American Energy Innovation Council

CASE STUDIES ON THE GOVERNMENT'S ROLE IN ENERGY TECHNOLOGY INNOVATION

Aeroderivative Gas Turbines

By Travis R. Doom | August 2013

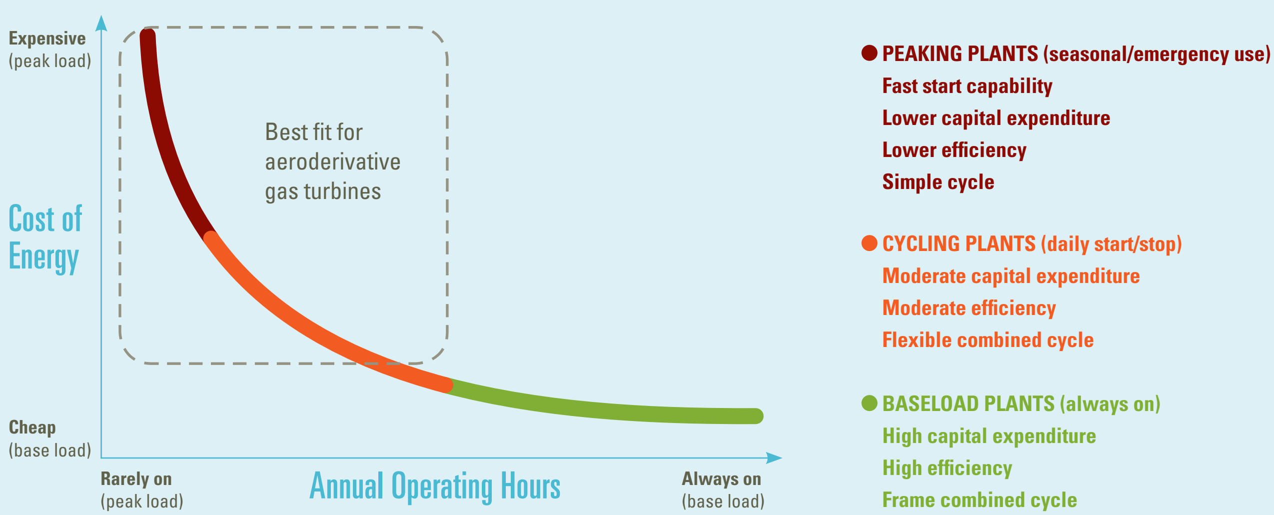
Introduction

For more than a half-century gas turbine engines pioneered for military jet fighters have hung under the wings of commercial airliners. For nearly as long, manufacturers have built industrial gas turbines to drive electricity generators and pump oil and gas. Many gas turbines, large and small, are designed specifically for these industrial applications. Aeroderivative gas turbines used for these industrial applications are adapted directly from existing aircraft engines. Aeroderivative gas turbines emerged in the late 1960s with unique performance attributes in comparison to the existing industrial gas turbines. Aeroderivative units could startup more quickly for peak and emergency electricity generation. Also, aeroderivative turbines offered lower weight in a smaller footprint, which was ideal for offshore platforms. Furthermore, their higher efficiency, coupled with simplified installation and maintenance, saved money for pipeline operators.

In the mid-1980s independent power producers began using aeroderivative gas turbines for combined heat and power generation, also called cogeneration. In this configuration, the exhaust heat of the gas turbine is used to produce steam to directly heat a building or industrial process. Aeroderivative gas turbines can convert 40 percent of fuel energy into electricity; when configured for cogeneration, system efficiency can exceed 80 percent, as far less of the fuel's chemical energy is lost as unused heat. Aeroderivative gas turbines are also being used to balance the integration of variable power sources, like wind and solar, into the electricity grid.

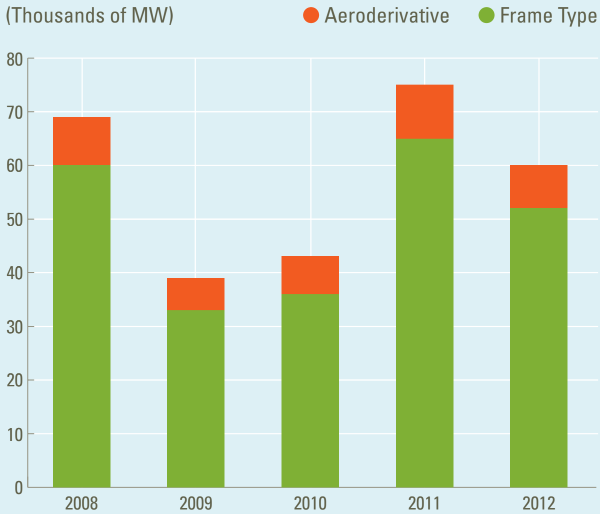
In 2010 the industrial gas turbine market — including aeroderivative gas turbines — was estimated to be $15.6 billion worldwide.[1] The electricity generation sector accounts for $12.9 billion of the total

Figure 1: **Operational characteristics of gas-fired electricity generation**[2]



Source: Adapted from Rolls-Royce Energy Systems

Figure 2: **Worldwide gas turbine orders by type, 10 MW and larger**



Source: Axford Turbine Consultants LLC, as cited in *Combined Cycle Journal*

production value and is undergirded by the $2.2 billion mechanical drive sector, which includes applications for oil and gas production. The marine sector accounts for the remaining $0.5 billion in production value, where aeroderivative models are used to power the world's navies, fast ferries, and luxury cruise ships.

In the United States, over 20 percent of electricity generated in 2011 was powered by gas turbines, nearly all fueled by natural gas.[3] Gas turbines are increasingly important for U.S. electricity generation, with the Energy Information Administration projecting that natural gas generation will increase to 27 percent of all generation in 2025 and 30 percent in 2040."[4]

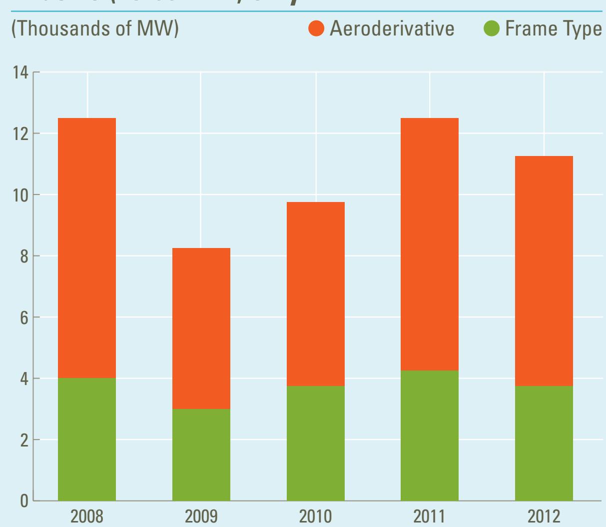
Most electricity generated by natural gas come from large industrial gas turbines designed specifically for that purpose, not aeroderivative units. These larger, heavy-duty or frame-type gas turbines for baseload power can exceed 200 megawatts (MW) each, and large plants may configure several of these units together in combined cycle. In this configuration, exhaust heat from one or more gas turbines drives a separate steam turbine to generate additional electricity, achieving an overall efficiency around 60 percent.

Aeroderivative gas turbines have historically been limited to midsize units of roughly 18 to 65 MW each, reflecting the size of their parent aircraft engines. While the capacity of aeroderivative units is smaller, these units add flexibility critical for sustaining large generating plants throughout the electricity grid. Moreover, aeroderivative units are well suited for highly efficient cogeneration, more flexible combined cycle plants, and in mechanical drive applications essential to production and distribution of oil and gas.

Worldwide, aeroderivative units account for approximately 10 to 20 percent of gas turbine capacity in recent years' orders, totaling roughly 6,000 to 8,000 MW per year. However, for mid-size units with capacities of 18 to 65 MW, aeroderivative units account for approximately two thirds of gas turbine capacity sold in recent years.[5] General Electric (GE), the leading provider of aeroderivative gas turbines, estimates having over 2,300 aeroderivative units in service for electricity generation worldwide, totaling 80,000 MW of capacity.[6] Rolls Royce projects that aeroderivative units used for electricity generation and oil and gas operations over the next 20 years will be worth $70 billion in sales plus another $50 billion for associated services.[7]

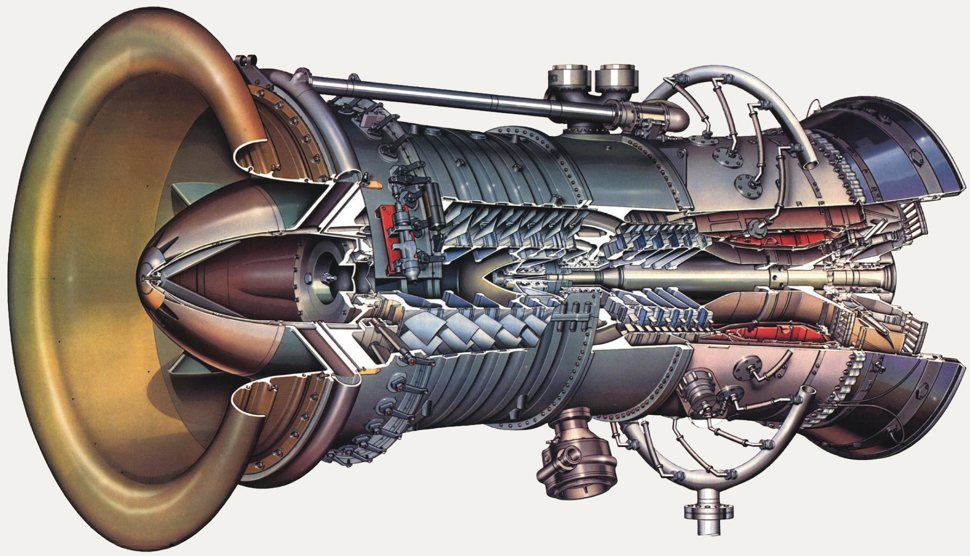
The entire industrial gas turbine market is just over half the size of the commercial and defense aircraft gas turbine engine market, which in 2010 amounted to more than $26 billion worldwide.[8] The performance of aeroderivative gas turbines is largely enabled by the engineering successes sustained in the lucrative aircraft engine market. The role and impact of industry-government partnerships in advancing aircraft engine technology is widely appreciated and has directly impacted the evolution of aeroderivative gas turbines.

Figure 3: **Worldwide gas turbine orders by type, midsize (18-65 MW) only**



Source: Axford Turbine Consultants LLC, as cited in *Combined Cycle Journal*

Figure 4: **Aeroderivative Gas Turbine Cutaway**



Compressor

Air moves through several stages of rotating blades and is pressurized and thereby heated. Higher pressure ratios between the air inlet and the combustor increases power and simple cycle efficiency.

Combustor

Fuel is burned in the combustor, heating the gas flow to the material temperature limit of the turbine blades. Materials and designs capable of higher temperatures increases power and efficiency.

Turbine

The expanding hot gas rotates the turbine blades and the shaft connecting the turbine to the compressor, continuing the cycle. Heat remaining in the exhaust can be captured for cogeneration or combined cycle.

Much of the core aircraft engine research and development (R&D) has doubled effectively as aeroderivative gas turbine R&D, as the most difficult and costly to develop components in aircraft engines are used in nearly identical form in aeroderivative gas turbines. For example, over the last decade, spending on aircraft engine R&D at GE has exceeded $1 billion per year.[9] By comparison, over the last four decades, spending on aeroderivative gas turbine R&D at GE is estimated somewhere above $2 billion in total.[10] GE, Rolls Royce, and Pratt & Whitney are the three manufacturers of aeroderivative gas turbines, and each of their aeroderivative models is descendent from a specific aircraft engine in their lineup.[11] As a result, tremendous gains in aircraft engine performance, led by the military and bolstered by the rise of commercial aviation, have resulted directly in improvements for aeroderivative gas turbines.

How Gas Turbines Work

Aeroderivative gas turbines, like all gas turbines, use a continuous intake of air and a continuous injection of fuel to create a hot, pressurized gas flow that expands through the turbine. In the compressor, a series of rotating blades pressurizes the incoming air in stages; this pressurization heats the air. In the combustor, chemical energy from the burning fuel adds far more heat. The hot, pressurized gas expands through the turbine blades and rotates the shaft that drives the compressor at the front of the engine, continuing the cycle. From this basic configuration, the remaining energy not used to drive the compressor can be captured in useful ways for various applications. In aircraft engines, the hot exhaust gas passes through additional turbines to rotate a shaft driving a propeller or fan that provides most of the aircraft's thrust. Aeroderivative and other industrial gas turbines work in a similar way, adding more turbines to extract energy from the hot exhaust gas to power a shaft. For industrial applications, the shaft is connected to an external electricity generator, a pump, or a ship's drivetrain.

History And Development

The U.S. military's competitive procurement process drove initial gas turbine development.

Gas turbine development arose in the early 1940s from the military demand for high-performance aircraft. This demand existed because of performance limitations inherent to the piston engine-propeller aircraft of the era, and because nations embroiled in conflict faced this common challenge. In the U.S., gas turbine innovation for aircraft superiority gained urgent and strategic focus under its national security mission, and the U.S. military fostered the competition necessary to explore a variety of initial designs. As a result, innovation accelerated through the 1940s and 1950s.

Gas turbine development in the U.S. began with several concurrent efforts. GE built a design borrowed from Frank Whittle for the Air Force, and Westinghouse built their own design for the Navy.[12] The Navy also helped to pull Pratt & Whitney into the competition by contracting them to manufacture Rolls Royce gas turbines. Pratt & Whitney quickly maneuvered to build and sell their own designs to the Air Force as well.[13] Early efforts were underway by the National Advisory Committee for Aeronautics (the predecessor to NASA) to study compressor aerodynamics, but it was the unsurpassed multitude of engine orders in the 1950s that motivated competing firms to develop advanced designs.

Amid this competition, Pratt & Whitney decided to pursue a high-compression gas turbine that would significantly improve fuel efficiency and power for the B-52 bomber. State-of-the-art compressors at the time reached a pressure ratio around 6 to 1, and Pratt & Whitney was aiming to more than double that. The major design change devised by Pratt & Whitney to achieve this radically higher pressure ratio let the compressor operate in two sections on independent shafts at different speeds. This twin-shaft configuration, enabling stable operation from startup to full throttle, led to the highly successful J-57 engine.[14] Pratt & Whitney built more than 20,000 J-57 engines for the Air Force and Navy between 1951 and 1965 and less than 1,000 J-57 engines for the nascent commercial aviation sector.[15] The J-57 soon evolved into the more powerful J-75 engine.

GE devised an entirely different solution to ensure a stable, high-pressure compressor for their J-79 engine to power the B-58 bomber. The GE variable stator design used a single shaft and mechanized parts of the compressor to adjust the geometry as airflow conditions changed.[16] Vigorous demand led GE to create fifteen new engine variations during the 1950s and build more than 17,000 J-79 engines for the military.[17] Importantly, the Pratt & Whitney J-75 and GE J-79 would become the parent engines for their first aeroderivative gas turbines. High-pressure compressors were the heart of these new engines, lending aeroderivative gas turbines their exceptional simple-cycle efficiency.

R&D efforts led by the U.S. military in partnership with gas turbine manufacturers continued to drive innovation, largely through new management and engineering approaches to jet engine development.

The drivers of gas turbine technology development shifted in the 1960s. The military began growing a technology base that, separate from enormous procurement programs, would sustain innovation in the decades ahead. The efforts of the 1940s and 1950s had resulted in innovative engine designs like the J-57 and J-79, but had also incurred huge costs with numerous, inexplicable problems:

> **Machinery when built did not behave as predicated. Nor could analytical methods provide much guidance on what to change. The difficulties encountered with a particular engine design might be overcome, but all too often the engineering group, in the absence of insight based on physical understanding, had no choice but to proceed by trial and error. Research was the necessary route to findings that could be generalized.[18]**

A concept took hold within the Air Force Propulsion Lab to conduct gas turbine research, not by constructing and testing complete engines, but instead by improving the core components. This "building block" approach was intended to develop the compressor, combustor, and turbine as a unit suited to a range of future engines:

> **[T]he lab had to convince the various contractors that this was the way forward, because the idea was radical at the time and its success was not assured or embraced. For contractors, this was a conceptual leap…several years and millions of dollars in contracts would not result in a particular contractor ending up with a singular, superior engine.[19]**

The reasons this concept took shape after 1959 were simple: the Aeronautical Systems Division, not the Air Force Propulsion Lab, was given responsibility for new engine programs in the U.S. Air Force. With much Air Force funding also being consumed in the Space Race, the Turbine Engine Division within the Air Force Propulsion Lab needed a more focused approach to assert their relevance.[20] This organizational shift was not a one-off effort, but rather part of much broader institutional change. The Air Force was learning to manage the development of an astounding array of complicated technologies. Gas turbine engines, like ballistic missiles and command and control computer systems, required new approaches to engineering and management.[21]

While the Air Force may have provided the initial nudge for the "building block" approach, within industry the shift towards a stronger technology base was further incentivized by the rise of commercial aviation. GE used the opportunity to take the same core components validated for military transport aircraft to launch their commercial engine line. In 1979, GE described this alignment as the "most significant business/technology achievement to date in GE aircraft engine history."[22] Big profits were on the horizon for firms who understood gas turbine technology well enough to balance tradeoffs and improve performance along all dimensions: power, efficiency, reliability, maintainability, and cost.

Aeroderivative gas turbines benefitted for decades from an uninterrupted stream of incremental innovations flowing from their parent aircraft engines. For example, GE continually improved its LM2500 aeroderivative model and, in 1990, introduced the significantly more powerful and efficient LM6000, which was based on an aircraft engine that "embodied all the aerodynamic and materials refinements since its 1970-predecessor."[23] These refinements came from both the engineering science supported by the Air Force and the millions of flight hours accumulated in the thriving commercial aviation sector.

The U.S. Navy implemented testing for marine gas turbines that guided advances in materials engineering and enabled better performance in non-aviation uses.

The U.S. Navy transitioned its fleet of ships from steam to aeroderivative gas turbine power beginning in 1970, following experiments in the 1940s and a concerted development effort throughout the 1950s and 1960s.[24] Not unlike the ongoing efforts with aircraft engines at the time, much of the learning first took place by repairing and improving marine gas turbines already in service.[25] Because initial testing proved inadequate at mitigating problems in development engines throughout the fleet, the U.S. Navy implemented more rigorous rating and qualification standards for marine gas turbines. Understanding, for example, how the severity of corrosion and oxidation varied for different alloys and coatings under realistic operating conditions required extensive empirical efforts: "The life of ultra-high temperature materials in gas turbine engines (shipboard or aircraft) is dependent on a complex combination of temperature-stress-environment-time variable fields."[26]

In 1968 Pratt & Whitney and GE aeroderivative units underwent extensive, side-by-side testing for the U.S. Navy.[27] Although some operating conditions, like high salinity, are unique to marine applications, the materials engineering knowledge cultivated through these efforts was valuable more generally for adapting aircraft engines for industrial service in harsh environments. For example, the high sulfur content in lower quality, non-aviation fuels presented service-life concerns for aeroderivative gas turbines installed in ships—a problem common to gas turbines on pipelines and at peak generator stations. The U.S. Navy played an important role early on to help advance aeroderivative gas turbines for more diverse uses, both by demanding a robust product and supporting the engineering and testing to further demonstrate durability.

Private industry built on knowledge gained from military and commercial applications to repurpose aircraft engines for electricity generation and mechanical drive applications, including oil and gas pipelines.

Since the late 1940s, firms were leveraging their knowledge and investment in aircraft engines to explore industrial gas turbine applications. Westinghouse, for example, built a pair of gas turbines that powered a Baldwin locomotive in 1948. When the experimental locomotive was scrapped, Westinghouse resold the gas turbines to power a peak electricity generating plant in Kansas and an industrial air compressor in Virginia.[28] Both GE and Westinghouse stood on many years of experience building steam turbines, but it was the very different challenge of designing military aircraft engines that provided a basis for their industrial gas turbine businesses. Even Siemens, who exclusively builds industrial gas turbines and who also relied in part on steam turbine experience, traces their history to a German aircraft engine built in the 1940s.[29]

Industrial gas turbine businesses utilized the aerodynamics developed for aircraft engines, but the industrial versions evolved apart from the design constraints unique to aviation. Industrial gas turbines were not engineered to minimize size and weight. Durability and affordability was prioritized for industrial gas turbine customers, which resulted in components with greater wall thickness and different material choices. Industrial gas turbines also tended to use moderate pressure ratios and rely on auxiliary devices like heat exchangers to improve efficiency. The niche for aeroderivative gas turbines that emerged in the 1960s was shaped by these design differences and strengthened by rapidly advancing aircraft engine performance.

When manufacturers started repurposing aircraft engines for industrial applications, aeroderivative gas turbines had 15 to 25 MW capacities with efficiencies near 30 percent. Pipeline operators could more easily transport, install, and maintain the lightweight and compact aeroderivative gas turbines in remote locations, and offshore platforms often needed the higher power in a smaller footprint that aeroderivative gas turbines offered. Blackouts in the U.S. and Europe in the 1960s also spurred the use of aeroderivative gas turbines for emergency and peak electricity generating applications. Aeroderivative gas turbines, with their thinner, lighter-weight components, could ramp up to operating temperature more quickly than other industrial gas turbines, a valuable feature for emergency and peak power applications.[30] Cogeneration, another major application using aeroderivative gas turbines, took off in the mid-1980s following a series of policies deregulating energy markets.[31] The Public Utility Regulatory Policies Act of 1978 prompted the expansion of cogeneration capacity, although it was at first limited mostly to coal-fired steam turbines.[32] After the price of natural gas resettled following deregulation completed in 1985, and after the Power Plant and Industrial Fuel Use Act was repealed in 1987 following newly available reserves, independent power producers became major customers for the aeroderivative gas turbine businesses.[33]

The momentous shift in natural gas price and availability, along with environmental concerns and changes in electricity markets, also resurrected the demand among utilities in the U.S. for larger, baseload industrial gas turbines.[34] Industrial gas turbine manufacturers were eager to infuse the latest aircraft engine technology in their products, but only GE could source this knowledge internally from their own aviation division (as Westinghouse had exited the aircraft engine business in the 1950s). In the 1990s, Siemens and Westinghouse managed alliances with aeroderivative turbine developers Pratt & Whitney and Rolls Royce, respectively. Although these industrial gas turbines would retain their own heavy-duty designs, the engineering tools needed for example to improve compressor blade efficiency and enhance turbine cooling were far better developed within the firms building aircraft engines.[35]

Public-private partnerships coordinated R&D efforts to resolve complicated design problems, ensuring diffusion of technical knowledge and allowing private sector participants to leverage funds.

One exemplary program, the GUIde consortium, highlights the contours of the aircraft engine technology base and details the kinds of partnerships that have long advanced innovation for gas turbines. Convened first in 1991, the GUIde consortium set as its goal mitigating certain low amplitude, high frequency vibrations that cause compressor blades and other components to fail. This type of failure, known as high cycle fatigue (HCF), became increasingly problematic:

> **As the decade of the 90s opened HCF became a more notable problem as the B-1 engine experienced two spectacular failures, one of which led to the engine separating from the aircraft…By the mid 1990s HCF issues became the dominant failure mode for fighter engines in the USAF. With tensions high on the Korean peninsula, specially equipped F-16s with the mission to suppress enemy air defenses were grounded due to an HCF issue…Also during this time HCF began to appear in commercial engines to a lesser extent than in military engines but with severe consequences to the manufacturer's development programs and revenue service for airlines.[36]**

The GUIde consortium was built around the reality that HCF was an industry-wide problem. HCF had persisted because the difficulty of the problem was beyond the reach of individual firms who had limited funds to improve their own design systems for predicting vibration.[37] The words of a leading expert from the Air Force capture the difficult nature of the problem that necessitated a cooperative approach among otherwise competitive businesses:

> **I can recall many meetings where, as a group of technical experts, we went through a systematic analysis of the conditions leading to an HCF failure and can prove, through existing data, knowledge, and analysis that a failure could not have occurred. Only the failed parts in our hands were able to convince us of our inability to completely describe the event accurately.[38]**

The GUIde consortium was structured with center directors at Carnegie Mellon University and Purdue University, with a steering committee of voting members, one each from the Air Force, NASA, and six participating companies. Industry provided approximately half of the funding for the six research projects approved by the steering committee, which were conducted mostly at universities, each at a level around $100,000 per year for four years. This arrangement allowed the individual firms to leverage their investment approximately 10 to 1, and it allowed the multidisciplinary problem to be effectively divided into key research areas, such as structural dampening and unsteady aerodynamics.[39] Although HCF did not afflict the existing generation of aeroderivative gas turbines, other industrial gas turbine manufacturers, including Siemens and Mitsubishi, joined the GUIde consortium. These firms needed better engineering tools to ensure their newest machines would not experience damaging vibrations operating across a range of speeds with more aggressive compressors—the same tools that the Air Force and its contractors needed to restore reliability in their fleet of fighter aircraft engines. NASA also joined the GUIde consortium, seeking better tools to predict vibration in rocket engines.

University researchers in the GUIde consortium needed data to develop models of the phenomena causing HCF, and the participating companies needed models that could be practically implemented in their existing design systems. Turbine performance data, such as force and flow measurements and detailed component geometries, was transferred from companies to researchers through subcommittees overseeing individual projects. The subcommittees facilitated closer interaction between the technology developers and the technology users, providing opportunities to clarify the objectives and validate the new tools. The GUIde consortium also provided the structure needed to share and analyze complete data sets from expensive rig tests at Air Force and NASA facilities. Additionally, review meetings and conferences strengthened the small community of dedicated experts.[40]

The GUIde consortium gained momentum in its first few years, and the fifth iteration of the program is planned to begin in the fall of 2013. Between 1995 and 2005 the Air Force led a comprehensive, highly successful $400 million initiative to mitigate HCF, with the GUIde consortium program continuing as one part. The field engine inspection workload for HCF declined by over 90 percent, and the proportion of engine mishaps resulting from HCF declined from 54 to 7 percent.[41] The GUIde consortium example illustrates the kinds of goal-oriented, incremental innovations that improve aircraft engine performance while further strengthening the knowledge base for industrial gas turbines, including aeroderivative models.

Current Status of the Technology

Aeroderivative gas turbines today remain a leverage business, enabling GE, Pratt & Whitney, and Rolls Royce to reach other markets while minimizing the cost and risk associated with new technology development. These firms utilize both methods and components developed from their lucrative commercial and military aircraft engine businesses. Much of this knowledge has diffused through the industry-government partnerships and alliances discussed above, ultimately improving the gas turbine technology for electricity generation and other industrial applications.

While the focus of this case study has been aeroderivative gas turbines, all industrial gas turbines have benefited from the aircraft engine technology base. In the 1990s, the firms that most effectively sourced aircraft engine R&D—GE internally and Siemens externally from Pratt & Whitney—became market leaders. Of course, the success of a firm's gas turbine business is based on far more than R&D; GE and Siemens have also proven adept at responding to technical mishaps through effective marketing and sales support.[42]

Many gas turbines today blur the boundaries that generally distinguish aeroderivative gas turbines. Siemens, for example, has acquired the knowledge needed to optimize certain designs for lower weight and compact footprints with faster startup times and higher simple cycle efficiency. GE now builds a gas turbine that couples an aeroderivative core with their larger, heavy-duty turbine components in a unit that produces 100 MW, a power level much higher than could be obtained by simply repurposing an aircraft engine. Moreover, as electric grid operators increasingly value flexible generation assets to deal with new challenges, aeroderivative gas turbines are being incorporated into a variety of combined cycle gas turbine configurations, thereby providing fast-start and cycling capabilities while retaining the overall efficiency of an integrated system. With power generation from natural gas and variable renewable sources on the rise in the U.S., the use of industrial gas turbines will increase and the competition to offer customers a full range of solutions will intensify.

Lessons Learned

The history of aeroderivative turbine development underscores the power of mission-oriented and demand-driven R&D. Procurement not only established the business case for private R&D efforts, but also ensured direct feedback from customers to the carefully managed industry development efforts. That said, the lessons for aeroderivative gas turbines are rooted in the unique context and history of aircraft engine development. It is critical to remember that the conditions created by World War II in the 1940s, the Korean War in the 1950s, and the Cold War in the years beyond are far from a practical context for budget-constrained energy technology policy planning today. One historian remarks:

> **Viewed from a distance, the development of jet propulsion in the US may appear to have been a chronicle of progress through skillful management of technology and organization. Examined closely, it stands rather as a shining example of non-linear, irrational, uncertain, multi-lateral, and profoundly passionate technological and business practice, yielding success not through planning but through dogged determination, a certain indifference to failure (which secrecy aided), and massive expenditures of public funds.**[43]

This excerpt perhaps best characterizes the earliest decades of gas turbine development. Lessons for innovation policy today may instead reside in the more recent, carefully planned and managed programs exemplified by the GUIde consortium. However, here too consideration is needed for the context unique to military technology development. The government role in advancing gas turbine performance was motivated by national defense objectives, not commercial or environmental aims.

In the 1990s, the short-lived Technology Reinvestment Project (TRP) tried to overcome this divide, bridging military and commercial needs. Despite sharing key attributes with the successful GUIde consortium, including a cost-sharing structure and industry led teams, TRP encountered serious difficulties that led to the program's demise. Tradeoffs between military and commercial requirements strained technology programs funded through TRP, and the partnerships threatened to undermine participating military contractors' competitive advantage in the defense acquisition process.[44] Features inherent to gas turbine engines have allowed program managers to navigate around such difficulties. Most military and commercial aircraft engines are not critically different, and gas turbines are sufficiently complicated that multidisciplinary partnerships do not hinder competition among engine builders. The core competency for these firms is the ability to integrate applied research into a useful design system, carried forward into a demonstrator engine, while minimizing risk and cost and following documentation and contractor guidelines through to manufacturing—an altogether enormous task.

The lesson for energy innovation is that aligning research with customer priorities and user needs is not a downstream or translational activity, but rather a central part of a successful R&D process. This remains a defining feature of the end-to-end military enterprise and is vital for pushing forward innovation in other domains. Gas turbine aircraft engines have been central to the culture of aviation surrounding the Air Force, from jet fighters to long-range bombers and huge transport aircraft. Not all energy technologies are simultaneously a public good and clear commercial value. Nor do all energy technologies have a proven architecture suited to incremental gains through engineering science and operational learning. The challenge for energy innovation is to craft policy that strengthens the public goods framework for technologies that can be built, improved, and will ultimately contribute to national goals for clean, reliable, and affordable energy.

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