Technology for Jet Engines: A Case Study in Science and Technology Development

Article *in* Journal of Propulsion and Power · September 2005

DOI: 10.2514/1.14149

2 authors:

William S. Hong
Institute for Defense Analyses

Paul D Collopy
University of Alabama in Huntsville

JOURNAL OF PROPULSION AND POWER
Vol. 21, No. 5, September–October 2005

Technology for Jet Engines: Case Study in Science and Technology Development

William S. Hong*
Institute for Defense Analyses, Alexandria, Virginia 22311-1882
and
Paul D. Collopy†
DFM Consulting, Urbana, Illinois 61803-0247

Large jet engine research and development in the United States from the 1960s through the establishment of the Integrated High Performance Turbine Engine Technology Program in the late 1980s and the role of development in advancing fielded airbreathing propulsion capabilities are examined. The focus is on science and technology management principles employed during that period and how they impacted the process by which technologies were introduced into production aircraft. Literature on the history of aircraft engine development through the 1980s was researched, and a number of current and retired personnel from U.S. government organizations and large engine companies who were active during the period were interviewed. The positive results of small focused teams with minimal oversight and strong leadership are shown. Programs also benefited from technically competent government managers with long job tenures, joint programs between government agencies, and personal, trust-based relationships between government and industry. The Integrated High Performance Turbine Engine Technology Program is shown to be an aggressive evolutionary technology development program with many attributes that have been copied by other science and technology management efforts.

Introduction

THE purpose of this paper is to examine the management of scientific research and technology development, using turbine engine development in the United States as a case study.

The first section of the paper addresses the period from about 1960 to 1985. This period was distinguished by a large number of new aircraft platforms of great variety and, consequently, a large and varied number of opportunities to design new aircraft engines (Fig. 1). Technology development of jet engines was on a steep trajectory: Most of the key technologies to modern aircraft engine performance were matured during this period.

The second section focuses on 1985–2000 when the Integrated High Performance Turbine Engine Technology (IHPTET) Program was the primary U.S. government vehicle for coordinating turbine engine science and technology research. It addresses the impact of management culture on technology development during both periods and the changes brought about by the IHPTET program management process.

The third and final section analyzes historical data and the IHPTET process, especially with respect to the general issue of radical vs incremental innovation in research programs.

Management of Turbine Engine Research Development from the 1960s to the 1980s

Before the 1960s, research into engine phenomena in the United States was generally carried out in the context of engine procurement programs. Requirements for the engine were established, and technology development was part of the process of designing a new engine. The time leading up to the 1960s saw significant advances in turbine engines because of the sheer number of different aircraft being developed and the attendant empirical findings that came with that experience. Every program provided opportunities to develop new components, explore new material temperature capabilities, and work in new aerodynamic regimes.

The following observations were made by Koff[1]:

> Engine programs were defined setting goals for performance, weight, reliability, cost and schedule. Contracts were let to industry upon evaluation of a proposal and based on perceived capability in meeting requirements. The Air Force and Navy set up Program Offices at Wright Patterson Air Force Base (WPAFB) and the Naval Air Station in Trenton, NJ, to coordinate, monitor and evaluate progress on engine development contracts. Both the Naval Air Station in Trenton and WPAFB had laboratories to develop specific technologies to support engine components. The Trenton facility also tested engines, and Navy personnel, using limited resources, worked with industry on improved technologies for fleet engines.
>
> Key engine development programs often fell short of meeting requirements in terms of performance, weight, cost and schedule. The compressors encountered blade fatigue failures and low stall margin causing engine instability in flight maneuvers; the combustors would burn out, flame out and send hot streaks to the turbine; while turbine blades would suffer oxidation, over-temperature and premature failure. Maintenance and lack of durability of the engine cores at Air Force bases was a major issue to be addressed.[1]

Nevertheless, the sheer number of engines developed in the 1950s and 1960s indicates that opportunities for technology advancements were plentiful (Fig. 2). According to Ray Standahar, these procurements addressed a full spectrum of sizes and classes, but had a tendency to be very scattered in terms of any technology developments.

The advancements were significant as a whole. For example, turbine engines became economically and technologically viable for use in commercial passenger aircraft at this time. However, in this period engines were frequently designed without specific applications in mind; instead, according to James Nelson, aircraft tended to be designed around available engines and the propulsion capabilities they represented.

The modern history of more formal scientific research programs for gas turbine engines in the United States started around 1960,

Presented as Paper 2004-6236 at the AIAA 4th Aviation Technology, Integration and Operations (ATIO) Forum, Chicago Hilton, 20–22 September 2004; received 21 October 2004; revision received 14 January 2005; accepted for publication 20 January 2005.

*Assistant Director and Member of Research Staff, Science and Technology Division, 4850 Mark Center Drive. Member AIAA.

†Engineering Economist, Post Office Box 247. Senior Member AIAA.

1950s	1960s	1970s	1980s	1990s
	B727			
	B737			
	Convair 880/990			
B707	DC-9			
DC-8	Gulfstream			
U-2	Learjet			
T-37	C-5			
B-52	C-141			
F-8	SR-71	B747		
F-100	T-38	DC-10		
F-101	A-4	L-1011	B757	
F-102	A-7	A-10	B767	B777
F-104	AV-8	F-14	B-1	MD-11
F-105	F-4	F-15	F-18	C-17
F-106	F-111	F-16	F-117	B-2

Manned Jet Aircraft, US Only, Date of Initial Production

Fig. 1 New platforms over time.

1950s	1960s	1970s	1980s	1990s
CJ805				
JT8				
JT3				
JT12				
T56				
JT4				
JT3				
TF33				
TF30			PW4000	
J85			PW2000	
J79	CF700	CFM56	F119	
J75	CF6	F404	F112	
J69	CJ610	F107	F110	AE3007
J65	JT9	F101	F109	GP7000
J60	TF41	F100	T800	GE90
J58	TF39	T700	T406	PW6000
J52	TF34	T55	J402	F414

Date is start of development. US only, military and commercial,
excludes commercial turboshaft engines and commercial turbofans of less than 10,000 lbf Thrust

Fig. 2 New engines over time.

when the Aero Propulsion Laboratory at Wright–Patterson Air Force Base found itself with zero budget resources for the development of new technology, partly based on the argument (which has periodically recurred since then) that turbine engines are a mature technology: Nothing more needs to be done. To counter the assertion, the Propulsion Laboratory management conceived the concept of a gas generator platform to develop a future engine technology base. Part of the rationale was that engine development time is much longer than airframe development time, and so engine components and technologies needed to be developed ahead of time so that they would be available off the shelf when an aircraft system development began. The first nascent effort at a technology demonstrator was called the Lightweight Gas Generator Program, which formed the basis for the advanced turbine engine gas generator (ATEGG), in the mid-1960s. ATEGG was set up to test components in a realistic full-scale core engine environment. The purpose of ATEGG was to use a proven existing platform to test out new technologically advanced components developed by industry.[2]

A leader at the Propulsion Laboratory at the time stated the following:

> It is a program which can be made successful by a contractor and success can be permitted by the government but success cannot be assured by the government. It is a program where the output thrust or airflow is only in appropriate “class,” it is not an engine and its purpose is to permit testing as cheaply and correctly in as close to engine environment as possible. . . . The contractor must establish that all component work which he does is accomplished to fit in the same airflow unit. This means that all agencies or organizations which pay for component work provide ultimately the hardware of the selected airflow so that the benefits and knowledge obtained from all sources benefit all.[2]

Ray Standahar told us that the core demonstrator concept required the engine components that were to test new technologies in designs and materials be made to a common scale to fit the demonstrator system. However, when the component technologies were transitioned to production engines, they merely had to be scaled up or down to the production application. The timescale for these transitions was on the order of two or three years. Whereas ATEGG was not an official interservice program, U.S. Navy supported technologies were included. Among the participating companies were General Electric (GE) Company, Pratt & Whitney, Curtiss–Wright Corporation, and Allison Engine Company, Inc.; later Teledyne Continental Motors and Textron Lycoming as components providers for turboprop/turboshaft engines were brought in.

Richard Hill said that ATEGG was created, in part, to provide a means of technology development for U.S. industry and government laboratories that would be of sufficient interest not only to the companies' military engines, but to commercial applications as well. In the early 1980s, ATEGG was expanded to include durability and life testing to create a more systematic approach to addressing engine failures, in contrast to point solutions common before.

The Joint Technology Demonstrator Engine (JTDE) program was set up in the mid-1970s as the first U.S. Air Force/Navy joint engine demonstrator effort. In contrast to ATEGG, JTDE was a program to demonstrate advances in the entire engine, including fans, low-pressure turbines, and mechanical systems and accessories, not just the gas generator components. The two services worked to a common set of requirements, but each did its own contracting from its own budgets. JTDE was driven by the same desire to advance capabilities, demonstrate new technologies, and provide experience to the personnel involved, like ATEGG. The result of these demonstrator programs was “real test data applicable to real engines,” according to James Nelson, rather than performance estimates from analytical models.

The idea for JTDE came from two program managers, T. Sims at the U.S. Air Force and J. Curry at the U.S. Navy, friends since their college days. This ongoing relationship enabled the elements of trust necessary to get the program started, not only within the services but at the level of the Office of the U.S. Secretary of Defense. The Joint label reflects the more formal Navy participation. A very important aspect of JTDE was that this program worked toward common problems using separately defendable budgets within each service. Later, this model was followed by IHPTET, which also included U.S. Army and NASA participation. The advantage in this arrangement was that each service could feel that they had control over their own budgets, while supporting efforts that addressed common problems. In addition, the engine research managers could point to the joint commitment to the programs as a way to defend budgets against raids from within their own service commands. The ATEGG cores and JTDE engines fed significant technology into the advanced tactical fighter engine demonstrators that led to today's F119, F135, and F136 engines.

Brief mention should also be made of the Aircraft Propulsion Subsystems Integration (APSI) program, which arose out of the problems encountered with the TF30 turbofan for the F-111 aircraft. APSI was devised to determine differences in performance of engines in their installed vs uninstalled states, with primary emphasis on thrust losses. The research program enabled better understanding of phenomena such as inlet distortion, incompatibility between inlets and fans, and nozzle drag. APSI continues to this day, recognizing the importance of full engine integration with airframe designs for best overall performance.

Lee Coons comments about the significance of these demonstrator programs:

> [They] . . . were an integration of existing component demonstrators. One of the great advances, I believe, in the mid to late 70s was the focus on demonstrators that resulted from system studies that looked at future weapon systems. These system studies looked at advances in technology at the component level and resulted in engine configurations from which advanced technology component programs were formulated and executed. At the conclusion of the component demonstrations, the components were

> easily integrated into a demonstrator engine that could easily be tied back to an advanced weapon system capability. One such system study that was conducted at Pratt & Whitney in 1976 was a company sponsored system study looking at the potential replacement of the F-15. The new capability postulated for this weapon system was sustained supercruise. Individual technologies were assessed as to their payoff in this weapon system and the key technologies selected to be pursued under company IR&D and government 6.2 and 6.3 [funding category] programs. What emerged from this technology planning and execution was a joint technology development effort between industry and the government that provided the technology base for the F119 and F120 engines.

The science and technology advances made in gas turbine aircraft engine programs had to be physically demonstrated by some means, whether by specialized demonstrator programs or by improvements and upgrades to fielded engines. The original performance demonstrator concept was later expanded to encompass elements of structural durability when durability problems in the field became dominant. The companies embraced this scope expansion because they could test ideas that had relevance not only to military applications but also to civilian aircraft and, hence, to their commercial business plans, according to William Heiser. A major source of research funding from the 1960s through the 1980s was independent research and development (IR&D). IR&D was nominally industry funding. However, U.S. government procurements allowed a limited amount of IR&D to be charged to contracts as allowable overhead expense, which meant that government funded a fraction of IR&D, up to the ratio of military revenue to total revenue. In the 1960s, IR&D was loosely managed and highly innovative, resulting in military turbofans, high-bypass commercial turbofans, film-cooled turbine blades, and a wide range of titanium components and manufacturing processes. By the 1980s, the government tied the IR&D funding limit to an annual review of IR&D programs. The government developed a bureaucracy to conduct the annual reviews, and industry developed corresponding bureaucracies to internally regulate IR&D activity and prepare reviews of each technology program. These reviews eventually incorporated technology roadmaps that showed where technologies would be inserted into fielded products. These roadmaps evolved, under IHPTET, into Advanced Turbo-Propulsion Plans. Possibly as a result of the oversight of these multilayered reviews, the level of innovation declined in IR&D-funded research. In the 1990s, the government disbanded IR&D reviews, which led to industry abandoning long-range research in favor of quick payoffs.[1] The review process was doomed, in any case, by shrinkage of military revenues relative to commercial business in the engine companies. By the mid-1990s, government was funding a minor fraction of IR&D budgets and, thus, had no leverage to wield in determining how the research money would be spent.

Transitions from Science and Technology to Fielded Engines

Among the engines developed during the period before IHPTET, the Pratt F100 engine program was a noted example of extremely aggressive technology advancement and the consequent problems that could arise. Ray Standahar wrote the requirements document for this engine and observed that, before the F100, engine performance tended to limit aircraft designs. The F100 program tried to build engines to serve the most advanced airframes, capabilities, and mission attributes. However, F100 teething problems (compressor stalls and durability, with failures common at 100 h) led to extensive efforts to improve serviceability and durability.[3] A major cause was that initial engine development programs did not always have sufficient resources to work out technical problems before the engines were put in the field, according to Ray Standahar and Richard Hill. Other sources contend that the F100 problems were caused by a lack of fundamental understanding rather than a lack of resources. In any case, the early TF30 and F100 turbofan engine designs outpaced the capabilities of materials and the execution of integration. Much of the research effort in the 1970s onward addressed engine durability problems, carried out under activities such as the Component Improvement Programs (CIPs), which were originally intended to enhance performance through field changes.

James Nelson told us that CIPs were started in the 1950s, as part of continuing engineering efforts, which were managed and funded as production line items. Their role in development is similar to spiral development processes. CIPs came about because engine use in the field often did not follow original design intentions. This caused problems in the F100, particularly thermal loadings from extreme throttle transients performed by pilots who were learning to exploit the full capabilities of the F-15 airframe.[3] The CIP concept was redirected in the 1980s toward safety and durability issues, although technologies that addressed durability and also enhanced performance were acceptable, according to Dean Gissendanner.

The F100 difficulties also led to the creation of the Engine Model Derivative Program (EMDP), which served as the vehicle by which the U.S. Air Force and Pratt and Whitney could qualify a new low-pressure turbine and other core components created under CIP to enhance durability. The introduction of the F100-220 via EMDP reflected this type of upgrade and appears to serve as a model for such improvements.

The most fruitful application of EMDP funding was the creation of GE's F110 engine, originally designated the F101 Derivative Fighter Engine. The F101 engine, which powered the B-1 bomber, evolved from the demonstrator engine that lost the F-15 competition to the F100. EMDP developed the F110 from the F101 to replace the TF30 in the F-14 and provide an alternative powerplant to the F100 in the F-16. The F110 was also qualified for the F-15, and a dry version of the F110, the F118, was used to power the B-2 bomber and reengine the U-2 reconnaissance platform.

In the 1970s through the mid-80s (leading up to the formal creation of IHPTET), the technological emphasis in turbine engines for the military was durability enhancement rather than performance factors such as thrust-to weight ratio:

> To a significant extent, the lack of increase in thrust-to-weight ratio in the 1970–1985 period was due to the desire for an engine life substantially greater than that achieved by the F100-100 in 1973. There was a great emphasis on durability during this 15-year period, which culminated with the introduction of the F100-220 and the competing F110-100 in 1985. The most tangible result of this effort was an increase in the mean-time-between overhauls of the latter engines by a factor of about 2 over the fully developed F100 (and an even larger factor over the F100 as originally produced). More specifically, data obtained in 1995 show the depot interval for the F100-100 as 450 engine flight hours (EFH), the F100-220 interval as 675 EFH, and the F110-100 interval as 950 EFH. It can also be speculated that with the introduction of production competition between the F100 and F110, the so-called "Great Engine War," emphasis by the manufacturers was devoted to cost reduction—particularly through life improvement—as opposed to performance improvement. Since the mid-1980s, the emphasis has returned to performance improvement while maintaining a long life. For example, the depot intervals of the engines introduced in 1989, again according to 1995 data, are 1725 EFH for the F100-229 and 1435 hours for the F110-129.[4]

Most of these improvements, however, did not result from advanced research programs. Initial work to address low reliability in the F100-100 was funded by CIP, which became a tool to fix production problems rather than perform research or develop new technologies. The durability increases in the F110-100 and F110-129 largely arose from commercial development work because the F110 shared a common core with the CFM56, which was being produced by the thousands. The funding for this work is identified as IR&D in the government accounting structure, but is better understood as postproduction engineering improvements like military continuing engineering funding. The F110-129 and F100-229 engine developments from the original F110-100 and F100-200 were funded as EMDPs, not science and technology programs. Direct contributions from U.S. government science and technology programs toward durability enhancement are not widely acknowledged within industry, although government direction to address durability problems through ATEGG[5] certainly played a role.

Where Did the Innovations Come from?

Gas turbine innovations in the United States between 1960 and 1985 resulted from industry development programs, industry research, military laboratories, NASA research, and joint military/industry work to correct problems with engines in the field. Even individual innovations seldom trace back to a single facility, but instead arose from complex interactions among several teams. Because of this complexity, the reported sources of innovation vary substantially depending on point of view. However, some elements of the picture are widely recognized. U.S. Air Force laboratories introduced several basic advances such as compressor aerodynamic models, which led to more stall-tolerant engines; heat transfer models for hot components and cooled turbine blades; computational fluid dynamic models, which led to more efficient compressor blade designs; vibratory analysis capability; and high work fans. NASA developed component performance models, computational fluid dynamics mathematics and software, and analysis methods to predict engine noise and emissions. Progress in analytical capability was synergistically tied to the development of computational capabilities. Not only did better computers enable more powerful analyses, major analytical tasks such as computational fluid dynamics provided a significant market for the most powerful supercomputers. Computer advances were key to improved stress analyses, which brought about the first credible predictions of engine part lifetimes.

However, the engine manufacturing companies actually put these and other advances into practice, and the implementation entailed a substantial portion of the basic research. For example, the U.S. Air Force Research Laboratory funded an advanced turbine cooling program at GE in the 1970s, which resulted in the one-piece cast blade with film and convection cooling, which is now used all over the world.

Industry used a combination of research contracts, funded by government laboratories, and internal funding (IR&D) to introduce new technologies. However, because of the close personal and intellectual working relationships between government and industrial technologists, partnership was a significant factor in advancing turbine engine capabilities. Also the frequent migration of technology personnel between different engine companies led to cross-pollination of innovations and transfer of technologies. According to Leland Coons, the interests of the government laboratories and industry were complementary:

> Because the interest of the companies was more near term than the government it brought a healthy tension. This tension was nicely resolved through the government and industry partnership commitment. This resulted in the companies funding nearer term and more conservative technologies and the government funding higher risk higher payoff technologies. If the more aggressive technologies fell short or missed achieving the goal on schedule, the more conservative (nearer term) technologies were used to keep the program moving forward.

IHPTET

In a very general sense, the creation of IHPTET in 1987 was a consolidation of ongoing demonstration programs rather than the start of something completely new. However, IHPTET was distinguished from its predecessor programs by its focus on a measurable leap in performance: doubling thrust-to-weight ratio. It was also distinguished by its success in maintaining funding stability. The Background section of the IHPTET Technology Development Approach (TDA) document states the following:

> The IHPTET initiative was formally initiated on 1 October 1987, but its roots can be traced back to 1982.
>
> The High Performance Turbine Engine Technologies (HPTET) effort began in 1982 as an advanced technology development study in the Air Force Wright Aeronautical Laboratories, Aero Propulsion Laboratory (APL). The APL initiated the "Integrated Technology Plan for the 90s" (ITP-90). Realizing that advanced materials development was a pacing item, the Materials Laboratory (ML) joined the initiative as a partner in 1984 with an increased emphasis being placed on advanced materials and structures. The assessment by the Materials Laboratory regarding the optimistic development time necessary for the critical materials was very influential in setting the technology demonstration dates.
>
> In 1985, in compliance with the direction of the Commander, Air Force Systems Command, to increase the gas turbine engine industry involvement in the HPTET, major planning reviews were held with the following seven aircraft engine companies: Allison Gas Turbine Division; Garrett Turbine Engine Company; General Electric; Lycoming; Pratt & Whitney; Teledyne CAE; and Williams International. The Navy and NASA also participated in the development of corporate long-range plans to accomplish the ambitious goals of the HPTET initiative by the turn of the century. The seven engine companies also made substantial commitments of company resources to their long-range plans which included company efforts that complemented the HPTET goals.
>
> At the urging of the Deputy Under Secretary of Defense for Research and Advanced Technology (DUSDR&E/R&AT), the Army, Navy, Defense Advanced Research Projects Agency (DARPA) and National Aeronautics and Space Administration (NASA) joined the Air Force in developing a coordinated long range plan embracing the goals of the HPTET initiative. The resulting technology development and demonstration plan represented a fully integrated Government/Industry activity, and thus the Integrated High Performance Turbine Engine Technology (IHPTET) program was born.[5]

When IHPTET was formed, it consolidated a number of existing demonstrator programs, including ATEGG, JTDE, and APSI. Additional participation by the U.S. Army, NASA, and DARPA contributed significant programs to IHPTET, though these were often existing activities in those agencies and services. IHPTET, like its predecessor demonstrator programs, was resisted at first within some parts of the laboratory structure because it took component development "sandbox" programs and forced them to consider transition paths.[1] However, once it was realized that these paths could result in the fruition of new ideas and concepts, resistance to technology transition planning decreased.

Whether IHPTET represents an incremental or a more radical example of technology change in turbine engines is a matter of perspective (Fig. 3). The aggressiveness of the performance goal (doubling thrust to weight ratio) suggests radical innovation. However, the individual technology innovations were incremental, such as higher specific strength materials applied in particular components, increased material temperature capabilities, and improved cooling systems. The state of gas turbine product evolution may preclude radical change because the basic components and the thermodynamic cycle are set. The fundamental architecture of military turbofans has not changed since the TF30 design in the 1960s. IHPTET's most eloquent proponent, Robert Henderson, states the case for radical improvement as a sum of incremental advances:

> It is clear that significant progress has been made in the last three decades; in terms of performance measures, this progress has been most noticeable in the last 15 years. In general terms, the mechanisms for such progress are well known. Higher maximum cycle temperatures and lighter weight components and structures increase the output-to-weight ratio—higher temperatures by increasing the output per unit airflow, and lighter weight

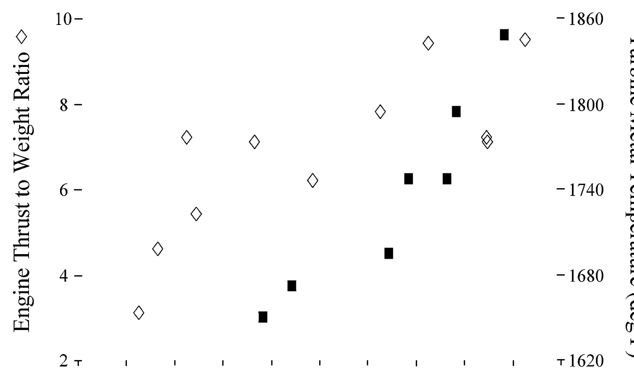

Fig. 3 Incremental technology improvements over time.[6]

> components and structures decreasing the weight per unit airflow. Higher combustion-initiation temperatures (higher pressure ratios in simple-cycle engines) and improved component efficiencies decrease the specific fuel consumption—the higher temperatures by increasing the theoretical efficiency and component efficiencies by achieving actual performance closer to the theoretical maximum.

However, Leland Coons saw the benefit of IHPTET primarily in the novel way it organized science and technology research:

> The IHPTET program brought several major things to the table. They include a broad set of agreed upon revolutionary propulsion system goals, a highly integrated and disciplined government and industry technology planning and review process, and a very integrated and disciplined resource commitment. The IHPTET goals brought unification of a vision for the future. In fact, IHPTET became so ingrained at PW [Pratt and Whitney], it was accepted as a core part of the overall technology development plan for all of PW. The program was actively supported by the executive team managing PW. Long range IR&D commitments were made and in general were more firm than in the past as the management team was familiar with how the money was being invested as opposed to the old days where there was a feeling of the money going into a black hole of sorts. The recognition of IHPTET by the management team allowed changes in personnel at several levels without the plan being put in jeopardy.

According to Robert Henderson, IHPTET requires technologies to have a transition plan before receiving support, with a user, such as the U.S. Air Force Systems Program Office, signing off to incorporate the particular technology once it has been demonstrated to IHPTET requirements. The user connection protects the technology development effort, whereas buy-in from the field activity and the engine contractor ensures eventual application. For example, the F119 relies on turbine cooling technologies developed under ATEGG and JTDE.

The 15 year commitment to IHPTET was a major step for both the government and the engine companies with respect to programs and funding stability. Further details on the origins of IHPTET and the personalities involved are in Chap. 19 of Ref. 3. The financially stable, multiyear nature of the program was essential to its success. Other critical elements were the early definition of key technologies, a division of responsibility among the participants, and allocation of resources to carry out the program. For many years, industry contributed roughly half of IHPTET's overall budget. Richard Hill told us, "A well planned program has the advantage of knowing where it will go even in times of budgetary constraint; whereas other programs which repeatedly redo their plans to fit changing (usually shrinking) budgets will be reactive in nature, and hence at a disadvantage."

Management Culture in the Turbine Engine Community

The success of U.S. turbine engine research programs derived in large part from the cooperative interaction between various technical and management personnel in government and industry, which allowed problems and solutions to be communicated readily. These relationships differed from more conventional government acquisition programs. The distinctive nature was partly due to the longevity of technical personnel in both government and industry: In many cases, careers were measured in decades, not years.[7]

One benefit of long job retention was the long-term working partnerships and relationships with counterparts in each community. Relationships based on trust between government managers and industrial personnel enabled them to keep each other informed of progress, work out problems, and encourage competitive solutions and activities. At the same time, the companies trusted that their trade secrets would be kept safe by government researchers. Trust enabled informal ground rules that both sides would not pursue avenues of inquiry or actions that were legally open to them, but which might undermine the established relationships. Long-term relationships between government managers in the different military services also helped to ensure that the government had a united position when negotiating matters with industry. This was key to resolving disputes that did arise.

Another attribute of the IHPTET organization was the high technical competence within government management. Often this resulted from managers having prior experience as working scientists or engineers. Albert Martino noted that U.S. Air Force program management tended to have more laboratory orientation, whereas the Navy emphasized experience in the fleet and experience dealing with field problems. Both organizations agreed that familiarity and training in engines was needed to manage research programs successfully. A level of technical competence was also required at upper levels in the Pentagon. There, a strong advocate of the programs could not only provide cover for the research programs at the laboratory level, but could also challenge the field management personnel to work outside of their comfort zones, according to Dean Gissendanner.

A downside to the deep relationships such as those in the turbine engine community is the possibility that new ideas or concepts perceived as generated outside a community may not get a full hearing or impartial evaluation. Another risk is that close relationships can prevent levels of technical oversight and skepticism that a more adversarial culture might generate. In this case study, however, no mention was made of the rejection of new propulsion concepts because they were from outside the community, and close relationships have not precluded vigorous technical exchange and disputes. Steering committees, with government and industry participation and input, are essential elements of the IHPTET model. Richard Weiss recalled that the IHPTET steering committee concept drew on successful experiences in the JANNAF Interagency Propulsion Committee. Although industry members cannot have veto or other powers over federal acquisition procedures, on a purely technical basis steering committees provide a nonproprietary informational role in the decision making. A side effect is that the participating services must act in concert on policy matters, to avoid being played against each other by the companies. As long as the steering group encourages ongoing technical exchange without getting bogged down in ways that hamper the research work through endless bureaucratic box-checking, they can provide a useful mechanism for building the types of relationships mentioned elsewhere. Such a system should allow sufficient freedom to support research managers in their extensive, ongoing planning processes. According to William Heiser, the IHPTET program incorporates continuous planning activities, which can be tedious and time consuming. However, if the contractors are doing the bulk of the heavy lifting, then it behooves the government managers to use their skills in making sure the work is responsive to the strategic plans. In the technology planning process, it is impossible to overestimate the work involved, but also impossible to overestimate the benefits that come with it.

These stable relationships and the resulting levels of trust and teamwork may not be possible in a current day government environment that institutes short-term management assignments and suffers from unstable funding. Today's challenge, according to James Williams, is that "complex systems will continue to require intuitive rather than analytical judgment; thus not having a sense of institutional memory for development of such systems puts the programs at risk."

Analysis: Radical Innovation in the Engine Community

The 1960s were glory days of aircraft engine development. The decade opened with the variable geometry J79 and high-altitude J75 entering service. The two most ambitious gas turbine engines to date, the Mach 3 J58 and J93, were developed early in the decade. Pratt and Whitney produced the first military turbofan, the TF30, and GE built the first (and to date, highest bypass) subsonic turbofan, the TF39. Three GE-1 demonstrators in the 1960s developed the core component designs for the F101, F110, F118, F404, CFM56, and by way of the TF39, the CF6 engines, essentially GE's entire large engine product line 30 years later (Fig. 2).

Major technology accomplishments (Fig. 4) delivered to production in the period from 1960 to 1975 include, according to Thomas Donohue, 1) titanium compressor airfoils and disks; 2) nickel alloy

1950s	1960s	1970s	1980s	1990s
			Hollow Fan Blade	
			Thermal Barrier Coatings	
			3D Aero Design	
			Acoustic Fan Case	
			Active Clearance Control	
Variable Stators		Composites	**Digital Controls**	
Clearance Control		Direct Solidified Blade	Thrust Vectoring	
Titanium		**Single Crystal Blade**	Ceramic Composites	
Mach 3 Flight	Supersonic Turbofan	Impingement Cooling	Brush Seals	Ceramic Bearings
Cooled Turbines	**Superalloys**	Shroudless Turbine	Counterrotating Turbine	Transpiration Cooling
Transonic Compressor	**Hi Bypass Turbofan**	Hi Temp Coatings	Variable Cycle	Dual Alloy disks
Turbofans	3-Spool Engine	Powdered Metal Disk	Dual Dome Combustor	Swept Blading

Fig. 4 Key technology advances; highest impact technologies in bold.

disks, beginning with Inconel 718 and progressing to powdered metallurgy turbine disks; 3) investment cast nickel alloy turbine blades, with cast-in cooling passages, resulting in production engine turbine rotor inlet temperatures of 2450°F; 4) turbofan architecture; 5) thermodynamic cycle modeling, to a level that was useful for performance prediction and control design; and 6) control strategies to deal with interacting components and manage compressor stall margin. For example, the CF6 achieved 2455°F (1345°C) in 1970. According to James Williams, 24 years later, the state of the art GE90 exceeded this by only 145°F (80°C).

Since 1975, the only comparable advances have been digital controls (an adaptation of technology from another industry) and higher turbine temperatures, in spite of billions of dollars expended on aircraft engine development. At the same time, engine development has slowed from two new engine models per year in the 1960s, according to Donohue, to a the point where, in the 1990s, Pratt and Whitney produced no all new large engines and GE only produced one. Explaining this precipitous dropoff in research productivity is key to understanding aircraft engine science and technology in the period. Three forces can be observed as contributing to the slowdown, without speculating on their relative importance:

1) The aircraft engine is a "mature product" (D. Edmunds) or a "commodity" (J. Fischer). This concept of maturity follows from the notion that technologies can be ranked by the ratio of payoff to development cost. The high-payoff low-development-cost technologies were developed first. By 1975, the only technologies left to discover were low payoff with high development cost. Technology investment has reached a point of diminishing returns. The commodity argument is similar: The performance of competing product lines have converged and airframes have matured so that competition is focused today on price and reliability. Therefore, product improvement is concentrated on making engines more rugged and less expensive. These improvements are best achieved by modifications to production engines rather than new models, so that they are seldom tracked as research or development. Both arguments presume that the array of potential technology improvements to engines is more or less fixed and has been known since 1960. The really good ideas for performance improvement are already taken, and so the opportunities are exhausted.

2) Complexity theory offers a more sophisticated view of the same phenomenon.[8] Early in the development of a complex product family, various architectures are explored. Design effort focuses on the most promising architectures, and they are refined into higher value products. Exploration of new architectures is reduced because, when a new architecture is compared with the current, refined architecture, it invariably comes up short, if only because it lacks the decades of incremental improvements that benefit the status quo. Furthermore, adopting a radical change entails substantial investment in the infrastructure that has been built up around the status quo design. Thus, to adopt a new and different architecture, the new concept in its unrefined state must be significantly superior to the refined status quo. This is unlikely to happen, even if the new architecture is very superior to status quo architecture, when compensation is made for the refinements. Thus, complex products tend to lock into particular architectures over time and radical technologies that entail major changes to the product become less and less attractive.

3) The third theory is organizational. Like Lockheed Skunkworks projects, the engines of the 1960s were developed by small, highly motivated teams of engineers and machinists with flat organizational structures, operating with a minimum of reviews and oversight. See, for example, the description of the development of the GOL1590, the demonstrator that led to the J79, by Neumann.[9] A great deal of responsibility was entrusted in a small number of people, so that if engineers wanted to incorporate a radical technology, they often had the latitude to do so without obtaining consent from many others. This could be an essential element of achieving radical improvements. Early on, the promise of radical technologies is not clear and seldom quantifiable. Support is often a matter of faith as much as reason. Such designs cannot survive multiple layers of top level reviews, but instead depend on champions and trust. When management funds a tight knit team and depends on trust rather than reviews and tollgates, there is a significant risk that, at the end of the day, there will be little to show for the investment. However, when layers of oversight and reviews are used, there is almost no chance of successful radical innovation. There are too many opportunities for someone to say no. Another advantage of small, tight knit teams with little supervision is their ability to develop technology rapidly and inexpensively so that a much higher failure rate becomes tolerable.

Numerous examples of Skunkworks-type programs exist in both industry and government. What is more interesting is that more structured research programs, such as the IR&D program in the 1980s and IHPTET of the late 1980s and 1990s, have featured bureaucracies on the industry and government sides who conduct systematic layered reviews of technology programs. These programs have notably failed to produce radical innovations that have transitioned to products in service as promised. They have succeeded in introducing many incremental technological improvements, particularly in raising cycle temperature limits. On the other hand, IR&D, IHPTET, and other government-funded programs have invested decades of research into programs such as ceramic matrix composites, metal matrix composites, analytical sensor redundancy, and performance seeking controls, many of which have so far failed to transition into full-scale production in a meaningful way, or at least to anticipated levels.

Many veterans of the period reinforced these points:

> Past experience dictates that the planning process be balanced, so that meticulous planning does not become incompatible with more radical innovative potential, and may require that some separation between the two activities could be warranted. (Richard Weiss)
>
> Bureaucracies grew up in the lab and in the industry to manage IR&D in meticulous detail, which may have detracted from its effectiveness. Although IR&D was supposedly contractor controlled, there was still Air Force oversight and review. IR&D was, in many cases, not effective. Research programs under IR&D were not often transitioned into products. (Thomas Donohue)
>
> The government has spent considerable funds and resources to introduce first low and then high temperature advanced composite materials to replace metals. The gas turbine engineers were not successful in applying these materials into many engine components due to their inherent lack of ductility. The government WPAFB materials personnel persisted in expending resources for

> high temperature composites for aircraft and ramjet engines at the expense of exploring and developing improvements in monolithic alloys. (Benjamin Koff)

R. Standahar told us that in the 1960–1970s Pentagon, propulsion research staff had considerably more discretionary power to make decisions on what research programs to fund. According to D. Gissendanner, this discretion went away by the mid-1980s.

As noted, a shortfall in turbine engine research during this period was inability to abandon lines of research that did not deliver results to products or to associated demonstrator programs. D. Edmunds made the following suggestion:

> An overarching group can be established to sort out which research projects go forward and which should be stopped. Component technology groups may not be able to do this effectively on their own. An overarching group may be assigned to each component, perhaps not a permanent group, but ad hoc. That is, a permanent management structure, but an ad hoc technical review group. The key role of the review group is vetting technologies so that money can be focused on worthwhile ideas.

A perspective on the materials side was given by James Williams. He noted that, in many research programs, continuous, incremental improvement needs to be pursued rather than counting only on radical innovation. An essential step is prioritizing the technologies that are critical to achieving a particular aircraft program success and pursuing those: In other words, start worrying sooner rather than later about technology to manufacture those components needed to build the desired systems. Designs should not get ahead of the necessary technologies or the implementation of technology. Otherwise, it is easy to lose momentum and group cohesion when disruptions occur due to lack of planning. One of the failures of the IHPTET program (from J. Williams's perspective, in sharp contrast to the opinions cited earlier) has been the delayed investment in the materials needed to realize program goals, due to a number of reasons such as a lack of resources or inadequate time to address unforeseen problems. Current business practices, which are moving toward engine leasing rather than purchases (especially in the commercial sector, which is now larger than the military) make questions of durability even more important to industry, which tends to further suppress any drive toward using innovative materials that have not undergone rigorous testing and manufacturing certification.

General Applicability of IHPTET Research Management Methods

Gas turbine engines rank among the most useful and most technically impressive artifacts of our age. The science and technology programs of the last half century have been remarkably successful, both for the revolutionary advances before 1975 and the steady stream of incremental improvements in cycle temperatures and thrust to weight ratio after 1975. The sustained flow of technology improvements in the United States since 1975 is largely due to the methods used in the ATEGG and JTDE programs, culminating in the disciplined IHPTET process, plus NASA programs such as Energy Efficient Engine. Can the IHPTET management processes be effective in other product domains? Leland Coons, who managed technology programs under the IHPTET system for many years, answers:

> The propulsion technology focus has probably not changed much over the years. The quest has typically been for improved performance and that usually means higher turbine temperature (for higher specific thrust) and better materials for lower specific weight. Aerodynamic technology was oriented towards higher efficiency and reduced number of stages (for reduced weight and cost). This was true for fans, compressors, and high and low pressure turbines. Combustors and turbines had to manage the higher temperatures with reduced cooling air. What IHPTET drove was an accelerated pace in achieving the higher levels of performance. It also brought an integrated government and industry team to attack the aggressive goals and a disciplined process for planning and program accountability. IHPTET, I believe created a new culture for effective development of propulsion technology at a pace that provides propulsion system capability that has helped the US develop and deploy superior weapon systems.
>
> I believe that IHPTET is a benchmark in best practices for research planning and execution and could serve as a model for other research efforts within the government. As in all successful efforts, it needs a high level champion with a passion to drive the process.

Currently, the Vehicle Systems Office at NASA Headquarters is exploring the application of the IHPTET process to its own program structure. IHPTET has also been consciously applied to research in rocket propulsion. The Integrated, High Payoff Rocket Propulsion Technology (IHPRPT) program reorganized itself in the 1990s along parallel lines to IHPTET, including the creation of a steering committee. The quantitative, goal-oriented approach that marks IHPTET, when applied to the rocket programs under IHPRPT, came up with mixed results, according to Richard Weiss. There are several reasons, which contrast rocket propulsion against the airbreathing propulsion industry: 1) lack of a truly commercial industry for rocket propulsion, 2) less settled technology options available until the systems development stage, and 3) less overall government support at a steady funding rate through the military or civilian (NASA) agencies. In addition, the rocket community requires a determined effort on the part of the government to set aside funds to support more fundamental, radical ideas. Industry will not do this due to lack of IR&D funds and any sort of commercial market from which to recoup research spending. Weiss, retired director of the Phillips Laboratory, recommends that some fixed percentage of the research budget, such as 10%, be set aside for this purpose.

It is not clear that the structured IHPTET approach can be effective in blue sky, first principles' basic research or research at the architecture and large platforms level of planning, where radical designs are the essence of research.

D. Edmunds, a consumer of IHPTET technology, made the following comment:

> The period from 1940 to 1970 or 1975 was ripe for new technologies in aircraft engine development. After 1975, the products have approached maturity and there have been correspondingly fewer inventions. IHPTET began in the early 1980's and is a program perhaps geared best to incremental technology development for a mature product. . . . One reason research in this period was so successful is that there was an architecture established for the engines (essentially the architecture of the TF30 and TF39). This allowed science research at the component level, where phenomena could be understood at a detailed level. In the 1940's and somewhat in the 1950's, a variety of architectures was investigated, so that it was hard to focus much attention on one component of one configuration.

Conclusions

From the observations of technology managers active in turbine engine development during the period concerned, we observe that the research management structure had the following general characteristics.

1) Joint interservice programs (for example, the U.S. Air Force and Navy in the JTDE, and the three services plus NASA in IHPTET) allowed work toward common problems but with separate, defendable budgets within each organization.

2) Technically competent government personnel in program management challenged field personnel (government and industry) to work outside of their comfort zone.

3) Stability of senior management in the laboratories and the Pentagon, in some cases for more than 20 years, enabled deep understanding of issues associated with particular technologies and consistent direction and support of technologies from concept to fielding.

4) Stable, multiyear funding allowed the establishment of long-term research teams in government and industry who could become deeply acquainted with technologies and challenges.

5) As management inevitably changed, the succession of leadership was closely attended so that the basic approach and philosophy remained stable.

6) Small, focused teams with minimal levels of management and strong leadership worked directly on the technologies in government and industry laboratories.

7) Open communications and high levels of trust between personnel in the government and in the companies assured the companies that the government would safeguard their competitive advantages.

8) The government encouraged competitive development by the engine companies on common problems, even when not all of the companies were selected for particular contracts.

9) Development programs were tied into technology transition plans for systems applications with buy-in by the user communities, particularly the engine companies.

10) A sufficient number of development opportunities were available for technology transfer, including military acquisition programs and commercial products. The evolving applications for engines in this period provided a path forward to anticipate technology needs.

11) Anticipated technology needs were prioritized so that planning and execution could be brought to fruition at the correct time. Development program delays waiting for the "appropriate miracle" to occur were, for the most part, avoided.

Beyond these management characteristics, several recurring themes were found in this case study's examination of the history of aircraft engine development in the United States between 1960 and 1985.

First, the primary value of basic research is to provide models, methods, and tools to predict the performance of a design configuration. Such tools allow designs to be refined before they are implemented in hardware.

Examples are compressor aerodynamic models (leading to better stall-tolerant engines), advanced high cycle fatigue analyses for compressor and turbine blades, heat transfer models for hot section and cooled turbine blade designs, and computational fluid dynamic models leading to more efficient compressor blade designs. Note that many of these basic advances and models came out of government laboratories, in the U.S. Air Force and NASA. These advances did not draw the same attention as technologies that could be embodied in a piece of hardware (such as a variable compressor vane) passed around a conference table. Thus, they often do not get the credit they deserve as critical steps in the creation of today's aircraft engine. However, in our interviews with technology managers, analytical models were consistently at or near the top of the list of critical developments during the 1960–1985 period.

Basic research is often credited with discovering and harnessing fundamental phenomena and thereby leading to technologies that apply the new phenomena to enhance products and systems (the linear model of technology development). However, we did not find technologies arising from basic research in this way during the period we investigated.

Second, full-scale demonstrators matured technologies, prototyped component designs, and explored system integration issues. They also vetted technologies, sometimes showing that investment in a once promising technology should be ended. These demonstrators were immensely valuable to technology development and transition.

One example is the GE-1 core engine demonstrator in the early 1960s. The GE-1 developed several critical technologies for contemporary engines and fathered two derivative demonstrators whose impact can be felt to the present day in military and commercial aircraft engines. Almost all of the profit stream of GE Aircraft Engines from 1980 to 2000 resulted from engines derived from these three demonstrators. The tests were funded by contributing engineering, an early form of IR&D, and the ATEGG program. Additional demonstrator programs at NASA in the 1970s also contributed technologies used on commercial engines. However, NASA full-scale demonstration programs began to be curtailed in the late 1970s, and component technology flowing from NASA into production aircraft engines has greatly slowed, if not nearly ceased.

Third, tight knit teams with a vision, long term commitment, minimal hierarchy, and minimal oversight can discover and deliver major technical advances.

Numerous examples of Skunkworks-type programs exist in both industry and government and are credited with advances such as the first variable geometry turbojet (J79) and the Mach 3 engines of the early 1960s (J58 and J93).

More structured research programs, such as the IR&D program of the 1980s and IHPTET of the late 1980s and 1990s have featured bureaucracies on the industry and government sides who conduct systematic layered reviews of technology programs. These programs have notably not produced radical innovations that have transitioned to products in service. They have succeeded in introducing many incremental technological improvements, particularly in raising cycle temperature limits.

On the other hand, IR&D, IHPTET, and other government-funded programs have invested decades of research into programs such as ceramic matrix composites, metal matrix composites, analytical sensor redundancy and performance seeking controls, many of which have so far not transitioned into production in a meaningful way, or at least to anticipated levels. These technologies have each survived dozens of annual reviews at many layers in industry and government.

Why do small, independent teams succeed at radical innovations? We speculate that it may be because they have the freedom to persist in developing high-risk technologies that hierarchical organizations would abandon. Early on, the promise of radical technologies is not clear. Support of them is often a matter of faith as much as reason. This distinguishes radical from incremental advances. Thus, radical technologies cannot survive layers of reviews. They depend on champions and trust. When an agency funds a tight knit team and depends on trust rather than reviews and tollgates, there is a significant risk that, at the end of the day, there will be little to show for the investment. However, when layers of oversight and reviews are used, there is almost no chance of successful radical innovation. Too many participants hold veto power. Additionally, small tight knit teams can develop technology rapidly and inexpensively so that a much higher failure rate becomes tolerable.

Fourth, a great deal of gas turbine technology development in the 1960s and 1970s came about to correct problems with engines already in service and was conducted as part of the product management of the engine rather than through offline technology development programs.

Examples such as the compressor stall and durability problems in the early TF30 and F100 turbofan engines for the F-111 and F-15 are classic cases. CIP funded most of the work to correct the deficiencies in these engines. One of the key technologies of this period, the ability to maintain the aerodynamic stability of a high-pressure compressor, particularly in a turbofan configuration, was developed primarily under CIP for these two engines.

The TF30 and F100 experiences provide positive and negative lessons for spiral development. On the positive side, the engines were fielded with minimal capabilities and successively improved. In the case of the TF30, the improvements never brought the engine to a satisfactory level of performance. The premature retirement of the EF-111 Raven was largely due to the unreliable TF30. On the other hand, the current F100-229 is an excellent, very-high-performance fighter engine.

On the negative side, the development of these engines in the field was very expensive and painful. The pain was due to performance falling short of promises, and this could be avoided in the best-managed spiral development programs. The cost impact is more intractable. Substantial time is required to develop and demonstrate technology improvements to aircraft engines. Every significant change to an engine requires lengthy requalification to ensure safety. Without major change to the product qualification process, the frequent product releases envisioned in the spiral development process cannot be as frequent or inexpensive in the aircraft engine domain as other types of products have experienced. This should provide cautionary deliberation to some proponents of spiral development.

When considering the applicability of turbine engine research processes to other domains, it is important to note that the turbine engine is a system whose basic architecture has not changed since the 1960s. Nevertheless, in this period turbomachinery used in Brayton cycle engines has undergone refinements in aerodynamics, materials, controls, and numerous other areas that have translated into countless performance and economic gains.

In very fluid domains, such as missile defense or net-centric warfare, where basic concept architecture is not yet fixed, the incremental methods used in IHPTET and other engine programs may not achieve the success experienced in the turbine engine research programs. IHPTET methods appear to be more applicable to systems acquisition programs in the spiral development phase. Such methods include the goals, objectives, challenges, and actions (GOTChA) process, which develops quantitative, phased goals for technological advancement. The GOTChA process works well for incremental programs where goals and objectives can be applied to development of technologies for existing systems architectures. It is less clear that blue sky, first principles' basic research will lend itself readily to this more structured approach, or that it will support architecture design and systems-of-systems concepts. In other words, the less well-defined the concept, the less the IHPTET model applies.

The extent to which the GOTChA process from IHPTET can apply to less well-defined research programs depends on the ability to define quantifiable goals as part of the exercise. The IHPTET planning process and model applies to the highest mission goals that can be quantified and, thus, verified. In very novel system design areas, such as network centric warfare or missile defense, goals may be hard to quantify at the system architecture level. The question in such programs is if it will work rather than how much, Still, IHPTET methods may work well on subsystems or components such as interceptor missile guidance systems.

Robert Henderson summarizes the impact of IHPTET in this way:

> Continual Pentagon oversight and interest by Dr. Donald Dix was particularly important throughout each year since the initiation of IHPTET in 1987, and, although painful at times, did much to keep the IHPTET program on track and focused on its long-term goals. IHPTET was often referred to as a revolutionary technology development program because of its aggressive goal of doubling propulsion system performance and operational capability in about 12–15 years. In fact, I would say it was an aggressive evolutionary technology program that resulted in a more accelerated technology development, demonstration, and transition of a number of key turbine engine technologies. Without the continual and dedicated focus of IHPTET by both government and industry during the past 15 years, progress in turbine engine capability would definitely have evolved at a much slower pace. Both commercial and military aircraft systems realized advanced capabilities many years sooner as a result of the work accomplished under IHPTET.

Acknowledgments

The authors thank the Missile Defense Agency of the U.S. Department of Defense, which funded this research at the Institute for Defense Analyses. Richard Van Atta led the technology management program under which this research was conducted. Also, Belcan Corporation generously arranged and supported a workshop at their headquarters to explore the issues. Attending the workshop were R. Atcheley, L. Burns, P. Combs, T. Curran, M. Eismeier, J. Fischer, J. Henderson, G. Knight, H. Maclin, J. Reed, and the authors. The authors interviewed a number of current and retired personnel from both the U.S. government (laboratory personnel to officials in the Pentagon) and the large engine companies (General Electric Aircraft Engines; Pratt and Whitney, United Technologies Corporation; Rolls–Royce, plc.; and others). The authors would like to acknowledge a debt to L. Burns, L. Coons, D. Dix, T. Donohue, D. Edmunds, D. Gissendanner, W. Heiser, R. Henderson, R. Hill, A. Martino, J. Nelson, R. Nelson, R. Standahar, R. Weiss, and J. Williams, who provided white papers and participated in extensive interviews.

References

[1] Koff, B. L., "Jet Engine Case Study for MDA," Inst. for Defense Analyses, Alexandria, VA, Nov. 2002.

[2] Simpson, E. C., *The Last Great Act of Defiance—The Memoirs of Ernest C. Simpson, Aero Propulsion Pioneer*, edited by J. St. Peter, U.S. Air Force Wright Aeronautical Labs., Wright–Patterson AFB, Dayton, OH, 1987.

[3] St. Peter, J., *The History of Aircraft Gas Turbine Engine Development in the United States... A Tradition of Excellence*, International Gas Turbine Inst., American Society of Mechanical Engineers, Atlanta, GA, 1999, Chap. 19.

[4] Dix, D., "Technology Trends in U.S. Aircraft Engines 1970–2000," Unpublished draft, Institute for Defense Analyses, Alexandria, VA, 2000.

[5] Henderson, R., and Martino, A., *IHPTET Technology Development Approach (TDA)*, Dept. of Defense, Office of the Secretary of Defense, Arlington, VA, 1998.

[6] Nelson, J. R., "An Approach to the Life-Cycle Analysis of Aircraft Turbine Engines," George Mason Univ., 18 April 2002.

[7] Belcan Corp., "Transcript of Workshop on Aircraft Engine Research Programs," Inst. for Defense Analyses, Alexandria, VA, Nov. 2002.

[8] Kauffman, S. A., *The Origins of Order: Self-Organization and Selection in Evolution*, Oxford Univ. Press, New York, 1993.

[9] Neumann, G., *Herman the German: Enemy Alien U.S. Army Master Sergeant #10500000*, Morrow, New York, 1984.