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STATUS REPORT: THE U.S. DEPARTMENT OF ENERGY'S ADVANCED TURBINE SYSTEMS PROGRAM

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Abstract

Advanced Turbine Systems (ATS) are poised to capture the majority of new electric power generation capacity well into the next century. The U.S. Department of Energy (DOE) led the programs supporting the development of ATS technology enabling gas turbine manufacturers to provide ATS systems to the commercial marketplace.

A progress report on the ATS Program will be presented in this paper. The technical challenges, advanced critical technology requirements, and system configurations meeting the goals of the program will be discussed.

Introduction

More than 7 gigawatts (GW) per year of gas turbine equipment is manufactured today in the United States. This translates to a product value of more than $3.5 billion when the balance of plant equipment is included.

The increased demand for electricity in the United States is projected to grow by 98 GW before the year 2010. Over this same period, natural gas prices are projected to remain relatively stable, increasing moderately from $2.10 to $2.49 per million Btu (1994 dollars)[1]. Increased demands for power coupled with low fuel costs and the relatively low capital cost of gas turbines will enable gas turbines to capture a large portion of the growing electric power market. The Energy Information Agency estimates that gas turbines will satisfy more than 75 percent of new electric power demands.

Financial support for the ATS Program is provided by DOE and the individual ATS Program participants. The level of cost-sharing required from the participants increases as technology risk decreases. During the final phases of the ATS Program, participants will provide more than 50 percent of the financial support needed to sustain the program.

The ATS Program is developing two classes of gas turbines. Simple cycle industrial gas turbines, less than 20 megawatts (MW) in capacity, are being developed for distributed generation, industrial, and cogeneration markets. Gas turbines, greater than 20 MW, used in combined cycles systems, are being developed for large baseload central station electric power generation markets. Turbines smaller than nominally 3 MW are not covered by the ATS Program.

Projects in the ATS Program are organized under two major activities: (1) *Major Systems Development*, and (2) *Technology Base Development*. The ATS Program participants under the *Major Systems Development* activity are turbine manufacturers actively engaged in developing an ATS. Currently, there are four turbine manufacturers working on detailed engine designs and hardware under the Technology Readiness or Phase III of the ATS Program. The *Technology Base Research* activity consists of projects to support the major systems development and evaluate future advancements for gas turbine systems. Academic research and applied research not currently targeted for incorporation into ATS demonstrations is supported under this activity.

Objectives

The objectives of the ATS Program are to develop low-cost, highly efficient gas turbine systems which possess superior environmental performance. The specific program objectives are--

- **Efficiency**--greater than 60 percent (lower heating value (LHV)) on natural gas for large-scale utility turbine systems or 15 percent improvement in efficiency for smaller industrial turbine systems.

- **Environmental Superiority**--nitrogen oxide (NO_x) emissions less than 9 parts per million (ppm) and carbon monoxide and unburned hydrocarbon emissions less than 20 ppm without post combustion cleanup.

- **Fuel Flexibility**--initially designed for natural gas fuel with adaptability for coal-derived and biomass fuels.

- **Cost of Power**--busbar energy costs of 10 percent less than state-of-the-art (1992 vintage) turbine systems meeting the same environmental requirements.

- **Reliability, Availability, and Maintainability**--equivalent to, or better than, current state-of-the-art systems.

Advanced Turbine Systems Market

A recent market study sponsored by Westinghouse Electric Corporation[2] (Westinghouse) projects a significant market for ATS. Total world electric power generation demand from the years 2000 to 2014 is estimated to exceed 1,690 GW. Table 1 is a breakdown of the projected world market additions from 2000 to 2014.

Table 1

Estimated World Market Additions (MW)[2]

Region/Sub-Region	Natural Gas	Coal
Asia/Pacific		
China	3,200	248,000
Pacific	11,000	6,800
Central Asia	53,100	109,300
Far East	30,100	37,600
North America		
Canada	8,700	1,000
United States	97,500	18,200
Mexico	21,100	10,200
South America		
North/Central	12,900	10,400
South	13,500	1,600
Former Soviet Union	42,400	13,800
Middle East/Africa	68,500	56,300
Europe	110,700	92,300
Total	**472,800**	**605,400**

Natural gas, the market entry fuel for ATS, is projected to supply 473 GW of the increasing world market demand for power during this period. Figure 1 depicts the projected breakdown for the natural gas power generation market. The potential market for industrial and utility-scale ATS is very large and exceeds 430 GW. One significant finding of the market study is the large market, 120 GW, for simple cycle ATS.

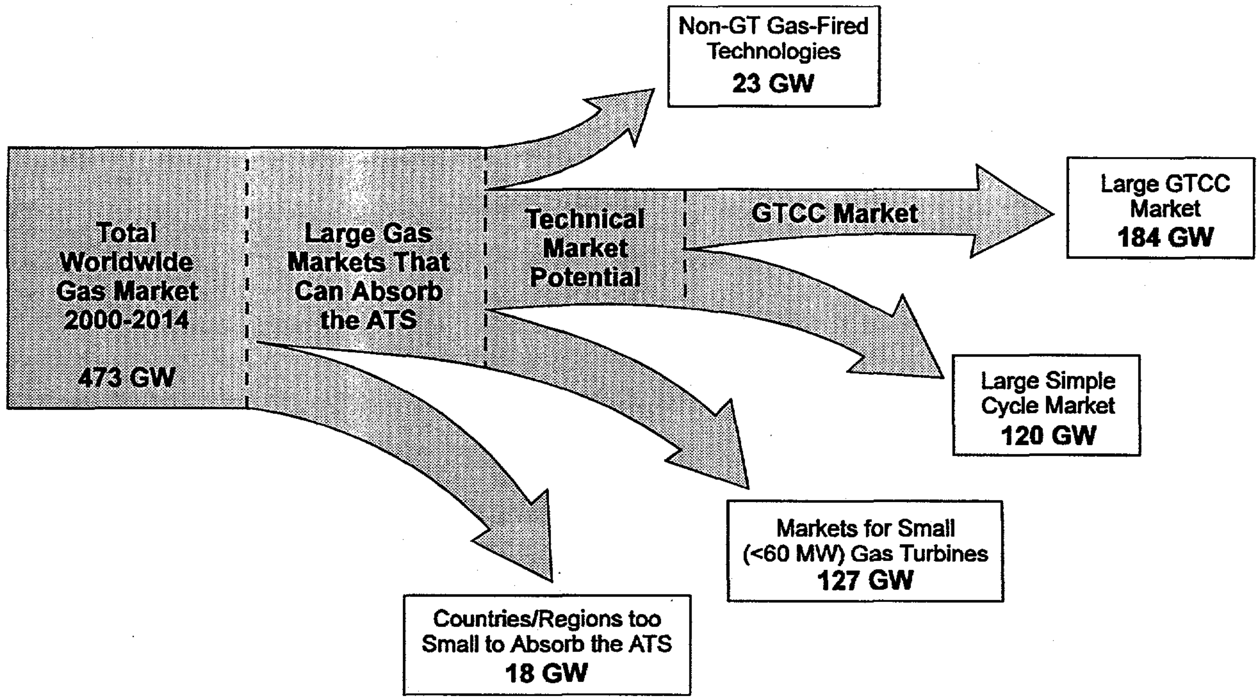

Figure 1
True ATS Technical Market Potential[2]

Integrated Gasification Combined Cycle (IGCC) systems will incorporate ATS technology. ATS penetration into the IGCC market is expected to increase in the post 2005 to 2010 timeframe, as IGCC commercialization accelerates.

Program Status

Currently, four major turbine manufacturers are participating in Phase III of the ATS Program, Technology Readiness Testing. Allison Engine Company and Solar Turbines are developing industrial-scale ATS. General Electric Company (GE) and Westinghouse are developing utility-scale ATS. The overall schedule of the ATS Program is shown in Figure 2.

Each of the major ATS developers has completed a conceptual design under Phase II of the program, Concept Development. While these designs differ in specifics, there are many common features. Generally, turbine manufacturers will increase turbine inlet temperatures; develop lean pre-mixed or catalytically enhanced combustors; reduce cooling air use through improved cooling schemes, improved materials, or improved seals; improve aerodynamic designs; scale-up materials manufacturing methods; and develop improved thermal barrier coatings (TBC's). Highlights of current cycle designs, methods to improve efficiency, approaches to achieve environmental superiority, materials development efforts, and university research activities are discussed below.

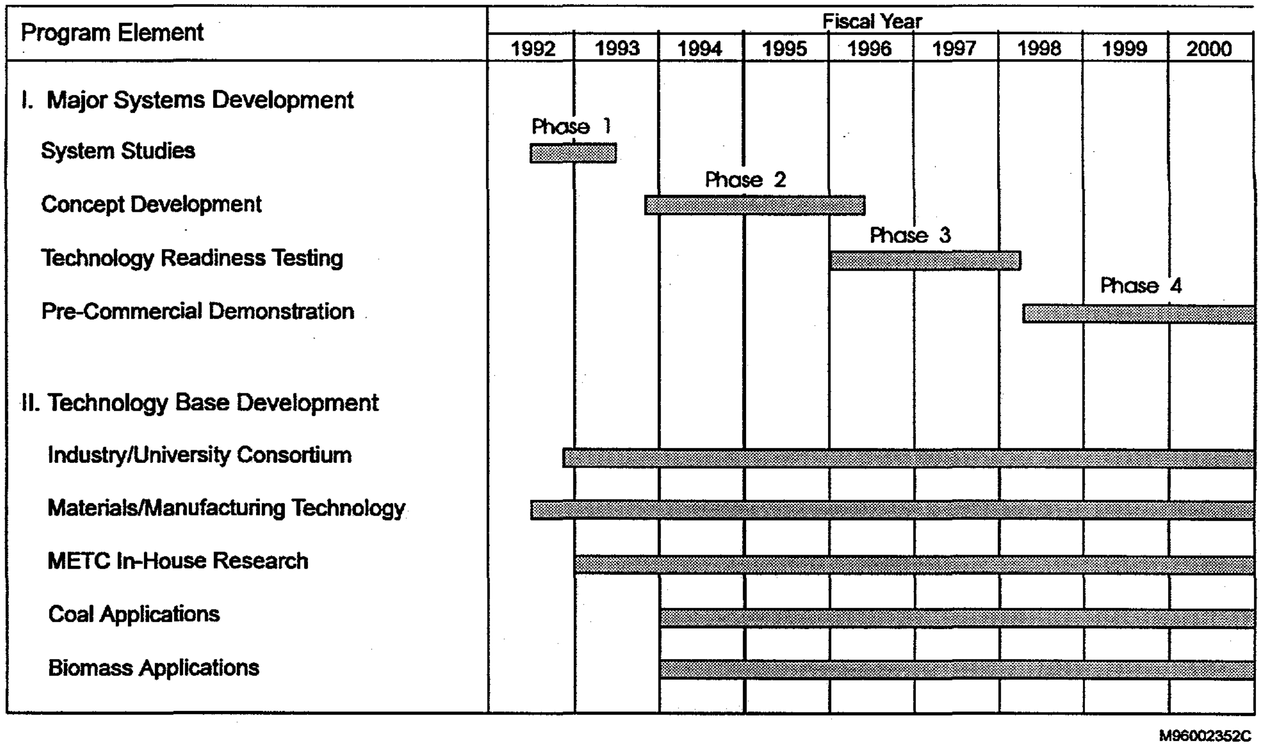

Figure 2
U.S. DOE FE/EE ATS Program Schedule

Cycle Designs

Industrial ATS developers are pursuing somewhat different approaches to achieve the cost and performance objectives of the program. Table 2 lists the general performance characteristics of the industrial ATS cycles.

Allison Engine Company is pursuing an approach based upon their extensive aircraft gas turbine experience. Increased efficiency for their simple cycle engine is achieved by raising the turbine inlet temperature (2,600 °F) and pressure ratio (29:1). Allison's approach is to develop a "core" ATS engine that will serve multiple applications (5 to 15 MW), with overall cycle efficiency approaching 50 percent[3].

Solar Turbines is pursuing an alternate approach which utilizes a recuperated cycle. The Solar concept takes advantage of a highly effective (greater than 90 percent) primary surface recuperator (PSR) with demonstrated long term performance and reliability. Solar's cycle provides high efficiency (45 percent) at a modest turbine inlet temperature (2,200 °F) and pressure ratio (9:1)[4].

Table 2

Industrial ATS Performance Characteristics

	Allison	Solar
Cycle Configuration	Simple	Recuperated
System Size (MW)	5-15	10
Turbine Inlet Temp. (°F)	2,400-2,600	2,200
Pressure Ratio	29:1	9:1
Nitrogen Oxides (ppm)	9	9
Efficiency (%LHV)	37-50	45

Utility-scale ATS developers, GE[5] and Westinghouse[6], are both developing large gas turbine combine cycle systems greater than 400 MW. Each of these systems incorporates a unique closed-loop cooling concept that improves system efficiency and maintains superior environmental emissions. Closed-loop steam cooling utilizes the superior heat transfer characteristics of steam, as compared to air, and also enables better integration between the gas turbine and steam turbine cycles. Table 3 lists the characteristics of both the GE and Westinghouse cycles.

Table 3

Utility ATS Performance Characteristics

	General Electric	Westinghouse
Cycle Configuration	Combine Cycle Closed-Loop Cooling	Combine Cycle Closed-Loop Cooling
System Size (MW)	400	440
Turbine Inlet Temp. (°F)	2,600	2,700
Pressure Ratio	23:1	25:1
Nitrogen Oxides (ppm)	9	9
Efficiency (%LHV)	>60	>60

GE has already made a commercial announcement and offering of their ATS system, designated as the STAG 107H.

Efficiency Improvements

Increased Turbine Inlet Temperature. All ATS developers will increase turbine inlet temperature to improve cycle efficiency. Both industrial ATS developers are evaluating the use of ceramic materials for use in the first-stage vanes and blades. Solar Turbines has tested a modified Centaur 50S engine incorporating ceramic blades and vanes in the first stage of the power turbine. Approximately 100 hours of operation has been achieved, to date, with no deterioration of the ceramic components. Ceramics offer the advantage of increased turbine inlet temperature without the need for blade and vane cooling air, thus improving system efficiency. While ceramic vanes and blades are under consideration and offer the greatest improvement and greatest risk, each industrial manufacturer has an alternative approach to achieve the ATS objectives.

Both utility ATS systems incorporate closed-loop cooling of the first and second turbine stages, which provides significant improvements in efficiency. Closed-loop cooling allows increased turbine inlet temperature without increasing combustion temperatures. This approach permits high turbine inlet temperatures without increasing environmental pollutants, such as NO_x. The advantages of closed-loop cooling can be seen in Figure 3. Current state-of-the-art gas turbines use compressor discharge air to cool the first-stage nozzle by injecting a stream air through the nozzle to provide film cooling. This maintains turbine blade materials at acceptable temperatures but results in an overall decrease in performance. With closed-loop cooling, media, either steam or air, is not injected into the gas stream, thus allowing more heat/energy to be transferred to subsequent stages in the gas turbine. This allows more work to be extracted from the gas flow and improves cycle performance. Studies by both GE and Westinghouse indicate that closed-loop cooling offers system efficiency improvements of up to 2 percentage points.

Improved Seals and Reduced Leakage. Methods to reduce leakages and improve seals are being developed to withstand the increased pressures and temperature of ATS. Seal designs and configurations are under evaluation to reduce leakage in the turbine nozzle, turbine shroud, and between turbine stages. New compliant materials and seal technology adopted from the aircraft industry, such as use of brush seals, are being adopted. Brush seals have the potential to reduce leakage by up to 90 percent in the compressor and turbine sections.

Environmental

Low Emission Combustors. To achieve single-digit NO_x emissions, all ATS developers are pursuing lean premixed natural gas combustion systems. Lean premixed combustors avoid the extremely high firing temperatures that produce thermal NO_x by thoroughly mixing fuel and air prior to combustion. Combustion instabilities (undesirable pressure oscillations) have become more pronounced while burning very lean combustion mixtures. Research is focused to properly

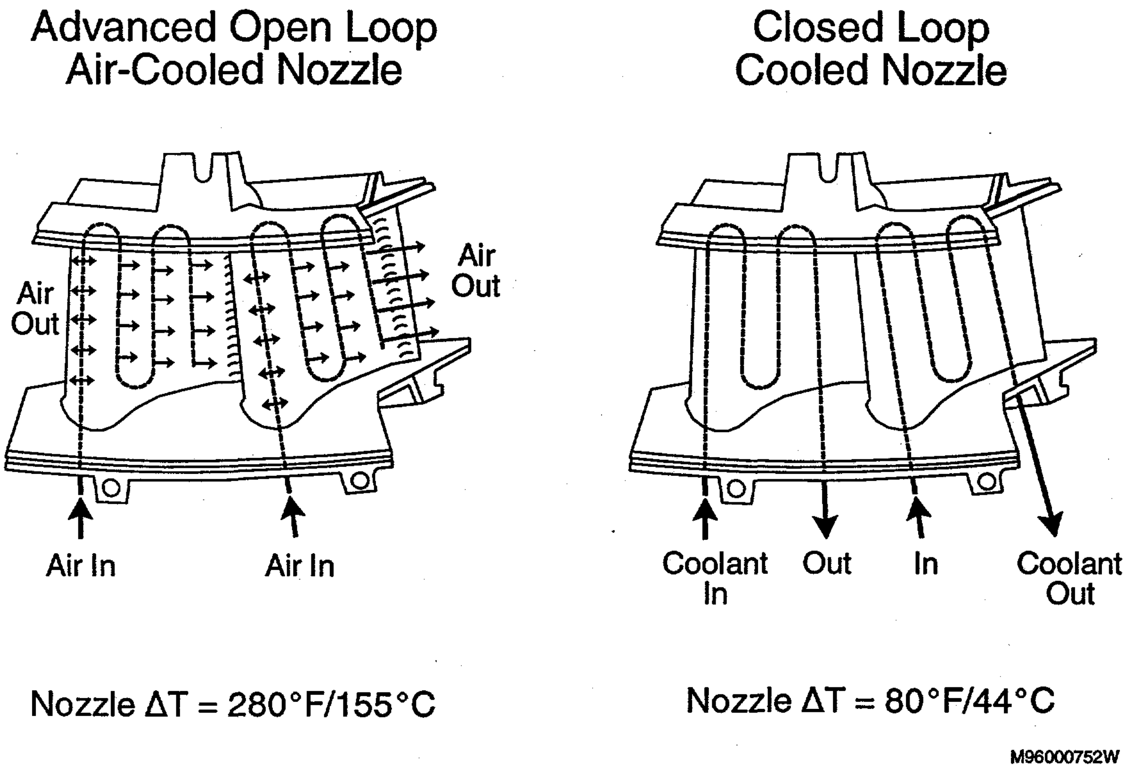

Figure 3

design combustion systems to eliminate the existence of combustion instabilities. The Morgantown Energy Technology Center (METC) is currently evaluating active as well as passive methods to control combustion instabilities[7].

Catalytic combustion is an alternative approach under evaluation by several ATS developers. Ultra-low emissions, less than 5 ppm, have been achieved with catalytic combustors without flame instability or flame outs. Longer term testing of catalytic combustors is ongoing to determine its viability for use.

Combustors for alternative fuels, such as coal gas, are under development for IGCC powerplants. High-temperature desulfurization, or hot gas cleanup, offers many advantages over conventional low-temperature desulfurization processes but does not reduce the relatively high concentrations of fuel-bound nitrogen (FBN) that are typically found in low Btu fuel. When fuels containing bound nitrogen are burned in conventional gas turbine combustors, a significant portion of the FBN is converted to NO_x. Under the ATS Program, GE has developed a rich-quench-lean (RQL) gas turbine combustor for use with low Btu fuels containing FBN. Tests with a full-scale RQL combustor[8] demonstrated NO_x emissions as low as 50 ppm (by volume) (on a dry, 15 percent oxygen basis) with 4,600 ppm of ammonia in the fuel. This corresponds to a conversion of about 5 percent ammonia to NO_x at a combustor outlet temperature of 2,100 to 2,200 °F. While this temperature is below ATS conditions, it indicates with proper design, FBN conversion can be minimized through proper design using an RQL combustor.

Materials Development

Emphasis on increased efficiency and higher firing temperatures requires the use of improved materials with superior creep and thermal resistance characteristics. Casting development is underway for large, single crystal blades and vanes capable of meeting the stringent thermal gradients imposed by high firing temperature (2,600 °F) turbines. First-stage airfoils will be single crystal with directionally solidified or conventionally cast airfoils in subsequent stages. Additional thermal protection will be provided by TBC's applied to blades, vanes, and other components exposed to high temperatures. Oak Ridge National Laboratory, under sponsorship of the ATS Program, is managing contracts for airfoil manufacturing technology and thermal barrier coatings.

Airfoil Manufacturing Technology. Howmet Corporation and PCC Airfoils are developing technology to reliably produce large, single crystal airfoils capable of meeting ATS requirements. Howmet is supported by a team including ASEA Brown Boveri, Pratt & Whitney, Solar Turbines, Westinghouse, Aracor, and Purdue University. The project focuses on four thrust areas--low sulfur alloys, casting process development, postcast process development, and casting defects tolerance definition. Castings produced by Howmet will be evaluated by the team members. Project completion is scheduled for April 1998.

PCC Airfoils is supported by GE Power Generation and is evaluating--alloy melt practices, modification and improvement of single crystal casting processes, core materials and designs, and grain orientation control. This project will be completed in July 1997.

Thermal Barrier Coating Development. Projects to develop advanced TBC's are underway at Westinghouse and Pratt & Whitney. The goal of these projects is to develop dependable TBC's that enable increased turbine inlet temperatures while maintaining airfoil substrate temperatures at levels to meet ATS life goals. Each of these projects will develop TBC's with enhanced temperature capabilities over existing state-of-the-art. Relative performance of bond coat systems, such as diffusion aluminides and overlay MCrAl-type compositions, is under evaluation. The effects of operating parameters of TBC application processes (e.g., electron beam-assisted physical vapor deposition and plasma spray processes) are being correlated to ceramic microstructure and thermal resistance. The performance of coatings will be evaluated by subjecting combinations of bond coats and ceramic layers to exposure tests intended to simulate the extreme corrosive and erosive environments to which actual components will be exposed. The most promising TBC's will be applied to airfoils, which will be used in bench testing that reproduce the essential features (thermal gradients imposed by cooling) of first-stage blades and vanes. TBC systems that achieve the performance goals of the bench testing phase will be applied to components that will be installed in actual operating engines. This optional phase of these projects will allow evaluation of TBC's over a 12-month period under actual engine conditions.

University Consortium

The Advanced Gas Turbine Systems Research (AGTSR) Program is a collaborative University-Industry Research and Development (R&D) Consortium that is managed and administered by the South Carolina Energy R&D Center. AGTSR is a nationwide consortium dedicated to advancing land-based gas turbine systems for improving future power generation capability. It supports the technology-research arm of the ATS Program and targets industry-defined research needs in the areas of combustion, heat transfer, materials, aerodynamics, controls, alternative fuels, and advanced cycles. Presently, 78 performing member universities and 6 cost-sharing U.S. gas turbine corporations make up the consortium. Thirty-one research projects are underway at member universities (Table 4). The AGTSR consortium nurtures close industry-university-Government collaboration to enhance synergism and the transition of research results, accelerate and promote evolutionary-revolutionary R&D, and to strive to keep a prominent U.S. industry strong, well into the 21st century.

Future Activities

The ATS Program is on schedule to have pre-commercial demonstrations operating in the year 2000. Phase III of the utility-scale ATS projects is scheduled for completion in December 1997. At that time, DOE will select one developer to demonstrate its ATS under the fourth and final phase of the program, Pre-Commercial Demonstration. GE and Westinghouse are aggressively pursuing sites to host the pre-commercial demonstration projects. Announcement of potential site hosts is anticipated during the first half of 1997.

Future enhancements to gas turbines systems that offer benefits beyond the ATS Program are under consideration. Integrating fuel cells with gas turbines has the potential to offer systems with exceptionally high efficiencies, exceeding 70 percent. The second of two workshops on Very High Efficiency Fuel Cell/Gas Turbine Power Cycles[9] sponsored by DOE at METC was held in August 1996. Significant interest to initiate development of integrated fuel cell/gas turbine systems was expressed by turbine manufacturers, fuel cell developers and potential user of combined fuel cell/gas turbine systems.

The ATS Program established the objective for gas turbine systems to achieve--greater than 60 percent system efficiency with superior environmental performance at a lower cost of electricity. Today, the market no longer perceives ATS as an objective but rather as a reality. Thus, the only task left is to complete the ATS Program and remove the remaining barriers to acceptance of ATS technology.

Table 4

Performing University Member	1993 Awards Research Topic
Brigham Young	3D Combustion Model
UC/Berkeley	Catalytic Combustion
Clarkson	Ice Formation Design Method
Lehigh	Functionally Gradient Materials for TBC's
LSU	Improved Blade Heat Transfer
Penn State	Superalloy TMF Analysis
Purdue	No_x Submodels
Texas A&M	Aero and Heat Transfer Improvements
Vanderbilt	NO_x and CO Submodels for LP Flames
VPI	Innovative Fuel/Air Flow Control
Performing University Member	**1994 Awards Research Topic**
UC/Irvine	Mixedness Effects in LP Combustors
Carnegie Mellon	UC/Irvine
Central Florida	Steam Effects on Superalloys
Clemson University	Film Cooling Computational Tool
Georgia Tech	Combustion CVD for TBC
Maryland	Enhanced Combustor Premixing
MIT	Rotational Effects on Heat Transfer
Michigan State	Steam Versus Air for Blade Cooling
Minnesota	Film Cooling Geometry Effects
Oklahoma	Intercooler Flow Path Analysis
Purdue	Multistage Turbine Aerodynamics
Wyoming	Turbulence Effect on Heat Transfer

Performing University Member	1995 Awards Research Topic
Arizona State	Disk Cooling Effectiveness
Clemson University	Closed-Loop Mist Cooling
University of Connecticut	Thermal Barrier Coatings
University of Connecticut	Heat Pipe Vane Cooling
Georgia Tech	Active Combustion Control
Penn State	Modeling Turbomachinery Losses
Penn State	Combustion Instability
Syracuse	Inverse Design Methodology
Vanderbilt/Cal Tech	Active Combustion Control Framework

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