THE INNOVATION OF ENERGY TECHNOLOGIES AND THE U.S. NATIONAL INNOVATION SYSTEM – THE CASE OF THE ADVANCED TURBINE SYSTEM

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ABBREVIATIONS

ABB	Asea Brown Boveri
ATS	Advanced Turbine Systems
CFD	Computational fluid dynamics
CO_2	Carbon dioxide
CRADA	Cooperative Research and Development Agreement
DLN	Dry low-NO_x Combustor
DOE	U.S. Department of Energy
EPAct	Energy Policy Act of 1992
FERC	Federal Energy Regulatory Commission
GE	General Electric
GEAE	General Electric Aircraft Engines
GE CRD	General Electric Corporate Research and Development
GEPS	General Electric Power Systems
GW	Gigawatts
Lb.	Pounds
MHI	Mitsubishi Heavy Industries
MW	Megawatt
MW-hr.	Megawatt-hours
NDE	Non-destructive evaluation
NO_x	Nitrogen Oxides
NSF	National Science Foundation
OECD	Organisation for Economic Cooperation and Development
OEM	Original Equipment Manufacturer
ORNL	Oak Ridge National Laboratory
ppm	parts per million
PURPA	Public Utility Regulatory Policy Act of 1978
R&D	Research and development
SWPC	Siemens Westinghouse Power Corporation
TBC	Thermal Barrier Coatings
USPTO	United States Patent and Trademark Office

EXECUTIVE SUMMARY

This case study examines the innovation of a complex commercial technology, using the advanced turbine system (ATS) development as a subject of study. The ATS was developed in concert with a U.S. Department of Energy (DOE) cost-shared, public-private partnership. The commercialized technology has reached performance levels that far exceed previous state-of-the-art technology, achieving 60 percent operating efficiency and nitrogen oxide emissions less than 10 parts per million. Two turbine manufacturers, General Electric Power Systems (GEPS) and Siemens Westinghouse Power Corporation (SWPC) have developed ATS technology and also were participants in the DOE ATS Program.

The case study focused on how the turbine manufacturers acquired the capabilities and knowledge that were necessary to develop subsystem technologies that led to the successful outcomes. In addition, the study examined the role of the U.S. government in fostering the innovation process. The study provided insights into the innovation of a complex technology and how various economic and social factors influenced its development. It also provided clues on how public policies and programs might be tailored so as to facilitate technologies that are beneficial to the public.

The study found that ATS development exhibited the characteristics of a transition pattern of innovation, which are distinguished by major advances in performance, as well as a qualitatively new design. The performance improvements centered on achieving significantly higher efficiencies and lower nitrogen oxide emissions than any previous models.

The turbine manufacturers created and utilized organizational networks as a means of capturing technical knowledge and capabilities in order to innovate the ATS. The actors in these organizational networks were resources of both tacit and explicit knowledge. There was also an indication that the extent to which the knowledge and capabilities of external participants is used is related to the depth and breadth of capabilities of the turbine manufacturers. In the case of GEPS organizational network, for instance, the actors consisted primarily of other General Electric business groups, i.e., GE Aircraft Engines, GE Corporate Research and Development, as well as external groups, i.e., Howmet and PCC Airfoils, companies with expertise in developing single crystal castings. GEPS relied mostly on the depth and breadth of capabilities the resided within other GE business groups.

SWPC also created and utilized an organizational network in its search for new knowledge and capabilities. Unlike GEPS, SWPC relied extensively on external actors as resources for knowledge and technical capabilities. SWPC utilized alliance agreements with

other turbine manufacturers, university researchers, government laboratories, and government testing facilities. It also relied on the casting companies, Howmet and PCC Airfoils.

The evidence shows that the DOE Advanced Turbine System Program was successful because it enabled the turbine manufacturers to acquire and create new knowledge from both internal and external resources residing within an organizational network. It is generally held by those most familiar with the technology that ATS Program accelerated the turbine development 5 to 10 years beyond what would have otherwise occurred.

In 2002, the advanced gas turbine technology was commercialized by GEPS and SWPC. General Electric installed their ATS in a 480 MW power generation plant in Baglan Bay, South Wales, United Kingdom, where operation has recently begun. They have also taken orders for 3 more units to be delivered to Tokyo Electric Power Company in 2006. SWPC has incorporated many of the ATS technologies into their existing model and providing their G System, effectively introducing the ATS technologies sooner. Many of their G systems, which achieve 58% efficiency, have been installed in several locations, most recently at Lakeland Electric plant in Florida and in Charlton, Massachusetts. The widespread deployment of these ATS turbines has yet to be realized; however these systems are expected to become the new standard in combined-cycle gas turbine technology.

The evidence also shows that the federal government contributed to the innovation process in three ways, including (1) “filling a gap” due to market failures associated with deregulation and low gas prices, (2) creating a learning environment that supported the knowledge creation process, and (3) supporting university research that was directed towards the needs of industry.

1

INTRODUCTION

In the 1990s, General Electric Power Systems and Siemens Westinghouse Power Corporation, spurred by the U.S. Department of Energy's Advanced Turbine System Program, undertook the development of an advanced gas turbine systems (ATS), an energy technology that significantly outperformed the state-of-the-art technology at the time, achieving high thermal efficiencies with low nitrogen oxides emissions. The story of how these two turbines manufacturers went about the development of these advanced turbine systems is the subject of this paper. In seeking to understand how the technological innovation of energy technologies occurs, important insights are gained in light of the national innovation system. These new systems represented a major improvement in the efficiency of combined-cycle gas turbine systems, moving from around 53 percent efficiency in the early 1990s to 60 percent efficiency in 2001. While this may not seem significant at first glance, it is useful to keep in mind that even a single percent point thermal efficiency can reduce operating costs by as much as $20 million over the life of a typical gas fired combined cycle power plant of 400 to 500 megawatts (MW). (Green 1999)

By most accounts, both General Electric Power Systems (GEPS) and Siemens Westinghouse Power Corporation (SWPC) were successful in the innovation of the ATS. GEPS has installed their ATS in a 480 MW power generation plant in Baglan Bay, South Wales, United Kingdom, where operation has recently begun. GE also has order for 3 more units to be delivered to Tokyo Electric Power Company in 2006. SWPC has taken a different approach in incorporating many of the ATS technologies into their existing model and providing their G System, which has been installed in several locations, recently at Lakeland Electric plant in Florida and in Charlton, Massachusetts. The widespread deployment of these ATS turbines has yet to be realized, however these systems are expected to become the new standard in combined-cycle gas turbine technology.

Both GEPS and SWPC have created a network of various organizations in their quest to create or acquire knowledge that was critical to the innovation of the ATS. Various institutional factors, including government research and development (R&D) policies, market conditions, universities, and other stakeholder groups act within the national innovation system and are evident in this case study as well. "Organizational networks" served as providers of knowledge and capabilities to the turbine manufacturers in the development of the ATS. The turbine manufacturers, or original equipment manufacturers (OEMs), were able to carry out the technological innovation of the ATS by acquiring the knowledge and capabilities residing within each of their organizational networks.

1.1 Focus of Case Study

This case study examines the innovation of the ATS, a utility-scale gas turbine that achieved a 60 percent efficiency with less than 10 parts per million (ppm) of nitrogen oxide (NO_x) emission, and a 10 percent lower electrical generation costs. More specifically, the study documents the case the advanced turbine system. It aims to offer a detailed picture of the turbine manufacturers' innovation process. The ability to overcome presumptive technological limits makes it an ideal study of how the OEMs seek out and create knowledge when faced with technological uncertainties.

Edward Constant described the adoption of jet engine technology over the piston engine as an example of what he termed a "presumptive anomaly." [Constant, 1980 #388]. He describes a presumptive anomaly that

> "…occurs in technology…when assumptions derived from science indicate either that under some future condition the conventional system will fail (or function badly) or that radically different system will do a much better job." (Constant, 1980, p.15.)

Prior to the ATS development, it was generally held that continued efficiency improvements were bounded by thermal efficiencies and NOx emissions. In order to achieve higher thermal efficiencies, higher combustion temperatures are needed; yet higher combustion temperatures exacerbate NO_x emissions at around 2,800 °F (1,540 °C). To combat excessive NOx emissions, oxygen is limited during the combustion process; yet this can lead to unacceptably high level of carbon monoxide and unburned hydrocarbon emissions. Further adding to the presumptive technological limitations, extremely high operating temperatures, greater than 2,350 °F (1,290 °C), were beyond the material tolerances of the turbine blades and vanes. Thus, the presumption was that achieving 60 percent efficiency while staying below 10 ppm of NO_x emissions was constrained by the thermal, emission reduction, and material limits of the turbine systems.

Today, the turbine manufacturers have overcome the presumptive limits by developing new technologies that were qualitatively different from predecessor designs. The advanced turbine systems have transition toed to a new technological trajectory, i.e., major changes in the performance of the previous technology requiring fundamentally new designs and technical capabilities. In making this transition that involve uncertain and unforeseen risks, firms often create new organizational networks in their search for and creation of new knowledge.

This study describes how the turbine manufacturers created and acquired the knowledge necessary in the innovation process. Inspired by the evolutionary perspectives of technological innovation of complex technologies, the research is based on the proposition that during periods of uncertainty and unforeseen risks associated with technological innovation, firms depend on organizational networks as resources for knowledge and technical capabilities. The uncertainties inherent in developing the underlying subsystem innovations of the ATS makes it an ideal test bed to assess how the OEMs adjusted their innovation approach. The study aims to offer a detailed picture of the dynamics of turbine manufacturers' innovation of the advanced turbine system. It also provided insights into the federal government's role in fostering the innovation of the advanced gas turbine system technology.

The study draws on a combination of qualitative and quantitative data to describe the knowledge creation process. Both methods were used to comprehensively describe the tacit and explicit knowledge used by the turbine manufacturers. Interviews were conducted with representatives of the major organizations to identify and describe the organizational learning processes and the government contributions in support of technological innovation. Quantitative data builds upon patent and citation statistics, which serve as a proxy for the flow of explicit knowledge both within and across organizational boundaries.

1.2 Overview of Gas Turbine Technology

A gas turbine is a heat engine that uses high-temperature and high-pressure gas as the working fluid. In its basic configuration, the gas turbine consists of a compressor to draw in and compress the air, a combustion system that mixes the high-pressure air with gas and ignites the mixture, and a turbine to extract power from the heated gas flow. To extract the power, the hot gas is directed tangentially by vanes directly on to the turbine blades. The turbine blades redirect the hot gas stream and absorb the energy from the gas stream, thereby producing power. In gas-fired power generation plants, combined-cycle systems are usually used because the gas turbine exhaust is used to heat water and create steam, which is then used to power a steam turbine for additional electricity generation. Figure 1-1 shows a schematic diagram of a combined-cycle gas turbine system.

There are four subsystem innovations that were critical in meeting the high efficiencies and low NO_x emissions, include: closed-loop steam cooling, single crystal superalloy castings, thermal barrier coatings, and lean pre-mix dry low NOx (DLN) combustors. Each of these subsystems are briefly described in the following paragraphs.

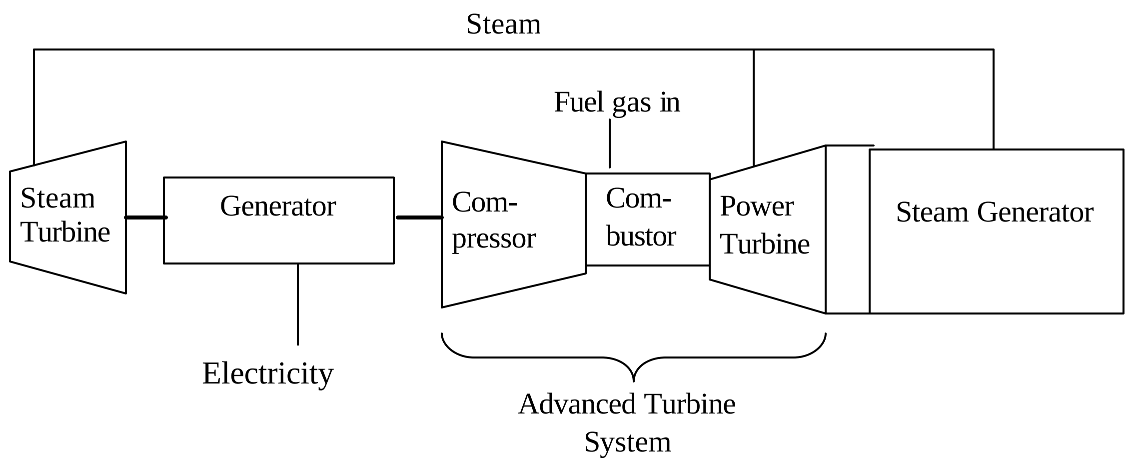

Figure 1-1: Combined-cycle Turbine System

Closed-loop Steam Cooling. Closed-loop steam cooling fundamentally changed the way turbine blades and vanes were cooled. In closed-loop steam cooling, the steam is transferred from the steam generator into the gas turbine blades and vanes, through a network of serpentine channels, and then returned to the steam generator. Because of its superior cooling properties over air, steam acts to transfer heat from the metal components and keep them from melting.

The turbine manufacturers agreed that closed-loop steam cooling was critically important in achieving a 60 percent efficiency. It allowed for a higher firing temperature (gas temperature when it first enters the turbine) without increasing the combustion temperature (gas temperature immediately after combustion and inside the combustor). The higher firing temperature results in a higher turbine efficiencies without requiring higher combustion temperatures that exacerbate NO_x emissions. Closed-loop steam cooling also provided superior heat transfer capabilities over air-cooling and, combined with exotic alloy materials, enabled the vanes and blades to withstand higher temperatures without melting.

Single Crystal Fabrications. A second critical innovation for the ATS machines was in the development of single crystal fabrications for the first- and second-stage blades and vanes inside the power turbine. These blades and vanes are exposed to the highest temperatures, around 2,600º F (1,430 °C).

Thermal Barrier Coatings. Thermal barrier coatings (TBCs) are applied to the vanes and blades and provide essential insulation and protection for the hot gas path components in the turbine. TBCs are comprised of two coatings, a ceramic topcoat and a metal bond coat. A ceramic coating provides thermal resistance, and a metal bond coat provides oxidation resistance and bonds the ceramic coat to the metal substrate. Both turbine manufacturers have developed their own proprietary TBC's materials and application processes.

Lean pre-mix, dry low-NOx combustors. Lean pre-mix, dry low- NO_x (DLN) combustors mix large quantities of gas and air in a chamber and ignite the mixture to produce the hot gases, which then drive the turbine.

1.3 Organization of Paper

The paper begins with a brief review of the literature as a background for the development of the analytical framework. Section 3 describes the socioeconomic forces that contributed to the environment of innovation. Section 4 provides a detailed account of how the manufacturers developed each of the major subsystems for their ATS technology. Section 5 analyzes patent and citation data as a measure of knowledge spillovers, and provides additional analyses in support of the qualitative study. Section 6 provides an evaluation of the costs and benefits of the ATS innovation and Section 7 presents conclusions and implications for policy decisions.

2

THE EVOLUTIONARY MODEL OF INNOVATION AS AN ANALYTICAL FRAMEWORK

The evolutionary theory of innovation describes how technological change occurs through a complex interaction of many factors and that technology *evolves* out of this interaction. (Freeman, 1994) (Rosenberg, 1994) Drawing parallels with the biological evolutionary theory, the evolutionary theory of innovation seeks to explain how technological change evolves within a *selection environment* that is made up of various social, economic, political, and technological influences. The forces influencing the advanced gas turbine systems included market failures, regulatory reform, political stakeholders, and government R&D investments that acted on the technological changes are the subject of this study.

The selection environment acts to shape and influence technological change along certain paths, or *trajectories*, which refers to a path of technological change. The most common way of illustrating a trajectory is the S-shaped curve, relating additional performance over time. A firm's decisions on technological innovation are *path dependent*, in that those decisions are shaped by the firm's current position, what paths lay ahead, and the experiences from the past. Simply stated, a firm's previous investments and its capabilities affect path dependency and also act as a constraint at times as the firm relies on previous experiences and routines as it seeks to develop new technologies. (Teece and Pisano 1998)

The trajectories of gas turbines (Figures 2-1 and 2-2) take on the appearance of an S-shaped curve. The efficiency performances improved incrementally in the 1960s and 1970s, followed by a substantial increase in the 1980s. In the 1990s, the efficiencies of both GEPS and SWPC gas turbine systems improved about 12 percent, reflected in the dramatic increase in performance. NO_x emissions control also improved during this same period, going from 40-50 ppm in the early 1990s to less than 10 ppm in 2001. During the same period, DOE's Advanced Turbine System Program, a public-private, cost-shared program, targeted the development of the advanced turbine systems.

Other scholars working within the tradition of the evolutionary-based perspective of technological innovation have carried out a number of studies directed at understanding how firms acquire knowledge and capabilities in their quest for innovation. Terms such as knowledge creation and core capabilities have been used in understanding the basis of a firm's competitiveness. (Prahalad, 1990)

2.1 Patterns of Technological Innovation

Robert Rycroft and Don Kash brought together the two bodies of literature on evolutionary theory of innovation and learning organizations in their model of the innovation of complex technologies. (Rycroft and Kash 1999) Based on their empirical research, Rycroft and Kash contend that complex technologies and organizational networks (described later in this section) *co-evolve* along parallel trajectories as illustrated in Figure 2-3. They describe how the innovation of complex technologies[1] occurs in patterns of innovation, normal, transition, and transformation patterns. Their model shows two lines in parallel to represent the co-evolution of the technology and the organizational network.

In a *transformation innovation pattern,* the organizational structures and processes produce a fundamental change in that the technology's performance and design, which differs from anything that existed before. The box in the lower left corner of Figure 2-3 represents the first-of-a-kind technology. In a *normal innovation pattern*, a technology goes through a series of incremental improvements that build upon established designs. The organizational network moves through a similar trajectory with minor or incremental changes in the resources of the network, as reflected in the circles in the figure. Periodically however, technologies undergo major redesigns, and this involves major changes to the organizational structures and processes. This is a point of disruption, and the normal pattern transitions to a new trajectory.

A *transition innovation pattern* characterizes the organizational structure and processes that produce major changes of existing technologies. New participants with new capabilities and knowledge are added to the organizational network while other participants, either internal or external to the firm, are removed. The triangle in Figure 2-3 represents the major redesign that moved the state-of-the-art turbines towards the advanced turbine systems. As will be described later, this transition requires the development of an organizational network that could synthesize diverse knowledge located within different organizations.

2.2 Organizational Networks

Organizational networks provide resources such as capabilities and knowledge necessary for the firm to carry out innovation. Although they may be supported by other social-economic-

[1] A complex technology is defined as a process or product that cannot be understood in sufficient detail so that the technology can be communicated to another individual across time and distance in a way that allows it to be exactly reproduced.

technical systems, organizational networks connect the diverse expertise in specialties such as R&D, design, and manufacturing, that reside in many different institutional settings (e.g., government laboratories, corporate manufacturing plants, universities, customers, suppliers, and more).

Organizational networks, or clusters, are a metaphor used to describe the actors involved in technological innovation. As defined by the OECD, "clusters" are,

> "…networks of interdependent firms, knowledge-producing institutions (universities, research institutes, technology-providing firms), bridging institutions (e.g. providers of technical or consultancy services) and customers, linked in a value-added creating production chain." (Organisation for Economic Co-operation and Development 2002, p. 26)

GEPS' and SWPC's organizational networks appear in Figures 2-4 and 2-5 respectively. Other participants in the turbine manufacturers' networks include:

- Suppliers and subcontractors who provide complementary assets, such as providers of components or subsystems,
- Public research organizations such as national laboratories who conduct R&D activities,
- Department of Energy,
- Alliance partners,
- Universities conducting sponsored research, and
- Customers, who establish the performance criteria.

As firms face new challenges or threats in the marketplace, they will add new organizations in their search out new capabilities and sources of new knowledge from other organizations, particularly during times of uncertain technological change. This process of adding new participants to the network and removing others has been described as a *self-organizing network*.[2] The self-organizing network is never static but continuously re-ordering itself into a new organizational network by acquiring new capabilities, knowledge, and assets that are needed to overcome technological barriers or create new market opportunities.

To remain competitive, organizational networks need to repeatedly acquire, integrate, and apply a wide variety of knowledge; that is, function as a learning organization. Organizational learning is essential in innovation; it is a process by which new capabilities and knowledge, both tacit and explicit in nature, are searched out and acquired. Tacit knowledge, including skills,

[2] Rycroft and Kash have described the concept of self organizing networks as an organizational structure that self determines its structure and identity by focusing its core capabilities and adapting quickly to new opportunities and perceived threats within the marketplace. Rycroft, R. W. and D. E. Kash (1999).

know-how, and experience that are held by both individuals and organizations, while explicit, or codified knowledge, is expressed in words and numbers, such as reports, computer codes, etc. Michael Polanyi cautioned against sharp distinctions between tacit and explicit knowledge, saying that, while tacit knowledge can be possessed by itself, explicit knowledge must rely on being tacitly understood and applied. In his view, all knowledge is *either tacit or rooted in tacit knowledge.* (Polanyi 1966, p. 144)

2.3. Organizational Learning and Innovation

The need for organizations to continuously learn and adapt to a changing market has been central concern to organizational learning theorists.[3] Organizational learning refers to ways firms acquire, create, supplement and organize knowledge and routines around their competencies and adapt and develop organizational efficiency through improving the use of their core capabilities. Richard Nelson and Sidney Winter use the term "routines" to describe the characteristics of firms that range from technical production, personnel management, inventory control, corporate management, to research and development. They views routines as the repository of the firm's knowledge. Furthermore, they view the important role of tacit knowledge held by the people within the organization as being the source of information. (Nelson and Winter 1982, pp. 99-104)

During periods of technological uncertainty, firms search for new knowledge more widely and across different industries, in order to retain and improve competitiveness, productivity and innovation processes. The greater the uncertainty facing firms the greater the need for learning. Dodgson argued that during these periods of uncertainty and rapid technological change, firms need to acquire knowledge at a higher level, that is, challenge some of their existing assumptions about what they do or how they do it, and transform their existing capabilities and routines. (Dodgson 1991)

The analytical framework used to examine the learning processes of the turbine manufacturers was adopted from the literature on organizational learning.[4] A typology used to describe the various learning processes is presented in Table 1-1 and summarized here. *Learning by doing* is highly dependent on using the tacit knowledge within the firm's staff and is illustrated by experimentation in the laboratory or shop floor. *Learning by formalized inquiry* refers to the firm's internal R&D activities, with outcomes codified in reports, computer codes, design documents, and other forms of explicit knowledge. *Learning by using* refers to feedback

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[3] For a review of the literature on organizational learning, see Dodgson, M. (1991).
[4] For elaborations on learning processes, see Nonaka, I. and H. Takeuchi (1995), Senge, P. M. (1990), and Senker, J. and W. Faulkner (1996).

provided by end users of the technology, largely based on experience and tacit in nature. *Spillovers* refer to tacit or explicit knowledge gained from others external to the firm, either voluntarily or involuntarily. *Interactive learning* refers to knowledge that is shared among the organizations within the network. *Advances in science and technology* relates to the conduct of R&D programs that are performed outside the firm, such as that conducted by the U.S. national laboratories or universities and is generally published or licensed technology.

The analytical framework presented in this chapter provides a context for exploring the learning processes used by the turbine manufacturers. As the evolutionary theory of innovation suggests, however, technological change occurs in response to other factors, which are described in the next chapter as drivers for innovation.

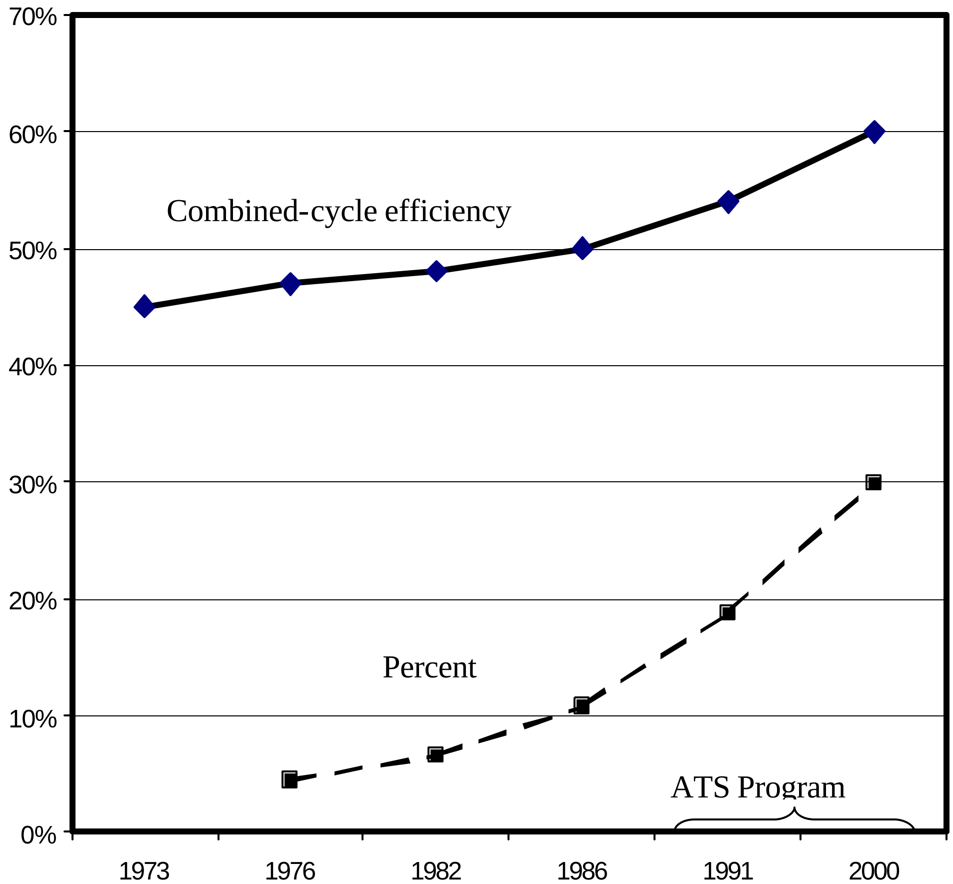


Fig. 2-1: GEPS' Gas Turbine Trajectory

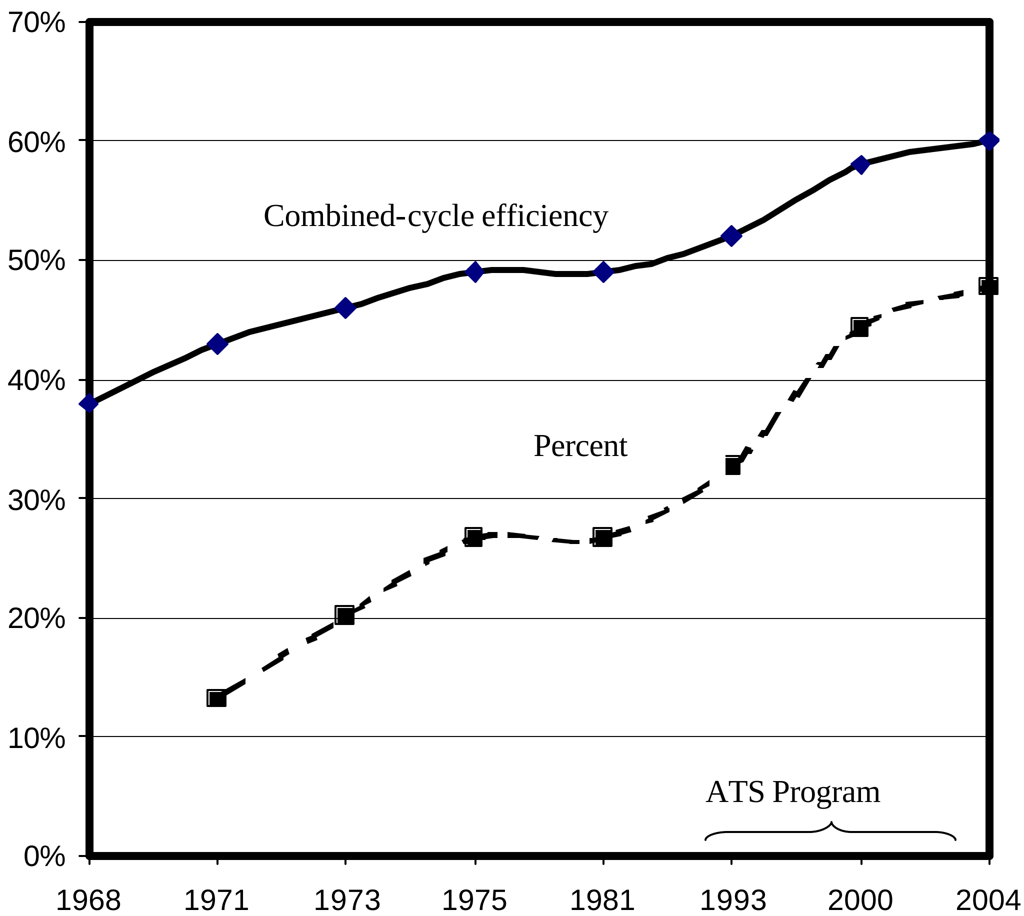


Figure 2-2: SWPC's Gas Turbine Trajectory

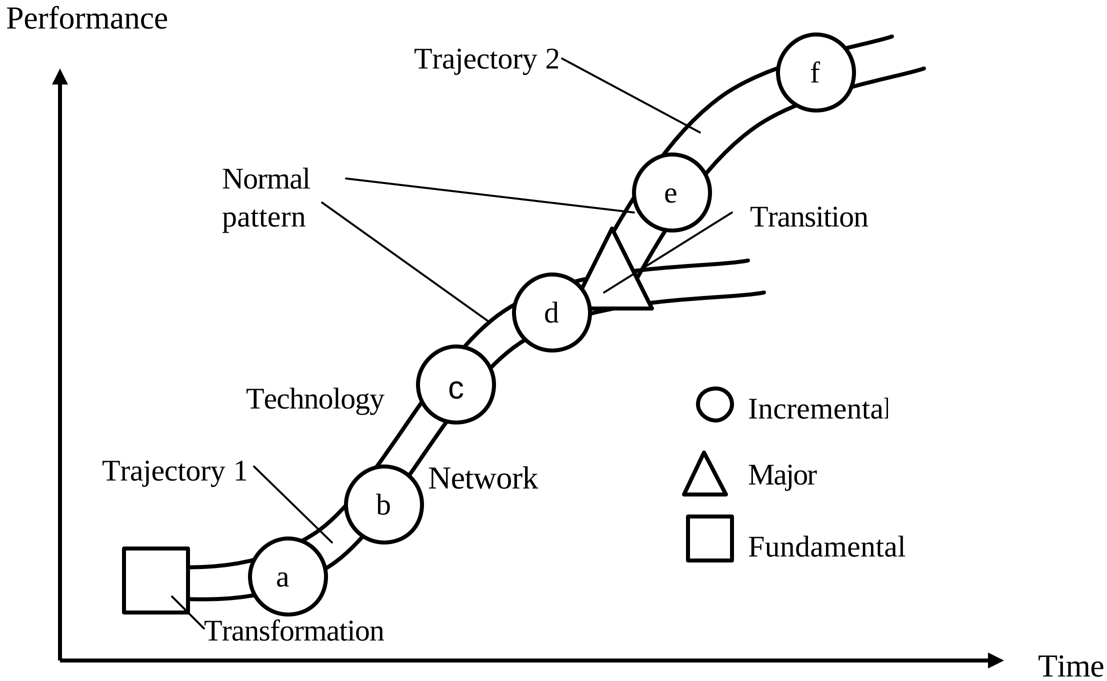
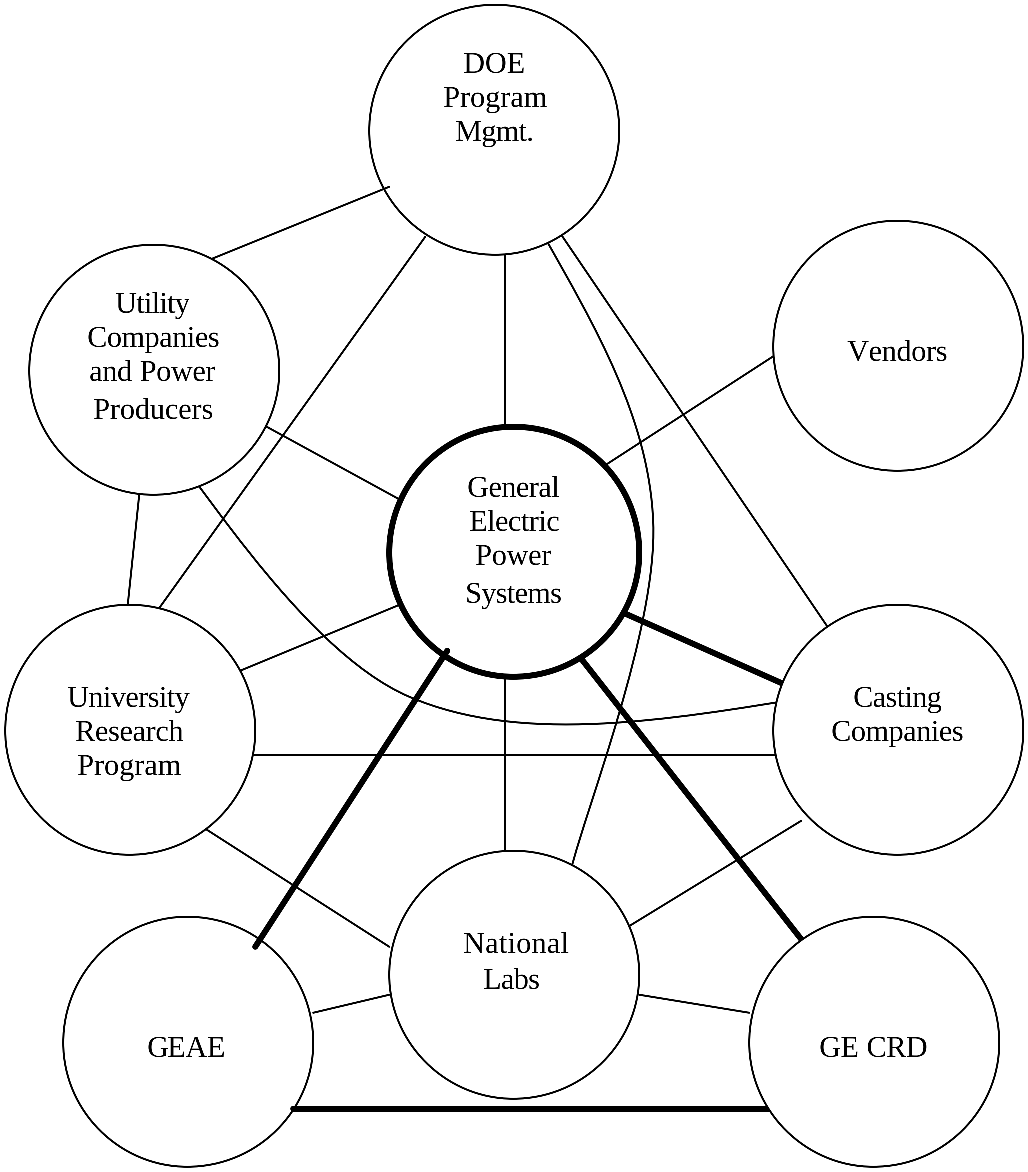


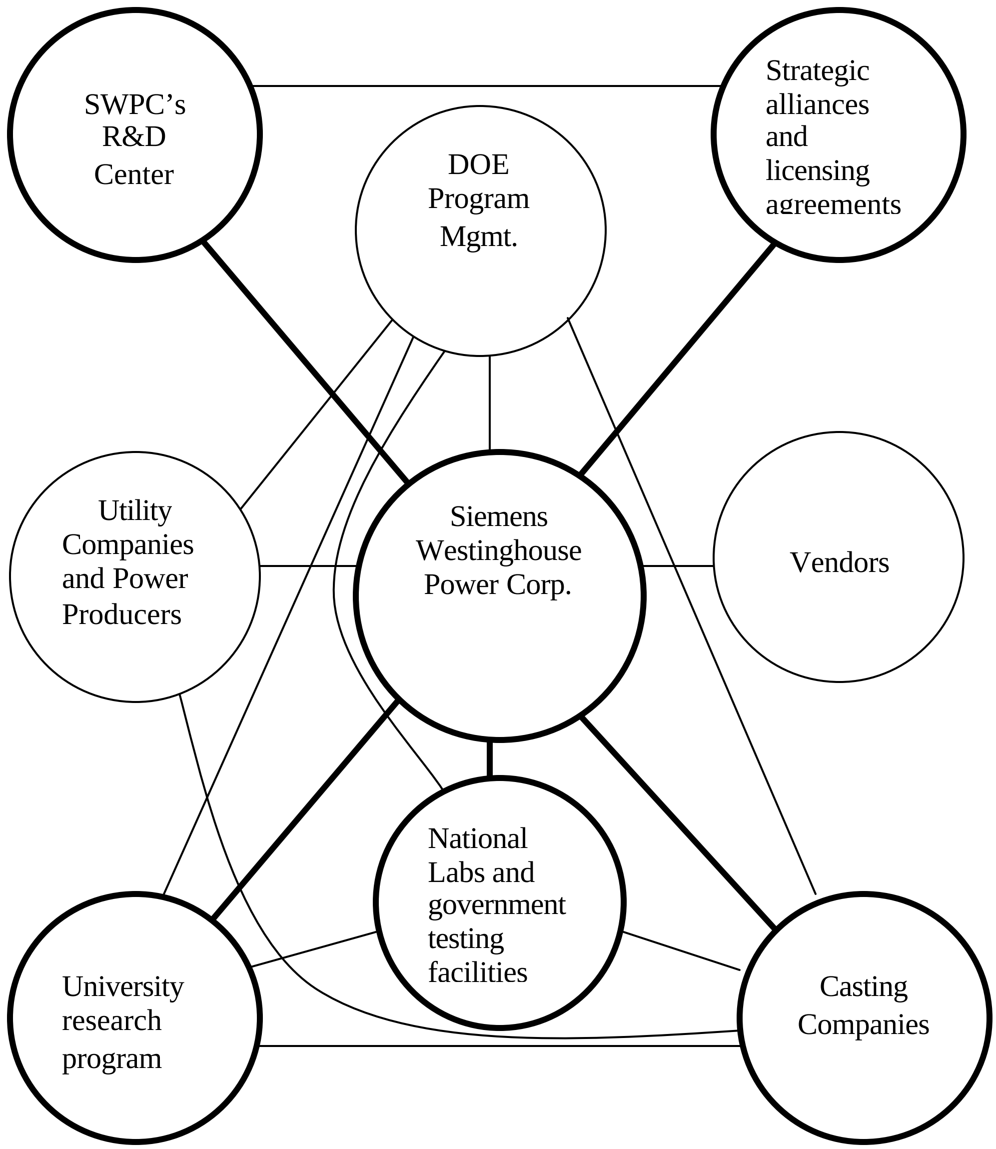
Figure 2.3: Patterns of Innovation of Complex Technologies

Source: Rycroft, Robert W., and Don E. Kash. *The Complexity Challenge -- Technological Innovation for the 21st Century,* London: Pinter, 1999, p.180.



Note: Bold lines represent primary resources for innovation

Figure 2-4: GEPS' Organizational Network



Note: Bold lines represent primary resources for innovation

Figure 2-5: SWPC's Organizational Network

Table 1-1. Typology of Learning Processes

Knowledge Source	***Learning Approach***	**Examples**
Internal – tacit	Learning by doing	In-house production experience. Trial-and-error methods, or "learning by trying"
Internal – explicit	Learning by formalized inquiry	In-house R&D, experiments, and tests.
External – tacit	Learning by using	Intimate interaction between users and producers in networks. Performance goals exist as a part of tacit knowledge.
	Learning from spillovers	Voluntary exchange of knowledge. Patent disclosure. Intra-industry spillovers. Reverse engineering. Licensing, publications or technical meetings. Movement of key people. Informal personal communications.
	Learning from interaction	Learn more about the network members. Information-exchange interactions. Learning by collaboration. Practical experience from vendors, partners, and other organizations.
External – explicit	Learning by using	User requirements and demands.
	Learning from advances in S&T	External R&D initiatives Monitoring and forecasting S&T. Published experimental and test data. Workshops published research.

3
DRIVERS FOR INNOVATION

The selection environment, made up of a number of socioeconomic forces, acts to influence the innovation process. A number of these forces converged at the beginning of the 1990s to facilitate the development of the ATS. This section highlights the key drivers of the technological innovation of the advanced turbine systems.

3.1 National Energy Policies and ATS Development

In the early 1990s, a new consensus on a comprehensive energy policy was about to emerge, influenced in no small part by events in the Persian Gulf region. At the outset, the first Bush Administration (1989-1993) continued to embrace the market-based approach that dominated energy policies in the 1980s. On August 2, 1990, however, with the Iraqi forces occupying neighboring Kuwait, and the United Nations imposing an embargo on Iraqi oil exports, a new approach was about to begin. With the removal of Iraqi troops from Kuwait by the coalition of military forces, the renewed attention of energy security was brought back to into the political debate with the call for a comprehensive energy policy.

A number of interests combined to move President Bush towards a new consensus for a national energy policy. The Gulf War highlighted concerns about the increasing dependence on oil imports, which were about 46 percent of consumption in 1989. (Energy Information Administration 1996) In addition, environmental concerns related to energy production that had entered the political debate. The Clean Air Act Amendments and the Senate version of a National Energy Policy, which was passed in 1989, contained numerous provisions for establishing a national energy policy to reduce global warming. By 1990, the Clean Air Act Amendments (CAAA) had passed, with particular attention given to environmental issues related to energy production, such as acid rain, clean coal technologies, and alternatives to gasoline as a transportation fuel.(Williams and Good 1994)

The Administration's energy policy emphasized continued development of domestic energy supplies in a manner consistent with environmental concerns, including greater use of renewable energy and energy efficiency alternatives, and renewal of a nuclear power.(Williams and Good 1994) In response, Congress supported the development of a national energy policy and passed the Energy Policy Act of 1992.

The Energy Policy Act of 1992, or EPAct, emphasized use of fossil fuels, renewable energy, nuclear energy, and energy conservation. Among other things, it refocused attention on energy efficiency and, important to this study, authorized the creation of the DOE Advanced Turbine System (ATS) Program. EPAct also expanded the authority of public-private collaborative programs to include energy efficiency, biomass, geothermal, fuel cell technologies, and other programs. It made provisions for 129 public-private collaborative programs that required industry co-funding. It restructured the federal research, development and demonstration (RD&D) programs to focus them on commercial applications as the principal objective.

The U.S. gas turbine market in the early 1990s was facing great uncertainty in the face of deregulation of the electric utility market and low natural gas prices, which can be attributed to two factors: electrical utility deregulation and low natural gas prices. Because of the uncertainty in the markets, the U.S. DOE initiated the Advanced Turbine System Program to accelerate the advanced gas turbine development.

3.2 Deregulation of the Electric Utility Industry

In the 1970s, electric utilities began to deregulate, primarily to encourage greater use of renewable energy resources. The 1978 Public Utility Regulatory Policies Act (PURPA) required utilities to purchase some of their power from renewable power generation sources, effectively subsidizing the renewable energy plants by requiring utilities to pay what it would cost them to generate the same amount of electricity at their own plants. (Bettelheim 2000, pp. 7-8)

The EPAct and subsequent rulings by the U.S. Federal Energy Regulatory Commission (FERC) were intended to complete the process of moving to open competition of the utility markets. It allowed utility companies greater freedom to buy electricity from power producers of their own choosing. The EPAct and FERC permitted wholesale power competition by creating independent power producers, referred to as "non-qualifying facilities" and "non-utility generators" to participate in the wholesale power markets. The EPAct also expanded the FERC's authority to order open transmission access to all power producers. (Bettelheim 2000)

3.3 Gas Turbine Markets in the 1990s

Markets for utility gas turbines in the early 1990s were impacted by uncertainty caused by deregulation in the electric utility industry and the declining cost of natural gas. Power plant developers delayed the construction of new power plants, waiting for the market adjustment. The gas turbine market was even murkier due to increased demand for electricity and excess capacity of the turbine manufacturers.

The price of natural gas remained low during the period of market uncertainty. The average price paid by utilities declined by more than ½ during the period of 1985 to 1994. In

1985, the cost of domestic natural gas was $5.36 per thousand cubic feet (1996 dollars) while in 1995, natural gas cost $2.76 per thousand cubic feet. (Energy Information Administration 2001) With natural gas costs falling, electric power producers had little market incentive to purchase more efficient turbines that consumed less natural gas for the same electrical output. The convergence of excess inventory of gas turbines, low natural gas costs, uncertainty effects of deregulation, and low profit margins, all converged to provide little in the way of market signals for new R&D investments in turbine technology.

Natural gas consumption for electrical generation remained relatively stable into the early 1990s, averaging around 2.9 trillion cubic feet per year. From 1996 to 2000, demand for natural gas for generation grew by an average of nearly 11 percent per year, to 3.9 trillion cubic feet in 1999 and 4.4 trillion cubic feet in 2000. The sharp increase in natural gas consumption for electricity generation since 1996 was due to an increased demand for electricity and from the growing use of gas in new generating plants. Electric utility retail sales have increased by 2.4 percent per year on average since 1995. (Energy Information Administration 2001, pp. 6-7)

The demand for new generation capacity increased in the mid-1990s. Natural gas turbines and combined-cycle plants were the units of choice for new plant construction because of their relatively low costs compared to coal-fired plants, high efficiencies, and short construction lead times. In addition, aging coal plants became targets for replacement with combined-cycle gas turbines that had better environmental performance records and lower permitting costs. From 1995 through 1999, natural-gas-fired capacity in the U.S. increased by 21.4 gigawatts (GW). The largest increase, 6.7 GW, was in 1999. Twenty-two GW of gas-fired generating capacity were added in 2000. (Energy Information Administration 2001, p. 7)

In conclusions, because of uncertainties associated with electrical utility deregulation and low private sector R&D investments in natural gas prices, there was little incentive for the private sector to invest in developing advanced gas turbine technologies.

3.4 Political Support for the ATS Program

In the early 1990s, senior managers at the DOE were convinced that new gas turbine technology for greater emissions was in the public's interest and that within several years there would again be greater demand for gas turbine technology. They believed that it was necessary to support the technology development early in order for the high efficiency gas turbines with lower NO_x emissions be ready for the market demands that were sure to come.

At the same time, there were also concerns about maintaining the U.S. competitive position in international turbine markets. There were concerns that foreign-owned turbine manufacturers were acquiring U.S. companies and gaining advantage in the U.S. market. For example, Asea Brown Boveri (ABB), a Swiss company had purchased Combustion Engineering, a U.S. firm. Also, with the decline of Westinghouse's gas turbine business in the 1980s, there were signs that Westinghouse wanted to sell its heavy electrical business to ABB in 1988. (*Energy Economist* 1997) Rolls Royce, a British firm, had also purchased Allison Engine Company, another U.S. turbine manufacturer.

Prior to the formal start of the ATS Program, two workshops were held in 1991 and 1992, bringing together representatives in industry, utilities, government, and university researchers for the purpose of developing a technology path forward for gas turbine development. The workshops concentrated on establishing "stretch" goals for the next generation of gas turbines, i.e., goals that industry thought they could achieve and DOE thought would be significant in providing long-term societal benefits. Of importance here is that the goals were establish through deliberations with industry, in a *bottom up* approach, rather than being established by DOE in a *top down* manner. The workshop thus contributed to building support for the program and indirectly led to enhancing political support for the program.

In 1992 appropriations language, initial funding was established for the ATS Program. A program plan was submitted in 1993 along with projected funding requirements, which established the program goals with beginning and ending dates, both of which were important to Congress. Since there was a strong political base of support, Congress continued to support the program with annual appropriations, totaling about $590 million over 9 years. Under the cost-sharing agreements between the Department of Energy and the turbine manufacturers, the companies also providing matching funds. Total contributions from all parties are shown in Table 3-1.

Table 3-1: ATS Program Costs ($ millions)

	Fossil Energy	Energy Efficiency	Total
DOE	325	165	490
Industry	265	0	265
Total	590	165	755

3.5 DOE's ATS Program Implementation

The DOE ATS Program was formally launched in 1992 as an eight-year program. Two classes of gas turbines were developed: industrial and utility-scale systems. This case study addresses only the utility-scale systems. For the utility-scale gas turbines, the program objectives included the development of high efficiency, environmentally superior and cost-competitive gas turbine systems for base-load application. Specific performance goals were set using natural gas as the primary fuel. These goals (U.S. Department of Energy 2000) included:

- The combined-cycle system efficiency of 60 percent on a lower heating value (LHV) basis,
- Nitrogen oxides (NO_x) emissions less than 10 parts per million (ppm) by volume at 15 percent oxygen, without external emission controls,
- A 10 percent lower energy costs compared to the then state-of-the-art turbine system,
- State-of-the-art reliability, availability, and maintainability (RAM) levels,
- Fuel-flexible designs that would operate on natural gas but also be capable of adapting to coal, coal-derived, or biomass fuels, and
- Commercial systems ready for the marketplace by the year 2000.

Most of the energy technology development projects at DOE are undertaken within the organizing frameworks of partnerships with industry, academia, national laboratories, and/or non-profit research institutions. Cost sharing is often required, not just as a means of leveraging Federal R&D dollars, but also as means of externally validating the R&D concepts. Business and other R&D partners must favorably evaluate the concepts, evidenced by their financial support of the concept, before any project can move forward. In long-term, multi-year projects, the federal share may be more than 50 percent in the early years, when risks are high, progress uncertain, and concepts yet to be proven. In the end, however, the total federal share will likely be less than 50 percent, as the R&D partners increasingly share more of the R&D cost in the later years as the technology is developed and demonstrated. DOE cost-shared programs typically do not fund commercially ready technology; rather the programs target longer term, technology possibilities that industry would not typically make R&D investments.

The early phases of these endeavors are critical, where the technology challenges are identified and the "visioning" of the research programs and roles of government and industry are parsed out. This process, sometimes referred to as "road mapping", can take a year or more. It is, in essence, a process for attracting and engaging prospective partners, stimulating interest in certain novel research directions, and agreeing on and parsing out respective roles for government, the R&D consortia, and individual private entities -- all in advance.

The ATS Program was no exception. When the Program was launched, DOE and at least a half-dozen industrial consortia worked together to establish future technology performance goals for large-scale, natural gas fired power turbines. Initially, these goals seemed unattainable, in overall thermal operating efficiency and in emissions of regulated pollutants, especially NO_x. A long-term, multi-year R&D program was outlined, for a period of eight years, involving a schedule of financial commitments from all parties, totaling more than $755 million. All aspects of the project were competitively bid, in several stages, with multiple contractors competing toward various decision points. In the early stages, DOE investment share was the greatest, but diminished progressively over time, as various technology hurdles were met, and confidence in the technology and integrating concepts grew. In the composite, the cost shares are approximately 50-50 between government and industry.

The ATS Program also provided funding for university research. Each year, Requests for Proposals (RFPs) were issued that identified gas turbine research needs that were identified in collaboration with members on the Industrial Review Board. Universities around the U.S. responded to these RFPs in early June of each year and an industrial review board, made up of eight representatives from the gas turbine industry, reviewed, ranked, and made recommendations for funding to the DOE. The DOE made final approval of award of research contracts.

The DOE national laboratories were involved in R&D activities in support of technology development. The Oak Ridge National Laboratory, for example, worked on materials development of single crystal castings and thermal barrier coatings. Oak Ridge also awarded contracts to PCC Airfoils, General Electric and Siemens Westinghouse to conduct R&D work on casting technology, low-sulfur alloys, silica core development, and transient liquid phase bonding. The National Energy Technology Laboratory conducted research on methods to improve combustion stability. SWPC, along with PCC Airfoils and Howmet, also worked with another the U.S. National Institute for Science and Technology on the development of single crystal castings for turbine blades.

4
INNOVATION OF THE ATS AND LEARNING ORGANIZATIONS

The development of the ATS reflected a major change in design and performance than any previous state-of-the-art turbines at the time. The question remains as to how the turbine manufacturers went about creating and acquiring the knowledge necessary to carry out the innovation process. This question is the subject of this section.

Interviews were conducted with many of the participants in the innovation process. The interviews focused on: (1) identifying the sources of knowledge, and consequently, defining the participants in the organizational networks, (2) describing the innovation process for each major subsystem, and (3) how the DOE ATS Program influenced the successful outcomes. Thirty-three representatives of government, turbine manufacturers, university researchers, vendors, and national laboratories were interviewed for this case study. In the sections that follow, the learning processes for each of the major subsystem innovations are described for GEPS and SWPC.

4.1 GEPS' Subsystem Innovations and Learning Processes

General Electric has, over a long period of time, established technical capabilities in three areas that have been used extensively in developing advanced gas turbine technology; power systems, aircraft engines, and a centralized research and development laboratory. The power generation business, GEPS has been a core business unit within GE for over a hundred years. GE Aircraft Engines (GEAE), another core business, has reached $ 1 billion in earnings in 1988. GEAE has become one of the three major producers of jet aircraft engines, the others being Pratt & Whitney and Rolls Royce. (Slater 1993, p.86, 201 & 249)

Those involved in the advanced turbine system development agree that the subsystem innovations most critical to the successful development of the advanced turbines were closed-loop steam cooling, single crystal fabrications, combustor improvements, thermal barrier coatings, and compressor improvements. With this as an understanding, the case study focused on describing the learning processes used in the technological innovation of these subsystems. Table 4-1 summarizes the learning processes used by GEPS. Knowledge sources are used in the table to describe whether the knowledge was acquired or created internal or external to GEPS. For example, if GEPS relied on a sister organization such as GEAE or GE CRD, then it was considered external to GEPS.

GEPS' organizational network consisted of other GE business groups, including GEAE and GE CRD, as well as suppliers and universities. GEPS was successful in accessing the capabilities and knowledge within the different business groups within the General Electric Corporation and access across business group boundaries did not appear to be hindered; rather, collaborative work groups were encouraged. GEPS used both tacit and explicit knowledge held within its organizational network as well as that existing in the technical literature.

GEPS relied mostly on other business groups within the General Electric corporate structure. GEPS appeared to turn to its corporate sister organizations, primarily GEAE and GE CRD for external capabilities. This reliance on other corporate entities is most likely due to the company's depth and breadth of capabilities. It might also be explained as a tendency of reliance on corporate resources, or "path dependency." As Wheatley stated, some firms may exhibit self-reliance, or in terms of evolutionary theory of innovations, firms may exhibit strong path dependencies (Wheatley 1992). If this is indeed the case, GEPS' innovation strategies were constrained by past practices, and are path dependent. This learning approach is clearly reflected in GEPS' approach to developing the closed-loop steam cooling.

It is the opinion of those knowledgeable in the advanced turbine systems that closed-loop steam cooling is the most important technological breakthrough needed to achieve the higher efficiencies and lower NO_x emissions in the advanced gas turbines. Closed-loop steam cooling process was a first of a kind" technology, which was not previously been developed. Its success permitted an increased firing temperature (firing temperature in the first rotating turbine stage) that was necessary to reach higher efficiencies without exceeding the NO_x formation. GEPS developed the closed-loop steam cooling in the first and second stage nozzles (vanes) and turbine buckets (blades) to reduce the differential between combustion and firing temperatures that permitted an increased firing temperature. To achieve reduced NO_x emissions with higher efficiencies rested with increased operating temperatures and closed-loop steam cooling.

GEPS used both its own technical capabilities as well as those of GE Corporate R&D (GE CRD) in furthering an understanding of the heat transfer within a rotating system in the closed-loop steam innovation. GEPS engineers could not simply make incremental improvements to previous air-cooled strategies, but rather took a novel approach for heat transfer in the blades and vanes. Rather than using air from the compressor, GEPS used steam, pumped through serpentine channels inside the blades and vanes of the first two stages. Steam has superior heat transfer properties to those of air. However, there were many uncertainties with this approach. GEPS relied on both its own knowledge and of cooling systems as well as those of GE's corporate R&D center and the GEAE group.

GEPS relied on the experimentation, analyses and validation testing capabilities residing within GE CRD and GEAE, including engineering design, heat transfer analysis, materials performance and CFD analysis. There was a collaborative effort between these three business groups, each providing core capabilities and expertise. GEPS also included participants with its manufacturing group located in North Carolina as well as the casting companies (Howmet and PCC Airfoils) who were making the turbine blades and vanes. Engineers and scientists in GEPS and GE CRD also stayed abreast of advances in their field through both formal and informal contacts. They are active in their professional organizations, conferences, and workshops where they monitor advances in their field and acquire useful information. They also maintain contacts with others outside of GE and as sources for discussing ideas and seeking advice.

Even with closed-loop steam cooling technology, GEPS also faced the problem of having a blade and vane material that could withstand the extremely high operating temperatures, reaching 2,350°F (1,290°C). GEPS relied on two casting companies, Howmet and PCC Airfoils, in developing the single crystal blades and vanes. Single crystal vanes and blades are used on the first two stages of the gas turbine. The casting companies hold specialized core capabilities in single crystal fabrications, sometimes referred to as "black art" by the industry, (Rycroft and Kash 1999, p. 121) because of the need for extensive know-how of casting complex geometric shapes with internal cooling passages. Most of this knowledge is difficult to codify and resides within experienced craftsmen. A high level of trust between GEPS and the casting companies enabled the sharing of both tacit and explicit knowledge between the companies. GEPS shared proprietary component designs with the casting companies and, in turn, the casting companies provided intimate information about their casting process.

The DOE ATS Program also provided research funds that enabled the casting companies to conduct additional trials, tests, and high-risk experiments that in effect accelerated the innovations related to fabricating the single crystal components. As a result, GEPS was able to acquire the resulting single crystal components from the casting companies faster than it otherwise would.

A similar learning pattern emerged when examining how the combustor innovations, thermal barrier coatings, and compressor improvements were carried out. GEPS relied primarily on its internal capabilities as well as those found in GE CRD and GEAE. The combustion innovations, for example, GEPS relied on its routines and heuristics it held along with those found in GE CRD to improve the lean pre-mix, DLN combustor technology. Many improvements were based on in-house experimentation and experience, followed by validation using full-scale testing. GEPS' thermal barrier coatings (TBCs) innovations were founded on technologies developed by GEAE, who has been using TBCs since the late 1980s. GEPS and GE

CRD conducted iterative trials and evaluation techniques in the laboratory. GEAE also provided support in application technologies.

Concluding that GEPS relied mostly on itself and its sister organizations within the General Electric family of organizations should not imply that other resources were not also involved. Engineers and scientists in GEPS, GE CRD, and GEAE also stayed abreast in the literature and through their formal and informal networks. However, in the main, most of the knowledge originated within the GE family of companies.

4.2 SWPC's Subsystem Innovations and Learning Processes

Prior to being acquired by Siemens, Westinghouse held core capabilities in power generation in three technology areas, large steam turbine generators, nuclear power plants, and gas turbines. Despite these technical capabilities, Westinghouse's market position in gas turbine designs has been erratic over the years. In 1960, the company pulled out of the jet engine market thereby removing one of its core knowledge bases for gas turbine development as well as access to government R&D funding for military uses. (Watson 1997) By the mid-1980s, the senior management began to rebuild its core capabilities in turbine technology. One approach used in this rebuilding process was to enter into strategic alliances and purchase licenses. By 1998, Westinghouse's power division was up for sale, with Asea Brown Boveri (ABB) apparently an interested buyer. (*Energy Economist* 1997)

Westinghouse and later SWPC entered into strategic alliances and purchased licensing agreements with other companies as a means of acquiring new core capabilities and knowledge. Westinghouse, before being acquired by Siemens, held alliance agreements with Mitsubishi Heavy Industries (MHI), Rolls Royce and Fiat Avio, which provided additional capabilities in the aircraft engine technology and utility gas turbine technology. In addition, Siemens held licensing agreements with Pratt & Whitney for aircraft engine technology. These agreements combined to provide the necessary capabilities that were believed necessary for SWPC to regain its competitive position in the market.

SWPC's learning processes used in the ATS development are summarized in Table 4.2. SWPC exhibited a strong preference for organizational networks as sources for new capabilities and knowledge. It relied on an external organizational network as a source of knowledge and capabilities and, in some cases further advanced the innovations by building upon the knowledge acquired from its external partners. It used its alliance agreements and licensing agreements with other manufacturers as resources for technical capabilities. To illustrate this preference, return again to the closed-loop steam cooling subsystem.

SWPC developed the closed-loop steam cooling with a combination of internal and external capabilities. Alliances with Rolls Royce, MHI, and Pratt & Whitney provided capabilities and knowledge in heat transfer, aerodynamics and design codes for turbines. SWPC's work with Rolls Royce, for example, provided access to knowledge in computer design codes (explicit knowledge) as well as access to experienced technical staff (tacit knowledge). University research also aided SWPC in using computational fluid dynamics to predict gas flow and heat transfer conditions, development of databases on characteristics of rotational parameters inside blades, and research in film cooling in open-loop air-cooling designs. SWPC also took advantage of the capabilities residing within the government laboratories and facilities and sponsored research and testing at the NASA's Glenn Research Center in Cleveland, Ohio, the U.S. Air Force's Institute of Technology at Wright Patterson Air Force Base in Dayton, Ohio, and the Arnold Engineering Development Center in Tennessee. That is not to say that SWPC relied solely on the alliance partners. Rather, SWPC's engineers and scientists provided the knowledge necessary for the knowledge to be used to develop the turbines.

The combustor work at SWPC also relied on the research at the universities, in flow visualization, flow mapping, and flow area measurements, carried out at Clemson University, laser-induced fluorescence fiber optic probes developed and experiments were carried out in collaboration with Carnegie Mellon University, and combustor stability work done with Georgia Tech.

SWPS, like GEPS, worked closely with the casting companies, Howmet and PCC Airfoils, in fabricating the complex geometric shapes and serpentine cooling passages in the blades and vanes. Relationships between SWPC and the casting companies were based on high levels of trust, where both tacit and explicit knowledge is openly shared. SWPC shares the component designs early in the development process to obtain the casting companies' feedback, something SWPC refers to as "concurrent engineering."

SWPC's innovations in thermal barrier coatings and compressor improvements were incremental in nature and were based on technologies used in utility gas turbines and in the aircraft engines. SWPC conducted internal R&D programs and worked with a DOE laboratory and universities. Alliances with Rolls Royce and research at universities provided other external sources of knowledge as well.

4.3 Casting Companies' Innovations and Learning Processes

Both GEPS and SWPC relied mainly on Howmet and PCC Airfoils for developing the single crystal blades and vanes that could withstand the extreme high temperatures. Both casting companies relied primarily on their internal capabilities in processes for casting the vanes and blades. This tacit knowledge is embodied in the heuristics and routines that are used in conducting experiments and tests. When asked how it carried out its work in developing the single crystal components, one Howmet manager answered this way:

> "Several of our experienced people in single crystal aero components [aircraft engine components] were brought together and transferred to the Hampton, Virginia facility to begin doing the evaluations… The production staff relied on the experience with smaller components [used in aircraft engines] as a place to begin and then expand the size capabilities. Most of this was done by trial-and-error. It was based on current production experience. We knew that, if we did it this way, then this would happen. If that didn't happen, then we would do the next experiment based on the outcome of the previous experiment. So, for us, it was a matter of continuing to evolve the technology with repeated iterations."

The statement illustrates the tacitness of knowledge embodied within the crafts workers that cannot be easily transferred in codified knowledge.

4.4 Conclusions

The review of the innovation processes of the key subsystems illustrates similar approaches by the two turbine manufacturers. GEPS relied principally on its own internal capabilities and knowledge as well as the other organizations with General Electric Company. It did not use the university research or government laboratories to the extent of SWPC. SWPC also used its internal resources, but more actively created an organizational network that included strategic alliance partners, consultants, universities, and government laboratories and testing facilities in its search for new knowledge, core capabilities, and complementary assets. The qualitative study in this section was useful in identifying the range of tacit and explicit knowledge and the source of such knowledge. In the next section, a quantitative analysis of patent and citation data is used to identify the source of explicit knowledge in the creation of new knowledge.

Table 4.1 GEPS' Learning Processes

Innovation	Knowledge Source	Learning Approach	Knowledge Creation Process
Closed-loop Steam cooling	Internal to GEPS – explicit	Formalized inquiry	- Experimentation, testing, and validation; heat transfer and CFD analysis of fluid dynamics. Used dynamic routines.
	External – tacit and explicit	Interactions	- Knowledge residing in Aircraft Engine, Power Systems, and CRD. Reliance on heuristics. Feedback from GE production group.
	External –tacit	Interactions	- Feedback on design from the casting vendors.
	External-explicit	Advances in S&T	- Stay abreast in the literature in discipline.
Single crystal castings	External – tacit	Interactions	-Casting companies review designs.
Combustor	Internal – tacit	Learning by doing	- Experience and iterative testing for instability. Used dynamic routines and heuristics. GE CRD work
	External – explicit	Learning by formalized inquiry and	- Contact with Wright-Patterson expert in fuel heating
	External – tacit	Learning from interaction	
Thermal Barrier Coatings	External – tacit	Learning by doing	- TBC experience from Aircraft Engine business. Learning by routines and heuristics.
	External – explicit	Formalized inquiry	- GE CRD materials and application development work in the laboratories.
	Internal - explicit	Formalized inquiry	- GEPS research and development
	External – tacit	Learning by interaction	- Learning from information exchange in professional organizations.
	External - explicit	Advances in S&T	- University R&D activities and published reports.
Compressor	External – tacit	Learning by doing	- Experience from Aircraft Engine business. CFD analysis on flow patterns.
	Internal - explicit	Formalized inquiry	-Full-scale evaluation, testing, and validation.

Table 4.2 SWPC's Learning Processes

Innovation	Knowledge Source	Learning Approach	Knowledge Creation Process
Closed-loop Steam cooling	Internal - explicit	Learning by formalized inquiry	- In-house studies for cooling medium and materials.
	External – tacit	Learning by interaction	- Technological capabilities from alliances.
	External – explicit	Learning by Interaction	- Licensing agreements from alliance partners.
	External – tacit	Learning by interaction	- Testing from government labs and testing facilities.
	External – explicit	Learning by interaction	- Building personal networks with university researchers and government laboratories.
	External – explicit	Learning from advances in S&T	- Reports from NASA and Wright – Patterson AFB research and testing. - Research network through the AGTSR on rotating blade cooling and film cooling.
Single crystal fabrications	Internal – tacit	Learning by doing	- Work on TLP bonding at Science and Technology Center.
	Internal – explicit	Learning by formalized inquiry	- Alloy selection and testing. TLP bonding process and NDE technology.
	External – tacit	Learning by interaction	- Personal contacts and experts. Experience from Howmet and PCC Airfoils.
	External - explicit	Learning from advances in S&T	- Iowa State researches. ORNL material research.
Combustor	Internal – tacit	Learning by doing	- Dynamic routines, heuristics.
	Internal – explicit	Learning by formal inquiry	- Combustor testing and CFD analysis.
	External – tacit	Learning from spillovers	- Hiring Ph.D. with combustor knowledge.
	External – explicit	Learning from advances in S&T	- University research.

Table 4.2 SWPC's Learning Processes			
Innovation	**Knowledge Source**	**Learning Approach**	**Knowledge Creation Process**
Thermal barrier coatings	Internal- explicit	Leaning by formal inquiry	- Laboratory analysis of optimum bond coat.
	External – tacit	Learning from spillovers	- In-house R&D on testing and evaluating different coatings.
	External – explicit	Learning by interaction	- Hired researcher from ORNL - R&D with ORNL and vendors. Testing at universities
Compressor	Internal – tacit	Learning by doing	- Incremental changes over existing technology; compressor testing.
	External – tacit	Learning from spillovers	- Licensing agreements and work with Rolls Royce
	External – explicit	Learning by interactions	- Licensing Agreements with other turbine manufacturers.

5
KNOWLEDGE SPILLOVERS ANALYSES USING PATENT DATA

Another method for evaluating learning processes is by using patent and citation data. Patent and citation data were used as a proxy for observing the spillover of explicit knowledge and supplements the observed results from the interviews. Using patent and citation data as an indicator of knowledge spillovers has been well established in the scholarly literature, particularly Jaffe, et al (1993, 1998), Narin (1993) and others. Some reservation is warranted in relying solely on patent and citation indicators as there are several counter arguments to its use. Some possibility exists that: (1) citations are indicated where there is no reasonable linkage to the new invention, or (2) patents are generated with citing a previous patent. Even so, patent and citation analysis is useful in supporting a qualitative study where knowledge flows are in question. The approach used in this study combines the patent and citation analysis to confirm the conclusions drawn from the interviews.

Table 5-1 presents the number of patents that were associated with research that was conducted as part of the ATS program. There were a total of 55 patents that were acquired as a result of the ATS Program research. Several methods were used in collecting the patent and citation data. First, searches were conducted in the U.S. Patent and Trademark Office database (USPTO) using advanced keyword searches. Three main categories of data were collected: (1) patent numbers and year the patents were issued, (2) citations to other patents and the issue year, and (3) citations to scientific literature. The citations to other patents were used as an indicator of sources of explicit knowledge. The turbine manufacturers, DOE program managers, and casting companies validated the USPTO database search results.

Table 5-1: ATS Program Patents

Organization	Total
GE - ATS	23
SWPC – ATS *	28
Howmet	0
PCC Airfoils	0
DOE	2
Universities	2
Total	55

* Note: All data for SWPC includes Westinghouse patents

A few simple statistics of the patent data for the turbine manufacturers are shown in Table 5-2. General Electric had a total of 23 patents that were issued between 1996 and 2001 and

SWPC had 28 patents issued between 1995 and 2001. The GE patents cited 289 other patents and SWPC patents cited 276 other patents. SWPC patents include both Westinghouse and Siemens Westinghouse Power Corporation. On average, both companies had a similar number of citations per patent; GE averaged 12.6 citations per patent and SWPC averaged 9.9 citations per patent.

Both companies had the majority of their patents related to the key technological areas that were identified in the literature and in the interviews, i.e., closed-loop steam cooling, thermal barrier coatings, combustor improvements, single crystal fabrications, and compressor improvements. Over 65 percent of GE's patents were associated with the key technological areas. SWPC had an even greater number of patents in these areas, with over 89 percent of its patents in these areas. Most of the patents were associated with the closed-loop steam cooling technology, which is not surprising given its novel characteristic.

Table 5-2: Simple Statistics of ATS Program Patents

	GE	SWPC
Range of citations (yr.)	1919-1999	1957-2000
Range of patents (yr.)	1996-2001	1995-2001
Total Patents	23	28
Total citations	289	276
Mean citations	12.6	9.9
Patents by field, %		
Closed-loop cooling	56.5%	42.9%
TBC	0.0%	25.0%
Single crystal	4.3%	7.1%
Combustor	4.3%	10.7%
Compressor	0.0%	3.6%
Cycle Improvements	0.0%	10.7%
Seals	26.1%	0%
Thermal matching	4.3%	0%
Flow controller	4.3%	0%

5.1 General Electric Patents and Citations

A breakdown of the GE patents and citations are presented in Figure 5-1. Of the five key technological categories, over one-half of GE's patents (13) were associated with closed-loop cooling and an inner turbine shell, which is used in closed-loop steam cooling conditions and provides a control for thermal expansion of the turbine blades. Of the other key technological categories, GE only had one patent each in single crystal fabrications and combustor improvements, and no patents in thermal barrier coatings or compressor improvements. The remaining patents were for inventions not directly related to the five key subsystem areas, including seals (6 patents), thermal matching (1 patent), and a flow discourager (1 patent).

The majority of GE's patents cited other GE patents. There were a total of 289 citations, 205 of which were self-citations. Of the other organizations, United Technologies received the most citations with 17. Seventy-one percent of GE's patents were self-citations, while only 29 percent were for patents belonging to other organizations. The only other company who received a significant number of citations was United Technologies, receiving 6 percent of the citations.

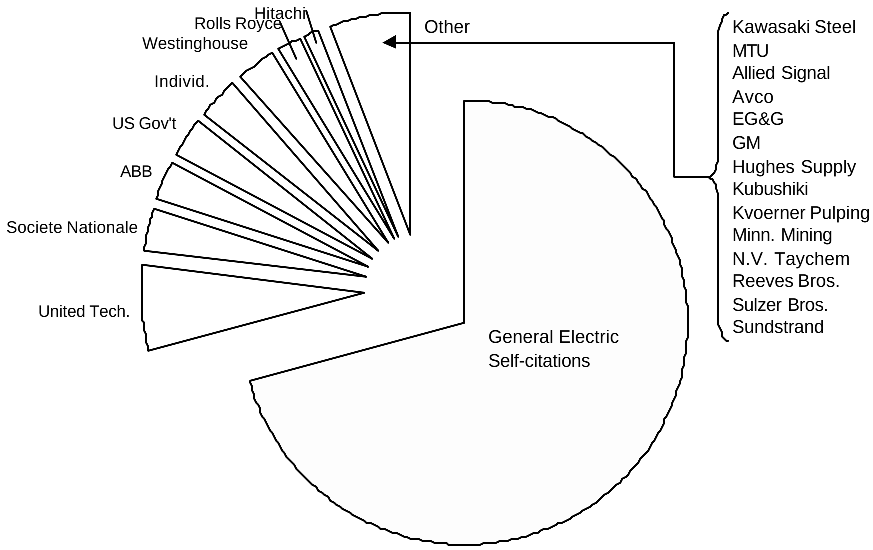


Figure 5-1: General Electric's Patent Citations Associated with the ATS Technology

5.2 Siemens Westinghouse Patents and Citations

A breakdown of the SWPC patents and citations are presented in graphically in Figure 5-2. In contrast to GE, most of SWPC's citations were to other organizations' patents. Of the total number of citations of 276, there were 236 citations for others' patents and 40 cited other Westinghouse or SWPC patents. General Electric received the most number of citations with 56, followed by United Technologies with 25. Fourteen percent of SWPC citations were self-citations, while 86 percent was to patents belonging to other organizations.

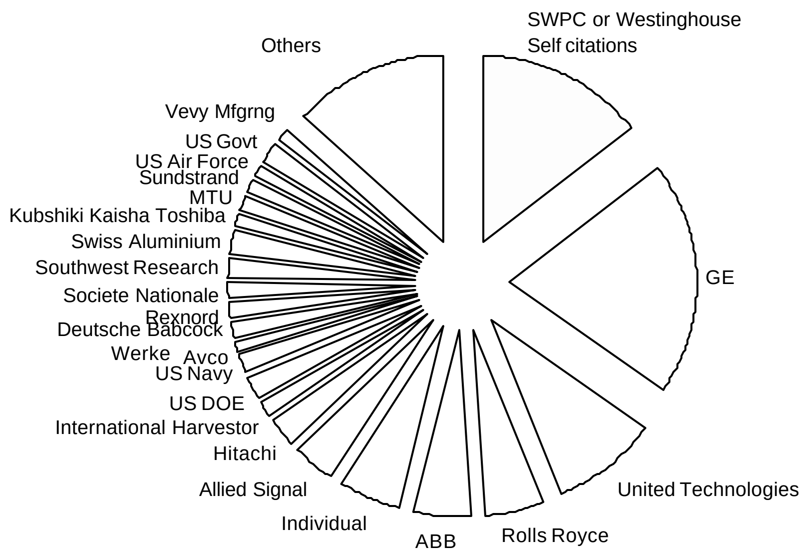


Figure 5-2: Siemens Westinghouse Patent Citations Associated with the ATS Technology

5.3 Trends Using Patent Data

The patent and citation analysis support the findings drawn from the qualitative study: GEPS tends to refer back on itself (or its sister organizations) during periods of uncertainty and transitional innovation. SWPC, on the other hand, added new organizations external to itself in search of new capabilities and knowledge. No attempt has been made here to investigate the differences between the two companies in regard to their corporate policies on this matter.

6
EVALUATION OF THE ATS PROGRAM

The National Academy of Sciences' Board on Energy and Environmental Systems conducted an analysis of some of the DOE's energy R&D programs and published the results of this study in 2001. (National Academy of Science, 2001) The Board developed an evaluation framework that was used to define the range of benefits and costs, both quantitative and qualitative that should be considered in evaluating programs. The matrix shown in Table 6-1 provides an accounting framework that the Board used to asses the benefits and costs of the energy R&D programs. The classes of benefits (corresponding to the rows of the matrix) are intended to capture types of public benefits appropriate to the objectives of the DOE R&D programs. Based on these stated objectives, the Board adopted the three generic classes of benefits – economic, environmental, and security benefits.[5]

The Academy study stated that

> "…the DOE ATS Program is an excellent example of a DOE/industry collaboration that (1) focuses on stretch (but achievable) goals that could have a significant impact on future energy use and environmental compatibility, (2) works with other government agencies and academia and the national laboratories to design and implement the program, (3) integrates basic research into the program very effectively, and (4) provides a framework where innovative ATS concepts can move from research to component test and finally demonstration with a continual increase in the non-government cost-sharing requirements. DOE structured this program to take the concepts through to a commercial-scale demonstration, an extremely critical element in a program of this type." (National Academy of Science, 2001, p. 95)

6.1 Funding and Participation

The ATS Program was a multiyear effort, estimated to total $490 million in DOE investments, and $265 million invested by the industry partners. Table 3-1 shows a breakdown of ATS funding and industrial cost sharing by the Fossil Energy and Energy Efficiency/Renewable Energy Programs.

6.2 Evaluation Matrix

By 2002, the advanced gas turbine technology was commercialized. The GE model 7H and 9H machines installed their ATS in a 480 MW power generation plant in Baglan Bay, South

[5] For an elaboration of the evaluation matrix, see National Academy Press, *Energy Research at DOE: Was It Worth It? Energy Efficiency and Fossil Energy Research 1978 to 2000,* 2001, pp. 3-5.

Wales, United Kingdom, where operation has recently begun. GE also has order for 3 more units to be delivered to Tokyo Electric Power Company in 2006. SWPC has incorporated many of the ATS technologies into their existing model and providing their G System, which has been installed in several locations, most recently at Lakeland Electric plant in Florida and in Charlton, Massachusetts. The widespread deployment of these ATS turbines has yet to be realized, however these systems are expected to become the new standard in combined-cycle gas turbine technology.

R&D programs were conducted at national laboratories and universities. These programs focused on development of critical technologies that supported the development of the ATS. Key areas of research included the control of combustion instabilities, testing of novel low-NO_x combustor designs, investigation of the chemical kinetics of pollutant formation, and development of advanced diagnostics for measuring heat transfer rates, flow velocities, and pollutant concentrations during turbine component testing.

Although the complete ATS systems will continue to penetrate the international combined-cycle gas turbine markets later in this decade, there are spin-off technologies that will have an impact on improvement to the gas turbine systems now in commercial service. It is difficult to accurately determine what the realized benefits will be from the spin-off technologies, some benefits are now being realized from the installations that have been made. Table 6-1 presents these estimates of costs and benefits.

The ATS technology has near-term application in natural gas fired turbine applications. IN the future, DOE anticipates that the ATS technology will be "fuel flexible," meaning that integrated gasification, combined-cycle concepts can incorporate the ATS technology. If this does indeed occur, it can offer significant environmental benefits for power generation as well as contributing to energy security. Table 6-1 has not addressed this potentiality.

Table 6-1: Costs and Benefits Matrix for the Advanced Turbine System

	Realized Benefits and Costs	Options Benefits and Costs	Knowledge Benefits and Costs
Economic Benefits and Costs	DOE R&D costs: $325 million Private Industry R&D costs: $265 million. ATS technology is now in operation. While it is still early in introduction and benefits have yet to be appreciably realized, economic benefits will become more apparent by the end of this decade. Some estimates put economic benefits at $5.7 billion over a 30-year life cycle.[i]	Technology may produce significant economic[ii] and energy[iii] savings. Improve the competitive position of U.S. turbine manufacturers in international markets.	- Assisted in the development of new closed-loop steam cooling concepts. - Development of improved turbine blade and vane life using single-crystal materials and internal cooling passages. - U.S. capability to manufacture thin-walled, complex, single-crystal castings for gas turbines. - 55 patents were attributed to the research performed for the ATS.
Environmental Benefits and Costs	Benefits are now becoming realized as a result of plants utilizing ATS technology. Environmental benefits include lower NO_x emissions and reduced CO_2 emissions.	As technology continues to penetrate the combined-cycle gas turbine markets, environmental benefits will continue to accrue through lower NO_x emissions and improvements to operating efficiencies, which in turn reduce the amount of CO_2, a greenhouse gas.	New concepts to improve dry, low-NO_x combustion New concepts to improve overall efficiency of combined-cycle gas turbines, thereby reducing the amount of natural gas consumed and amount of CO_2, a greenhouse gas, released.
Security Benefits and Costs	No realized benefits.	Improved the manufacturing capacity in the U.S.	None.

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[i] DOE Fossil Energy Program Office contends that the economic benefits of lower power costs from ATS installations put in place by 2005 will amount to $5.7 billion over a 30-year life cycle. National Academy Press, *Energy Research at DOE: Was It Worth It? Energy Efficiency and Fossil Energy Research 1978 to 2000*, 2001, p. 348.

[ii] DOE estimates that the potential economic benefits of reduced power costs from ATS installations through 2020 will total $28 billion. *Ibid*, p. 348.

[iii] DOE estimates that the ATS could save 1 quad annually by 2020, compared with today's best gas turbine technology and assuming that ATS will achieve 50% market penetration.

7. CONCLUSIONS AND IMPLICATIONS FOR PUBLIC POLICY

This study has examined the innovation of the advanced gas turbine system, a complex, energy technology. The innovation of the advanced gas turbine technology exhibited characteristics of a transition pattern, distinguished by major advances in performance, as well as a qualitatively new design. Of the five key subsystem innovations that were studied, closed-loop steam cooling represents a fundamental change from any previous designs was a critically important development needed in achieving the performance goals.

The ATS was a useful test of the turbine manufacturers approach to the development of a complex technology that significantly outperforms previous models. This study has provided insights into the innovation of a complex energy technology and how various economic and social factors influenced its development. It also provided clues on how public policies might be tailored so as to facilitate technologies that are in the public's interest. In the concluding chapter, some conclusions are presented as well as suggested policy implications.

7.1 Knowledge Creation and Organizational Networks within Transition Patterns of Innovation

The study found that the turbine manufacturers created and utilized organizational networks as a means of acquiring knowledge and capabilities. Actors in these networks became resources of both tacit and explicit knowledge. There was also an indication that the extent to which the knowledge and capabilities of external participants is used is related to the depth and breadth of capabilities of the OEMs. In the case of GEPS, its organizational network consisted primarily of other General Electric business groups, i.e., GE Aircraft Engines, GE Corporate Research and Development, as well as external groups, i.e., Howmet and PCC Airfoils, companies with expertise in developing single crystal castings. GEPS relied mostly on the depth and breadth of capabilities the resided within other GE business groups.

GEPS had developed an organizational network that provided core capabilities and knowledge that were used for the innovation of the advanced gas turbine system. Its organizational network consisted primarily of other GE business groups, including GEAE and GE CRD. GEPS relied mostly on the depth and breadth of capabilities that resided within the GE business groups. GEPS was successful in accessing the capabilities and knowledge within the different business groups and that access did not appear to be hindered by business group divisions, rather collaborative work groups are encouraged. GEPS used both tacit and explicit knowledge held within its organizational network as well as that existing in the technical literature. The scientists and engineers in the GEPS networks also stayed informed about the advances in their particular discipline through professional networks and publications and the AGTSR program. However, these external resources were not the primary resources of knowledge.

GEPS' organizational network did include some external participants who held core capabilities. It relied on Howmet and PCC Airfoils for the development of single crystal vanes and blades for the gas turbines. The relationship between GEPS and the casting companies has existed since the 1960s and has evolved into a high-trust relationship where both tacit and explicit knowledge is easily shared. The ATS Program, however, enabled the casting companies to conduct additional trials, tests, and high-risk experiments that in effect accelerated the innovations related to fabricating the single crystal components. As a result, GEPS was able to acquire the resulting single crystal components from the casting companies faster than it otherwise would.

The GEPS case study indicates that organizational networks do not necessarily require external resources when developing complex technologies that are within a transition pattern. This conclusion calls into question whether other variables may also determine the firm's behavior when facing technological uncertainties. In the case of GEPS' innovation of the advanced gas turbine system, other factors seem to be important determinants as well. It may be that depth and breadth of capabilities within the GE business groups lead it to first refer back to its own resources when facing technological uncertainties. As Wheatley stated, some firms may exhibit self-reliance, or in terms of evolutionary theory of innovations, firms may exhibit strong path dependencies. (Wheatley, 1992)

GEPS' innovation strategies appear to be path dependent in that its strategies are constrained by past practices, history does matter (Dosi, *et al.*, 1988) not only for technological change but also for learning. The result however, remains that GEPS did reach the goals of the program being able to learn at a higher level, that is, use the core capabilities and learning processes held within business groups and use them towards new innovations.

The evidence indicates that SWPC did use organizational networks including both internal and external participants in its search of knowledge and new core capabilities in the innovation of the advanced gas turbine system. SWPC exhibited learning processes that sought out knowledge from other organizations during periods of uncertainty in the outcomes of the development. SWPC acquired knowledge through a "socialization" process as described by Nonaka and Takeuchi (1995) in that it acquired tacit knowledge from working closely with other organizations. It relied on an external organizational network as a source of knowledge and capabilities and, in some cases further advanced the innovations by building upon the knowledge acquired from the external organizational network. In other words, SWPC used tacit and explicit knowledge from external sources to create new knowledge.

SWPC acquired and created new knowledge within the organizational network in several ways. First, it has used its strategic alliances and licensing agreements, created independently of the ATS program, to access the resources residing within its alliance partners. In this regard, SWPC's own capabilities overlapped in some ways with its alliance partners, which was important in aiding the learning process. Second, SWPC developed relationships with researchers from universities, national laboratories, and government testing facilities, which were accessed through the ATS program. Finally, SWPS has worked with the casting companies that provided the capabilities for single crystal fabrications.

7.2 Public-private Partnerships and the Innovation of Complex Commercial Technologies

The evidence from this case study suggests that the DOE sponsorship of the ATS Program spurred the learning and innovation process that was essential to the ATS development. A number of benefits were identified, including: (1) stimulating the restructuring of networks and learning processes, (2) filling gaps, (3) creating an industry-led program, and (4) supporting university research. These benefits are further described in the following sections.

7.2.1 Stimulating a Restructuring of Networks and Learning Processes

At the beginning of the DOE ATS Program, GEPS and SWPC, or Westinghouse at the time, had established organizational networks for the development of gas turbine systems. GEPS had already begun development of an advanced gas turbine system for international markets using its capabilities as well as those of GEAE and GE CRD. It had started development of a 50-Hz gas turbine for an international customer. The casting companies, Howmet and PCC Airfoils, were also participants in GEPS' network.

SWPC, at the time Westinghouse, had also established its organizational network for its development of gas turbine systems. It had begun rebuilding its capabilities in gas turbine systems after a hiatus in the 1980s, using strategic alliances and licensing agreements with other manufacturers of both aircraft engines and utility-scale gas turbines. SWPC's network also included both Howmet and PCC Airfoils as resources for single crystal fabric ations.

When the DOE ATS Program was introduced, it stimulated a restructuring of the organizational networks of both turbine manufacturers. The ATS Program helped to direct GEPS toward development of a 60-Hz gas turbine for U.S. markets. The ATS Program also provided SWPC access to university research, the national laboratories, and the government testing facilities as resources in its innovation process.

The DOE ATS Program also stimulated the learning processes within the companies' networks. The additional funding for research allowed for more trial-and-error experiments, testing, modeling, and analysis that used the tacit and explicit knowledge residing within the networks' capabilities. The casting companies were also able to conduct more iterative trial-and-error testing using routines and heuristics, which more than likely would not have occurred absent the government funds.

The ATS Program, in short, *accelerated* the rate of technological change by stimulating the search and acquisition of knowledge and capabilities within the manufacturers' organizational networks.

7.2.2 Filling the Gap

The ATS Program as a means of filling a gap left by the market failures in the early 1990s. The market conditions in the early 1990s was not conducive to the development of advanced gas turbine systems, primarily due to deregulation in the electric utility industry and low natural gas prices. The effect of these market conditions was a low demand for new gas turbines and little incentive for the companies to spend corporate R&D funds on new technology development. The ATS Program's cost-sharing arrangement filled the gap left by weak market demand and provided the incentive for the manufacturers to develop the technology at a faster rate than would have been the case without the program. Those close to the program estimate that it accelerated the development of gas turbine systems by 5 to 10 years. Because the government started the ATS program over 10 years ago, the technology is now entering commercialization at a time when combined-cycle gas turbines systems are in high demand in both domestic and international markets.

7.2.3 Creating an Industry-led Program

Another function of the ATS Program was in the establishment of an industry-led program that was centered on the needs of industry. Workshops were held in 1991 and 1992 whereby industry, government, and university representatives met and identified the program goals, technological uncertainties, and research priorities. These initial workshops were valuable in setting the technology goals that were believed to be achievable and yet significant enough to garner funding support from Congress. The workshops also helped to validate whether the technology could be developed to accomplish the goals. Validation was further provided by the companies' willingness to cost-share in the technology development.

7.2.4 Support for University Research

The university research program, included in the ATS Program, provided additional network resources for the turbine manufacturers. SWPC used the university research program as a way of acquiring new capabilities and knowledge for its organizational network. The research also added to advances in fundamental understanding of gas turbine technology as well as supporting the education of a new generation of engineers and scientists for the industry.

7.3 Guidelines for Public Policy

The study has illuminated several policy implications that serve to encourage the successful development of complex energy technologies. The first policy implication is to enhance organizational learning through closer collaboration between companies that hold core capabilities in specific areas. More often, companies are moving more in the direction of inter-firm collaborations as a means for gaining technological advantage. Such collaborations enable both tacit and explicit knowledge to flow more easily, thereby fostering a learning environment. Policies can also enhance network resources through supporting education and training programs. The ATS Program is one example where educational opportunities for students were provided along with research targeting the needs of industry.

A second policy implication lies in shaping the selection environment in a direction that is desirable from a societal viewpoint. As Henry Etzkowitz and Magnus Gulbrandsen observed, under *laissez faire* ideologies, prevalent in U.S. policies, government cannot be perceived as taking the leading role, lest it draw unwanted political attack. Government can only establish general outlines for innovation goals and then leave it to industry to determine the best course; otherwise, government will be seen as "picking winners." (Etzkowitz and Gulbrandsen 1999) Commercial technology policies that employ a bottoms-up approach using cost-sharing strategies within a competitive selection process helps to bring industry, government, and university representatives together to establish the realistic goals and implementation plan and can avoid the perception of picking winners.

A final policy implication is to use collaborative programs that involve highly uncertain and high risk technological outcomes. Access to collaborative programs can be especially important for organizational networks that are dealing with the development of high-risk technologies where the outcomes are uncertain. Government R&D policies must not only support basic research but also technology development projects where knowledge is acquired through the exchange of tacit knowledge, embodied in experiences, know-how, routines, etc. that are held by many actors within the network. In the realm of complex energy technologies, it is important to recognize that learning processes occur within organizational networks, which provide many sources of knowledge. Programs that have uncertain outcomes are best undertaken with knowledge from many sources, including, but not limited to basic science.

Using cost-sharing arrangements within public-private partnerships are an effective means of validating the program goals. Industry and other R&D partners must favorably evaluate the concepts, evidenced by their financial support of the concept before the program continues to move forward. The ATS Program reflected this model of a cost-shared partnership. The early ATS program workshops conducted in 1991 and 1992 was a process for stimulating industry's interest and getting agreement on the "stretch" goals that were both technologically possible and politically attractive. By fully engaging industry in the beginning, the program goals are validated and yet significant enough to provide for congressional support.

7.4 Final Thoughts

The study of the innovation of advanced turbine systems suggests that public-private collaborative programs within the U.S. national innovation system can be an effective means of influencing technological change in a direction that is beneficial to society while being commercially attractive. While it is assumed that technological change cannot be determined *ex ante, w*ith the advantage of hindsight, the case study of the ATS innovation process provides important insights into ways that improve the chances for successful outcomes.

Policies geared towards technology development like the ATS have at times come under attack as "corporate welfare," a reflection of the U.S. political culture. Such attacks can act to constrain the use of policy tools that support commercial innovation within organizational networks. The debate needs to move beyond such labeling and recognize the importance of collaboration that fosters a learning environment that is needed during periods of uncertainty.

Public policies can play an important role in stimulating organizational networks that foster a learning environment and thereby influence the direction and speed of technological innovation in ways that serve the public's interest, and also the interests of the private sector. Institutional configurations where government, industry and universities work together can help to navigate the uncertain waters of discontinuous technological change.

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