Appendix B

AN OVERVIEW OF MILITARY JET ENGINE HISTORY

This appendix presents a historical overview of military jet engine development in the United States, with a focus on high-performance fighter jet engines. We have divided military jet engine history into four developmental periods, or generations, of jet engines that resulted in major leaps forward in technology and performance: (1) the original centrifugal and axial flow turbojets (first generation); (2) twin spool turbojets, variable stator turbojets, and turbofans (second generation); (3) augmented (afterburning) turbofans (third generation); (4) and supercruise, stealthy "leaky turbojets" (fourth generation).

FIRST-GENERATION JET ENGINE DEVELOPMENT

Initial development of the first practical turbojet aircraft engines began nearly simultaneously in the mid-1930s in Germany and the United Kingdom (UK). Enterprising young engineers and enthusiasts, independent of the established aircraft engine companies, conducted the earliest development work on their own, with little formal financial or technical assistance from either government or industry. Eventually, with the threat of general European war looming closer, European industry and government interest in turbojet engines grew. It was not until World War II was underway, however, that U.S. government and industry committed major resources to the development and production of usable military gas turbine aircraft engines, and the aircraft that they would power.

These early major engine development programs were concentrated in Germany and the UK, with Germany taking the lead. The United States lagged significantly behind Germany and the UK, although the relative lack of U.S. research in jet engine development at that time has been exaggerated (St. Peter, 1999). Nonetheless, jet-powered military aircraft developed in the United States during and immediately after World War II largely depended on British engines and British engine technology.

Although turbine engines had been in industrial use since the nineteenth century, major technical and engineering obstacles prevented their application to aircraft and serious aircraft jet engine development until the mid-1930s. In the late nineteenth century, Englishman Charles Parsons invented a practical industrial steam turbine. It was soon successfully applied to the generation of electricity. By 1900, the British Royal Navy had procured at least two destroyers powered by steam turbines; less than a decade later, commercial ocean liners were equipped routinely with the same type of propulsion. Early in the twentieth century, engineers also began experimenting with gas-powered turbines. One of the most successful early efforts was carried out by Sanford Moss at General Electric (GE), who developed an operational laboratory gas turbine prototype in 1907. Unfortunately, those very early gas turbines were extremely fuel inefficient, using about four times the amount of fuel of an equivalent gas piston engine (Heppenheimer, 1995).

Gas turbines for use on aircraft posed truly daunting technical problems, the most significant of which were obtaining the appropriate lightweight heat-resistant materials and developing adequate compressor efficiency. Another major technical barrier was the need for development of a workable, robust, and reasonably fuel-efficient combustor system to drive the turbine and compressor. For these reasons and others, development efforts for gas turbine aircraft engines languished for decades. In the United States, research at GE and elsewhere focused on the development of turbochargers for conventional piston aircraft engines. These efforts met with great success and resulted in powerful high-altitude piston engines for U.S. Army Air Corps fighters and bombers.

In the UK, theoretical and experimental research on gas turbine engines suitable for aircraft started in the 1920s, led by a few maverick engineers, and continued on through the 1930s on a small scale. As early as 1926, Alan Griffith, a scientist who worked at the Royal Aircraft Establishment at Farnborough, England, developed the concept of a gas turbine based on an axial-flow compressor and turbine arrangement, with the blades acting as airfoils. Griffith envisioned such an engine being used to power a propeller. Some basic research was conducted to determine if this concept would work, but progress on it was slow (Gunston, 1989).

The key early British pioneer, however, was Frank Whittle, a Royal Air Force (RAF) pilot and engineer, who in 1929 began focusing on the concept of a gas turbine engine that used jet propulsion as opposed to one that was used to turn a propeller to power aircraft. Nevertheless, he based his concepts on a centrifugal-flow compressor similar to those used in turbochargers, rather than on the modern axial-flow concept put forward by Griffith.

At this time, Whittle's concept was more feasible than Griffith's given existing technology. In 1935, Whittle obtained venture capital from a private investment-banking firm and began building his first prototype engine on his own time. By 1937, Whittle was conducting successful bench tests of his prototype Whittle Unit engine. By that time, Griffith had become convinced that compressor and turbine technology had made sufficient progress to permit further development of his axial-flow concept. By mid-1937, Sir Henry Tizard, an influential scientist serving in the RAF, recommended government support for development of gas turbine aero engines.

Whittle began receiving small amounts of RAF funding. In June 1939, just a few months before the Nazi invasion of Poland, he demonstrated a more advanced bench prototype for David Pye, the RAF director of scientific research. Pye was extremely impressed, and as a result, the UK government decided to support a major effort for the development of an aircraft jet engine. In July 1939, Whittle's small company called Power Jets received a promise of large-scale government funding for the development of an operational jet engine for flight. A few months after the beginning of the war, Gloster Aircraft won a government contract to develop the aircraft that would use Whittle's new engine. That aircraft became the Gloster Meteor.[1] Finally, a major engine company became impressed with Whittle's work and in June 1939, Rolls-Royce hired Griffith to begin major de-

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[1] See St. Peter (1999) and *A Tribute to a Cambridge Engineering Student …* (1998).

sign work on an axial-flow jet aero engine. Rolls also soon became involved in advanced development of the Whittle engine concepts.

The British government's effort to develop an aircraft jet engine increased substantially after the fall of France in May 1940. By early 1941, Tizard launched an additional program by giving Whittle's and Griffith's research results to de Havilland aircraft, which then was directed to develop its own jet engine and aircraft (the de Havilland Goblin and de Havilland Vampire, respectively). Thus, by 1941, the British government was supporting the development of three military jet engines and two jet fighters.

As impressive as the British program had become, Germany was already far ahead of the UK. The German effort, like the British one, had been initiated by individual entrepreneurs. The first key players were a graduate student in physics at the University of Göttingen, Hans von Ohain, and a chief garage mechanic, Max Hahn. In 1934, von Ohain began design on an axial-flow turbojet engine prototype. He and Hahn built a test article with their own money, but it did not prove to be successful. Von Ohain then approached Ernst Heinkel, a developer of high-performance military aircraft, who became interested in the project. Heinkel hired Von Ohain and Hahn, and began funding their efforts with his company money. By 1939, Von Ohain and other Heinkel engineers had successfully bench tested a usable engine. Heinkel then authorized development of an experimental aircraft for the engine, later called the Heinkel He 178, using company funds. In late August of that year, five days before Hitler invaded Poland, the aircraft made its first successful flight. Although much development work remained, the first jet fighter prototype had now flown, funded entirely by private and corporate money. Around this same time, the German aircraft company Junkers was also attempting to develop an even more advanced turbojet with its company money, but it was lagging behind Heinkel in the development effort. Whittle had only just demonstrated his centrifugal-flow engine to the RAF director of scientific research, and he was just beginning to receive funding to develop a flight-capable jet engine.

In mid-1939, the German Aviation Ministry (or Reichsluftfahrt-Ministerium [RLM]) was supporting a few other jet engine and rocket programs on a small scale, which were based on different technologies. By late in the year, Heinkel and Junkers had both been able to win government financial support for their engine development programs, primarily through the influence of the visionary Brigadier General Ernst Udet, head of the Technical Office of the RLM. At the same time, the RLM let a contract to Messerschmitt to develop a jet fighter design, the Me 262. The RLM also began supporting another jet engine effort at BMW.

Thus, by the end of 1939, only four months into the war, the German government was financing four military jet engine programs: the Junkers Jumo 004, two programs at Heinkel, and the BMW effort. In addition, two jet fighters were under development: the Me 262 and the He 280 (a successor to the He 178). At the time, the British government had launched development of an improved Whittle engine and the Gloster Meteor, both of which would prove to be substantially less capable than their competition coming out of Germany. Griffith was working on his axial-flow concepts at Rolls-Royce but was not making rapid progress.

Meanwhile, in the United States, many companies had begun developing turbojet or turboprop design concepts, including GE, Pratt & Whitney, Lockheed, and Northrop (St. Peter, 1999). In early 1941, however, General Henry "Hap" Arnold, chief of the Army Air Force, along with some GE officials, learned about the British jet engine development programs and the existence of the Whittle engine. Arnold arranged for the transfer of the Whittle technology to GE's turbocharger division at Lynn, Massachusetts, so that the United States could develop a jet fighter quickly. Bell Aircraft received a contract to develop an aircraft, the XP-59A, for the GE-built Whittle engine, which was called the GE 1-A. For the development of future high-technology indigenous engines, many U.S. companies, including GE, Pratt & Whitney, Westinghouse, Lockheed, Northrop, and others, began receiving government research and development (R&D) funding. Unfortunately for the immediate war effort, the XP-59A, like the Gloster Meteor, proved a disappointment due to the shortcomings of the centrifugal-flow concept of the Whittle engine that powered both aircraft.

The Whittle engines could not provide the thrust necessary to make the aircraft competitive with the most advanced piston fighters entering service at the time. The XP-59A first flew in October 1942 with two 1,250-pound-thrust GE 1-A engines. Later variants had the more powerful GE I-16 (later J31) turbojets with 1,650 pounds of thrust. The Meteor, which first flew in March 1943, was powered by two Rolls-Royce–built Whittle W.2B engines with 1,700 pounds of thrust. Advanced piston fighters such as the Republic P-47D and North American P-51D Mustang significantly outclassed both of these heavy and underpowered two-engine aircraft.

De Havilland’s axial-flow engine, by comparison, promised twice as much thrust as the Whittle engines, permitting the development of a lighter, higher-performance, single-engine fighter. In September 1943, a de Havilland Vampire prototype powered by a single de Havilland H-1 Goblin turbojet with a thrust rating of 2,700 pounds successfully completed its first flight. Three months earlier, Lockheed received the go-ahead to develop an aircraft using a single de Havilland-built Goblin H-1 engine. The XP-80 Shooting Star first flew in January 1944 powered by this engine, exceeding 500 miles per hour in level flight. But the development program continued to be delayed by engine problems. The Goblin H-1, planned for production in the United States by Allis-Chalmers as the J36, was plagued with problems, and the Air Force began looking around for a substitute.

GE had immediately set out on improving the Whittle-based GE 1-A engine used on the XP-59A. The GE-improved Whittle variants included the I-14, the I-16 (J31), and the I-18, culminating in the dramatically improved and virtually all-new axial-flow 4,000-pound-thrust I-40 (J33) adopted for the XP-80. However, adoption of the GE J33 necessitated major redesign of the XP-80A. The new prototypes did not begin flying until summer 1944. Although the J-33–powered P-80 (later F-80) proved to be a very successful first-generation jet fighter, it completed development too late to see combat during World War II (St. Peter, 1999).[2]

The British war experience with developing jet engines was similar to the experience the United States was having with new jet engine technology. The Gloster Meteor Mk 1, powered by a variant of the Whittle engine developed and manufactured by Rolls-Royce, became operational in 1944 but performed poorly and was retained in the UK for homeland defense. While Allis-Chalmers had experienced prob-

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[2] For a history of XP-80 development, see Knaack (1978).

lems with the XP-80, de Havilland experienced development problems with the axial-flow Goblin engine, and the aircraft did not perform as well as anticipated. In the end, only 174 Vampire F Mk1s were built for the RAF, and they did not become operational until after the war (Gunston, 1989).[3]

Germany, however, was significantly ahead of the UK in the jet engine development effort, and one authority has estimated that Germany had at least a five-year lead in development over the Americans at the beginning of the war (St. Peter, 1999). With their strong lead in 1939 in axial-flow turbo jets, it is not surprising that the Germans proved to be the only combatant to field a successful jet fighter during the war. However, only two of the German jet engine development programs produced reasonably successful operational engines. They were the 2,000-pound-thrust Junkers Jumo 004 engine, two of which powered the Me 262, and the 1,800-pound-thrust BMW 003 engine. Many observers argue that the best and most maneuverable German jet fighter of the war was the Heinkel He 280, powered by the HeS8 that had been developed by von Ohain and others, which first flew in April 1941. The Heinkel He 280 was tested in a mock dogfight against a Focke Wolf FW 190, Germany's best conventional fighter, and beat it badly. But the Heinkel HeS8 engine experienced numerous development problems, and for that and other reasons, the He 280 never entered production.[4]

The very fast but much less maneuverable Me 262, powered by the Jumo 004, first flew in July 1942. The production version of the Jumo 004, however, had to be significantly redesigned to reduce its use of scarce vital war materials such as nickel, chromium, and cobalt. This not only delayed the program but resulted in an unreliable engine. By late 1944, the Me 262 had achieved high-rate production in underground facilities. But by this time, the Allies had near total air superiority and were bombing German industrial facilities and the country's transportation infrastructure around the clock.

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[3] Also see Green and Swanborough (1994); Donald (1999); and Taylor (1995).

[4] For example, see the "Heinkel He 280" link on the Hot Tip Aircraft Web page at www.stud.uni-hannover.de/user/67700/he280.htm and Green and Swanborough (1994).

Nonetheless, the Germans deployed several other very advanced combat aircraft during the last months of the war. Two Jumo 004s powered the world's first operational jet bomber, the Arado Ar 234 Blitz. The Heinkel He 162 Salamander fighter powered by a single 1,800-pound-thrust BMW 003A-1 turbojet became quasi-operational for a very brief period at the end of the war. The rocket-powered Messerschmitt Me 163 Komet fighter also briefly saw combat late in the war. Even more amazing was the Bachem Ba 349A "Natter," a vertically launched rocket fighter tested against allied bombers at the end of the war. Had some of these aircraft, especially the He 280 or Me 262, been operationally available in large numbers earlier in the war, they could have had a major effect on the Allied strategic bombing campaign against Germany. When U.S. Air Force officers, scientists, and engineers visited German R&D facilities after the war, many of them were shocked at how far advanced the Germans were in jet aircraft design compared with the Americans. The U.S. was determined more than ever to develop advanced jet-powered military aircraft. They knew that significant new engine technology would be crucial to that effort.

SECOND-GENERATION JETS REVOLUTIONIZE MILITARY AND COMMERCIAL AIRCRAFT

Three key jet engine technological developments in the 1950s revolutionized aircraft performance: twin spool turbojets, early low- and medium-bypass turbofans or fanjets, and variable compressor technology. These developments led to the realization of supersonic military jet fighters, competitive carrier-based jet fighters, and long-range jet-powered military and commercial transport aircraft.

In the immediate post-War years, GE, Westinghouse, P&W, the Allison Division of General Motors, and Curtiss Wright were considered the leading U.S. turbojet manufacturers, while Rolls-Royce remained dominant among many jet engine manufacturers in the UK. German companies such as Junkers and Heinkel had their facilities severely damaged by the war and were forbidden by treaty to continue developing militarily useful technologies.

During the war, the UK government had required British industry to cooperate and share information in the development of turbojet engines. Using a much different approach, the U.S. government had encouraged competition among firms and discouraged sharing of information. The U.S. approach promoted development of different technical solutions. GE had begun with the basic Whittle technology and improved on it greatly until it had achieved its own indigenous engines, the J33 and J35 turbojets. GE developments had been largely sponsored by the Air Force; GE engines were widely used to power first-generation Air Force fighters and bombers. Westinghouse had a long history of steam turbine development and expertise. During the war, its turbojet development activities were sponsored by the Navy, and most first-generation Navy fighters were powered by Westinghouse engines. Allison initially produced mostly GE-designed engines for the Air Force due to GE's lack of production facilities. With little independent wartime turbojet R&D experience of its own, P&W decided to produce the Rolls-Royce–licensed Nene engine, a very advanced successor to the original Whittle W.2B turbojet. With the German firms in ruins, Rolls-Royce was considered by many in the early post-War period to be the most advanced turbojet manufacturer. P&W Nene-based engines were used on both Navy and Air Force aircraft.[5]

All turbojets during the immediate post-War era suffered from at least four major shortcomings: high fuel consumption, relatively low thrust, sluggish acceleration, and loud noise. These problems greatly complicated the development of naval carrier-based jet fighters, long-range land-based fighters, long-range strategic bombers, and commercial jet airliners. P&W decided that it was at least five years

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[5] Wright Aeronautical, a division of the Curtiss-Wright Corporation, along with P&W, a division of United Aircraft, had been the most important U.S. aero engine manufacturers during World War II. Indeed, by 1940, Curtiss-Wright was the largest U.S. company in the aircraft industry. During the last year and a half of the war, the government officially prohibited Wright Aeronautical and P&W from pursuing jet engine development research in order to force them to concentrate on war production. After the war, Wright received jet R&D contracts, gained access to Westinghouse J34 engine technologies, and built GE J-47 engines. During the Korean War, Wright license produced two British jet engines. The Air Force chose Wright to develop its own higher-thrust J-67 turbojet for the Convair F-102, but cancelled the program because of perceived poor performance by Wright during the Korean War. Wright never recovered from the cancelled business and ceased to be a jet engine prime contractor. Lockheed and Northrop also exited the engine industry soon after the war. Westinghouse also left the industry after producing several engine developments in the 1950s. See Gholz (2000).

behind the other major turbojet companies in R&D expertise and had to achieve a major leap forward in technology to stay competitive in the post-War environment. License-producing Rolls-Royce engines was a dead-end approach, so beginning in 1946, P&W made a major corporate strategic decision to invest substantial amounts of its own funds in new R&D and test facilities to catch up with its competitors.

The focus of P&W's R&D efforts was aimed at solving the two most significant shortcomings of existing turbojets, especially for military use: low thrust and high fuel consumption. The best engines in the early post-War years produced 4,000 to 5,000 pounds of thrust. P&W established the goal of doubling this thrust level by developing a 10,000-pound-thrust engine that also had better fuel efficiency. P&W's corporate leadership focused on the military market but also recognized the possibility of later commercial applications.

Of the five main U.S. jet engine companies, only P&W believed that dramatically increasing the compressor pressure ratio was the way to solve the thrust and fuel efficiency problems. P&W engineers developed the key concept to make the technological leap in this area: the "twin spool" engine (Heppenheimer, 1995; St. Peter, 1999).[6] The concept called for two different sets of compressor and turbine combinations in the same engine. A low-pressure compressor at the front of the engine would be driven by a low-pressure turbine connected by a rotating shaft inside a second rotating shaft. The outer shaft would connect a high-pressure compressor behind the low-pressure compressor to a high-pressure turbine located in front of the low-pressure turbine. This approach promised a substantial increase in the overall efficiency of the compressors and improved performance during engine acceleration and deceleration, while also enhancing fuel efficiency and increasing thrust.

The new P&W engine, designated the J57, first ran on a test stand in 1950 (Heppenheimer, 1995). The J57 proved to be a huge, even revolutionary, advance in axial-flow turbojet technology. It was the first jet engine to develop 10,000 pounds of thrust, double that of most of its contemporaries. Later versions developed up to 18,000

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[6] Gunston (1989) indicates that Rolls-Royce engineers were also examining the concept of dual-spool engines immediately following the end of the war.

pounds of thrust. At the same time, it had nearly twice the fuel efficiency of the most successful German World War II engine, the 2,000-pound-thrust Junkers Jumo 004. The J57 made development of the first true long-range strategic jet bomber possible, the Boeing B-52. It also helped make supersonic flight possible. In May 1953, the North American YF-100 fighter became the first combat aircraft in the world to achieve sustained-level supersonic flight. In addition to the B-52 and the F-100, the J57 powered numerous other Air Force aircraft such as the McDonnell F-101 fighter, the General Dynamics (GD) Convair F-102 fighter, and the Boeing KC-135 aerial tanker. Navy tactical aircraft equipped with this engine included the Vought F8U and the Douglas F4D, F5D, and A3D. The improved J-75, which was based on the same fundamental principles but used more-exotic higher-temperature materials to produce greater thrust, powered the Republic F-105 and Convair General Dynamics F-106 fighters, and other military aircraft.

Finally, the J57 also made the development of successful long-range commercial and military jet transports possible when its commercial version, the JT3, was used to power the Boeing B-707. But to achieve the full potential of this capability, another major innovation was borrowed from the British by P&W and added to the JT3, resulting in the JT3D. This innovation was the development of the low-BPR turbofan or fanjet. Rolls-Royce engineers had been considering bypass jet engines since the end of World War II. These engines have larger low-pressure compressors that permit a portion of the air to be ducted past and around the core of the engine and expelled with the hot jet gas from the core. This feature results in lower specific fuel consumption, higher thrust, and lower noise. The dual-spool configuration is necessary for fanjets because the low-pressure spool and high-pressure spool turn at different speeds. Rolls-Royce developed a low-bypass turbofan called the Conway, which was used on the de Havilland Comet jet commercial transport and entered service in May 1952. Because of the wing-buried installation on the Comet, and on early British jet bombers such as the Vulcan, the engine could not be optimized with a large enough fan for optimal fuel efficiency and transatlantic range (Gunston, 1989).

P&W engineers were initially skeptical about fanjets. GE, however, developed its own successful version of a fanjet based on a slightly different approach—the "aft fan" concept in which the fan is mounted with and behind the turbine near the back of the engine. This concept was successfully bench tested in 1957 as the CJ-805. P&W decided to move ahead with a fanjet when Boeing threatened to go with the GE engine for its new long-range 707s.

P&W engineers successfully modified the standard J57 military turbojet with a larger front-end compressor/fan, turning it into a high-efficiency low-bypass turbofan engine suitable for very-long-range flight. Suddenly P&W had a large advantage over GE because the modification to the J57 was relatively minor, and that engine was already proven to be a highly capable engine. GE's rear-fan engine was just a test article. The Air Force quickly became interested in the P&W JT3D and eventually used the military variant (TF33) for the KC-135 aerial tanker and other aircraft. Besides the Boeing B-707, the JT3D commercial variant powered the competing Douglas DC-8, as well as the Boeing 720. More than 21,000 J57/JT3s were eventually produced well into the 1980s. Most important, the low-bypass turbofan later led to advanced new fighter engines and to high- and very-high-bypass turbofans, which revolutionized commercial transport power plants.

The move toward high-pressure-ratio engines first advocated by P&W soon confronted designers with new difficulties. As pressure ratios increased for optimal efficiency at cruise conditions, problems arose with the design of the compressor operating efficiently at low speeds and especially during acceleration. Under these conditions, airflow patterns over the compressor airfoils were very different than they were under their design conditions, and small disturbances that could cause compressor stall became common. GE made the revolutionary technological breakthroughs that solved this problem by developing variable-geometry compressor systems, which used variable-geometry stators. A row of stators redirects the airflow between each row of rotating compressor blades in the compressor assembly. Variable stators change their angle of attack for different airflow conditions, thus addressing the compressor stall problems. This technological breakthrough led to the development of the famous J79 turbojet engine, made Mach 2 flight possible, and was critical for the development of modern very-high-bypass commercial engines that power today's large airliners.

The GE X24A design concept emerged in response to an Air Force requirement for a high-thrust, fuel-efficient, Mach 2 fighter engine. GE received a study contract; in 1952, the Air Force designated the new engine the J79. Full development began with Air Force funding a year later. The production prototype had its first test run less than a year later, and flight testing began in mid-1955. The J79 was originally slated for use on the Convair General Dynamics B-58, the world's first Mach 2 bomber, and the Lockheed F-104, the world's first Mach 2 fighter. The J79 also powered Navy aircraft, such as the Douglas F4D fighter and the North American A3J carrier-based bomber. Perhaps most important, the J79 powered the world's most important combat aircraft of the 1960s and 1970s, the McDonnell-Douglas F-4 Phantom, used by many foreign countries as well as by both the U.S. Air Force and Navy. About 5,200 F-4 Phantoms were manufactured from 1958 through 1979, more than any other U.S. fighter since the North American F-86 in the 1950s or any other U.S. fighter since.[7]

Thus, the P&W J57 and the GE J79 were clearly the most important and revolutionary jet engines of the 1950s and 1960s. The J57/JT3D, originally developed through industry initiative and with company funds, laid the groundwork for all modern jet engines, made sustained supersonic flight practical for jet fighters, and pioneered the fan jet concept that later led to far-more-advanced fighter and commercial engine concepts. The J79 illustrated the tremendous thrust and speed potential of modern jet engines and demonstrated beyond a doubt the world leadership of the U.S. jet engine industry.

AUGMENTED TURBOFAN ENGINES

By the end of the 1950s, U.S. engine developers began focusing on new military engines that combined unprecedented high-speed capabilities through the use of high thrust-to-weight ratios and afterburners with the efficiency and lower specific fuel consumption resulting from fanjet technology. The performance demands required by the services were high, and the technical challenges were numerous. The first of these engines pushed the edge of the feasible technical and performance envelopes of the era. As a result, several of the

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[7] By 2001, production of the General Dynamics/Lockheed F-16 had reached 4,300 in number and additional sales of the F-16 were likely.

early augmented turbofan programs experienced serious developmental problems. The major technical problems revolved around inlet airflow and compressor stall. There were also problems with reliability and maintainability.

The P&W TF30 was the first operational afterburning turbofan, and so it was a challenging development. P&W had experimented with a duct-burning turbofan in 1956, but the TF30 burned both fan and turbine exhaust air in the same afterburner. The TF30 began development in 1959 in support of what later became the TFX program in 1961. The TFX program, which resulted in the General Dynamics F-111, called for the development of a large supersonic fighter/bomber to meet both Air Force and Navy carrier-borne aircraft requirements. The government selected two airframe and engine finalists in January 1962: General Dynamics/Grumman teamed with P&W and Boeing teamed with GE. Secretary of Defense Robert McNamara overruled the source selection team's choice of Boeing, and in late 1962, the selection team awarded the GD/Grumman/P&W team what was, at the time, the largest aircraft development and production project in history.[8]

The TF30 went through at least 12 years of development and various fixes before its reliability and performance became operationally acceptable, yet all of its problems had not yet been solved. Flight testing by GD of the F-111 with the P&W YTF30 engine began in 1964. From the very beginning, developmental testing showed serious engine problems with compressor stall and catastrophic rotor failure at high speeds. At great expense in money and time, GD, P&W, and the government attempted to solve these problems with several redesigns of the aircraft's engine inlet, but the problems were never totally fixed. The Navy withdrew from the F-111 program in 1968 and went on to develop its own air-superiority fighter, the Grumman F-14 Tomcat. This new Navy fighter also used the TF30 engine. Like the F-111 program, the TF30 experienced serious developmental problems on the F-14 program. The TF30 program had been a pioneering development effort, but its many problems seriously damaged P&W's reputation with both the Air Force and the Navy (St. Peter, 1999).

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[8] For a more detailed discussion of this controversial decision, see Lorell and Levaux (1998).

The TF30 development was followed by a new P&W effort aimed at developing a second-generation high-performance augmented turbofan, the F100. The Air Force requirement called for a major leap in performance capabilities for this engine compared with earlier engines. Simply put, the Air Force asked for a new engine that would approximately double the thrust-to-weight ratios of previous generation engines then in use, such as the J79.[9] The F100 program was technically very demanding and high risk. Not surprisingly, it resulted in another major controversy and in a significant change in the way the Air Force approached development and procurement of fighter engines. The F100 development experience led the Air Force to be much more receptive to supporting simultaneous competing engine development and production programs, as the service had routinely done in the 1940s and 1950s.

The story of the F100 began after the Navy withdrew from the F-111 program and after the formulation of requirements for a new Navy fighter (the VFX, ultimately the Grumman F-14), and for a new Air Force air-superiority fighter (the F-X, which became the McDonnell-Douglas F-15). The Department of Defense mandated that both services use the same engine core for their respective fighters.

The Air Force took the lead in the early developmental stages of the F100 program because the Air Force Aero Propulsion Laboratory had taken the lead on the Advanced Turbine Engine Gas Generator (ATEGG) program. Like the current IHPTET program, ATEGG brought together advanced prototype components from P&W, GE, and Allison to see how they would work together as a system. The Advanced Technology Engine program for the FX and VFX, led by the Air Force, grew out of this effort. In 1968, P&W, GE, and Allison submitted competitive design proposals. The Air Force selected P&W and GE to continue the competition by building and demonstrating two prototype engines over an 18-month period. In early 1970, the Air Force selected P&W to develop its JTF-22 design, which later became the F100 turbofan. Ironically, P&W won the bid for the JTF-22 work in part because of its demonstration of a greater understanding of engine/inlet compatibility phenomena, which was acquired in

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[9] St. Peter (1999) puts the thrust-to-weight ratio of the J79 at 4.67:1, while the TF30, the first-generation augmented turbofan, is rated at 5.26:1. The F100 is listed with a thrust-to-weight ratio of 7.7:1.

part through years of problems with the TF30 on the F-111 and the F-14.[10]

The F100 was an extremely innovative engine that pushed the boundaries of contemporary technology, especially in the area of exotic high-temperature materials. A tight Air Force schedule and budget left little room for dealing with the inevitable technical problems, schedule slippage, and cost growth. In June 1971, the Navy pulled out of the program because of continuing technical development problems, dramatically increasing the program costs for the Air Force. Not only did development problems continue through full-scale development and flight testing, but the engine went into production before development was completed. Fixes done under government-funded Component Improvement Programs continued after the engine entered service with the F-15 in late 1974. The engine was extremely powerful and capable but continued to experience severe operational and reliability problems.

The F100 engine was so powerful and the F-15 so maneuverable that pilots began pushing the aircraft to the edge of the performance envelope in ways that stressed the engine far more than had been anticipated. These stresses resulted in much worse reliability and maintenance problems than were originally expected. In addition, new heavy-maneuvering air-to-air combat tactics developed by Air Force pilots revealed another problem: compressor stall caused by strong dynamic airflow distortion in the engine inlet. Severe compressor stall could lead to engine flame out, requiring the pilot to restart the engine in flight. This problem caused particular concern because the F100 was planned for use on the single-engine General Dynamics (now Lockheed) F-16 as well as on the dual-engine F-15. The compressor stall problem also contributed to another major shortcoming—turbine blade fatigue and failures that had the potential of destroying the aircraft in flight. To avoid potentially catastrophic accidents, performance limitations were placed on pilots, and mechanics had to de-rate the engine.

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[10] There are several studies of the development of the F100 and the resulting “Great Engine War” between P&W and GE. They include Camm (1993); Ogg (1987); Drewes (1987); Kennedy (1985); and Mayes (1988).

As these problems became evident, relations deteriorated between P&W management and the Air Force. The Air Force wanted P&W to fix the engine under the existing contract. P&W argued that it had delivered an engine that met the original performance specifications. The problem, according to P&W, was that the Air Force began operating the engine in a much more demanding environment than had originally been specified. Therefore, P&W argued that the Air Force should provide additional developmental money to fix the problems.

The many problems with the F100 led the Air Force to become increasingly interested in funding an alternative engine development and production program for both the F-15 and the F-16. The obvious source for competition was GE. GE's entry into the Advanced Technology Engine competition had been its F101 design.[11] Learning from the F100 development problems, GE decided to assume less technological performance risk on its F101 and focus more on reliability and maintainability. GE finally received government funding in 1972 to complete the F101 development as an afterburning turbofan to power the North American Rockwell B-1 bomber. In 1979, the Air Force was able to acquire funding to support further development of the F101 as a possible alternative to the P&W F100.

The Air Force had originally viewed its support of the F101 primarily as a ploy to force P&W to be more responsive to fixing the F100 problems. However, Congress soon entered the fray and mandated that the Air Force and Navy fund full competitive engine programs for alternatives to both the Air Force F100 and the Navy's TF30. By 1980, this had been formalized as the Alternate Fighter Engine program. GE entered into the competition its F110 turbofan, an outgrowth of its F101 effort, and P&W went ahead with its improved engine, the F100-220. Between 1984 and 1989, the Air Force pit GE against P&W for orders for new engines for the F-16, making for an intense annual competition. Each year, the engine buy was split between the two companies, but the percentage shares could vary widely from year to year. Yet, at the end of the six years of procure-

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[11] After losing the FX competition, GE moved ahead with further development of the engine using its own money, and teamed with Northrop on the YF-17 Lightweight Fighter program in competition with the General Dynamics/P&W YF-16 team.

ment competition, each contractor had ended up receiving almost exactly half of the total overall orders.

Most studies find little or no evidence that the Air Force enjoyed a significant net savings in total R&D and procurement spending as a result of this competition. On the other hand, it is widely believed that the Air Force acquired better-performing, more-reliable, and more-maintainable engines from more-responsive contractors.

Meanwhile, GE had also moved ahead with and developed the F404 low-bypass turbofan (sometimes called a “leaky turbojet”) out of its J101 work for the Navy’s McDonnell Douglas/Northrop (now Boeing) F/A-18, the developmental outcome of the YF-17. This was intended to be a relatively simple and reliable engine, in the same thrust class as the J79 but with half the weight and far fewer parts. Interestingly, although the Navy was pleased with this engine, the Navy designated P&W as a second source to ensure the possibility of competition. The Navy leadership also noted that of all the U.S. suppliers only P&W and GE were capable of designing and manufacturing advanced jet fighter engines like the F110 and F100 (Dabney and Hirschberg, 1998).

Thus, the era of the augmented turbofan was a stormy period of dramatic increases in engine capability in which P&W pushed the bounds of technology and skirted with failure, while GE benefited from traveling a slightly more conservative route. At the end of the period, the quasi-institutionalized competition between the two remaining key contractors during the “Great Engine War” was viewed by many in the services as being critical to obtaining reliable high-performance military engines.

SUPERCRUISE AND STEALTH

In the early 1980s, the Air Force and Navy formally began developing requirements for next-generation fighters to replace the F-15 and the F-14 and the engines that powered them.[12] The Navy eventually dropped out of this joint effort, later developing its own new fighter,

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[12] This section is based primarily on Hirschberg (1997) and Aronstein, Hirschberg, and Piccirillo (1998).

the F/A-18E/F, powered by the GE F414, a derivative of the F404. The Air Force continued to develop the Advanced Tactical Fighter (ATF) program, which resulted in the F-22 Raptor fighter. The key new performance requirements imposed on the engine developers were supercruise (sustained supersonic capability without afterburner), stealth or LO characteristics, thrust vectoring, short take-off and landing capabilities, high reliability, and low unit cost.

Once again, the primary competitors for the engine business were P&W and GE. Ironically, it can be argued that P&W and GE switched strategies compared with the strategies used previously in the F100 versus F101/110 "Great Engine War" competition. In view of the painful developmental problems that had plagued both the TF30 and F100 programs and the resulting loss of business due to the Air Force's encouragement of GE's reentering the competition, P&W management seemed to have shifted to a strategy of emphasizing somewhat-lower-risk technology and high reliability to win the new engine competition. Yet GE had lost the previous initial FX/VFX competition to P&W in part because of the perceived technological virtuosity of the P&W design. GE was then forced to struggle for more than ten years to reenter the high-end fighter engine market, which it finally did by stressing the reliability and simplicity of its F110 and F404 engines as compared with P&W's problem-prone engines. This time, GE management was determined to win the initial competition and seemed to have concluded that it could be done by adopting P&W's earlier strategy of demonstrating very high performance and unparalleled technological sophistication.

Similar to the earlier Advanced Technology Engine effort that preceded the F100 engine program, a series of government-sponsored component demonstration and concept development programs preceded the development of prototype competitor engines for the ATF. These included such efforts as the Advanced Technology Engine Studies (ATES) program led by the Navy and the Aircraft Propulsion Subsystem Integration program that included development of the Joint Technology Demonstration Engine (JTDE).

In June 1981, the Air Force issued a formal Request for Information to industry for the ATF engine. P&W proposed its ATES design, which drew heavily on its work conducted under the ATEGG and JTDE programs. This was a very-low-bypass turbofan (or leaky turbojet) with counter-rotating spools. GE's ATES efforts examined a series of different design approaches, including variable-cycle engines.

ATES was followed by the Propulsion Assessment for Tactical Systems studies, which teamed the competing engine developers with the competing airframe integrators to conduct more-advanced design studies. During this period, GE decided to adopt a variable-cycle engine concept, which had been demonstrated in various advanced technology programs. In 1984, GE also demonstrated and adopted another novel technical approach: a counter-rotating vaneless interface between the high-pressure turbines (HPTs) and low-pressure turbines (LPTs).

In September 1983, GE and Pratt were awarded contracts to develop prototype ground-test engines to demonstrate the technical capability to develop supercruise, two-dimensional nozzles, and 30,000 pounds of thrust for the new ATF engine. These demonstrator prototypes did not have to meet the weight requirements necessary for flight testing. After a little more than four years, government officials originally planned to select one design to enter into a six-year, full-scale development program, during which flight testing and development would occur.

P&W's XF119 ground demonstrator engine focused on technical issues such as reducing the number of compressor stages in order to lower costs and weight and increase reliability. GE's XF120 ground demonstrator engine moved ahead using the more complex variable-cycle engine concept with the vaneless HPT-LPT interface. The XF120 was also a very-low-bypass leaky turbojet but used a variable-bypass system based on a fairly complex double-bypass concept. Both engine designs employed counter-rotating spools.

In the mid-1980s, several changes implemented by the government and the airframe prime contractors had a major impact on the engine program. In 1985, the Air Force lowered the production unit price target and applied more stringent LO requirements to the ATF engine. More important, in mid-1986 the Air Force decided that the engine contractors must flight test their demonstrator engines before final down-select and the beginning of Engineering and Manufacturing Development (EMD), formerly called Full Scale Development. This meant redesigning the demonstrator engines to flight test the weight standards. This requirement was made more complex when, in 1987, teams from the two primary airframe contractors—GE and P&W—concluded from their extensive design trade studies that a more powerful engine with 35,000 pounds of thrust would be needed.

GE and P&W were permitted to make their own decisions on how much new technology and what capabilities they would demonstrate in their flight-test engines and how much new technology and what capabilities they would demonstrate on ground tests. GE again chose a higher-risk approach than P&W did by choosing to demonstrate more capability in its flight-test demonstrator. Again, the strategy was to win in the final selection by demonstrating greater performance during the flight tests.

P&W's YF119 design for flight demonstration was only slightly different from its XF119 design for ground testing and could not meet the new higher thrust and other requirements in a flight demonstration. GE's YF120 engine, by comparison, was far closer to its proposed EMD design baseline. As a result of these two different approaches, both the Lockheed/GD/Boeing YF-22 and the Northrop/McDonnell-Douglas YF-23 ATF demonstrator aircraft showed higher performance levels with the GE flight demonstration engine than when equipped with the P&W flight demonstration engine. However, the Air Force did not consider this demonstration to be a performance "fly-off" but rather a demonstration of the technical and management capability needed to meet the program objectives during EMD with the least technical risk and the lowest cost.

In April 1991, Secretary of the Air Force Donald Rice announced the selection of the Lockheed team and the P&W engine to proceed into EMD for the new ATF. It appears that Lockheed and P&W were selected on the grounds that their proposals represented lower technical risk and lower cost. GE's variable-cycle approach and vaneless HPT-LPT interface concepts were perceived as new technical approaches that were less than fully proven and complex, and that increased technical risk. P&W successfully portrayed its engine as being more conservative technically, less complex, and, based on incremental improvements, still fully capable of eventually meeting all engine performance requirements at lower risk and cost.

The P&W F119-PW-100 production prototype first flew in 1997. The engine appeared to be experiencing relatively few technical difficulties during the F-22 EMD flight test program, especially in comparison with the F100 and TF30 programs. According to one source, the F119-PW-100 performed “without fault” during the first 500 hours of flight testing on two F-22 EMD prototypes (“F119 Engine Takes F-22 Raptor …,” n.d.). Apparently, Pratt & Whitney had learned its lesson and had been wise in adopting a slightly more conservative technical approach.

Selection of the F119 for the F-22 and successful initial development of the F119 made it a likely candidate for other fighter programs. In spring 1995, Boeing, Lockheed Martin, and McDonnell Douglas, the three contractors that had teams competing during the concept-development and risk-reduction phase of the Joint Strike Fighter (JSF) program, all selected a derivative of the F119 as the engine to power their JSF designs.[13] Key performance requirements were very high reliability for the single-engine Navy JSF variant and sufficient nonaugmented thrust for the short takeoff and vertical landing (STOVL) JSF variant. All three contractor teams decided to start with the F119-PW-100 core and tailor the nozzle, fan, controls, and other features for each variant. The Boeing and Lockheed designs required redesigned fans and low-pressure turbines. At the time, it became clear that the JSF F119 program would become a fairly significant development effort.

With P&W supplying the engine for both the F-22 and all the JSF prime contractor contenders, not to mention all F-15s and a good number of F-16s, concerns grew about the need to provide greater competition and continue support for GE, the country’s sole second source for high-performance fighter engines. In the summer of 1995, Congress directed the JSF Joint Program Office to pursue a second engine source to maintain engine competition during production in the JSF program, as had existed in the 1980s with the F-16 “Great Engine War.” In late November 1995, initial development contracts were awarded to P&W for an F119 derivative and to a GE/Allison team for design studies for the YF120 and F110 variants for the JSF.

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[13] The tri-service international JSF program is intended to replace U.S. Air Force F-16s and A-10s, U.S. Marine Corps AV-8Bs, and British Royal Navy and Royal Air Force Harriers, and in addition augment U.S. Navy F/A-18E/Fs.

In early 1997, P&W received an EMD contract which, when added to earlier JSF engine contract money, amounted to a nearly $1 billion development effort. By that time, GE, Boeing, and Lockheed had settled on the YF120 as the baseline for development of a second engine for the JSF in what had now become the Alternate Engine Program (AEP).[14] Rolls-Royce also now teamed with GE, mainly because of the British firm's acquisition of Allison. Rolls-Royce's share of the YF120 Advanced Technology Engine core development effort stands at 25 percent.[15]

The GE alternative engine is not expected to be available for competition with the P&W engine until the production of JSF Lot 7 commences in 2013. However, Congress has increased funding for the AEP in several annual budgets, and it is possible the GE engine could be available for procurement competition by 2010, or very early in the planned JSF production effort.

The P&W and GE engine variants for JSF are expected to benefit from the ongoing research efforts taking place in the IHPTET program. Initiated in 1988, IHPTET is another ambitious government/industry technology development and demonstration program, which includes the continuation of some earlier efforts mentioned earlier in this appendix. For example, in the interim between the YF120's loss in the ATF competition and its entrance into the AEP for the JSF, the Air Force continued to work with GE through the IHPTET program to mature the YF120's advanced technologies. IHPTET's flagship goal is to double the thrust-to-weight ratio of military turbofans while reducing production and maintenance costs by 35 percent by 2003.[16]

IHPTET, which is half funded by industry and half funded by government, is expected to eventually make possible the development of more-reliable next-generation engines with dramatically higher

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[14] By that time, McDonnell Douglas had been eliminated from the competition.

[15] In addition, Rolls-Royce also plays a significant role in other aspects of the JSF propulsion system that are unassociated with the AEP. For example, Rolls is developing the lift fan mechanism for the Lockheed STOVL design and is developing nozzles and various other parts for the Boeing STOVL design. These efforts are contractor-furnished equipment outside of the government-furnished equipment P&W program and the government-furnished equipment AEP.

[16] See "Integrated High Performance Turbine Engine Technology" …, 2001.

thrust. This development continues the tradition of U.S. leadership in development of gas turbine combat aircraft engines, established definitively in the 1950s with the J57 and continuing on to this day.