficient and higher airflow fan with lower-aspect-ratio blades. As in the F110-PW-232, the F110-132's improved fan can be used to increase the thrust of the engine or to extend the hot section design inspection interval to 6,000 TACs. All three rotors in this fan are blisks. In addition, the F110-GE-132 has a redesigned afterburner, which incorporates technologies developed by GE for the F414-GE-400 afterburner. This enhanced afterburner is less complex and produces more thrust than its predecessor, and should also be more reliable (Kandebo, 1996a and 1998b).

Under an Air Force contract, GE has also developed an ejector nozzle, which has 400 fewer parts than current F110 nozzles. In addition to its normal thrust-producing function, this nozzle draws cool air from the engine bay and across the nozzle flaps and seals to keep the nozzle cooler. GE predicts this cooling effect will quadruple the nozzle's life and will reduce its infrared signature. This advanced nozzle can be used on most F110 engines, just not the F110-GE-132 (Jane's Information Group, 1999b).

F404-GE-F1D2

This GE engine is a nonafterburning, low-bypass-ratio, mixed-flow turbofan used in the subsonic F-117 stealth aircraft. It is derived from the family of afterburning and nonafterburning F404s, which the U.S. Navy and other services operate in F-18A/B/C/D and other aircraft. Under takeoff conditions, the F404-GE-F1D2 produces 10,000 pounds of thrust ("F-117 Engine Design …," 1990, p. 27).

TF34-GE-100

This GE engine is a high-bypass-ratio turbofan engine used in the subsonic A-10 attack aircraft. It was first used in the Navy's S-3A antisubmarine aircraft. The civilian variant, CF34, has been very successfully grown to increased thrust levels and employed on regional jets. Under takeoff conditions, the TF34-GE-100 can produce 10,540 pounds of thrust (*The Engine Handbook,* 1998, p. 39).

FUTURE ENGINES FOR AIR FORCE TACTICAL AIRCRAFT

F119-PW-100

This is a low-bypass-ratio, mixed-flow afterburning turbofan being developed for the Air Force's new F-22 fighter. The engine will enable the F-22 to supercruise (cruise supersonically without afterburning). The F119's component designs push the state-of-the-art to give it exceptional performance; it should also provide exceptional reliability. In fact, P&W's YF119 was chosen for the F-22 over GE's YF120, primarily due to the lower development risk, production cost, and expected maintenance requirements (Bond, 1991).

The F119 is equipped with a 2-D thrust-vectoring nozzle to enhance the F-22's maneuverability. The engine's full authority digital engine control is integrated with the aircraft's flight control system. Further, this will be the first operational engine in which the low- and high-pressure spools rotate in opposite directions. (A *spool* is essentially a compressor and the turbine that drives it, along with the shaft that connects the two rotating components.) All compressor and fan stages are integrally bladed. The fan's first-stage blades are also hollow to save weight and enable the engine to respond more rapidly to throttle changes. The F119's floatwall combustor design should reduce the problems that are typically associated with thermal stresses in combustor liners (Jane's Information Group, 1999c).

Engine maintenance improvements have been designed into the F119 based on lessons learned from previous engines. For example, almost none of the line replaceable units that are external to the engine are stacked on top of one another, fasteners are standardized, and key portions of the external plumbing are flexible hosing. The engine's main case is split at the fan and at the compressor to permit rapid access to those components. Overall, the engine has 40 percent fewer parts than the F100 ("P&W to Test …," 1994). P&W has predicted that engine deployments will require 75 percent less airlift and will require 220 pieces of relatively compact ground support equipment, compared with the 400 pieces required by the F100-PW-229. F119 maintenance personnel will use electronic tech manuals, replacing approximately 85,000 pieces of paper that would have been required with traditional manuals. In addition, electronic updating of these manuals will save extensive flightline maintenance manpower, compared with traditional methods (Kandebo, 1995b). Using the F100-PW-220 as a baseline, P&W expects shop visit rates to be reduced 74 percent, unscheduled engine removal rates to be reduced 33 percent, and maintenance man hours per flight hour to be reduced 63 percent ("F119 Configuration …," 1991).

F135

The P&W F119 was also chosen as the engine to power the JSF demonstrators in the concept development phase. However, the F135, a derivative of the F119-PW-100, is being developed to meet the JSF requirements. Rear Admiral Craig Steidle, former U.S. Navy JSF program director, stated that the propulsion system is the greatest technical challenge for the JSF (Warwick, 1997).

For all the JSF variants, maximum thrust will increase from 35,000 pounds to approximately 40,000 pounds. The primary technology enhancements that enable the F135's increased airflow and higher RIT will be the incorporation of P&W's "superblade" cooling in the high-pressure turbine, gamma titanium aluminide blades in the last compressor stage, an enhanced cooling airflow pattern in the combustor, and high-temperature fuel nozzles to prevent coking (Kandebo, 1998a and 1998d). As in the case of the F-22, the JSF will have integrated flight and propulsion controls. To test and refine these highly integrated control systems, the manufacturer's engineers will run their aircraft simulators with the engine control systems integrated and controlling engines running on thrust stands.

All variants will also have electronic prognostics, which may include the capability to inform maintenance personnel of repair requirements before a component fails and before the JSF lands (Smith, 1999, and Kandebo, 1998d). Norris (1999) reports that the prognostic and diagnostic systems being developed and considered for the JSF include acoustic, electrostatic, and eddy current monitoring. If fielded, these systems will be capable of detecting and discriminating between types of FOD entering the inlet, "hearing" changes in bearing noises, and sensing when the exhaust stream contains unusually high levels of charged particles. High levels of charged particles in the exhaust stream are characteristic of a damaged engine or one undergoing abnormal wear (Norris, 1999, and Nordwall, 1992).

As of 1998, P&W was predicting that F119-JSF deployments would require 60 percent fewer C-141 loads per fighter wing, support costs would be 60 percent lower, and the mean time between maintenance would be twice that of today's engines. In addition, the Conventional Takeoff and Landing versions of the JSF would have 50 percent fewer in-flight shutdowns than the F100-PW-220, and the STOVL version would have 80 percent fewer in-flight shutdowns than the AV-8B's "Pegasus" engine (Kandebo, 1998d).

Boeing's X-32 used a thrust-vectoring 2-D nozzle. It also incorporated a second stage in the F119's low-pressure turbine to help drive a fan that flowed 10 percent more air than the F119-PW-100. The STOVL variant diverted the engine's exhaust through rotating and retractable lift nozzles located near the center of the aircraft and some fan air through a "jet screen" nozzle located a few feet in front of the lift nozzles (Jane's Information Group, 1999c). The resulting jet screen was a barrier of cool clean air from the engine's fan, which provided some lift and prevented the engine exhaust from recirculating into the engine inlet. Minority partner Rolls-Royce developed the lift nozzles and jet screen hardware. Small pitch, roll-and-yaw nozzles were integrated near the engine's main nozzle to provide stability control during STOVL operations. The engine was also stretched several feet by inserting an extra duct (essentially a large tube) upstream of the afterburner in order to move the main engine forward, enabling placement of the vertical lift nozzles in the appropriate location with respect to the aircraft center of gravity.

Lockheed-Martin's X-35 (the winner of the competition) used a low-observable axi-symmetric nozzle. Its STOVL variant used a shaft driven vertical-lift fan just behind the cockpit, roll control ducts in the wings, and a large three-bearing swivel duct to rotate the main nozzle to point vertically downward during STOVL operation. The lift fan's shaft was driven by the F119's low-pressure spool and connected by a clutch and gearbox. Minority partner Rolls-Royce developed the three-bearing swivel duct and roll control duct. Similarly, Allison, a division of Rolls-Royce, developed the lift fan hardware (Kandebo, 1998d, and Warwick, 1997).

F120

The Air Force and GE have continued to mature and enhance the F120 through the IHPTET program since the Advanced Tactical Fighter program source selection in 1991. This has reduced the risk and uncertainty of this variable-cycle afterburning turbofan. Due to the large number of JSFs to be built and the desire to use competition to keep prices low and performance and reliability high, the JSF program has selected the F120 to be the "alternate engine" for the JSF. If this program follows the precedent set by the F-16, the Air Force will have JSFs fielded with both derivatives of F119 and F120 engines starting after 2010. The JSF version of this engine will be developed and built by a team led by GE, with Rolls-Royce participating.

The F120's variable-cycle capability allows the engine to change its bypass ratio as appropriate over the aircraft's flight envelope. This functionality requires additional control logic and flow control hardware. Other advanced technologies in the F120 include combustor and high-pressure turbine blades and vanes made of Rolls-Royce's (Allison's) "Lamilloy." Lamilloy is essentially a material made of laminated layers of high-temperature perforated metal materials. Compressor bleed air is blown into and through the Lamilloy components to effect transpiration-like cooling of those components. Also included are counter-rotating high- and low-pressure spools, without the traditional stationary turbine vanes between the turbine rotors. The shafts will turn on bidirectional tapered roller bearings. The F120 will have an advanced afterburner, based on technologies from GE's F414 engine, used in the F/A-18 E/F (Kandebo, 1997). The nozzle will be an advanced low-observable axi-symmetric nozzle, which GE states will have half of the weight and 40 percent of the cost of a 2-D nozzle (Kandebo, 1996a).

SUMMARY

The United States continues to lead the world in fielding state-of-the-art jet engines. The implications of integrating new technologies into military aircraft engines are both positive and negative. The Department of Defense and industry are making a concerted effort to enhance affordability, extend component life, increase reliability, automate prognostics and diagnostics, simplify maintenance procedures, and enhance performance. However, the continuous integration of new technologies into existing and new engines, and expanding flight envelopes, will likely continue to create a corresponding flow of technical challenges and costs. We hope the brief descriptions we supplied in this report of some current and future U.S. tactical aircraft jet engines will assist military weapons system program office personnel in understanding military jet engines and estimating their life-cycle costs.