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Proceedings of the Advanced Turbine Systems Annual Program Review Meeting
Volume I

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Charles M. Zeh
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U.S. Department of Energy
Office of Fossil Energy
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October 17-19, 1995

Foreword

The Advanced Turbine Systems Annual Program Review Meeting was held October 17-19, 1995, at the Morgantown Energy Technology Center (METC) in Morgantown, West Virginia. About 250 persons attended this meeting, which was sponsored by the Office of Fossil Energy and the Office of Energy Efficiency and Renewable Energy, U.S. Department of Energy (DOE). The meeting was hosted by METC. The goals of this 8-year program are to develop cleaner, more efficient, and less expensive gas turbine systems for utility and industrial electric power generation, cogeneration, and mechanical drive units. Projects are funded jointly by the DOE Office of Fossil Energy, DOE Office of Energy Efficiency and Renewable Energy, and private industry.

This conference is held annually for energy executives, engineers, scientists, and other interested parties in industry, academia, and Government. The purpose is to provide a forum for the exchange of ideas and discussion of results and future plans related to research on advanced turbine systems.

Advanced turbine systems topics discussed during five technical sessions included policy and strategic issues, program element overviews and technical reviews, related activities, university/industry consortium interactions, and supportive projects. Twenty one papers presented during the technical sessions are contained in Volume I of this proceedings. Volume II contains 28 poster presentations and appendices. Note that Volume I begins with papers presented during Session 2; there are no papers for Session 1.

The papers printed in this document have been produced from camera-ready manuscripts or electronic files submitted by the authors. They have been neither refereed nor extensively edited.

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Introduction

The Annual Program Review, along with these proceedings, summarize the annual activities of the Advanced Turbine Systems (ATS) Program. The objective of the Program is to develop more efficient gas turbine systems for utility- and industrial-scale gas turbine systems. Under the Program, base-load power systems are being developed for commercial offering in the year 2000. Although the target market is natural gas, advanced turbine systems will be adaptable to coal and biomass fuels.

The ATS *Comprehensive Program Plan*[1] outlines an 8-year program. Funding is estimated at $700 million and consists of approximately $450 million as the Government share and approximately $250 million cost-shared by turbine developers. The U.S. demand alone will require up to 15 gigawatts (GW) per year of new and replacement electric-power generating capacity after the year 2000. More efficient advanced turbine systems should fill a share of this need, which will save significant amounts of fossil fuel and will be more beneficial to the environment.

Implementation of the ATS Program will keep U.S. manufacturers on the cutting edge of turbine technology for power generation applications and will enhance the nation's economic competitiveness. The ATS Program has four elements: innovative cycle development, utility system development/demonstration, industrial system development/ demonstration, and technology-based development. The basic program strategy is to fund teams led by U.S. turbine manufacturers to develop advanced turbine systems from concept and component development to full-scale demonstration.

Since the meeting in October, Phase III *Full-Scale Component and Sub-System Testing* awards have been made to utility and industrial-scale developers. Utility developers selected are General Electric Company and Westinghouse Electric Corporation, and industrial developers are Allison Engine Company and Solar Turbines, Inc.

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[1] *Report to Congress Comprehensive Program Plan for Advanced Turbine Systems*, February 1994, DOE/FE-0279-1.

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Poster Session

Appendices

Session 2A

ATS Program Element Overviews

2.2 Industrial Advanced Turbine Systems Program Overview

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Introduction

The U.S. Department of Energy (DOE), in partnership with industry, has set new performance standards for industrial gas turbines through the creation of the Industrial Advanced Turbine System Program. Their leadership will lead to the development of an optimized, energy efficient, and environmentally friendly gas turbine power systems in this size class (3-to-20 MW). The DOE has already created a positive effect by encouraging gas turbine system manufacturers to reassess their product and technology plans using the new higher standards as the benchmark.

Solar Turbines has been a leader in the industrial gas turbine business, and is delighted to have joined with the DOE in developing the goals and vision for this program. We welcome the opportunity to help the national goals of energy conservation and environmental enhancement. The results of this program should lead to the U.S. based gas turbine industry maintaining its international leadership and the creation of highly paid domestic jobs.

In a complementary paper at this conference, the details of our ATS Phase II program are discussed. This paper will describe Solar's approach to meeting the DOE objectives for the ATS Phase III program. It also covers the development of ceramic components under the Ceramic Stationary Gas Turbine (CSGT) program and the complementary High Performance Steam System (HPSS) Development Program.

Background

Government (DOE/Energy Information Agency) estimates of required new or additional power generation capacity in the U.S. are currently at 15 gigawatts annually after the year 2000. The products required to meet the increased demand for power will have to be highly efficient and environmentally benign. This expanding market will require products that have a life cycle of approximately 30 years. Additionally, and outside the scope of the aforementioned estimates, much of the old power generation equipment is reaching the end of its life and will need to be repowered or replaced with efficient and environmentally clean advanced systems.

The DOE has stated in its request for ATS Phase III proposals "... commercial implementation of the innovative technology is the principle goal of the Solicitation ..." The required program goals are:

[1] Research sponsored by the U.S. Department of Energy's Morgantown Energy Technology Center, under Contract DE-AC21-93MC30246, DE-AC02-2CE40960, and DE-FC21-95MC31173 with the Chicago Operations Office, under Contract DE-AC02-87CD40812 with Solar Turbines Incorporated, 2200 Pacific Highway, P.O. Box 85376, San Diego, CA 92186-5376; telefax: (619) 544-5669.

- **Efficiency** -- A 15 percent improvement compared to the best technology in its class, available in 1991.

- **Environment** -- Emissions will be lowered by 10 percent to achieve acceptance in severe non-attainment areas.

- **Fuel Flexibility** -- Natural gas-fired systems must be adaptable to future firing with biomass and coal derived fuels.

- **Cost of Power** -- Busbar energy costs should be 10 percent less than current state-of-the-art turbine systems, meeting the same environmental requirements.

- **Reliability, Availability, and Maintainability** -- Equivalent to current state-of-the-art turbine systems.

The DOE goals parallel those that Solar Turbines has set for its future products. The issue of product durability is a major buying criterion for users of industrial size gas turbines, and therefore Solar adds **Durability** to the above bulleted point of Reliability, Availability, and Maintainability. Solar's nomenclature for this combined issue is **RAMD**.

Maximizing Program Value

The ATS program is designed to foster national goals of (1) global competitiveness of U.S. industry, (2) public health benefits, (3) reduction of dependence on imported oil, and (4) the expansion and retention of industrial employment through more affordable electric power. Other components of national value include increased product exports and reduced fuel imports. To achieve these goals the industrial partners must maximize the potential market volume, the market penetration by ATS technologies, and the technical performance gains. Market penetration has two components, (1) market acceptance and (2) time to market. Solar has taken each of these elements of program value into consideration when developing its plans for its ATS offerings.

ATS Markets

Market Size

The worldwide market for industrial gas turbine systems has doubled since 1985. Growth in market size is expected to begin around the year 2000 and continue at least through the year 2010. Acceptance of gas turbines into the growing power market is due to high availability, low initial cost, short delivery times, and the capability for dual-fuel operation and unattended (remote) operation.

Market Characteristics

Because the ATS will have system electric conversion efficiencies approaching 47 percent without heat recovery, the amount of thermal energy contained in the engine exhaust is relatively small compared to traditional cogeneration systems in the >70 percent range, depending upon site conditions and system operating requirements. Consequently, an ATS cogeneration system (e.g., unfired waste heat boiler) will have a higher electric-to-process steam production ratio (i.e., 5:1 versus 2:5) than traditional systems using less efficient gas turbines. Duct firing can be used to augment thermal energy output, when required.

Industrial prime mover applications, in general terms, have the following characteristics:

- Prime movers are dispersed at or close to the site where their output is used.

- The prime mover, and often the entire site, is either unattended or attended by personnel whose primary assignment is either elsewhere or unrelated to the prime mover.

- The output of the prime mover is a critical element in the production of the site product but, unlike production machinery, must be transparent to the user.

- The prime mover is frequently a significant cost element to the user.

These application characteristics will combine to produce a set of buying criteria similar to the set shown in Figure 1. These criteria vary somewhat from industry to industry, and trends can be observed over time. For example, emissions as a buying criteria, is growing rapidly in importance as regulatory activity increases. In non-attainment areas, emissions already heads the list, but still does not necessarily overpower reliability, availability, maintainability, and durability (RAMD) or cost. In the present economic milieu, first cost ranks very high but could yield to lifetime cost where fuel costs become high because of market pressure, or as a result of taxes on fuel usage.

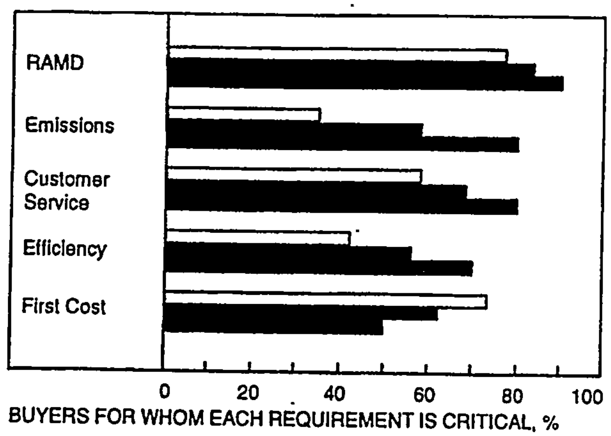

Figure 1. Buying Criteria

Market Segments

The potential ATS applications within this large market are summarized as:

Power Generation/Cogeneration

- Power Generators: The industrial ATS can be used as prime movers in electric power generation systems to meet the demands of electricity users. The owners and operators of ATS electric power plants can be investor-owned utilities, rural electric cooperatives, municipal utilities, and independent power producers. The continued growth of electricity demand at or above the nation's Gross Domestic Product (GDP) through the remainder of this decade and beyond will create major opportunities for the ATS owning to its high efficiency, low capital cost, low prices for natural gas, short lead times for installation, and compliant environmental emissions.

- Cogenerators: Typically, users of gas turbine cogeneration systems have had high heat-to-power ratios to justify supplying their process needs. With the development of the ATS systems, however, new markets with low-to-medium heat-to-power ratios will be able to justify cost-effective turbine cogeneration. Users in these markets will choose an industrial ATS system that meets their power and heat requirements.

- **Dispersed Generation**: In the broadest context the ATS can be used in both traditional (i.e., baseload and cycling) and new (such as distributed generation) applications. Ease of siting and permitting, plus the improvement in the quality of power over that now available at great distances from the central station, or not available due to lack of capacity, are major attractions. Additionally, the ATS can be installed in areas where nuclear or older fossil fuel plants are scheduled for retirement.

Traditional Industrial Markets

- **Oil and Natural Gas Production, Transmission, and Storage**: These industry sectors with a capacity between 5,000 hp and 30,000 hp, which depend extensively on compression and pumping equipment, represent clear opportunities for the ATS. The ATS, with its efficiency of nearly 47 percent, its low capital and maintenance cost, and its compliant emissions performance will be a very competitive option for the oil and natural gas industries. In addition, an American gas industry study [1] was conducted which concluded that gas turbines will continue to be the driver of choice for large compressors. Small gas turbines and electric motors will increasingly replace reciprocating engines on existing natural gas transmission pipelines.

- **Industrial Prime Movers**: The ATS can be used for many industrial processes such as manufacturing power generation, mechanical shaft power for compressors and pumps in petrochemical and other energy intensive applications. Others uses include electric/thermal cogeneration to serve a portion of on-site electric and process steam demands in manufacturing plants which depend extensively on low-cost reliable electricity supplies.

- **Transportation**: Propulsion applications in the commercial "fast ferry" and "fast freight" merchant marine industries appear to be the greatest opportunities for the ATS in marine applications because these applications emphasize fuel efficiency and power density. Gas turbine/electric motor drive combinations will power locomotives, in addition to the traditional diesel or diesel/electric drivers now in use. These applications are designed to use liquid fuels.

As currently envisioned, the ATS will have many attributes (e.g., low emissions, high availability) which will make it superior to advanced gas-fired power systems available in the marketplace after the year 2000. The projected cost and performance advantages clearly distinguishes it in contrast to its expected competitors.

Market Transformation

The industrial ATS program benefits will be maximized by (1) ensuring market acceptance and (2) getting the product to market early. These two issues combine to maximize the penetration of the ATS into the marketplace. The benefits provided by the ATS will accrue to both the customer and the public in general.

Market Acceptance

The customers in the markets discussed in the preceding sections share a common characteristic - risk aversion. While the benefits of new technology are seductive, each of the market segment users wants to see proof of the new technologies before committing to purchase. Solar's approach to this issue is to involve customers in the evaluation of the technologies early in the program. Because of the large number of existing gas turbine systems supplied by Solar (over 9,400) in the industrial market segment alone, technologies can be introduced singularly and early into the field to gain acceptance. This process also ensures that early benefits are realized from each technology.

Customers look to Solar for upgrades to their equipment at the time of overhaul and understand the increase in value to their operations of dealing with a vertically integrated manufacturer. Prime mover, packaging and controls coordination has proven to suit the needs of the industrial gas turbine user.

Another facet of market acceptance is the company's reputation to stand by the customer. Solar's extensive field service network and service tools ensure that any problems encountered during the introduction of new technology are promptly resolved.

Acceptance of new technologies has been achieved by careful attention to the customer needs. Customer acceptance of industrial ATS technologies will hinge on proof of performance. Inclusion of the technologies into existing products as they are developed will help assuage the fears of customers who are not likely to accept unproven technologies. Therefore, Solar can incorporate the newly developed concepts and components into existing new products and to retrofit them into systems returned for overhaul. An example of this approach is the SoLoNOx™ dry, lean premixed, pollution prevention combustion system now available. Solar developed this technology and since its introduction in 1992, has sold over 250 of these systems. Two-thirds of the systems have been installed in new units for use worldwide, and the remaining one-third have been retrofit on units that have been returned for overhaul, upgrades, and uprates.

A similar process is planned for ceramic components which are being developed under the DOE Ceramic Stationery Gas Turbine (CSGT) program. These components are being designed for retrofit into a Solar Centaur® 50 gas turbine system. By investing in technology development, there have been significant accomplishments integrating the CSGT components into an existing gas turbine. Once proven in a field test engine, the components will be introduced to both new and retrofit markets in a low-risk approach.

Early to Market

Getting the product to market early, to help achieve the goals of the industrial ATS program, will be accomplished, only in part, by the retrofit process noted above. The bulk of the proof of concept comes in the investment in high-technology design tools and through the concept of rig testing. Solar uses the latest computer-based engineering design and analysis tools to reduce the uncertainties and time required for new developments. The proof of each design concept is confirmed through the extensive rig testing of each of the new component designs to assure performance and reduce the risks associated with placing unproven technologies into test engines. Of course, full field testing of all new concepts is completed before placing them in the marketplace.

This approach will allow the successful marketing of newly proven technologies, while satisfying the conservative, risk-averse nature of the industrial gas turbine user. The success of the above-mentioned SoLoNOx systems was based upon standard industrial gas turbines that were retrofit with the development hardware and field-proven prior to market release.

Distributed Generation

In response to established national priorities, the DOE has provided partnering leadership through a number of cooperative programs with industry to significantly improve efficiencies and diversify fuel usage in industrial power generation equipment. The effect of these will be to satisfy our national energy requirements, while decreasing the amount and type of pollutants emitted to the atmosphere. The overall ATS program will provide an affordable solution for private industry, in cooperation with electric utilities, to restructure power generation technology toward the goal of dispersed electrical power production. To accomplish this goal, a new approach to supplying the capital equipment is required. Considerations for new power generation are becoming more involved. As a result, there are strong indications that today's central plant, coupled to extensive transmission and distribution systems (Figure 2) will undergo a metamorphosis toward a new form of service called distributed generation.

Customer Choice

The advent of distributed generation brings with it a new challenge for the manufacturers and the end users of power generation equipment. Unlike the past practices, the customer or user of power now has a choice of technologies from which to choose (Table 1). The push of technological development and the associated market pull of users who select from the various alternatives will help

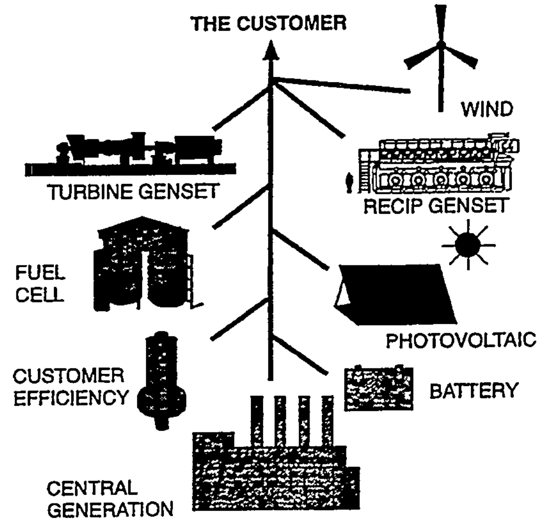

Figure 2. Tomorrow's Distributed Generation?

determine which becomes the technology(ies) of choice. What is clear at this time is that the concept of distributed generation will offer the user highly reliable, quality power at an overall lower total energy cost.

Technical Performance Improvement

The market characteristics and customer buying criteria are essential inputs to the decision on product characteristics. Solar performed an extensive Quality Functional Deployment (QFD) analysis to quantify the customer needs in the industrial marketplace. A second set of key inputs came from the DOE program goals, especially early commercialization of ATS technologies. Commercialization demands market acceptance. Thus, Solar evaluated the types of technology that could be sold into the marketplace by the year 2000. Evaluation of numerous cycles against these criteria led Solar to select the optimized, recuperated gas turbine as the first step along the path of more complex cycle development (Figure 3). The development path will, of course, depend on the rate of customer

Table 1. Competing Systems for Electrical Generation [2]

System	Availability, %	NO_x Emissions, ppmv	Installed Cost, $/kW	Thermal Efficiency, %
Advanced Turbine Systems	98	5	650	42.8
Gas Turbine Combined Cycle	92	9	700	58
Conventional Gas Turbine	95	25	650	34.5
Molten Carbonate Fuel Cell	97	Trace*	3000	52.9
Reciprocating Gas Engine	91	42	600	39

* Does not include all emissions at other sources.

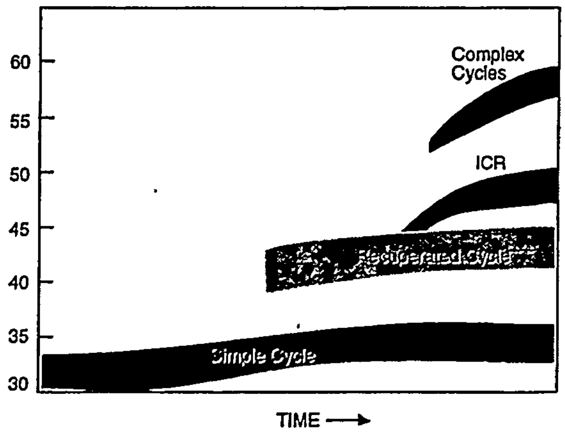

Figure 3. Evolution of Industrial Turbine Efficiency

acceptance of the new approaches to higher efficiency products. The currently-selected recuperated turbine system meets or exceeds all of the industrial ATS program goals. The technologies employed have or will be individually tested in full scale tests before ATS product introduction, reducing the technical risk.

The optimized, recuperated gas turbine is designed to provide the highest efficiency and lowest emissions that can be introduced and accepted at this time. It is not a simple-cycle engine with a traditional recuperator added to it. The turbine pressure ratio, firing temperature, and cooling flows are carefully selected to meet program goals. The resulting gas turbine has a shaft efficiency goal of 47 percent (LHV) and a NO_x emissions goal of 8 ppmv (at 15 percent O_2) on natural gas fuel. This performance is possible because of the incorporation of the technologies listed in Table 2.

Industrial customers also require high thermal efficiency over a broad load range. The Solar ATS will achieve this with a variable area turbine nozzle (VATN). With this component the engine delivers almost flat heat rate over the 50-to-100 percent load range. A second advantage of the VATN is the flat or constant combustor firing temperature over the same load range. Because of this characteristic it is easier to maintain low emissions over the same load range.

Advanced Turbine Systems include more than the gas turbine driver. "Systems" includes the air inlets, exhaust silencers, gear boxes, generators, lube oil systems, fuel gas compressors, and controls. Each of these

Table 2. Technology Development Categories

Materials	Coatings	Efficiencies	Combustion
Advanced Single Crystal Turbine Blades, Nozzles	Thermal Barriers	Compressor & Turbine Components	Lean Premixed
Bi-metallic Recuperator Air Cells & Turbine Disks	Rub Tolerant	Primary Surface Recuperator	Ultra-Lean Premixed
Ceramics	Clearance Control	Cooling Improvements	Catalytic

items has an effect on system efficiency, cost, and availability. Some have an effect on air quality because of "fugitive" emissions. Calculations on a typical gas turbine system shows that eight percent of the engine output is not available at the busbar. Solar has addressed each item in the system reducing its parasitic power consumption and fugitive emissions. When these technologies are implemented, the optimized recuperated gas turbine system should have ~95 percent of shaft energy available at the busbar.

In conjunction with the industrial development of the energy conversion equipment, noted universities, led by Clemson, and including various campuses of the University of California working on combustion technologies, contribute to the technological research by analyses and experimental testing of the theories and/or future concepts developed under DOE contract to the industrial partners. A listing of the partners is shown in Figure 4.

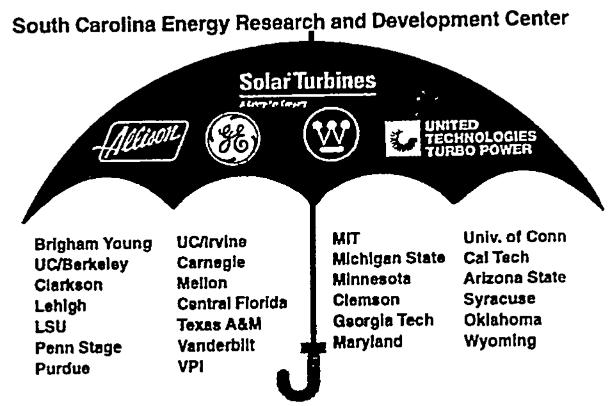

Figure 4. Industry/University Consortium

Ceramic Stationary Gas Turbine Program

Introduction

The Industrial ATS program has been designed to have associated technology development programs used as feeder programs into the main program. The Ceramic Stationary

Gas Turbine (CSGT) program is one such feeder program. CSGT is predominantly a materials development program that advances the enabling technologies that will feed into and help develop the ATS turbine system design as a forward-fit development, and will enable retrofit to existing systems when the materials are proven.

Objective

The overall objective of the DOE Ceramic Stationary Gas Turbine (CSGT) Development Program is to improve the performance of existing stationary gas turbines through the selective replacement of metallic hot section parts with uncooled ceramic components. The successful demonstration of ceramic gas turbine technology, and the systematic incorporation of ceramics in existing and future gas turbines will enable more efficient engine operation, resulting in significant fuel savings, increased output power, and reduced emissions.

The objective of the CSGT program is to demonstrate and ultimately commercialize ceramic gas turbine technology with the intent of providing national energy savings and emissions reductions. The economic and technical potential of the ceramic gas turbine technology has been analyzed and described in the Phase I Final Report for the CSGT program. The application of ceramic components benefits gas turbine performance because it enables a higher component temperature in a simpler and therefore, less costly, design and/or it reduces the need for part cooling and the use of protective coatings. When considering the cost associated with utilizing ceramic blades and nozzles, one can assume that ceramics will be (1) more expensive than uncooled parts of conventional superalloys, (2) are of comparable cost as cooled conventional superalloy parts, and (3) can be significantly less expensive than parts fabricated of cooled and coated advanced superalloys.

Estimates of potential national energy savings and emissions reductions as a result of implementing ceramic gas turbine technologies in industrial engines (0.5-25 MW output) have been made as part of the Phase I work. Potential annual national energy savings have been estimated to range from 0.076-0.28 quads (1 quad = 10^{15} Btu) or between 14 and 56 million barrels of oil, by 2010. The lower end of this range assumes a modest penetration of the projected engine fleet with first generation retrofits. The higher end of the range assumes that the entire installed fleet will consist of second generation ceramic engines.

Phase II work to date includes the completion of the first generation ceramic component designs and the design of the interfacing metallic support structures, fabrication of subscale components, and full scale prototypes. The set-up and modification of test rig facilities, testing of specimens, and subscale components has also been completed. The generation of a long term data base and the development of supporting technologies, such as NDE have been generated. Testing of full scale prototype components in rigs and in the program engine was started at the end of the reporting period. The full-scale test of the first ceramic hot-section components in an industrial gas turbine has been successful.

High Performance Steam Developments

Possibly the world's highest temperature steam power plant has successfully completed the development test phase. Results represent a breakthrough in steam technology. Based upon a successful 500 hour test cell demonstration of a 1500°F (815°C), 1500 psig

(10,342 kPa) generator in 1991, the complete full-scale system has been designed, fabricated, and completed development testing. Included in the system is an industrial size steam generator fired by natural gas, a triple function steam valve, and a 4 MW topping steam turbine. All of the three major components and the piping are innovative and represent a major advancement in design, materials applications, process development, and manufacturing technology.

To cost effectively develop and introduce advanced steam systems to industry, a natural gas-fired industrial-sized combined cycle was selected as the optimum configuration for development by the DOE. A gas turbine used extensively for cogeneration was used for calculating steam generator sizes for a combined-cycle system with a back pressure steam turbine arrangement (Figure 5). A supplementary exhaust firing system providing a temperature of 2500°F (1371°C) was selected on the basis of maximum economic performance in cogeneration while maintaining ultra-low emissions capabilities. At an exhaust flow of 38 pounds (17.2 kg) per second the output steam flow is 57,000 pounds (25,855 kg) per hour at 1500°F (815°C) and 1500 psig (10,342 kPa). In a combined-cycle configuration with a back pressure steam turbine the system is designed to produce 9 MW of electrical power, and 990°F (532°C) high quality process steam. The overall process efficiency, steam and electricity, is above 90 percent fuel utilization efficiency and about twice the amount of electric power is produced per pound (kg) of steam to the process.

The steam generator employs a once-through water steam flow path with a horizontal gas flow path. The majority of the heat transfer area is in carbon steel fins brazed to high nickel stainless steel tubes. In the final superheater section specially developed

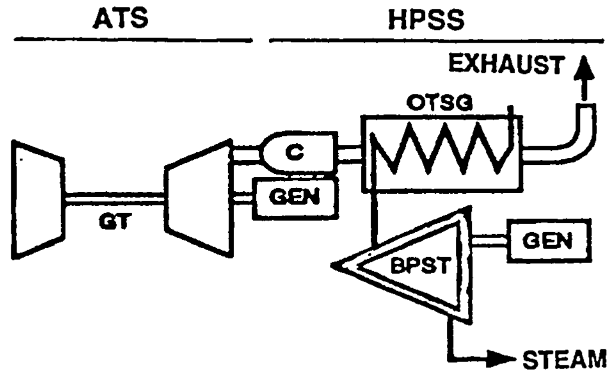

Figure 5. HPSS for Cogeneration

Inconel 617 tubes are used above metal temperatures of 1300°F (704°C). All three major components, steam generator, piping, and valve were operated at full steam flow and at a temperature of 1500°F (815°C) and 1500 psig (10,342 kPa) prior to operating the steam turbine. Outlet temperature of the 26 circuits was adjusted to obtain outlet temperatures of within +95°F about an average measured mixed temperature of 1508°F (820°C). Emissions at natural gas firing rate of 110 million Btu (116 million kJ) per hour were equivalent to 9 ppm NO_x and 7 ppm CO at 15 percent oxygen (test was at 3.2 percent oxygen).

The steam turbine design is a synthesis of gas turbine design concepts and steam turbine materials. The diameter of the turbine is small to permit high temperature and pressure operation. With a blade pitch diameter of 11.5 inches (29.2 cm), the operating speed is 30,000 rpm using a single-stage supersonic impulse design. It is a full admission with an overhung single rotor. This provides for centerline axial flow steam admission with complete symmetry. Only the static superalloy investment cast inner case is exposed to 1500°F (815°C) steam. Over 2.5 billion forcing pulses at full power were applied to each blade at their undamped natural frequency during the test. During the 100 hour technology proof tests, the steam generator, triple control valve, and steam turbine and interconnecting piping system performed extremely close to analytical estimates. The expansion efficiency from 1500°F (815°C) and 1500 psig (10,342 kPa) to 165 psia and 990°F (532°C) was 68 percent for the single-stage turbine. The rotor and case steam cooling system kept cooling steam on the nozzle side of the rotor only 70°F (21°C) above the exhaust of 990°F (532°C).

Successful advancement of steam temperature conditions in the HPSS program can further the basic goals of the ATS programs. Those ATS systems with high gas turbine exhaust temperatures can consider HPSS topping steam turbines to obtain higher efficiency and more power. Lower exhaust temperature ATS systems will obtain significant advantages through use of supplementary firing and using HPS concepts for cogeneration applications.

Summary

Under the continuing ATS Conceptual Design and Product Development (Phase II), market studies were conducted to help establish the product configuration(s) acceptable for use in the newly emerging dispersed/distributed electric power generation market. In parallel, the future technology needs of the established industrial markets in mechanical drive gas turbines were addressed. These studies revealed a mix of acceptable future power generation technologies. The initial responses have led to the design of a gas-fired, recuperated, industrial size gas turbine. Solar has recently been awarded Phase III, for development and demonstration of this design.

The CSGT Phase II program, which commenced in April 1994 continues. A full-scale test of the first ceramic hot-section components in an industrial gas turbine has been successful. Long-term testing of ceramic components for performance and life assessment is continuing.

The HPSS Phase III development program takes a substantial step toward increasing industrial and electric utility prime mover efficiency. A 100 hour development test to prove the advanced, 1500°F, 1500 psig system full-scale hardware has been successfully completed.

The DOE ATS program will advance the development of environmentally clean, highly efficient gas turbine and related products for new markets, and for retrofit and repowering markets where there will be a need for large blocks of power. However, a market transformation will take place, where the customer will be offered a choice of energy conversion technologies to meet heat and power generation needs into the next century.

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2.3 H Gas Turbine Combined Cycle

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Abstract

A major step has been taken in the development of the Next Power Generation System - "H" Technology Combined Cycle. This new gas turbine combined-cycle system increases thermal performance to the 60% level by increasing gas turbine operating temperature to 1430 C (2600 F) at a pressure ratio of 23 to 1. Although this represents a significant increase in operating temperature for the gas turbine, the potential for single digit NOx levels (based upon 15% 0_2, in the exhaust) has been retained. The combined effect of performance increase and environmental control is achieved by an innovative closed loop steam cooling system which tightly integrates the gas turbine and steam turbine cycles.

The "H" Gas Turbine Combined Cycle System meets the goals and objectives of the DOE Advanced Turbine System Program. The development and demonstration of this new system is being carried out as part of the Industrial/Government cooperative agreement under the ATS Program. This program will achieve first commercial operation of this new system before the end of the century.

Research sponsored by the U.S. Department of Energy's Morgantown Energy Technology Center under contract DE-AC21-93MC30244 and Cooperative Agreement DE-FC21-95MC31176 with GE Power Generation, One River Rd., Schenectady, NY 12345 (518) 385-7779

H Gas Turbine Combined Cycle

Introduction

A key advantage of gas turbine power generation systems is the ability to continue evolving to higher firing temperatures. Each increase in firing temperature yields a dual benefit: *increased efficiency,* that is, lower fuel use, and *increased specific work,* that is, output per unit of air flow, reducing capital cost. In a gas-turbine/steam-turbine combined cycle mode, performance is optimized by selecting a pressure ratio to achieve both high efficiency and high specific work. In order to produce an attractive system, pressure ratio and firing temperature must advance together.

Environmental compatibility continues to be a major concern. For a gas turbine, the main emission issue is nitric oxide (NOx). To achieve low NOx in a gas turbine, the maximum temperature in the combustion chamber must be reduced below the levels of conventional diffusion combustion. In order to achieve low combustion temperatures, a new combustion concept called "premix lean" was developed. With premix lean, a large fraction of the compressor discharge air is mixed with the fuel prior to combustion, creating a lean mixture that produces low gaseous emissions when combusted in a fluid-mechanics-stabilized combustion chamber. The dry low NOx (DLN) premix combustion system, has moved through the laboratory development stage and has been successfully introduced in commercial service. This combustion system is capable of achieving single-digit NOx levels.

Rationale for a Next-Generation Power System

The goal of advanced gas turbine development has been to achieve increased performance through increased firing temperature. The increase in performance was obtained by applying advanced airfoil cooling techniques and using new alloys. The additional constraint of emission control for environmental compatibility creates a conflicting set of parameters. Higher performance requires higher firing temperatures, but lower NOx emissions require lower combustion temperatures.

Both performance and emission targets can be met by changing the gas turbine cooling system. The rationale for the change lies in the difference between the controlling parameters for performance and emissions—combustion temperature and firing temperature.

The most critical element of an advanced gas turbine is its hot gas path, Figure 1. The compressor discharge air and fuel are mixed and combusted in a chamber at a specific condition, combustion temperature. The flow stream of high-pressure, high-temperature combustion products is accelerated as it passes through the first stationary airfoil (first stage nozzle segment). The firing temperature—the flow stream temperature at the inlet to the first rotational stage (first stage bucket)—establishes the power output (ultimately, the cycle efficiency). The difference between firing temperature and combustion temperature is the temperature drop (nozzle ΔT) required to cool the first stage nozzle, Figure 2.

In the current line of advanced gas turbines, the first stage nozzle is cooled with compressor discharge air flowing through the

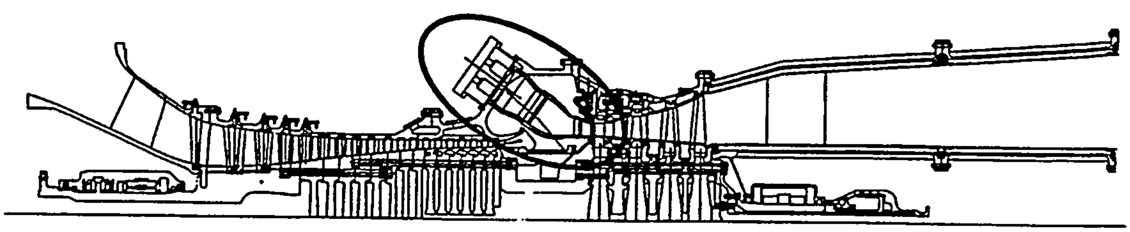


Figure 1. Gas Turbine Hot Gas Flow Path

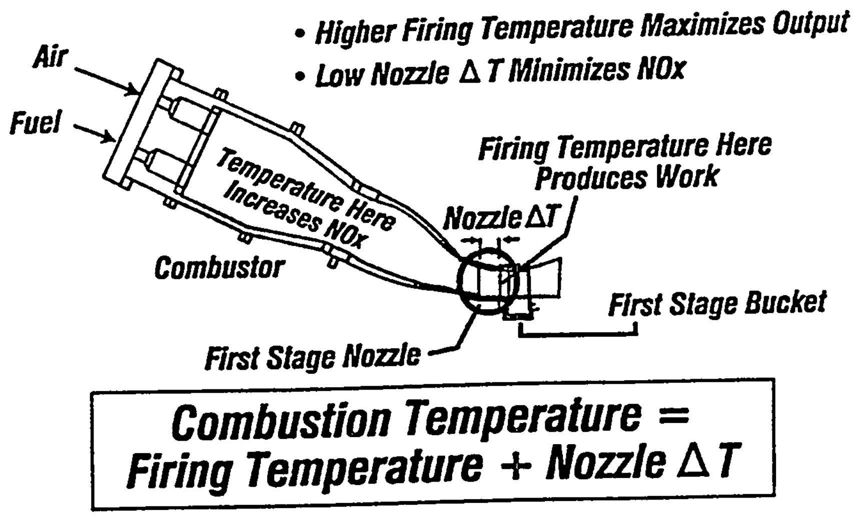


Figure 2. Combustor/1st Stage Nozzle Interaction

airfoil and discharging out into the combustion gas stream as the airfoil is film cooled. This cooling process causes a temperature drop of up to 155 C (280 F) across the first stage nozzle, Figure 3. If the nozzle can be cooled with a closed-loop coolant without film cooling, the temperature drop across the first stage nozzle would be less than 44 C (80 F), which would permit a 110 C (200 F) rise in firing temperature with no increase in combustion temperature.

The key to single-digit NOx capability at increased performance (increased firing temperatures) is closed-loop cooling of the first stage nozzle. The cooling concept has a dual effect: allowing higher firing temperatures to be achieved without combustion temperature increases and permitting more compressor discharge air to flow to the head-end of the combustor for fuel premixing.

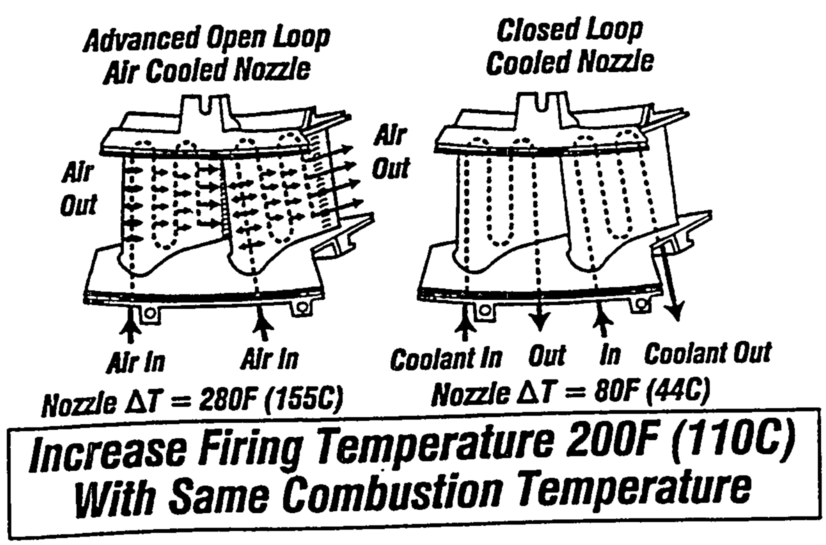


Figure 3. First Stage Nozzle Cooling

A change in cooling strategy for the first stage stationary nozzle will therefore resolve the conflicting requirements for higher performance and lower emissions. However, once a closed-loop cooling system is established, it can do much more to benefit performance. In conventional gas turbines, compressor air is also used to cool the remaining rotational and stationary airfoils. This air also enters the combustion gas flow path and is classified as "chargeable air," reducing cycle performance. If this chargeable air is also replaced with a closed-loop coolant system, a cycle benefit of up to two points can be achieved, a dramatic improvement.

The move to a higher level of gas turbine power generation performance while meeting emission control targets can be achieved by a change from open-loop air cooling to closed-loop cooling of the gas turbine hot gas path parts. However, in order to achieve effective cooling thus maintaining hot gas path part integrity, an improved coolant medium is required.

In a power generation application, the high levels of performance for gas turbine systems are achieved by means of a combined cycle. The high temperature exhaust from the gas turbine is used to generate steam in a heat recovery steam generator (HRSG). This steam is then expanded through a steam turbine. For the gas turbine combined cycle power generation application, there is another coolant alternative—steam.

The airfoil cooling requirements of the gas turbine are met by using steam—a cooling fluid that is much more effective than air—to cool the hot gas path parts without relying on film cooling. This coolant is provided in a closed-loop system integrated with the steam bottoming cycle.

Advanced H Combined Cycle System

The integration features of the H Combined Cycle System include the flow of coolant steam from the steam cycle to the gas turbine, as shown in Figure 4. The high-pressure steam from the HRSG is expanded through the high-pressure section of the steam turbine. The exhaust steam from this turbine section is then split. One part is returned to the HRSG for reheating; the other is used for cooling in the gas turbine.

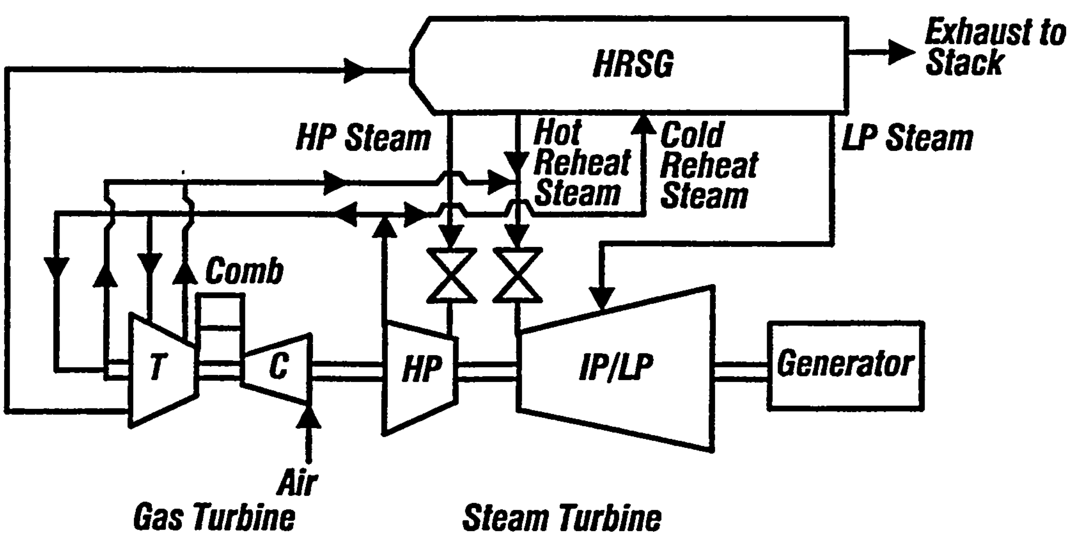


Figure 4. Stag 109H and 107H Combined Cycle System Description

Steam is used to cool both the stationary and rotational parts of the gas turbine. After cooling the hot gas path parts, the steam temperature is increased to approximately reheat temperature. The gas turbine cooling steam is collected and returned to the steam cycle, where it is mixed with the reheated steam and introduced to the intermediate-pressure steam turbine section for energy recovery.

The H Combined Cycle is composed of the H gas turbine, at increased operating conditions; the three-pressure-level HRSG, and a reheat steam turbine. These three components can be configured in a single-shaft or multi-shaft arrangement for an efficient, low emission power generation system.

H Gas Turbine

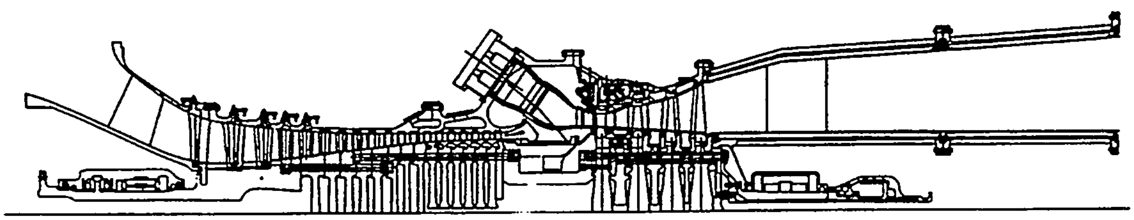
The attractive operational characteristics of the H Combined Cycle system are a direct result of the gas turbine performance level. This new gas turbine, Figure 5, features closed-loop steam cooling for the first and second stages of its four-stage turbine. In order to optimize the efficiency and specific work with the 1426 C (2600 F) class of firing temperatures, a higher pressure ratio compressor derived from the GE Aircraft Engine CF6 80C2 has been used. The DLN combustion system now in service across the commercial product line has been adapted to the H gas turbine. These are the three key components for the H technology.

Compressor

The H compressor uses a proven aircraft engine design that is scaled to appropriate utility application size. The CF6 design geometry was scaled by a factor of approximately three to match the H requirements. The result is an eighteen-stage compressor with a 23.2 to 1.0 pressure ratio and an air flow of 558 kg/sec (1230 lb/sec) at 60 Hz and 685 kg/sec (1510 lb/sec) at 50 Hz.

Combustor

The H combustion system is a lean premix DLN system. In order to meet the increased flow requirements, the combustor diameter has been increased by approximately 20% from the FA



Features

- ***Closed Loop Steam Cooling***
- ***4-Stage Turbine***
- ***Compressor Scaled From Proven Design***
- ***Dry Low NO_x Combustor***

Figure 5. Cross Section H Gas Turbine

family of designs. This proven can/annular design permits a 14-can configuration at 50 Hz and a 12-can configuration at 60 Hz. The combustion system has been staged for significant turndown capability while retaining low emission characteristics.

The DLN development has been carried out in a parallel program to the ATS activity. This combustion system is now operational in close to 100 GE gas turbines in commercial service. The DLN system has demonstrated an ability to achieve single digit NOx and CO at combustion temperature close to that required for the ATS gas turbine. This major component availability supports the ATS Development.

Turbine

The innovative part of the H gas turbine is the turbine section. The pressure ratio was increased to match the 1426C (2600F) firing temperature while retaining a turbine exhaust temperature of approximately 593C (1100F) for good combined cycle performance. To achieve high turbine efficiency, a four-stage turbine design was selected to maintain optimum work loadings on each stage.

The flow path of the turbine employs optimized 3D geometry with closed-loop steam cooling for the first and second stage rotational and stationary airfoils. This effective cooling medium will allow the firing temperature of the H gas turbine to increase to 1426C (2600F) while retaining the same design life specifications as the current gas turbine products. In fact, the bulk airfoil metal temperatures will be lower than those of conventional air-cooled gas turbines. (Although the conventional machines operate at lower firing temperature).

The first stage of the H gas turbine uses an aircraft-engine-proven, single crystal alloy and thermal barrier coatings (TBCs). The second, third, and fourth stages use directionally solidified materials. The third stage is air-cooled; the fourth stage is uncooled.

H Technology Product Performance

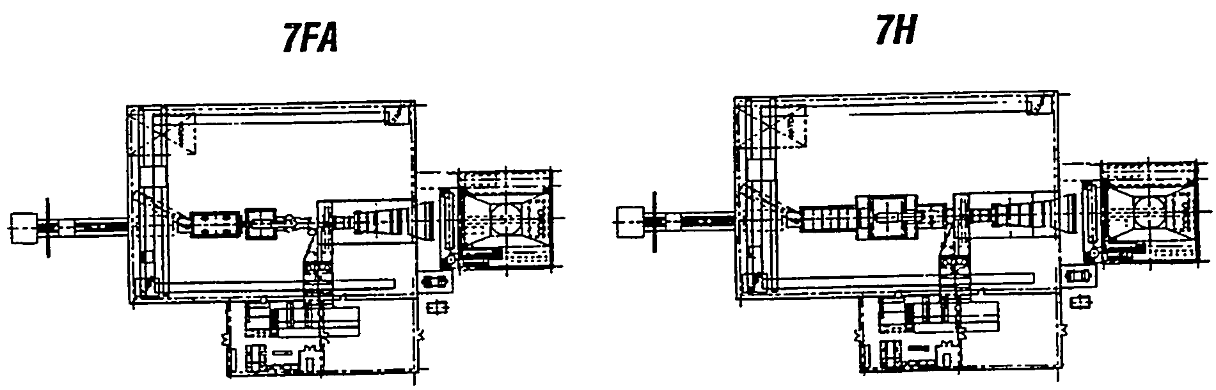
The H combined cycle power generation systems are designed to achieve 60% net plant efficiency. The operational and performance characteristics for the H technology gas turbine/combined cycle products are summarized in Table 1. The significant efficiency increases over the FA technology product line are achieved by advancing the operating conditions—pressure ratio and firing temperature. These advantages are achieved while maintaining single-digit NOx and CO capability.

Power Plant Configuration

The output of the H family of products is 400 MW at 60 Hz and 480 MW at 50 Hz in a single-shaft combined cycle. One extremely attractive feature of the H family of combined cycle power plants is the high specific output, which permits compact plant designs resulting in reduced "footprint" and the potential for low plant capital costs. In a 60 Hz configuration, Figure 6, the result is a 58% increase in output over the FA plants with an increase of just 8% in plant size.

Table 1. 60 Hz Characteristics & Performance

	7FA	7H
Characteristics		
Firing Temperature Class, F (C)	2350 (1300)	2600 (1430)
Air Flow, Lbs/sec (Kg/sec)	974 (442)	1230 (558)
Pressure Ratio	15	23
Emissions		
NO_x, ppm	9	9
Combined Cycle Performance	STAG 107FA	STAG 107H
Net Output, MW	253	400
Net Efficiency, %	55	60
Specific Output, MW/Lb/sec (MW/Kg/sec)	.26 (.57)	.33 (.72)



7FA vs. 7H
58% Increase in Output
With Only
8% Increase Footprint

Figure 6. Advanced Machine Plant Layout

DOE/GE Advanced Turbine System Program & Schedule

In response to the market opportunity, the initial H technology design effort has been focused on the MS9001H (50 Hz) gas turbine, with a full speed no load (FSNL) test, and subsequent shipment, of the first unit scheduled for the second half of 1997. The MS7001H (60 Hz) follows directly thereafter, and benefit from the significant design commonality with the MS9001H. The ATS government/industrial partnership has provided support for the establishment of the technology base for this Advanced Turbine System. The information developed under this program has been integrated into the Design Methods used to configure the machine. The component tests, now underway, are providing validation of the design.

The ATS Phase 4 Cooperative Agreement will provide an opportunity to work with a user at a host site to install and test the first ATS combined cycle unit. It is expected that this "first commercial" unit will be completed before 2000.

Conclusion

The H technology gas turbine/steam turbine systems provides an opportunity to move up to the next plateau for power generation systems. The innovative cooling system for the H gas turbine permits a step change in firing temperature, reaching record levels of efficiency and specific work, while retaining low emission compatibility.

The design for this next generation system has proceeded through the development stage and has achieved a design freeze status. This will permit both 50 Hz and 60 Hz gas turbine combined cycle systems to enter commercial service before the end of the decade. The H family of advanced power generation systems will set the performance, emission control, and operational standards well into the 21st century.

Acknowledgments

METC Contracting Officer's Representative:
Ms. Abbie Layne
Period of Performance:
Phase 2 - 8/25/93 to 3/31/96
Phase 3 - 9/29/95 to 12/31/97

2.4 Overview of Westinghouse's Advanced Turbine Systems Program

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Introduction

Westinghouse's experience with land based gas turbines started in 1945 with the development of a 2000 hp gas turbine-generator set that consisted of a single reduction gear, compressor, 12 combustors and turbine. A thermal efficiency of 18%* was obtained. By 1954, Westinghouse had developed a 15 MW unit (with a regenerator and intercooler) that was designed for a full-load simple cycle efficiency of 29%. As the initial step in the Advanced Turbine Systems (ATS) program, Westinghouse has already developed a 230 MW gas turbine that has a simple cycle efficiency of 38.5% without the use of regeneration and intercooler concepts.

In 1967, Westinghouse developed its first gas turbine combined cycle, a synergistic combination of the Brayton and the Rankine cycles. In a combined cycle the heat rejected by the higher temperature topping cycle is recovered in the lower temperature bottoming cycle to produce additional power from the energy initially released by the fuel. In this first Westinghouse combined cycle, a 1450°F burner outlet temperature gas turbine, rated at 25 MW, supplied exhaust heat which was used in a boiler to furnish steam to drive an 85 MW steam turbine. This plant achieved an annual average efficiency of 39.6%.

In the early 1990's, Westinghouse combined cycle efficiencies were in the 53 to 54% range. Today, with a Westinghouse 501G gas turbine, a net efficiency of 58% is obtainable for a 350 MW single-shaft gas turbine and steam turbine combined cycle arrangement.

As applicable, technology advances from the ATS Program are being incorporated into our 501G design. This paper reviews some of the natural gas-fired and coal-fueled cycle concepts that have been evaluated by Westinghouse to support ATS objectives. Also, features of the Westinghouse single-shaft ATS combined cycle are highlighted in this paper.

Objective

In cooperation with the U.S. Department of Energy's Morgantown Energy Technology Center, the Westinghouse Electric Corporation

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* All efficiency values in this paper will be lower heating value

is working on an 8-year, four-phase program to develop and demonstrate a highly efficient (greater than 60% plant cycle efficiency), environmentally superior (NOx < 10 ppmv), and cost-competitive (busbar energy costs 10% less than current technology) utility for baseload utility scale power generation. The natural gas-fired gas turbine must be capable of being adapted to operate on coal or biomass fuels. Availability is to be equivalent to modern advanced power generation systems, and the concept must be commercially available by the year 2000.

Approach

In Phase 1, Westinghouse concluded that a plant efficiency greater than 60% can be obtained with an advanced combined cycle, which includes an increased gas turbine firing temperature (2600°F), increased component efficiencies, and reduced cooling air usage (Little et al., 1993). In Phase 2, in which Westinghouse is currently working with DOE, gas turbine cycle efficiencies were reevaluated using established principles such as intercooling and recuperation, and newer concepts such as thermochemical recuperation and partial oxidation. Also, efficiency enhancements within the ATS cycle were evaluated to determine the best approaches to raising overall thermal plant efficiencies (Bannister et al., 1994). Within Phase 2, Westinghouse has developed a conceptual gas turbine design for an advanced combined cycle.

Project Description

Current large natural gas-fired combined cycle power generation systems are capable of net efficiency levels in the range of 58%. Within the ATS Program, Westinghouse was given the opportunity to reevaluate cycle efficiencies. Results of some of the analyses are summarized in this paper. In addition, efficiency enhancements within the ATS selected cycle have been evaluated. The concepts considered in the Westinghouse analyses are required to be capable of demonstration within a two-to-three year time frame. From a baseline cycle definition, this paper reports briefly on how different concepts will affect the overall plant thermal efficiency (Briesch et al., 1994).

The Phase 2 Westinghouse ATS Program is defined within eight major tasks. Task 1 (Management Plan), Task 2 (National Environmental Protection Act [NEPA]), Task 3 (Select Natural Gas-Fired Advanced turbine System [GTFATS]), and Task 4 (Conversion to a Coal-Fueled Advanced Turbine System [CFATS]) have been completed. The remaining tasks, Task 5 (Market Study), Task 6 (System Definition and Analysis), Task 7 (Integrated Program Plan), and Task 8 (Design and Test of Critical Components), have started.

Cycle Studies

Baseline Cycle

In order to evaluate different technologies and concepts applicable to combined cycle power generation systems, a baseline combined cycle configuration was developed to provide a basis for comparison of all the cycle concepts and technologies to be considered. A conventionally configured combustion turbine coupled with a three- pressure level reheat steam cycle was modeled to provide a baseline cycle. The gas turbine rotor inlet temperature (RIT) was set at 2600°F to approximate near-term temperature capabilities. Compressor pressure ratio was set at 18. High pressure steam conditions entering the steam turbine were specified at 1450 psi and 1000°F, and the hot reheat steam temperature was also set at 1000°F. This configuration utilized turbine rotor cooling air heat to produce additional low-pressure steam in the steam cycle via a heat exchanger located in the heat recovery steam generator (HRSG). Also, the natural gas fuel was preheated by feedwater recirculation flow.

Steam Cycle Enhancements

The basic reason for raising the steam pressure and temperature of the Rankine cycle is to improve the potential thermal efficiency. The cost effective steam cycle was determined to be at 1800 psi with 1050°F high pressure superheat steam and 1050°F reheat steam.

Closed-Loop Cooling

Most current technology gas turbine engines utilize air to cool the turbine vanes and rotors. This allows the turbine inlet temperature to be increased beyond the temperature at which the turbine material can be used without cooling, thus increasing the cycle efficiency and power output. However, the cooling air is a detriment to cycle efficiency. First, air is ejected from the turbine air foils earning a disruption in the surrounding flow field. Secondly, the cooling air is ejected from the airfoil into the gas path which results in irreversible pressure losses due to non-ideal mixing. The third loss mechanism is caused by the reduction in gas path temperature which reduces the work output of the temperature. Finally, the turbine cooling air must be pumped to pressures significantly higher than gas path pressure to assure that cooling flow rate is sufficient. By using a closed-loop cooling concept, the loss mechanisms can be reduced while still maintaining turbine material temperatures at an acceptable level.

Higher Compressor Pressure Ratio

Aircraft gas turbine engines are designed with high overall pressure ratio to maximize simple cycle efficiency. For a Westinghouse type industrial gas turbine engine with a 2600°F RIT, the simple cycle efficiency curve is relatively flat above a pressure ratio of approximately 40. In a combined cycle, steam cycle efficiency decreases with increasing gas turbine pressure ratio due to the reduction in gas turbine exhaust temperature. This in turn reduces the maximum steam temperature and pressure and the steam's availability, and results in lower steam cycle efficiency.

Compressor Intercooling

Compressor intercooling reduces the compressor work, because it compresses the gas at a lower average temperature. Since the gas and steam turbines produce approximately the same output as in the non-intercooled case, the overall cycle output is increased. Since the compressor exit temperature is lowered, the amount of fuel that must be added to reach a given turbine inlet temperature is greater than that for the non-intercooled case.

The ratio of the amount of compressor work saved to the amount of extra fuel energy added is about equal to the simple cycle efficiency. Intercooling adds output at approximately the simple cycle efficiency. Since combined cycle efficiencies are significantly greater than simple cycle efficiencies, the additional output at simple cycle efficiency will reduce the combined cycle net plant efficiency for the intercooled case.

Recuperation

In recuperative cycles, turbine exhaust heat is recovered and returned to the combustion turbine combustor usually via a heat exhange between the turbine exhaust gases and the compressor exit air flow. The discharge from the compressor exit is piped to an exhaust gas-to-air heat exchanger located aft of the gas turbine. It is then heated by the turbine exhaust and returned to the combustor.

Since the resulting combustor air inlet temperature is increased above that of the non-recuperated cycle, less fuel is required to heat the air to a given turbine inlet temperature. Because the turbine work and the compressor work are approximately the same as in the non-recuperated cycle, the decrease in fuel flow results in an increase in thermal efficiency.

Other Cycles

Some of the other innovations studied included use of a reheat gas turbine, design of a partial oxidation gas turbine and the concept of thermal chemical recuperation. The analytical results for these cycles were interesting, but the concepts are not ready to be demonstrated by Westinghouse within the two-to-three year time frame required by the ATS Program.

ATS Cycle Analyses

As an initial step in the ATS Program, Westinghouse developed a 230 MW gas turbine that has a combined cycle efficiency of 58%. Parameters evaluated during the ATS cycle analyses helped set the 58% efficiency level. (Features of Westinghouse's 501G gas turbine are discussed in a paper by Southall and McQuiggan, 1995.) Incorporated into our latest commercial offering are aerodynamic engine design codes, materials and design concepts, including directionally solidified blade materials and thermal barrier coatings. Full three-dimensional viscous flow modeling, analysis and optimizations have been used in the design of compressor and turbine blades and vanes.

The cycle analyses discussed in this paper were used along with an in-depth evaluation of emissions, cost of electricity, reliability availability-maintainability, and program schedule requirements to select the best ATS. Features of the Westinghouse ATS single-shaft combined cycle include:

- Advanced Aero/Heat Transfer/Materials Technology
- Closed-Loop Cooling
- Single Crystal and Directional Solidified Blades
- Improved Thermal Barrier and Anti-corrosion Coatings
- Ceramic Ring Segments
- Active Tip Clearance Control
- Brush Seals
- Reduced Inlet and Exhaust Losses
- Fuel Preheating
- Advanced Steam Turbine Design Technology

Conversion to Coal-Fired ATS

A number of advanced, coal-fired power generation technologies have been under development that could be applied to a natural gas-fired ATS. These include a broad range of coal gasification technologies (fixed bed, fluid bed, and entrained bed), second generation pressurized fluidized bed combustion (PFBC), and a direct coal-fired turbine. Two advanced, coal-fueled technologies have been selected for consideration as a coal-fired ATS: air-blown integrated gasification combined cycle (IGCC) with hot gas cleaning based on the KRW fluidized bed gasifier; and second generation PFBC (Newby et al., 1995).

The selection of a coal-fired reference system for the conversion of the natural gas-fired ATS to a coal-fired ATS was based on performance potential (power conversion and emissions), cost potential and state of development. Estimated thermal conversion performance, cost potential, and the status of development of several advanced, coal-fueled technologies that could achieve the desired turbine inlet conditions were considered. Comparisons were made to natural gas-fired turbine cycles, as well as to conventional coal-fired power plants - atmospheric pressure fluidized bed combustion and pulverized coal combustion boilers with flue gas desulfurization. The air-blown IGCC technologies with hot gas cleaning (Newby et al., 1993) and second generation PFBC appeared to have the greatest thermal performance and cost potential with combined cycle efficiencies in the range of 51 to 53%. Their respective status of development is categorized as early demonstration which is suitable for the ATS Program.

Conceptual Design of ATS Engine

The ATS engine will be the next model in the series of large heavy-duty gas turbines developed by Westinghouse. Westinghouse gas turbine genealogy began in 1943 when the first wholly American designed and manufactured jet engine went on test (Scalzo et al., 1994).

From the first industrial turbine introduced in 1949 (5000 hp) to the 501G (230 MW) introduced in 1994, improvements in turbine performance and mechanical efficiency improvements have been made continuously. Since 1949, Westinghouse has made the technological advances in the areas of combustion, aerodynamic design, cooling design, mechanical design, leakage control, and materials to advance gas turbine power generation for simple cycle and combined cycle applications.

When Westinghouse started the ATS Program in 1991, the fifth generation Westinghouse gas turbine (501F) was rated at 160 MW with a combined cycle thermal efficiency of 54%. As part of the Westinghouse ATS Program, the 501G engine was introduced that has a combined cycle efficiency of 58%.

Information on the 501G and a discussion of the component development programs under way to support the ATS engine (Task 8) are given in a companion paper presented at the 1995 ATS Annual Review Conference by Diakunchak and Bannister entitled, "Technical Review of Westinghouse's Advanced Turbine Systems Program."

Market Assessment

Westinghouse is in the process of forecasting the worldwide market potential for the ATS gas turbine technology. The time period of interest is the year 2000 through the year 2014. The objective is to develop a forecast of the market based on the proposed size and performance characteristics of the ATS gas turbine. Market feedback on unit size preferences and interest in the product will also be obtained, through telephone interviews with utilities and independent power producers.

For the years 2000 through 2014, a worldwide market for natural gas-fired power generation of 473 GW is predicted. Coal power generation additions are estimated at 530 GW. The majority of the power generation additions will be in the Asia/Pacific area.

Within this study markets that are inaccessible to the ATS concept will be estimated. (For example, countries and regions too small to absorb the ATS output or technology, markets for small gas turbines, and non-gas turbine gas-fired technologies, etc.) For this analysis we are looking at both the potential for natural gas-fired combined cycles with a plant efficiency greater than 60% and also the large simple cycle market whose efficiency is greater than 40% due to the incorporation of the

ATS technology. For the coal additions we are estimating the world-wide IGCC market.

Conclusions

This paper presented an overview of the Westinghouse ATS Program. Our proposed approach is to build on Westinghouse's successful 501 series of gas turbines. Our 501F engine offers a combined cycle efficiency of 54% and our 501G increased this efficiency to 58%. The proposed single-shaft 400 MW class ATS combined cycle will have a plant cycle efficiency greater than 60%.

Westinghouse's strategy to exceed the ATS Program goals is to build upon the next evolution of technological advances in the areas of combustion, aerodynamics, cooling, leakage control, materials and mechanical design. Westinghouse will base its future gas turbine product line, both 50-Hz and 60-Hz, on ATS technology.

The 501G, just introduced by Westinghouse, shows early influences of ATS. Some key components to support the ATS Program have already been evaluated and incorporated into advanced design processes.

Acknowledgment

This program is administered through the Morgantown Energy Technology Center under the guidance of METC's Program Manager, Dr. Richard A. Johnson. The period of performance is August 1993 through July 1996.

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Session 2B

ATS Program Technical Reviews

2.5 Allison Engine ATS Program Technical Review

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Introduction

Gas turbines in industrial and utility applications can help meet future national and worldwide power generation requirements. Turbine systems burning natural gas offer environmentally sound and economical power generation and cogeneration. Since U.S. demand alone will require up to 15 gigawatts per year of new and replacement capacity after the year 2000, the availability of Advanced Turbine Systems (ATS) to fill a share of this need will save significant amounts of fuel and benefit the environment. Implementation of the ATS Program will also keep U.S. manufacturers on the cutting edge of turbine technology for power generation applications and enhance the nation's economic competitiveness (Ref 1).

Allison's ATS addresses the program goals in the following manner:

- **Efficiency** — The turbine selected for the ATS uses Allison's latest single crystal alloys incorporating the most efficient component cooling technology Allison has developed. These features allow the turbine to operate at a rotor inlet temperature (RIT) of 1427°C (2600°F). The compression system for this engine has an overall pressure ratio of more than 20:1 and is based on technology previously demonstrated at Allison. The engine that uses these components will demonstrate a thermal efficiency that is 18% better than the best in class today.
- **Environment** — The combustion system selected for this engine incorporates a catalytically stabilized, lean premix system with ceramic components requiring no significant wall cooling. This system will achieve acceptance in severe nonattainment areas, producing less than 8 ppm for oxides of nitrogen (NOx), with acceptable carbon monoxide (CO) and unburned hydrocarbon (UHC).
- **Fuel Flexibility** — Allison has production engines in commercial service that are operating on biomass fuels. Previous DOE-funded programs have allowed Allison to develop and demonstrate coal-fueled gas turbine technology. The ATS program will use this experience to create a design that will be adaptable for the use of these fuels in the future.
- **Cost of Power** — The busbar cost of energy for the Allison ATS ranges from 23.6 to 27.6% lower than the current state of the art for systems meeting ATS environmental requirements. The requirement of the program is a 10% reduction in busbar cost. This improvement is the result of the high efficiency and the low emissions inherent in Allison's system design.
- **Reliability, Availability, and Maintainability** — The Allison ATS will be designed to have high reliability and low maintenance costs. Critical components will be designed using Allison's latest life analysis methods. Component and materials tests will

Research sponsored by the U.S. Department of Energy's Morgantown Energy Technology Center, under contract DE-AC21-93MC29257 with Allison Engine Company, P.O. Box 420, Indianapolis, IN 46206-0420 — fax No. 317-230-3691.

be conducted to verify these analyses. The engines and skids will be modular by design to allow field maintenance and service in the minimum time possible.

Objectives

Allison was awarded an ATS Phase 2 program in August 1993 with an 18-month period of performance. The specific primary objectives for this program were:

- select the design thermodynamic cycle for the ATS
- complete the preliminary design of the engine components
- complete preliminary design of the engine skid and all ancillary components
- test the prototype high pressure turbine section to 2600°F and analyze the resultant data
- validate and refine the fabrication of turbine blades using the existing Castcool®* process
- accomplish sufficient testing of combustor components to determine the best approach to achieving the emissions requirements
- perform laboratory tests on a turbine vane design utilizing two-phase cooling to reduce airflow requirements
- select coating systems for turbine blades and vanes for oxidation/corrosion protection

Results

Previous reports and papers (Ref 2, 3, and 4) have presented results of Phase 2 program effort in the following areas:

- selected ATS configuration
- tested prototype to 2600°F
- completed testing of low NOx combustor components
- provided ATS long-term planning document to DOE
- completed all program reporting requirements

This paper summarizes the accomplishments finalized during the past year, in particular:

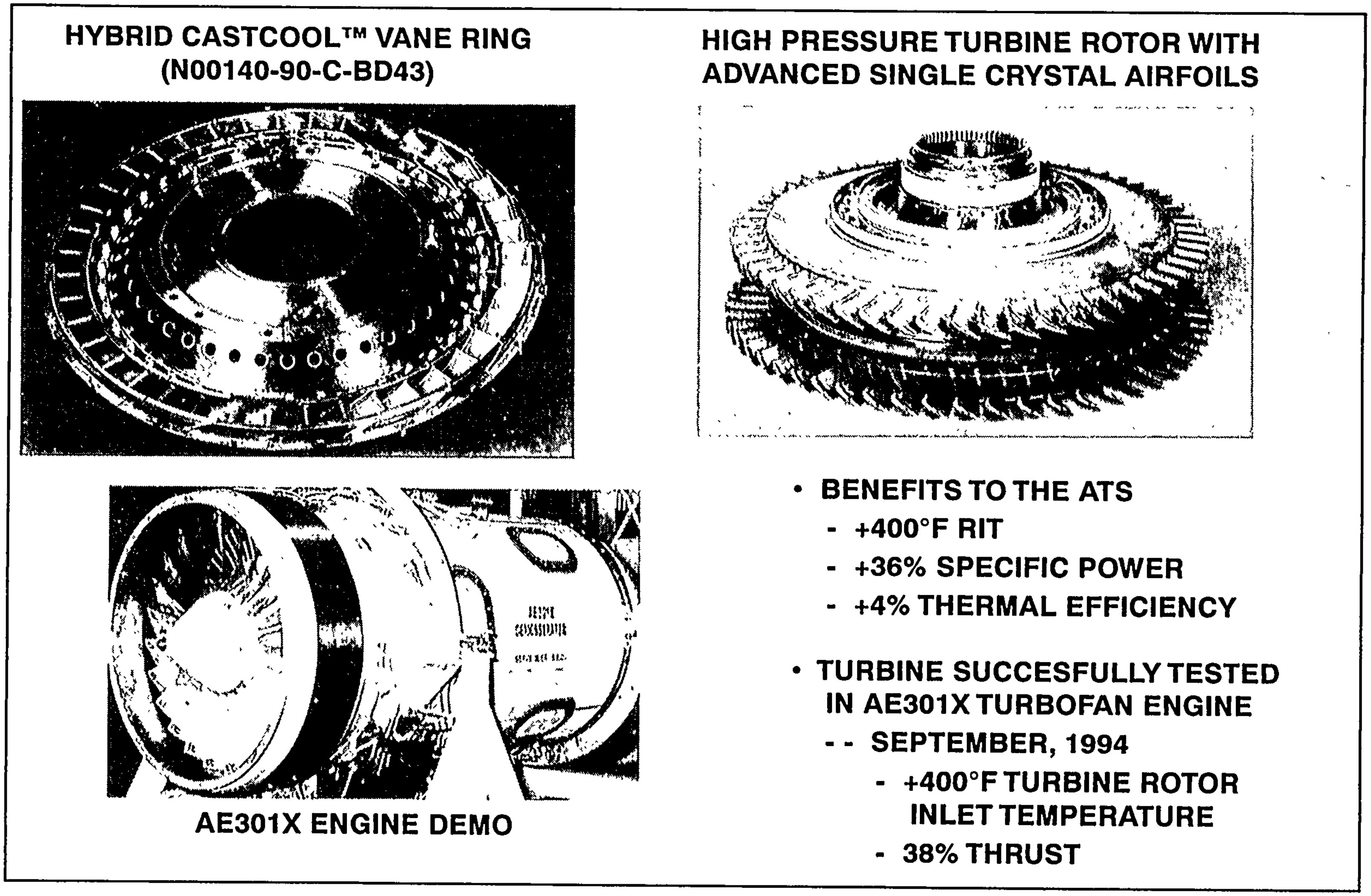
- analyzed test data on 2600°F prototype turbine
- completed development of casting process for Castcool high pressure turbine blades
- finalized configuration of low NOx combustor
- completed preliminary design of engine
- completed preliminary design of skid for demonstrator phase
- completed 5000-hr oxidation test and long-term corrosion test
- provided market study
- rig test of two-phase cooled turbine vane
- defined a direct coal-fired "ruggedized" configuration
- completed all reporting requirements

Test of 2600°F High Pressure Turbine Component

Figure 1 shows the major ATS prototype high pressure turbine components tested in late 1994. This turbine was previously designed under combined Allison/U.S. Navy sponsorship. Allison's goal of achieving a design incorporating Castcool hardware and capable of operating at 1427°C (2600°F) was achieved. This test also proved proper turbine performance, both from a cooling effectiveness and thermodynamic point of view. The tested full-scale prototype included the Castcool turbine vane in its first test in an engine at full operating conditions.

The Castcool process is a method by which extremely complicated cooling configurations can be cast in single crystal components in a one-step process. Minimal machining requirements of these components result in a very cost effective part.

* Castcool is a registered trademark of Allison Engine Company.



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VS95-0827

Figure 1. Allison Successfully Tested the Prototype ATS Turbine to 2600°F

One primary goal of this test was to prove performance of the Castcool vanes. Figures 2 and 3 show that the predicted vane leading edge metal temperature agrees very well with measured values and the coolant pressure ratio across the vane leading edge (the critical section of the vane) agrees with design calculations. These test results confirm all aspects of the Castcool design process from the heat transfer calculation through the casting process to the prediction of in-engine operating conditions. This provided the basis to proceed to the next step in incorporating Castcool into this turbine — manufacture of Castcool high pressure turbine rotor blades.

Castcool Turbine Rotor Blade Process Development

Castcool blade process development efforts performed during this program focused on pattern assembly and shelling process adjustments. A total of 7 molds were cast during this effort, resulting in a total of 56 blades. A photograph of the resulting blades from molds designated M/N 014 to 017 is shown in Figure 4, both in as-cast and finished form. The results of this effort increased yield by 60%. This effort resulted in a process with a production rate and yield acceptable for making initial engine sets of blades to rigorous quality standards.

Finalize Configuration of Low NOx Combustion System

The low NOx combustion system presents a significant challenge in terms of NOx and CO requirements, and in terms of achieving these requirements at very high firing temperatures. The following technologies were evaluated under this program:

- lean premix modules
  - mixing efficiency
  - velocity field
  - combustion characteristics
- catalytic element
  - bench reactor combustion efficiency
  - operability window definition
- combustor-to-turbine transition
  - aerodynamic integration

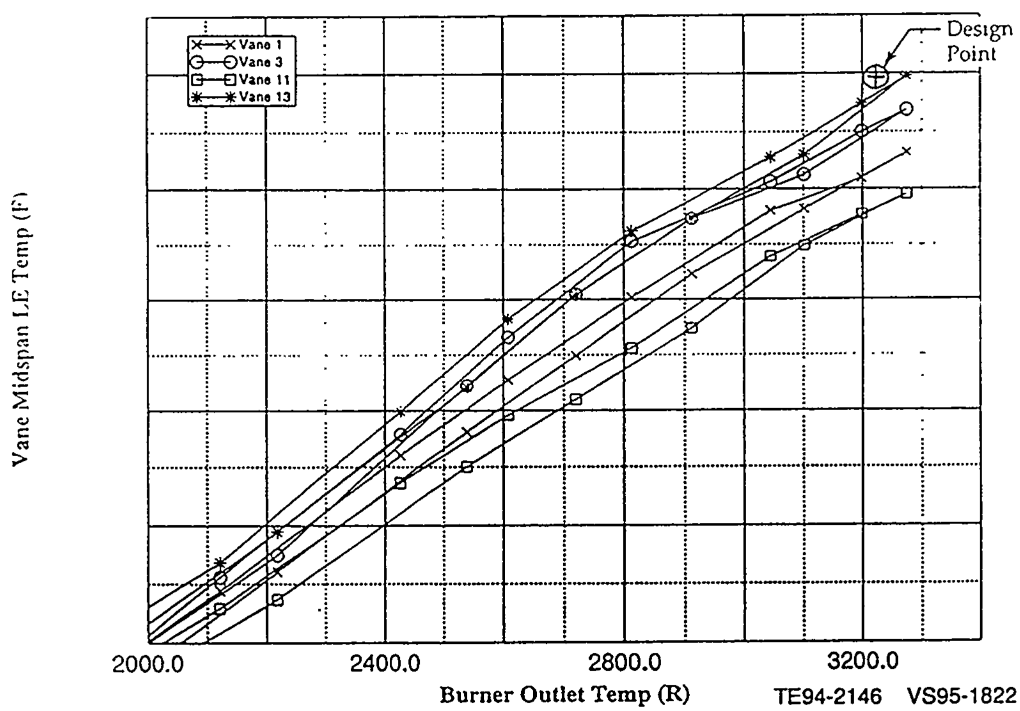


Figure 2. Measured Castcool Vane Leading Edge Midspan Temperature Data Within Predicted Levels

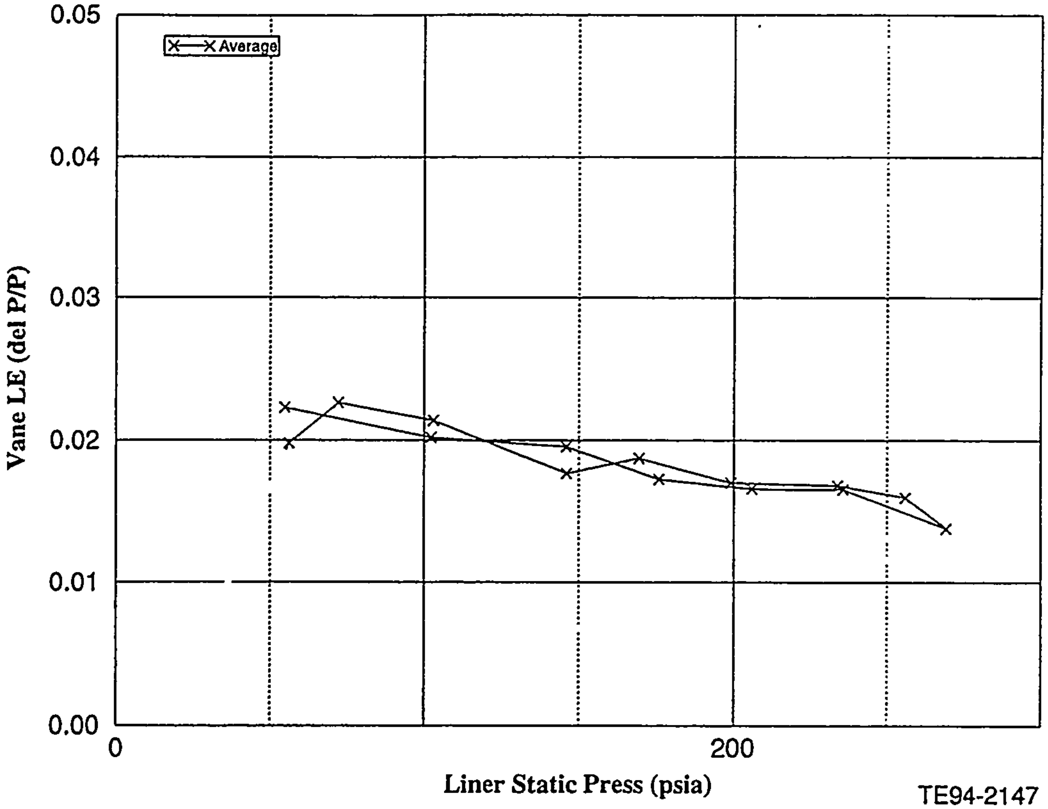


Figure 3. Measured Castcool Vane Leading Edge Supply Pressure Data Show Adequate Margin

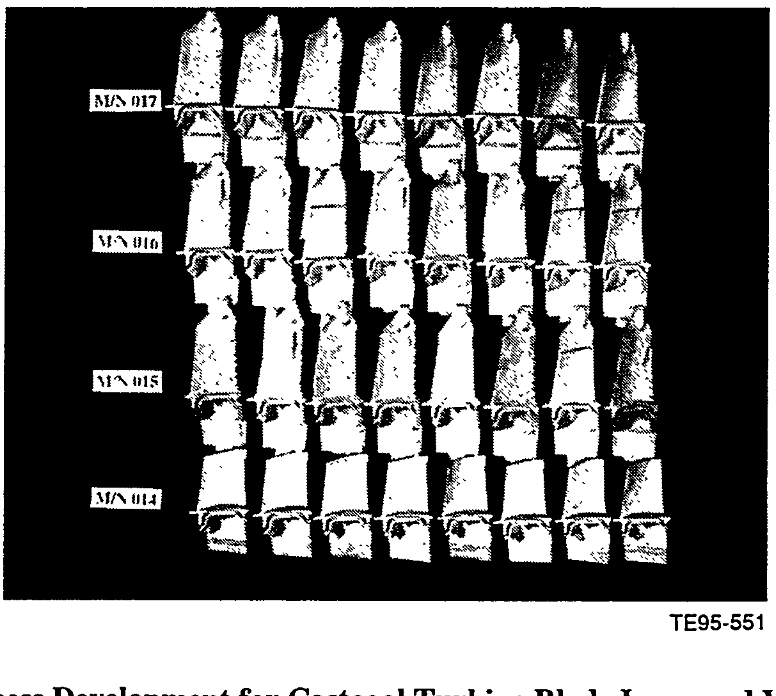


Figure 4. Process Development for Castcool Turbine Blade Increased Yield by 60%

Figure 5 shows that a lean premix system can achieve an 8 ppm NOx goal within the required CO goal at the ATS level of firing temperature. The module testing indicated, however, that sufficient margin to guarantee 8 ppm in production was not available. A catalytic reactor was selected as the best approach to achieving sufficient production margin. Figure 6 shows the test results of a candidate catalyst system at Catalytica, Inc. This system provides sufficient NOx production margin and has the potential to provide sufficient life at low enough cost to be used competitively in production engines.

Allison has selected a silo combustor configuration for ATS that requires a diffuser to transition to the silo and a hot transition duct to accomplish the 90-degree turn into the turbine annulus. Minimal cooling of this hot transition duct is required to achieve very low NOx levels. Computational fluid dynamics analyses of this system showed that aerodynamic design of these transition sections are also critical to proper distribution of any hot spots exiting the combustor into the turbine section.

Preliminary Design of the Gas-Fired ATS Engine Configuration

The key elements in the design Allison selected for ATS are:

- high pressure ratio/simple cycle unit at 2600°F rotor inlet temperature
- metallic Castcool first turbine vane and rotor
- reduced internal leakage with advanced brush and film-riding face seal
- silo configured lean premix system with catalytic section
- single crystal and advanced directionally solidified alloy for turbine
- ceramic matrix material for combustor liner and transition duct

Allison concluded this configuration not only met the program technical goals but provided a system which:

- could be demonstrated for 8000 hr in the year 1999-2000

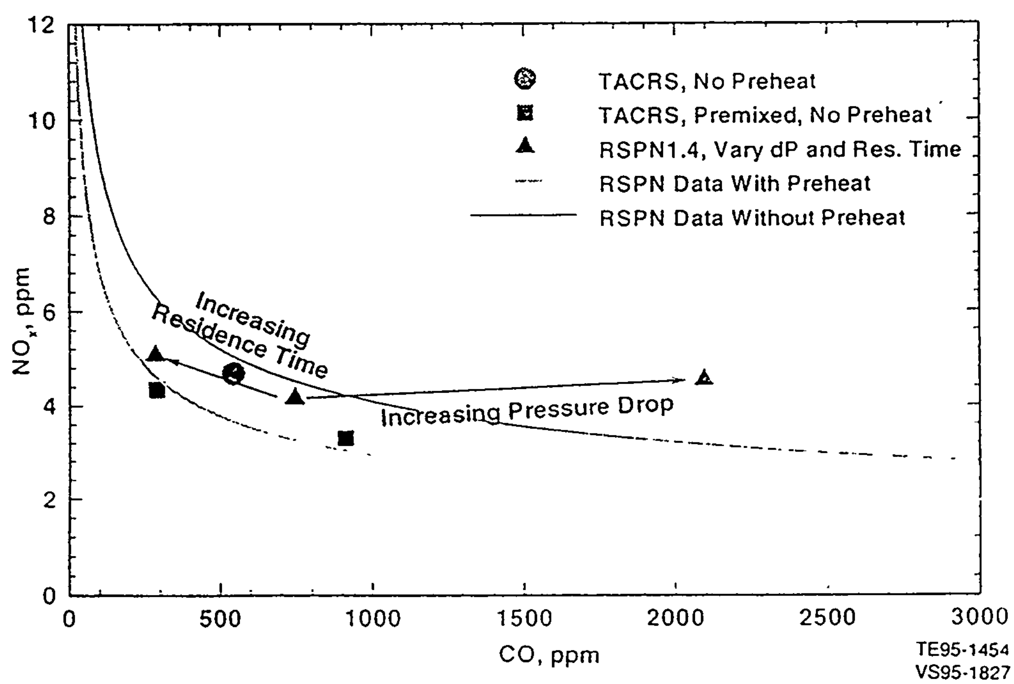
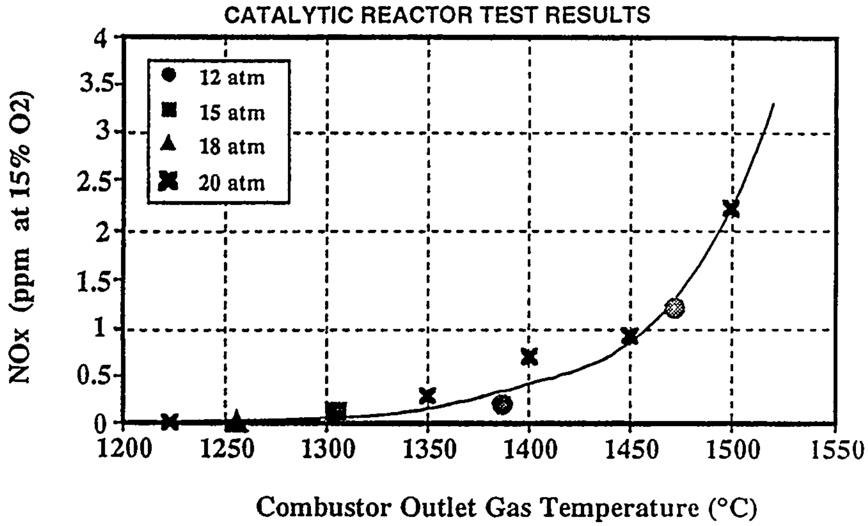


Figure 5. Atmospheric Bench Test of Lean Premix Modules



- NOx FORMATION INDEPENDENT OF PRESSURE
- NOx~2ppm FOR ATS APPLICATION GIVEN TEST DATA AT 1500°C (2730°F) BOT

TE95-1455
VS95-1828

Figure 6. Catalytic Reactor Test Results

- would result in no new requirements for the end user to operate the system effectively
- would provide a family of engines to increase market penetration

The ATS engine design is sufficiently defined to proceed into full-scale development.

Preliminary Design of Engine Skid

The engine is only one key to a successful final product. The customer buys a system and expects the system to provide value. Allison works very closely with high quality and low cost suppliers to optimize engine skid configuration and components for the customer. Figure 7 shows a side view of the skid design for the ATS. This preliminary design not only considers component layout but also design improvements, which increase value to the customer. The ATS skid is sufficiently defined to proceed into full-scale development.

Turbine Blade/Vane Oxidation and Corrosion Coating Selection

One advantage of the use of high strength materials such as single crystal and improved directionally solidified alloys is that they can be operated at higher metal temperatures than current practice with no decrease in life. This operation at higher metal temperatures requires reassessment of oxidation/corrosion coatings. As part of this program Allison performed a 1000-hr accelerated corrosion test and a 5000-hr dynamic oxidation test of various turbine blade/vane materials and coating combinations. Figure 8 shows the results of this test. We have selected the PtAl coating for single crystal components and the standard aluminide coating for the CM-186 improved vane directionally solidified (DS) material.

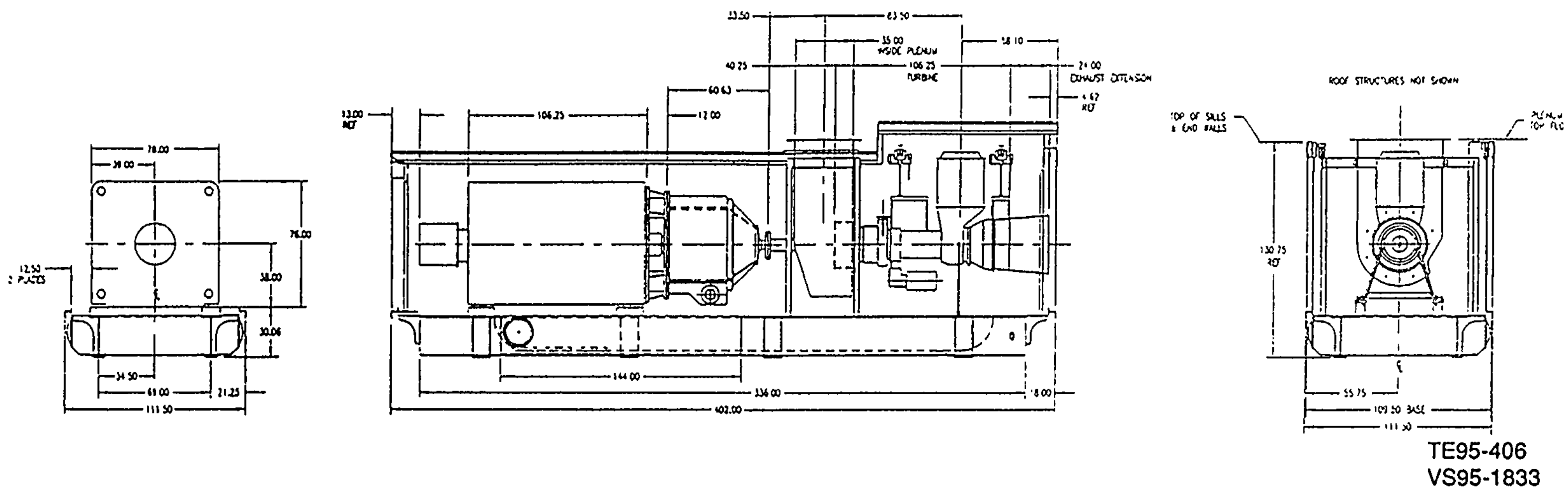


Figure 7. Preliminary Engine Skid Design

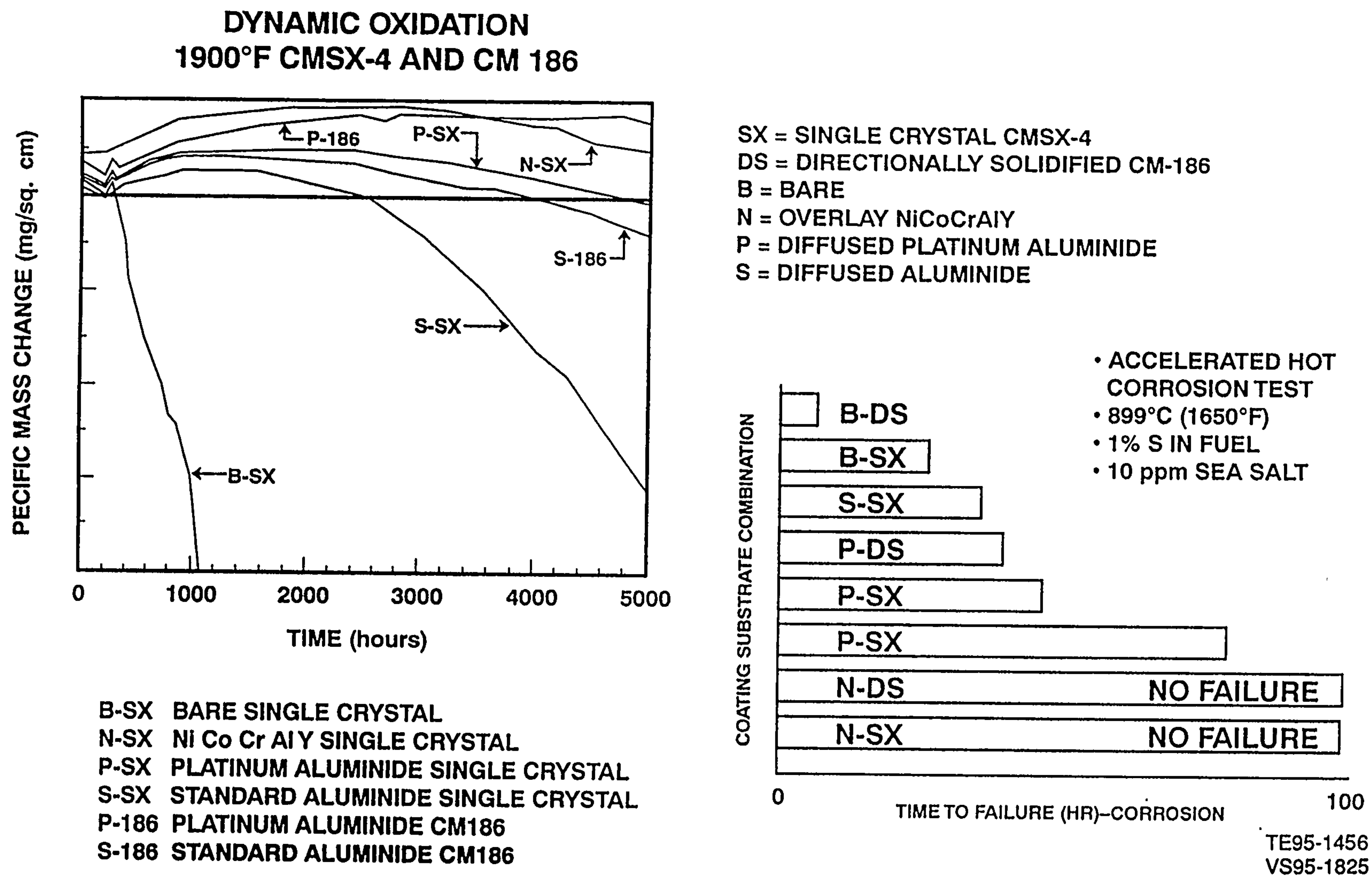


Figure 8. ATS Oxidation/Corrosion Test Results

Laboratory Test Of Two-Phase Cooled Turbine Vane

The phase change (evaporation) of certain liquids, including water, is a very strong endothermic process. Allison had developed a concept for use of this process to cool turbine vanes. ATS Phase 2 allowed Allison to design, fabricate, and laboratory test a 3X scale version of this vane cooling system in a cascade. Figure 9 shows detail of this concept as applied to an airfoil. Figure 10 shows this concept can achieve the same cooling effectiveness as even the most advanced air-cooled vanes with 1/3 to 1/4 the cooling air usage. Detail temperature and pressure data are available on this concept both chord and spanwise.

Definition of a "Ruggedized" Version of ATS Turbine for a Coal-Fired Configuration

The following defines the objectives, assumptions made and results of this study (Ref 5).

- objective
  - define ATS with coal/biomass fuel capability
- assumptions
  - cogeneration plant with rich-quench-lean combustor
  - cooling of metallic high pressure turbine gas path components to 1000°F for deposition/corrosion protection
  - two-phase cooling system on blades and vanes
- results
  - 22% efficiency loss for a coal-fired ATS plant
    - 9% associated with coal combustion
    - 13% associated with high pressure turbine cooling
  - hot section endwall cooling penalty may be conservative

The conclusion of this study is that deposition/corrosion protection is a primary driver in coal-fired systems. As indicated by past tests of alternate fuels at high gas tempertures, the very large airflows of gas turbine engines combined with the very good but imperfect cleanup systems likely to be available in the near future results in the requirement to cool metal surfaces

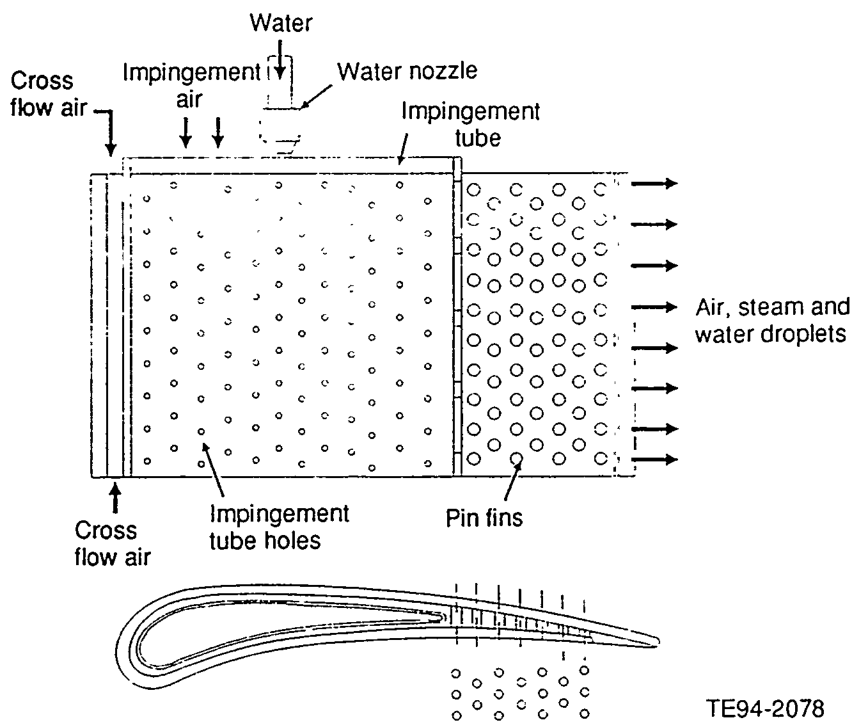
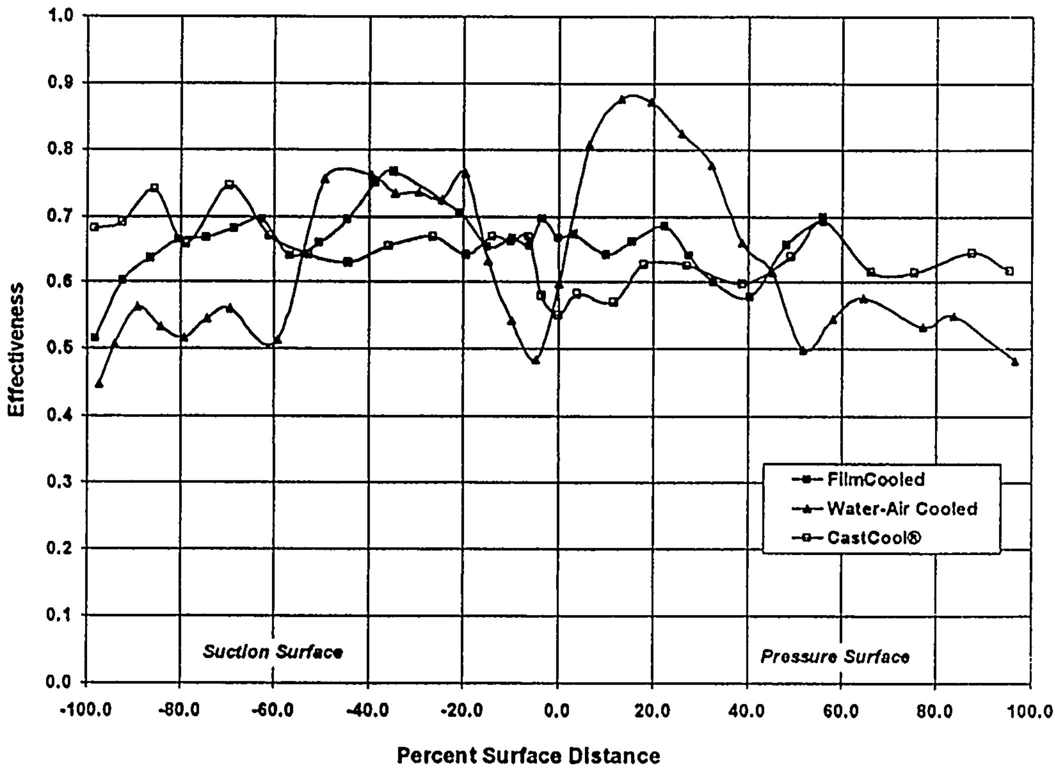


Figure 9. Concept of Two-Phase Cooling as Applied to an Airfoil



Water-Air Cooled	
Air:	2%
Water:	0.4%
Avg Eff:	0.6323

CastCool®	
Air:	5.83%
Avg Eff:	0.6487

Film Cooled	
Air:	7.30%
Avg Eff:	0.6654

TE95-1457
VS95-1830

Figure 10. Comparison of Two-Phase Cooling Effectiveness with Air-Cooled Airfoils

far below levels currently used in gas or liquid fueled machines.

Benefits

Development of the selected ATS system provides benefits to Allison, the Allison customer base, and the general public.

Allison can move several important turbine engine technologies from prototype phase into full-scale development and into the product base. In many cases these technologies represent conversion of defense developments to commercial use. This results in more competitive technology being offered to customers and a resulting increase in sales.

Our customer base benefits from a more efficient system operating at lower pollution levels. Customer IRR is improved dramatically.

The public benefits from cheaper products produced by more efficient manufacturers at reduced levels of pollution

Acknowledgments

The performance period for this contract (Modification 8) is 3 August 1993 through 31 March 1998. I wish to thank the Contracting Officer Representatives who have ably supported and guided this effort: Diane Hooie, Abbie Layne, and Leland Paulson (current).

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2. "Proceedings of the Ninth Annual Coal-Fueled Heat Engines," October 1992, DOE/METC-93/6129.
3. "Proceedings of the Joint Contractors' Meeting," August 1993, DOE/METC-93/6132.
4. "Proceedings of the ATS Annual Program Review Meeting," November 9-11, 1994, DOE/OR-2025.
5. "Rugged Turbines for Alternate Fuels," R. Wenglarz, N. Nirmalan, and T. Daehler, ASME paper 95-GT-73.

2.6 Advanced Turbine Systems Program Industrial System Concept Development

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Objective

Phase II

The objective of Phase II of the Advanced Turbine Systems Program is to develop conceptual designs of gas fired advanced turbine systems that can be adapted for operation on coal and biomass fuels. The technical, economic, and environmental performance operating on natural gas and in a coal fueled mode is to be assessed. Detailed designs and test work relating to critical components are to be completed and a market study is to be conducted. (Reference 1)

Background Information

Throughout its 35 year history as a supplier of industrial gas turbines, Solar has maintained a careful surveillance of the marketplace into which the company's product is sold. This effort has paid off in the growth of Solar into the world's leading supplier of mid-sized industrial gas turbine systems.

Based on this ongoing evaluation of the marketplace, Solar established short- and long-term product development goals which coincide exactly with ATS goals as set by the DOE in four areas:

- Reduced exhaust emissions.
- Increased Reliability, Availability, Maintainability, Durability (RAMD).
- Reduced cost of power.
- Increased thermal efficiency.

Entering into Phase II of the ATS Program, Solar has quantified goals in these four areas as shown in Table 1.

Table 1. Advanced Turbine System Goals

Parameter	Solar's ATS
Thermal Efficiency	50%
Exhaust Emissions NO_x	8 ppm
Exhaust Emissions CO and UHC	15 ppm
Cost of Power (COP)	10% Reduction from Today
Reliability, Availability, Maintainability, and Durability (RAMD)	Equal to or Better than Today

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Research sponsored by the U.S. Department of Energy's Morgantown Energy Technology Center, under Contract DE-AC21-93MC30246 with Solar Turbines Incorporated, P.O. Box 85376, San Diego, California 92186-5376; telefax: 619-544-2682.

Project Description and Results

Reference 2 identified an intercooled and recuperated (ICR) gas turbine as the power plant best suited for development to meet ATS objectives. The technologies that will need to be incorporated into an ICR to meet these objectives are within the capability of development by a manufacturer of **industrial** gas turbines, i.e., Solar. More importantly, these technologies are likely to find ready acceptance in the **industrial** gas turbine marketplace, i.e., characterized by moderate risk and reasonable cost. Many of these technologies will also find application in Solar's current product line and as retrofit improvements in Solar's 9200-unit installed fleet.

Recuperation of the classic Brayton cycle gas turbine is a well-known efficiency improvement that has been applied at levels of success primarily established by the cost and durability of the required heat exchange device. At any given level of peak temperature a recuperated Brayton cycle will have an optimum overall pressure ratio. At pressure ratios above this optimum, recuperation capability is reduced by the narrowing gap between exhaust temperature and compressor discharge temperature.

The addition of one or more stages of intercooling into the compression process of the Brayton cycle will significantly reduce the work input required by the compression process. The combination of intercooling and recuperation into an ICR cycle produces an increase in both specific power and thermal efficiency. The thermal efficiency improvement derives from an increased temperature differential between the exhaust gas stream and the compressor discharge air. This enables the recovery of a greater portion of the thermal energy in the exhaust gas. In a modern ICR, thermal efficiency continues to increase with pressure ratio and with temperature.

Task 3 of Solar's ATS Phase II program is entitled, "System Selection." (Tasks 1 and 2 fulfilled certain non-technical contractual requirements.) Task 3 optimized the design of an ICR gas turbine cycle as shown in Figure 1 at a pressure ratio of 16:1 and a firing temperature of 2500°F (TRIT). Based on state of the art component performance this cycle will operate at the 50 percent thermal efficiency stated as the ATS goal in Table 1. However, achievement of this level of thermal efficiency also requires the use of ceramic materials in the high pressure turbine stages. The application of cooling technology which is achievable within the ATS planned timeframe results in a reduction of one to two points of thermal efficiency below the 50 percent level.

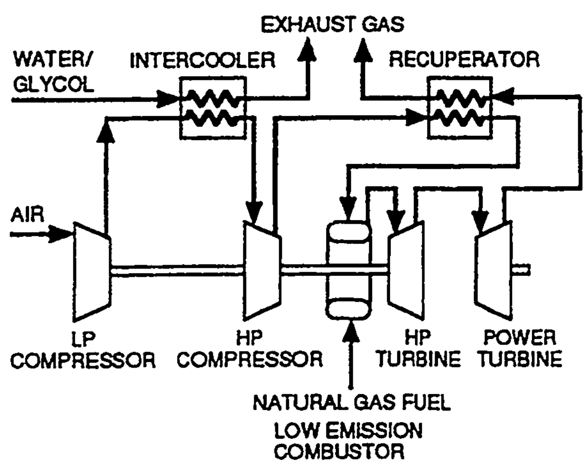

Figure 1. ICR Gas Turbine With Free Power Turbine

This ICR design included the following components:

- Low-Pressure Compressor -- Three to five stage axial compressor with variable guide vanes.

- Intercooler -- Two stages (air to liquid + liquid to air) at 85 percent thermal effectiveness.

- High-Pressure Compressor -- Four to six stage axial compressor with variable guide vanes.

- Recuperator -- Solar's proprietary primary surface recuperator (PSR) at 90 percent thermal effectiveness.

- Combustor -- Can-annular, low emission catalytic system.

- Turbines -- One or two stage (depending on whether a one- or two-spool design is selected) axial gas producer turbine. Two stage free power turbine with a variable area nozzle (VAN) in the first stage.

This arrangement of an ICR gas turbine was carried forward into Task 6 - System Definition and Analysis - for further development. Early in the performance of Task 6 it became apparent that the ICR gas turbine was not the ideal candidate for development and field test in Phases III and IV of the DOE's ATS program. The following factors led to this conclusion:

- The DOE's Solicitation for Cooperative Agreement Proposal (SCAP), Reference 3, specified a 60 month program culminating in commercialization of an "industrial" ATS in the year 2000. Preliminary studies of a development program indicated that an ICR gas turbine could not be developed to the point of commercialization in that timeframe. It would have been better suited to the DOE's original schedule of commercialization in the year 2002.

- The ICR's thermal efficiency of 50 percent far exceeds the ATS program goal of a 15 percent improvement over current industrial gas turbines. Fifty percent is actually 43 percent greater than the current base of 35 percent.

- The Market Study of Task 5 provided the following input that indicated against the ICR as the best choice for early commercialization of and industrial ATS:

  - The industrial gas turbine marketplace can be characterized as "risk-averse." This term describes a reluctance on the part of industrial gas turbine users to accept major technological changes that are not validated by substantial operational experience in their application. Features of the ICR that fall in this category include the very high (for an industrial gas turbine) firing temperature of 2500°F, the presence of a liquid-cooled intercooling system with its associated liquid handling equipment, and the complexity of the engine control system. Such a reluctance to accept unproven technologies would limit the ATS to relatively few specialized applications. Thus the benefits of an ATS to the nation's economy, energy supply and environment would be both delayed and diminished.

  - The presence of "Availability" (which includes reliability) at the top of the list of desired characteristics of gas turbine systems argues against the complexity of the ICR as well as against the requirement for fuel gas compression up to the pressure required for the ICR cycle.

- The Task 5 Market Study indicated a strong future demand for an ATS of approximately 5 MWe capacity. Two characteristics of the ICR argue against its use in this small size:
  - The very high specific power of the ICR will result in extremely small size of airfoils in the high pressure regions of both the compressor and the turbine. This raises their cost in both components and, in the turbine, makes a robust cooling design quite difficult.
  - The relatively higher cost of the ICR system will render it less competitive to other technologies in this small size. Its specific cost (dollars per kilowatt) will be more competitive in larger sizes (> 20 megawatts).

As a consequence of these market- and program-driven considerations, Solar's efforts in Task 6 were redirected toward the definition of an optimized recuperated gas turbine. An optimized recuperated gas turbine is defined as one in which all components and operating parameters of the core gas turbine are optimized in support of the recuperated cycle with no requirement for operation as a simple cycle gas turbine. Most recuperated gas turbines in operation today are based on the addition of a recuperator to an existing simple cycle machine and, as such, fall short of the performance potential of an optimized recuperated cycle.

Recuperated Gas Turbine Arrangement and Characteristics

The recuperated gas turbine (Figure 2) is arranged in a manner similar to the ICR gas turbine of Figure 1. Note that there is now no intercooler shown as part of the compressor. Without the intercooler to maximize recuperation potential by reducing compressor exit temperature, an effective level of recuperation must be sought through careful selection of compressor pressure ratio.

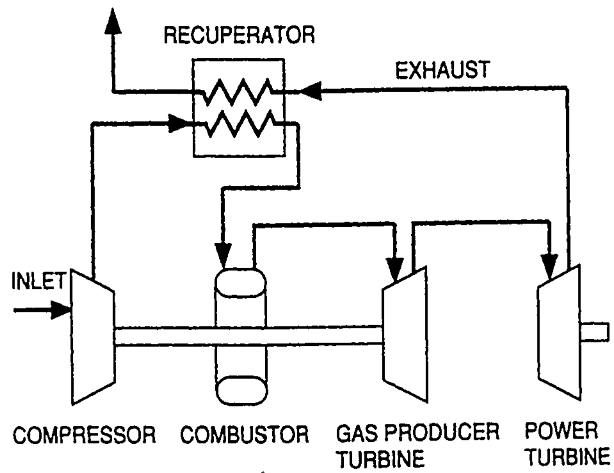

Figure 2. Recuperated Gas Turbine

With the firing temperature (TRIT) of a recuperated gas turbine fixed by the material and cooling system selected for the stage one turbine airfoils, maximum thermal efficiency will be found to occur at an optimum pressure ratio. Below this optimum, pressure ratio itself rules and is too low to provide useful efficiency from the core engine itself. Above this optimum, recuperation will be reduced by a decreasing differential between compressor discharge temperature and the temperature of the exhaust gas leaving the expansion turbine(s).

Beyond the firing temperature limit imposed by the turbine material and cooling technology, a secondary limit is presented by the exhaust temperature that the recuperator material will withstand.

The optimum efficiency for a recuperative cycle, based upon technology consistent with the ATS program timeframe occurs between pressure ratios (PR) of 7.5:1 to 8.9:1 and turbine inlet temperatures (TIT) of 1121 to 1238°C (2050 to 2260°F). Solar selected the higher PR because of its increased potential for higher thermal efficiency through the application of future high temperature turbine blade and recuperator materials growth. In particular, sensitivity studies indicated benefits of higher PR cycles are enhanced to a greater degree by cooling flow reductions and increases in TIT, both of which will be achieved during the program through improved materials and hot section cooling technology. Component material and cooling strategy selection plays a key role in the selection of the design point, as shown in Table 2. The highest overall thermal efficiency is *not* achieved at the highest TIT in the range, but by the configuration that most efficiently uses the range of material, cooling, cycle, and mechanical design options available.

Further "fine-tuning" of this cycle will take place during the final design of Solar's ATS as detailed component performance parameters are established.

Compressor Description

The ATS compressor (Figure 3) will be scaled directly from several stages of the proprietary Solar Advanced Component Efficiency (ACE) compressor. The goal of the compressor portion of the Solar ACE program is to design and develop a state-of-the-art multistage axial-flow compressor which can be used in the next generation of simple-cycle and recuperated industrial gas turbines. The ACE compressor utilizes controlled diffusion airfoils in a 15-stage axial design with a pressure ratio of up to 20:1 and adiabatic efficiency of 87.6 percent. The compressor is being designed using all of the latest aeroengine design tools and technologies. Moreover, without the obvious envelope and weight constraints of aircraft engines, the ACE compressor will have design goals of lower cost and improved ruggedness. For those reasons it has light aerodynamic loading for high efficiency, low aspect ratio blading and long blade chords for ruggedness and low cost (fewer blades in each stage).

Recuperator Description

The ATS Primary Surface Recuperator (PSR) is a compact design that provides high effectiveness, moderate pressure drop, and long life (Table 3). The construction is rugged and the modular nature of the design gives it superior flexibility to handle thermal stresses. It is made of 0.08-0.12 mm (0.003-0.0045 in) thick sheets of Type 347 stainless steel (SS 347) folded into a corrugated pattern. This pattern maximizes the primary surface area that is in direct contact with exhaust gas on one side and compressor discharge air on the other. Pairs of these sheets are welded together around the perimeter to form air cells (Figures 4 and 5), the basic building block of the PSR. Each air cell is pressure checked before it is welded into the recuperator core assembly (Figure 6). There are no internal welds or joints within the air cell, and the lack of welds between cells renders the assembly free from the effects of thermal expansion and contraction that plague other recuperator designs.

The PSR has been extensively analyzed using a model which are described later in the

Table 2. Range of TIT, Cooling and Efficiency at Selected PR for Solar's ATS

Configuration	TIT °C (°F)	PR	Efficiency (ISO, LHV, No Losses)	Total Cooling	Limiting Component
All Metallic	1204 (2200)	8.92:1	43.1%	13.3% Wa*	347 SS Recuperator
Metallic/Ceramic	1185 (2166)	8.92:1	45%	9.7% Wa*	347 SS Recuperator

* Engine inlet airflow.

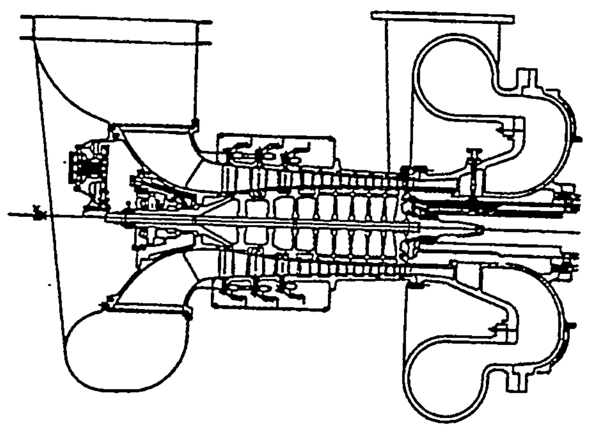

Figure 3. ATS Compressor

Subtask 8.1 topical report. The effectiveness of the ATS recuperator for the cycle conditions was calculated from the model to be 90%, with an associated pressure drop of 7.0 percent. To satisfy ATS requirements, the model predicted a recuperator core of 2667 cells, representing an overall length of 249 inches. Alternatively, two cores at 124.5 inches could accomplish the same goal.

The Solar PSR design is inherently resistant to low cycle fatigue (LCF) because it flexes to relieve stresses whereas the typical rigid designs, including plate-fin, tend to concentrate stresses at critical locations. High cycle fatigue (HCF) has not been a problem for the PSR due to its inherent damping characteristics. The stacking of cells in the PSR results in multiple friction interfaces for energy absorption. These characteristics also provide excellent exhaust sound suppression.

Solar has had extensive experience with various recuperator technologies, including shell-and-tube, brazed plate-fin, and PSRs. During the 1970s, Solar industrial gas turbines were delivered to customers with shell-and-tube and brazed plate-fin types of recuperators. A high percentage of these types of designs failed to meet users' expectations. The plate-fin is joined by brazed joints severely limiting repair options. In addition, the braze joints in the plate-fin usually suffer from dissimilar metal corrosion problems which are aggravated at high temperature. As a plate-fin recuperator increases in size, it becomes less capable of handling thermal transients.

PSRs present several major advantages over plate-fin and shell-and-tube type recuperators. They are smaller and lighter, have better performance, improved reliability and maintainability, and are scalable without sensitivity to thermal transients.

Table 3. ATS Recuperator Performance

Feature*	Recuperator Technology			
	Solar's PSR	Compact Plate Fin	Traditional Plate Fin	Shell and Tube
Relative Volume	1.0	2.8	7.6	11.8
Effectiveness, %	>90	87	79	84
Installation Flexibility	High	High	Moderate	Low
Thermal Mass	Low	Medium	Medium	High
Warmup/Cooldown Cycles	No	Yes	Yes	No
Required Maintenance	Low	Medium	Medium	High

* Based on 10 MW installations.

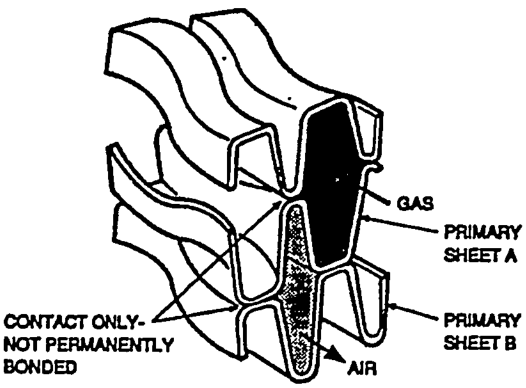

Figure 4. Primary Surface Sheets

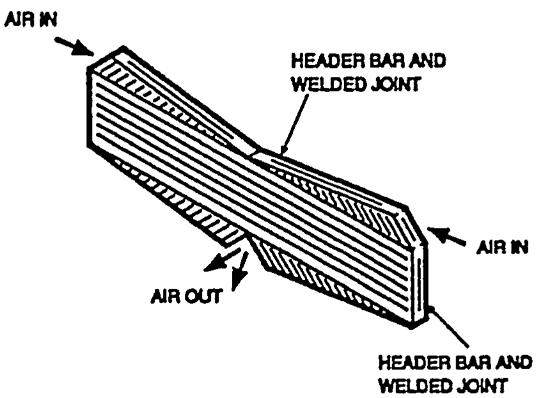

Figure 5. PSR Air Cell

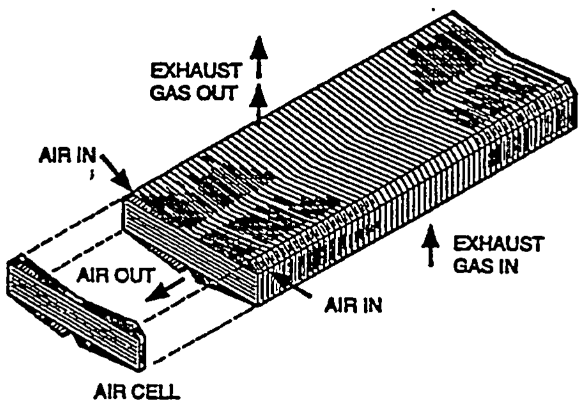

Figure 6. PSR Core Assemblies

Combustor Description

The selection of a combustion technology for ATS was influenced strongly by the goals of reducing NO_x emissions to 8 ppmv initially and 5 ppmv ultimately. Solar has selected catalytic combustion and ultra-lean premixed combustion (ULP) as the technologies with the highest probability of achieving these goals within a timeframe consistent with the program schedule.

Laboratory testing of catalytic reactors has demonstrated NO_x levels consistently below 5 ppm. Internally funded and ATS Phase II, Tasks 8.2 and 8.5 work has already demonstrated the viability of Solar's catalytic approach. However, significant challenges remain in applying catalytic combustion to an industrial gas turbine. To ensure timely commercialization of ATS, Solar will develop ULP combustion systems in parallel with the catalytic combustion system. Technology advancements in the areas of premixing, variable geometry controls, and advanced combustor cooling will allow ultra-lean premixed operation at NO_x levels down to 8 ppmv. Solar's combustor design will accommodate either combustion technology with a minimum of redesign.

As a backup to the catalytic combustor (Figure 7) development, a ULP system will be developed in parallel path in the event that catalytic system development time exceeds expectations. The selection of the combustion technology for the ATS demonstrator will be made approximately one year after the start of Phase III. In the event catalytic combustion is not deemed ready for the demonstrator, catalyst development can continue and the technology will be retrofitted into existing engine designs.

The ULP combustion system (Figure 8) will build upon Solar's lean premixed combustion technology (SoLoNOx™) that was recently introduced to the gas turbine market (Figure 9). Lower NO_x emissions are achieved by operating the combustor primary zone at a lower average temperature (leaner).

In addition, pre-mixing the fuel and air before combustion avoids large temperature excursions from the average temperature within the primary zone. These hot spots are traditionally identified as significant NO_x sources in gas turbine combustors.

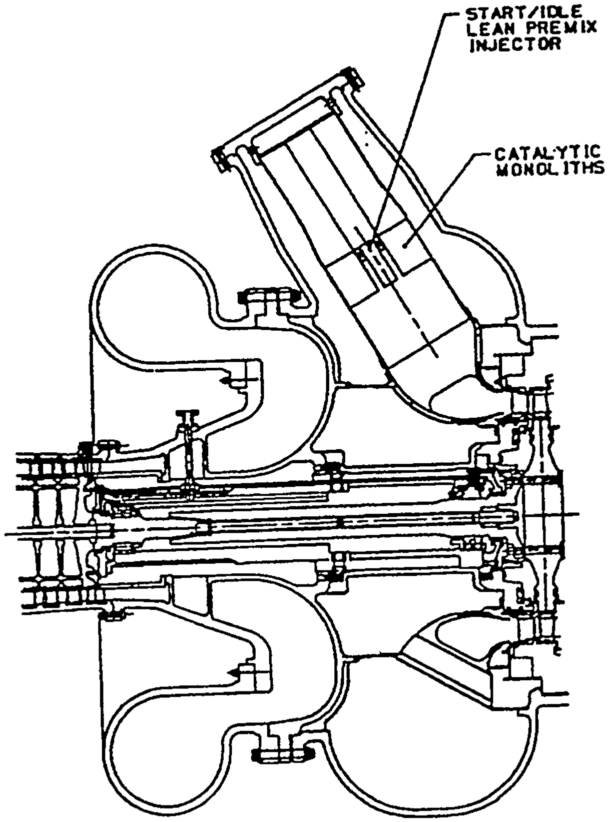

Figure 7. Engine Cross-Section Showing Can-Annular Catalytic Combustor

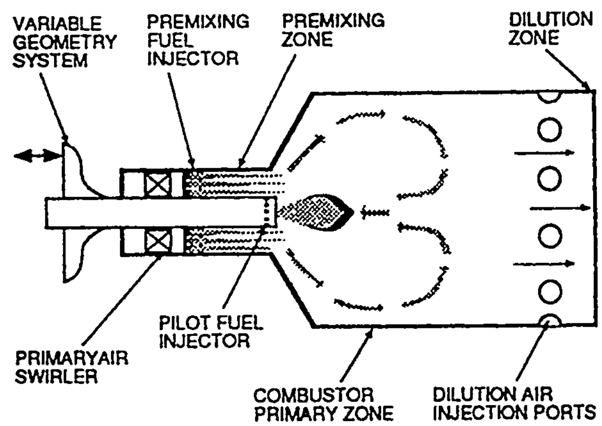

Figure 8. ATS Ultra Lean Premixed Combustor Approach

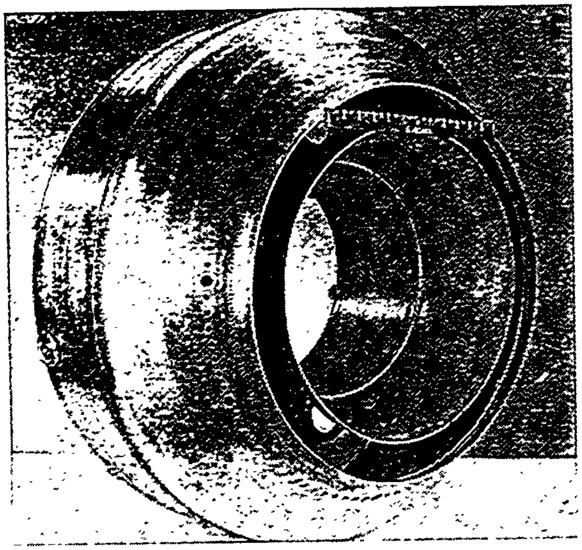 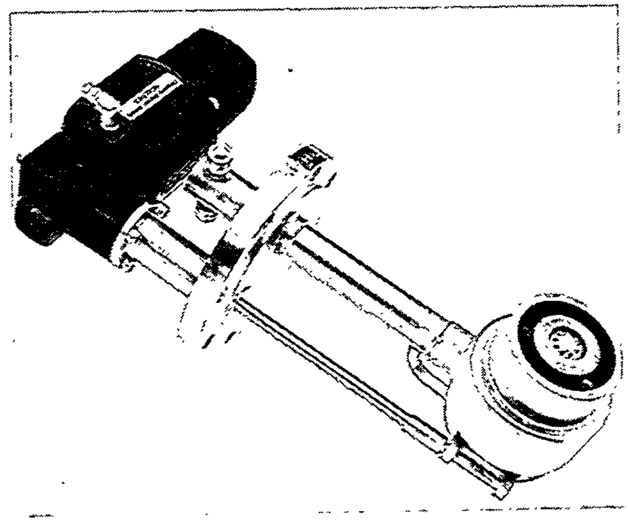

Figure 9. SoLoNOx Combustor Liner (left) and Fuel Injector (right)

The major elements of the ULP system are the combustor liner, the fuel injector, and the variable geometry system. The combustor liner is similar to a conventional combustor in terms of general geometry but is larger in volume to allow complete combustion at lower flame temperatures. The liner design employs conventional high temperature sheet metal construction; advanced cooling techniques beyond traditional film cooling are employed to maintain acceptable liner wall temperatures. As a result, the design combines convection/impingement cooling and effusion cooling. Selective use of ceramics will be considered to mitigate liner cooling requirements. Ceramics are also expected to help reduce CO emissions by preventing flame quenching in the liner boundary layer. Tests in the DOE/Solar Ceramic Stationary Gas Turbine (CSGT) program will guide the application of ceramics in the ATS combustion system.

Turbine Description

The design of all turbine stages is optimized for aerodynamic performance while maintaining mechanical integrity over the required life. The performance of the turbine stages - one gas producer stage and three power turbine stages - is based on Solar's "ACE" aerodynamic technology program mentioned earlier.

Turbine Cooling and Material Selection

Any Brayton Cycle efficiency gain to be realized with increase in peak (firing) temperature is very dependent upon the energy expended in cooling the turbine materials to the temperature level required for commercially practicable life. Normally this energy expenditure takes the form of air flow bled from the compressor which then bypasses the combustion process and varying portions of the expansion process. This is true of all Brayton Cycle forms, simple or complex.

runs in three self-aligning tilting pad radial bearings with a tilting pad thrust bearing and the power turbine is a two bearing overhung design also with a tilting pad thrust bearing. Both thrust bearings are accessible for field replacement if necessary. A tapered joint system similar to the current Solar products connects the compressor aft hub to the GP shaft. The surface speed of the bearings will be slightly higher than current engine experience, but is not expected to present any design challenges.

Solar's ATS Phases III and IV Program Plan (Task 7)

Solar has been awarded a cooperative agreement for ATS Phases III and IV based on our response to the DOE's SCAP (Reference 3). As a part of this proposal, Solar has prepared a Research, Development, and Test Plan that builds upon ongoing ATS Phase II work, as well as related research activities, to ensure attainment of all program goals in a timely manner. Solar has identified parallel path approaches for items considered to have relatively high technical or schedule risk. In addition, Solar has designed its test activities in a manner that incrementally tests components and subsystems before incorporation and test in the full ATS system, further reducing overall risk.

This RD&T Plan includes the following:

- Rig testing to ascertain that the performance characteristics of components meet ATS requirements. These include compressor, turbine, recuperator, and combustor rig tests.
- Rig testing of cooling and sealing systems which will isolate the performance of these systems from the rest of the gas turbine in order to examine their performance and compare it with ATS design requirements.
- Advanced materials evaluation and testing.
- Engine testing to include evaluation of both mechanical integrity and aerodynamic and thermal performance.
- Performance testing of the integrated gas turbine system to include the control system, all support systems, and the driven equipment.
- Durability/reliability and performance evaluation of the integrated gas turbine system (package) under realistic field conditions at a host site for a minimum of 8000 hours.
- A risk management plan based on highly successful Solar disciplines that include:
    - A New Product Introduction (NPI) system based on principles of teaming and concurrent engineering that has resulted in reduced time-to-market for new products.
    - The use of Quality Function Deployment (QFD) techniques to ensure that new product characteristics are in full support of customer needs and expectations.
    - The use of PERG (Prediction and Evaluation of Reliability Growth), a corporate (Caterpillar) technique that provides for early identification of

problems and identifies the evaluation program required to validate problem solutions.

In recognition of the critical importance of successful commercial introduction of the ATS product and technologies, Solar has also designed a commercialization plan that encompasses all necessary aspects of manufacturing, marketing, and servicing the new product. Solar's commercialization plan also envisions the spin-off of appropriate technologies, providing an early return on joint development funding, expanding the overall market opportunities, and reducing marketplace risk associated with introducing new technologies.

This commercialization plan includes the following:

- A technology spinoff plan which recognizes that many of the advanced technologies developed for Solar's ATS can be applied to the existing product line. This spinoff plan examines these technologies and will alert Product Engineering to possibilities for their application in improving performance, reducing emissions, reducing cost, and otherwise improving Solar's non-ATS product line.

- A Market Readiness Plan intended to accelerate awareness of the need for ATS products, to continuously monitor emerging market requirements and to foster market pull during the market introduction phase. Specific activities will include customer surveys, customer roundtables, and participation in technical conferences and seminars. Tools will include educational literature trade shows and presentations.

- A Manufacturing Readiness Plan that will assure that Solar's ATS is producible at an economical cost and that adequate manufacturing processes and capacity will be in place to support the commercial introduction of the ATS.

- A Product Support Plan which will ensure that all customer services are in place at commercial introduction of the ATS. These will include trained field service technicians and commissioning teams, Solar-furnished operation and maintenance programs and training, and field service tooling as well as tooling for selected overhaul facilities.

Solar has established systems and organizational structures assuring an efficient program control. These systems are designed to take full advantage of concurrent engineering and cross-functional teaming in order to reduce the development to production schedule and to reduce overall program costs. The Work Breakdown Structure and Organizational Breakdown Structure are set up in a manner ensuring the ability to assign responsibility for the performance of the contract to individual cost account managers to the subtask level; and the implementation of earned value accounting will enable effective performance measurement and management of the work.

These systems and structures include:

- An ATS New Product Introduction (NPI) team with full-time representatives from Sales and Marketing, Engineering, Manufacturing, System Integration, Finance, Business

Development, and Customer Services. This team is responsible to two sponsors -- Solar's Corporate Products Committee and the U.S. Department of Energy.

- A detailed Work Breakdown Structure (WBS) and Schedule.

- A dedicated Contract Administrator.

- Procurement Administration incorporating Purchasing and Material Requirements disciplines accustomed to operating in a competitive commercial environment.

- Cost Tracking and Cost Accounting systems that operate in accordance with generally accepted accounting principles (GAAP) and meet all current DCAA requirements.

- Project monitoring according to an "Earned Value" system that measures performance against both budget and schedule.

- A quality assurance plan that includes control of equipment, control of materials, preservation of product development data, design reviews, and monitoring of teaming partners and subcontractors.

These systems and organizational structures are all ISO 9000 certified and have recently passed their re-certification requirements.

Market Study (Task 5)

In the performance of Task 5 of ATS Phase II, Solar called upon extensive internal knowledge of the gas turbine marketplace which has installed over 9000 Solar gas turbine packages to date. In addition, two outside agencies were subcontracted to provide Solar with an independent view of future opportunities for gas turbine power in general and ATS power in particular.

- The ATS can be used as an electrical power generation system to meet the requirements of electric utility customers. The market is generally defined by the types of electrical generators, such as investor-owned utilities, municipal utilities, rural electric cooperatives, and independent power producers.

- The ATS can be applied in both traditional (baseload and cycling) setting, and the most recent development, distributed dispersed generation applications. As electricity peak demand continues to grow at or above the nation's Gross Domestic Product (GDP) through the remainder of the decade and beyond, this trend will create major opportunities for the ATS due to its strategic application as well as its high efficiency, low capital cost, short installation lead time, and compliant environmental emissions.

- The largest existing market for the ATS includes Solar's traditional gas and oil pipeline and storage industries, including production and processing as well as transmission and storage companies. This industrial segment will be growing in response to increasing worldwide demands for energy and fuel. Hence, these oil and gas sectors, which depend extensively on pumping equipment and systems, represent clear opportunities for the ATS with a capacity between roughly 1,000 and

40,000 hp. With a high-efficiency level of around 43 percent, a low capital and maintenance cost, coupled with compliant emissions performance, the ATS is a very competitive option for the oil and natural gas industries.

- Deregulation is occurring much more slowly in the gas production segment. However, as a result of the pipeline deregulation, local gas utilities and large users increasingly deal directly with gas producers to obtain their supplies. Deregulation has also placed pressure on increased operating efficiency and cost reduction. Reducing maintenance and energy costs, and the use of remote operation will become important management and operation goals within the gas industry.

- The increasing difficulty of environmental compliance is a key issue facing the pipeline industry. Regulations regarding exhaust emissions (primarily NO_x) and noise are making environmental compliance a major hurdle, which has essentially become a go/no go issue in driver/compressor purchasing decisions. There is some sentiment within the industry that electric drives may be the only practical solution to some siting problems.

- The industrial sector accounts for more than 36 percent of total end-use energy consumption. Process heat accounts for the largest share of energy consumption in industry overall, and mechanical shaft drive represents another large use of energy in many industries. This sector represents a significant opportunity for the ATS.

- The ATS can be used for industrial manufacturing power generation to meet on-site plant requirements, including mechanical shaft power for compressors, and pumps in petrochemical and other process energy intensive applications, and in electric/thermal cogeneration to serve a portion of on-site electric and process steam demands in manufacturing plants depending extensively on low-cost, reliable electricity supply.

- In cogeneration applications, the recuperated ATS is best suited for industries with low thermal requirements because of its very high electrical efficiency. Because its combustion gases are relatively low in energy, the ATS is best suited to industries with a high ratio of electric energy needs to thermal energy needs (E/T ratio). Low cost duct firing greatly contributes to flexibility in meeting demands of such users with highly cyclic or seasonal process heat requirements.

A market segment that has recently emerged with a potential for the ATS-size power system, and which Solar has recently entered, is high-speed light craft propulsion. While the shipping industry overall has not grown substantially in recent years, the high-speed segment has demonstrated strong vitality and growth. Prospects for future growth remain strong as the increasing speed and ride quality of today's fast ferries make them very competitive with other forms of surface transportation and short-haul airlines. The growth of passenger vessels has been especially strong in developing countries in the Asia-Pacific Region. Larger, high speed vehicle and passenger ferries have shown strong growth in northern Europe, the British Isles, and the Mediterranean.

Representative input from these market segments states their requirements as follows (in order of importance):

- Availability (a function of reliability, durability, and maintainability).
- Emissions.
- Customer support.
- Fuel efficiency.
- Life cycle cost.
- First cost.
- Project execution.
- Financing.

These requirements were balanced against various possible ATS product characteristics in a QFD analysis in order to arrive at the ATS defined in Task 6. Thus, as has been the case in over three decades of Solar experience in the gas turbine marketplace, Solar's ATS design has been shaped by user requirements.

Based on the characteristics of the ATS defined in Task 6 and volumes forecast by the Market Study of Task 5, the following view of the year 2020 was formulated:

- 26,880 MWe (36 million shaft horsepower) of Solar ATS power will have been installed and commissioned.
- A total of 0.82 quadrillion Btu of fossil fuel will have been saved worldwide. This compares fuel consumption with that of an energy economy that would have developed on its own without the DOE/Solar effort.
- Worldwide emissions of NO_x will have been reduced by 343,000 tons per year, again compared to a future without a DOE/Solar ATS.
- Exploitation of the ATS opportunity defined by the Task 5 Market Study will have provided over 7000 new jobs at Solar, its suppliers, and at user locations.
- Reduction in the cost of the energy used in the production of U.S.-manufactured products will reduce the cost of these products and make them more competitive in a worldwide marketplace.

Development of Critical Technologies (Task 8)

The DOE has recognized that, if new technologies are to be incorporated into an ATS in a timely manner, an early start on their development is good insurance. Accordingly, such technology development has been written into Phase II contracts. This element of Solar's Phase II contract - Task 8, titled "Design and Test of Critical Components." Task 8 includes materials development in support of the ATS recuperator and turbine disks, advanced ceramic materials development, low emissions combustion research, and advanced control technology.

Materials Development - Recuperator

The temperature capability of the recuperator sheet material - presently Type 347 stainless steel - limits attainable thermal efficiency at all levels of pressure ratio. This limiting exhaust temperature is approximately 1230°F for Type 347 stainless steel. A low-cost alternative being examined in Task 8 is one or more of the high temperature ultrafine precipitate strengthened (HT-UPS) austenitic stainless steel alloys under development at Oak Ridge National Laboratory.

Large increments of temperature capability can be obtained through the use of nickel-base alloys such as Inconel 625 or Haynes 230. Cost of these alloys approaches four times the per-pound cost of Type 347 stainless steel. Task 8 will determine the prospects for using such alloys only in regions where temperature will be above the limit for Type 347, thus minimizing cost. Methods of joining the two alloys will be examined along with the formability and other critical characteristics of the joined pair.

Using a laser welding technique developed by a subcontractor, successful joining of 347 stainless steel to Inconel 625 alloy has been accomplished. The resulting joint is sufficiently free of any sort of raised bead so that samples are being sent directly to Solar's recuperator sheet forming process for formability trials. It does not appear at this point that any sort of final roll process will need to be introduced following the weld operation.

Materials Development - Turbine Disks

The current material of choice for turbine disks is a forged high temperature - usually nickel based - alloy. This material is chosen for its high low-cycle fatigue strength required for survival of the large strain excursions involved in gas turbine start-run-stop cycles. Near the rim at the point of blade attachment, these materials lack the creep resistance of cast versions of the same or a similar alloy. Adequate creep life of this region of the disk is maintained by cooling with compressor bleed air, at the cost of cycle efficiency. Increasing cycle firing temperature requires more cooling air. Flattening of combustor outlet temperature profiles as required to maintain low stress levels in ceramic airfoil at a constant average temperature will also raise disk rim temperature and require additional cooling.

Task 8 efforts are developing a method of producing a strong bond between a turbine rim section cast of creep-resistant high temperature alloys and a center section which maintains the low cycle fatigue properties of the present materials. Once the right alloy pair and bonding process is identified, its characteristics will be defined to the gas turbine designer for application to Solar's ATS as well as for introduction to the balance of Solar's product line.

Mar-M-247®, the material chosen for the high-temperature (rim) portion of the dual-alloy disc has been successfully spray-cast into rings suitable for bonding with the central portion of the disc. Coupons of Mar-M-247 have been HIP-bonded to coupons of Udimet® 720 hub alloy and the resulting joint is undergoing metallurgical evaluation.

The spray-cast process provided by subcontractor Howmet offers additional possibilities for application to Solar's non-ATS product line. These include parts which cost less than those made from forged rings, and parts requiring creep-rupture properties not obtainable in forged alloys.

Materials Development - Ceramics

Going beyond the wealth of ceramic technology that will flow into the ATS from Solar's Ceramic Stationary Gas Turbine

(CSGT) Program with the DOE, Task 8 will focus in two specific areas:

- Candidate ceramics for use in association with the catalytic combustor and its associated ducting will be identified. In ATS machines, these materials will serve to free cooling air applied to metallic ducts for use in emissions reduction.

- A second focus will be on developing the manufacturing process and accurately determining the life characteristics of parts made from ceramic composites. The combustor can-to-turbine nozzle transition duct in the ATS gas turbine is the candidate part selected for this evaluation with subcontractor B.F. Goodrich Supertemp and based on a SiC/SiC material.

Component Development - Combustion

As a part of Task 8, Solar is evaluating a subscale ATS combustor in an existing high pressure test rig (Figure 12). The objective of this test is to determine performance of the catalyst bed and the fuel-air premixer under ATS conditions. This program will next progress to a full-scale single can of the multi-can annular catalytic combustor intended for the ATS. Working with a subcontractor supplying the catalyst in a ceramic matrix, Solar is developing the combustor to meet the ATS requirement of 8 ppmv of NO_x and 15 ppmv of CO and UHC.

Once key characteristics of the catalytic reactor in the subscale rig have been determined, these will be applied in a full scale rig now being designed. This rig will model the entire catalytic combustion system on the basis of one can sized for the ATS gas turbine. This system will consist of the catalytic reactor developed in the subscale rig together with associated elements such as the fuel-air mixer and the post-catalyst combustion region.

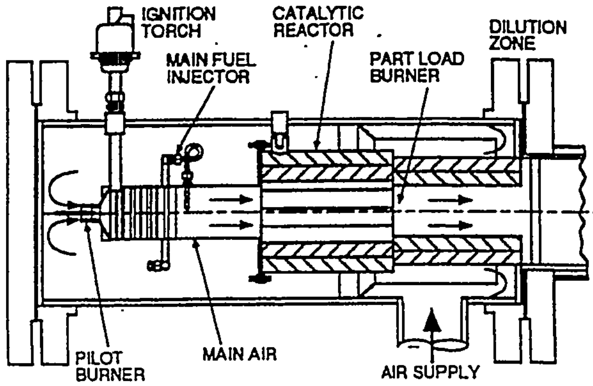

Figure 12. Subscale Catalytic Combustor Rig

To date, the sub-scale rig has been operated under stable conditions with NO_x emissions below 5 ppmv. The subscale rig has also produced valuable information on the design of a fuel-air premixer that will deliver evenly distributed fuel concentrations to the inlet face of the reactor. The design of the full-scale rig is being completed with a post-catalyst combustion region sized using NASA-derived chemical kinetics software to provide complete CO burnout.

Component Development - Recuperator

In addition to the recuperator material task previously discussed, a second task deals with recuperator thermal and flow performance required in support of ATS cycle performance goals. The geometric parameters of the primary heat transfer surface can be varied in order to provide the combination of heat transfer effectiveness and static pressure loss required by the cycle. In the case of the ATS, the goal is to preserve the 90 percent thermal effectiveness used in prior applications of the primary surface recuperator (PSR) while reducing the static pressure loss in both air and exhaust gas streams.

The design of the new surface was accomplished using codes derived both empirically from previous test work and by application of textbook heat transfer principles. Thermal and flow performance of the ATS recuperator has been validated at the Caterpillar Technical Center, using the apparatus described in Reference 4. Under ATS design point operating conditions, thermal effectiveness was measured at 90.3 percent (versus 90.0 percent required by the ATS cycle) and total (air- and gas-side) static pressure loss at 6.8 percent (versus a maximum of 7.0 percent) allowed by the ATS cycle.

Component Development - Autothermal Fuel Reformer (ATR)

Work on the ATR under Solar's ATS Phase II contract as described in Reference 4 has been completed. Concentrations of 70 percent free hydrogen in the secondary fuel reformed from natural gas were achieved. Reformation of liquid fuel (Diesel No. 2) produced 60 percent free hydrogen. Satisfactory resistance of the reforming catalyst to poisoning by fuel-borne sulfur was also demonstrated.

The ATS to be developed by Solar during Phase II does not include an ATR; however, Solar considers this process to be a significant contributor toward the clean burning of a wide variety of fuels in future gas turbines including the ATS. Accordingly, ATR development will continue at Solar using internal R&D funding.

Component Development - ATS Control System

In order to fully realize all of the benefits of ATS, program activity has to proceed beyond the boundaries of the gas turbine itself and through the entire **system**. Within the **system** all support subsystems must be optimized for full support of the ATS goals designed into the gas turbine itself.

One such subsystem of critical importance is the control system - not just a gas turbine control but an ATS **system** control. During Phase II, Solar is designing an advanced Man/Machine Interface (MMI) which will apply microprocessor technology so as to provide improved efficiency and RAMD along with reduced cost and emissions. Important features of this system are described below:

- The system will provide easy communication with other system/plant computers and control equipment over industry standard networks. This will allow optimization of the complete system of which the ATS is a part, improving efficiency and reducing emissions.

- Automatic intelligent reduction/analysis of control system data into advisory information. This will assist the operator in the diagnosis of plant operation and to set maintenance schedules which will result in higher levels of RAMD. He will also be able to optimize plant operation for increased efficiency, lower emissions, and lower cost of power.

- Long range communication ability will be improved by utilizing media such as telephone lines, microwave links, and communications satellites. This will allow operation, data collection and analysis and diagnostics and maintenance to be performed on multiple units from a central location. The system will also interface with Solar's Customer Services Center to provide rapid response to problems.

- Modular options, easily integrated at low cost into the customer's MMI will be provided based on the customer's needs. These can include remote starting and operation, interfacing with existing plant and process controls, on-line economic analysis and many others.

- Easy, in-field reconfiguration of the MMI will minimize the cost of future updates that may be required by changing requirements of the system.

Other ATS-Related Technology Development Programs at Solar

Ceramic Stationary Gas Turbine (CSGT)

This DOE-sponsored program with Solar as the prime contractor and eight cost sharing subcontractors is a technology demonstrator program with the retrofit of ceramic components into existing industrial gas turbines as its ultimate goal. Starting with the development of design methodology for these components, this program has produced detailed designs for components to be tested in a Solar Centaur® 50 gas turbine. Component rig and engine tests are under way, preceding final validation of CSGT technology in a 4,000 hour field test. Commercialization of the retrofit design for the Centaur 50 and other gas turbine models will follow successful completion of this field test.

During the current quarter, the Centaur 50 test engine completed two successful two-hour test run (one hour each at temperature) with stage one turbine blades of Norton NT164 material and Allied Signal GN10 material. Blades were mounted in a conventional metal disc using dovetail-shaped attachments.

Materials/Manufacturing Development Programs with ORNL

Solar is involved in a manufacturing program with the Oak Ridge National Laboratory (ORNL) as a subcontractor - along with other gas turbine manufacturers - to prime contractor Howmet. This program, awarded in September, 1994, has as its goal the development of lower cost, high performance single crystal components. Field demonstrations of the resulting components are scheduled in the fourth year of the program, making Solar's ATS field test a candidate host for these tests.

In addition to its key contributions to ATS, both of this program will provide spin-off technologies for inclusion in Solar's current product line as well a for retrofit into Solar's fleet of more than 9200 gas turbine systems sold around the world.

Summary

Solar approached Phase II of the ATS program with the goal of providing a system that would be capable of 50 percent thermal efficiency. An intercooled and recuperated (ICR) gas turbine was identified as the ultimate system to meet this goal in a commercial gas turbine environment. Proceeding with commercial input from detailed market studies and examining the boundaries of the DOE's ATS program as defined in the

Solicitation for Cooperative Agreement (SCAP) for Phases III and IV, Solar redefined the company's proposed ATS to fit both market and sponsor (DOE) requirements. The resulting optimized recuperated gas turbine will be developed in two sizes, 5 MWe and 15 MWe. It will demonstrate a thermal efficiency of approximately 43 percent -- a 23 percent improvement over current gas turbine product in the industrial size range. Other ATS goals -- emissions, RAMD (reliability, availability, maintainability, and durability), and cost of power will be met or exceeded. During FY 1995, advanced development of key materials, combustion and component technologies proceeded to the point of accepting them for inclusion in ATS Phase III development along with parallel path risk-reduction approaches.

Future Work

The DOE has awarded Solar the Cooperative Agreement for performance of Phases III and IV of the ATS Program as a result of Solar's proposal based on Phase II technical and commercial studies. In anticipation of this award, Solar has begun work on the final design of the ATS and was proceeding rapidly on this project at the time of the award. Fiscal 1996 will see the completion of Phase II technology work as well as the addition of the Phase III efforts to these and associated projects. Technology projects and the basic ATS product design project will lead to an 8000-hour field evaluation test of both ATS sizes (5 MWe and 15 MWe) beginning early in CY 1998 and commercial availability of the Solar/DOE ATS in the year 2000. This progress will be supported by concurrent DOE programs at Solar such as the ceramic retrofit (CSGT) program.

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2.7

Advanced Turbine System Program Phase 2 Cycle Selection

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Abstract

The objectives of the Advanced Turbine System (ATS) Phase 2 Program were to define a commercially attractive ATS cycle and to develop the necessary technologies required to meet the ATS Program goals with this cycle. This program is part of an eight-year Department of Energy, Fossil Energy sponsored ATS Program to make a significant improvement in natural gas-fired power generation plant efficiency while providing an environmentally superior and cost-effective system

Background

By the year 2000 electric power generation demand is expected to increase domestically and on a worldwide basis. To meet this projected increase in power generation, advanced gas turbines are being developed through a Government/industry partnership. This effort, sponsored by the Department of Energy's (DOE) Advanced Turbine System (ATS) Program, is directed toward meeting the program goals of ultra-high efficiency, environmentally superior, and cost-competitive gas turbine systems for the future.

ABB is one of several gas turbine manufacturers participating in the DOE's Fossil Energy (FE) Conceptual Design and Product Development Phase of the ATS Program. As part of that program, tradeoff studies are conducted by utility engine manufacturers to evaluate and select the most commercially attractive advanced turbine system which meets the ATS Program goals. The results of ABB's tradeoff studies and Advanced Turbine System selection are discussed in detail.

Nomenclature

GT=Gas Turbine
LHV= Lower Heating Value
NOx=Nitrous Oxide Emissions
CO=Carbon Monoxide Emissions
UHC=Unburned Hydrocarbon Emissions
PPM=Parts Per Million
RAM=Reliability, Availability, and Maintainability
EV=Environmental Combustor
SEV=Sequential Environmental Combustor
HP= High Pressure
LP=Low Pressure

Introduction

The objectives for the DOE's Advanced Turbine System (ATS) require development and demonstration of an ultra-high efficiency, environmental friendly, cost effective power generation system by the year 2000. These ATS program objectives are to be met by achieving the following goals:

Research sponsored by the U.S. Department of Energy's Morgantown Energy Technology Center, under Contract DE-AC21-95MC30245 with ABB Power Generation, Inc., 5309 Commonwealth Centre Parkway, Midlothian, VA 23112;
Telefax 804-763-3070

- Natural gas-firing but fuel flexible for adaptation to biomass and coal derived fuels
- High firing temperatures >1427°C
- High combined cycle efficiency (LHV) >60%
- Low emissions (<10 PPM NOx, <20 PPM CO and UHC)
- Reduced bus-bar costs (10%) than current vintage systems
- Equivalent RAM to today's systems
- Demonstration/commercialization by the year 2000

Cycle Studies

To achieve these goals both innovative cycle and high temperature turbine technologies were evaluated. These included intercooling, recuperation, chemical recuperation, high temperature simple cycles, and numerous water/steam based cycles. These cycles were rejected because of system complexity, unproven components, high operating temperatures, high operation and maintenance costs, excessive water demands, and the physical size of the system and system components.

In lieu of these cycles, the ABB Model GT24 Advanced Cycle System (ACS)™ was selected as the reference plant. The GT24-ACS already incorporates several innovative cycle improvements including a reheat cycle, an annular low-NOx sequential combustion system, and a high pressure ratio compressor which makes the size and cost of plant hardware comparable to smaller size plants. In addition, the GT24-ACS has been able to take advantage of the development and field experience of the ABB Model 13E2 Engine which operates at 50 Hz and shares annular combustor and turbine features with the GT24-ACS.

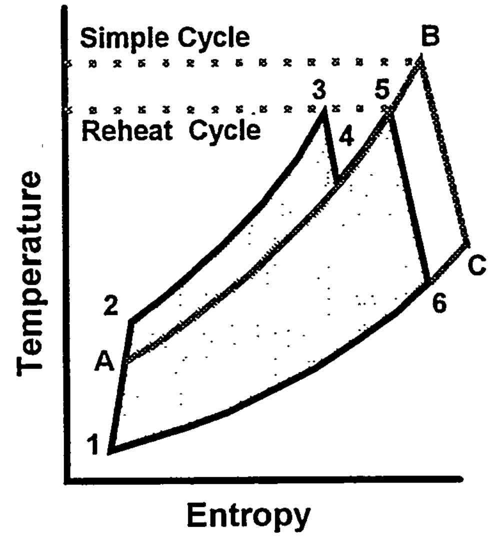

Figure 1 - ABB Advanced Cycle System (ACS)™

The ABB Advanced Cycle System (ACS) is shown in the Temperature versus Entropy graph in Figure 1. The reheat cycle follows a path of 1-2 for compression, 2-3 for combustion in the first combustor (EV), 3-4 for expansion in the HP turbine, 4-5 for combustion in the second combustor (SEV), and 5-6 for expansion in the LP turbine. The simple cycle follows the path of 1-A for compression, A-B for combustion, and B-C for expansion. To achieve the same power output, the simple cycle requires operation at higher firing temperatures to achieve improved cycle efficiency. With the reheat cycle, this power level can be achieved at lower firing temperatures as virtually all of the cooling air used for the EV combustor and HP turbine can be recycled through the SEV combustor and LP turbine cycles for improved efficiency.

The performance characteristics of the GT24-ACS which make it suitable for upgrading to meet ATS program goals include the following:

- Pressure ratio of 30:1 for smaller hardware size, higher specific power, and reduced tip speeds and stresses

- Firing temperature of 1255°C
- Simple cycle efficiency of 37.5% (LHV basis)
- Net combined cycle efficiency of 58% (LHV basis)
- Net power output of 165 MW in simple cycle and 251 MW in combined cycle
- Excellent part load performance and emissions from 60-100% load

ABB ATS Definition

To meet the ATS program goals, the combined cycle efficiency level of the GT24-ACS needs to be increased by 2%, the firing temperature increased by 170°C, and NOx emissions reduced to lower single-digit values. Considering the analysis results conducted at ATS temperature levels and GT24-ACS test data, ABB is confident that the ATS program goals can be met with minimal risk by upgrading selected parts of the GT24-ACS. Designating this new, higher efficiency plant as the Model GT24-ATS, this new system would consist of the following components:

Compressor

The GT24-ATS will utilize the existing GT24-ACS engine compressor. This compressor consists of 22 stages, 16 LP stages and 6 HP stages. Three variable geometry stages are utilized which allow for mass flow reductions of up to 50% for efficient operation between 60-100% load. The compressor blading utilizes controlled diffusion airfoils (CDA) with low stage loading to maximize efficiency levels and surge margin.

Scale model LP compressor rig tests were completed to verify performance levels. The compressor test rig is shown in Figure 2. Blading aerodynamic and stress levels have also been verified through bench and rig testing No modifications to the compressor are required for the GT24-ATS.

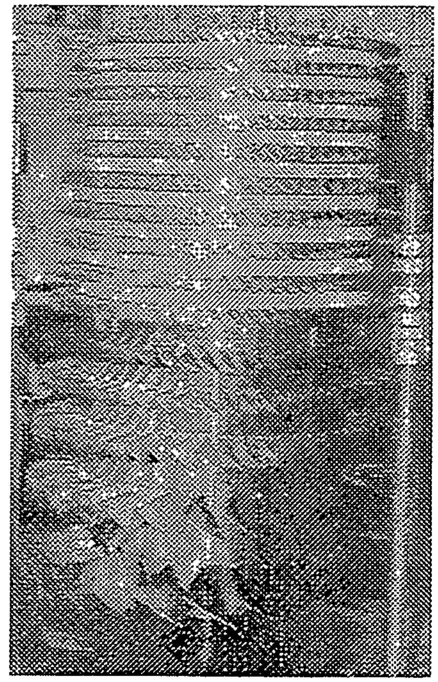

Figure 2 - GT24 Compressor Test Rig

Combustor

The GT24-ATS combustor will utilize the existing GT24-ACS sequential combustion system with only minor modifications to incorporate ABB's third generation EV combustor technology. The sequential combustion system consists of an annular EV combustor downstream of the HP compressor stages. Thirty (30) EV burners are located in the dome of the combustor as indicated in the general arrangement in Figure 3. These burners reflect ABB's patented EV technology whereby low NOx levels are achieved by aerodynamic control of mixing and flame stabilization. ATS levels of NOx will be achieved by improved mixedness in the EV burners. No changes to the combustor wall cooling system are required. Combustion rig testing at ATS firing temperatures indicated wall temperatures less than 900°C.

The output of the EV combustor discharges through the HP turbine stage into a mixing area and then into the sequential annular combustor, designated as the SEV combustor. Virtually no NOx is produced while extremely high combustor efficiencies are achieved. Twenty-four (24) air cooled lance-type fuel injectors admit gas to the combustor which ignites without the need for ignitors. Combustion rig testing at ATS firing temperatures also resulted in wall temperatures less than 900°C and emission levels in single-digits. This high level of combustion system performance is achieved without the use of variable geometry, steam cooling, or any moving parts. Because the combustors are annular, the amount of surface area required to cool is less than required for typical can-annular systems. In addition, crossover tubes are not required. The annular combustors provides a more even temperature profile to the turbine which is highly desirable for RAM considerations at these higher ATS firing temperature levels.

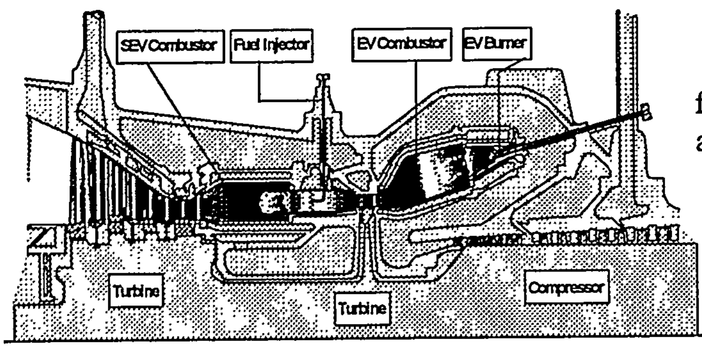

Figure 3 - GT24 Sequential Combustion System Arrangement

Turbine

The GT24-ATS will utilize the GT24-ACS turbine with several improvements. The existing GT24-ACS turbine consists of 5 turbine stages, 1 HP stage and 4 LP stages. Advanced aerodynamics (3-D) and cooling technologies are utilized in the turbine blading to keep metal temperatures below design limits. The blading has been tested aerodynamically and performance levels verified. A welded rotor construction has been maintained consistent with other ABB engine models. DS materials, honeycomb seals, and shrouded blades are used in the turbine for high levels of turbine performance. In addition, the turbine exhaust temperature is higher than conventional simple cycle machines for improved combined cycle performance. The first GT24-ACS turbine is shown in Figure 4 during assembly in Richmond, Virginia, for Jersey Central Power and Light's Gilbert Station.

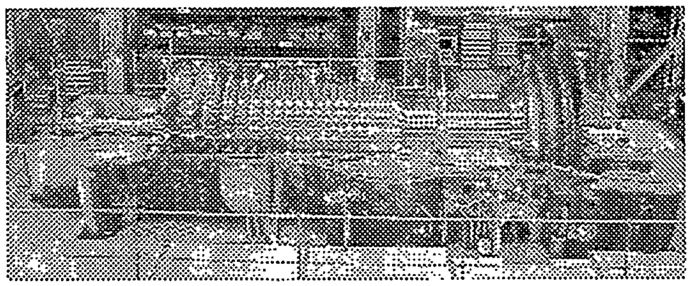

Figure 4 - First GT24 During Assembly

To meet the ATS program goals, the following improvements to the GT24-ACS turbine are required:

- Incorporate turbine cooling advances (turbulators and advanced wall cooling features)
- Utilize single crystal blading for the air-cooled rotor blade stages
- Integrate thermal barrier coatings (TBC) with turbine cooling advances and single crystal blading to reduce airfoil cooling air needs
- Steam cooling of the GT24 turbine vanes
- The turbine exhaust temperature is increased further to improve combined cycle performance

ABB has prepared development programs to achieve these goals. High temperature blading programs include development of high effectiveness turbulators and advanced wall cooling concepts. These items are tested with full coverage liquid crystals to determine heat transfer rates and to subsequently optimize cooling of components and passages. Similarly, ABB continues with the development of single crystal materials utilizing combinations of casting simulations, casting trials, and heat treatments in a concurrent engineering approach to optimize the casting process for high yields and reduced costs. ABB continues to evaluate TBC coatings on blading to fully integrate coating characteristics with base materials properties to achieve a satisfactory system. Development program plans included TBC coating and base materials testing at the bench test level and in-situ testing in existing ABB gas turbines. Steam cooling of the turbine vanes is not new to ABB and existing advanced cooling technologies will be applied to optimize the design. To meet the combined cycle efficiency goals of ATS, steam cooling of the combustor and turbine blades are not required.

Performance

Based on the combustor and turbine improvements identified, the estimated performance of the GT24-ATS system as compared to the GT24-ACS system is indicated below:

Parameter	GT24-ACS	GT24-ATS
Firing Temp	1255°C	1427°C
Simple Cycle Efficiency	37.5%	>41%
Combined Cycle Efficiency	58.0%	>61%
Simple Cycle Power	165 MW	200 MW
Combined Cycle Power	251 MW	300 MW
Exhaust Temperature	617°C	677°C
Exhaust Airflow	373 Kg/Sec	375 Kg/Sec
NOx	<25 PPM	< 9 PPM
CO	<20 PPM	<20 PPM
UHC	<20 PPM	<20 PPM

These performance numbers are based a on triple pressure heat recovery steam generator (HRSG) with reheat.

Commercialization

From a commercialization standpoint, the ABB GT24-ATS can take advantage of GT24-ACS experience. The first GT24-ACS was sold to Jersey Central Power and Light and delivered to their Gilbert Station in July, 1995, as shown in Figure 5. This first unit has completed first ignition, full speed running, and synchronization. Five outages are scheduled for RAM testing and evaluation purposes. Commercial operation is scheduled to begin in June 1996. These efforts will substantially enhance and minimize the technical risks in meeting ATS program RAM goals with ABB's GT24-ATS.

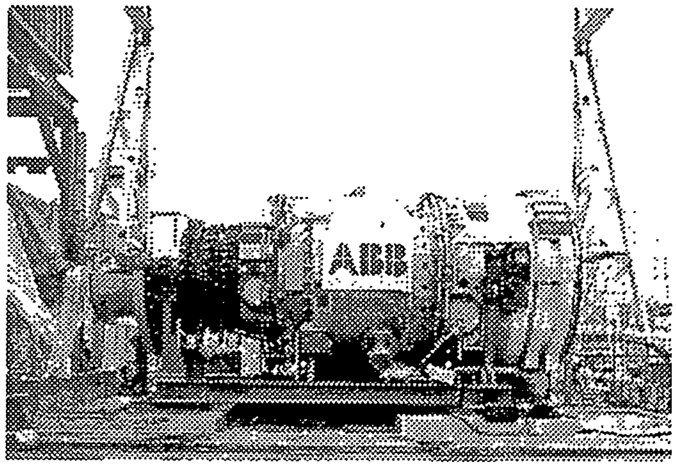

Figure 5 - GT24 Delivered to Gilbert Site in July 1995

ABB has not limited introduction of the Advanced Cycle System to 60 Hz machines such as the GT24-ACS. ABB is also introducing a 50 Hz version of the GT24-ACS designated at the Model GT26-ACS. This machine has a combined cycle efficiency in excess of 58% and will provide power levels of 240 MW in simple cycle operation and 345 MW in combined cycle operation. It is planned that the GT24-ATS improvements will be extended to this product line as well. Currently, two GT26-ACS machines have been sold which will allow for accumulating experience with both ACS and ATS technologies on a worldwide basis.

Conclusions

ABB's GT24-ATS can meet or exceed the ATS program goals with minimal risk. In summary, the GT24-ATS:

- Uses the existing and tested GT24 compressor
- Requires only minor modifications to the GT24 EV/SEV combustors to meet NOx goals without using
  - ⇒ Variable geometry
  - ⇒ Moving parts
  - ⇒ Steam cooling
- Utilizes improvements to the GT24 turbine for:
  - ⇒ Turbine cooling advances
  - ⇒ Single crystal blading in air cooled stages
  - ⇒ Integration of thermal barrier coatings with single crystal airfoils
  - ⇒ Advanced steam cooling of GT24 turbine vanes
- Utilizes the rest of the existing GT24 plant since the proposed changes are internal to the gas turbine only.

Since ABB does not require steam cooling of the turbine rotor or rotor blading to meet the ATS combined cycle efficiency goals, the technical risk to the GT24-ATS is reduced which also eliminates problems associated with leakage of steam to and from rotating hardware.

Acknowledgements

This ATS program effort was conducted in a partnership with the U.S. Department of Energy, Fossil Energy Office, Morgantown Energy Technology Center (METC), Morgantown, West Virginia, with the guidance of the METC Contracting Officer's Technical Representative, Mr. Charles T. Alsup.

The technical content in this paper also includes information provided by Dr. Prith Harasgama of ABB Power Generation, Ltd., and by Mr. Mike Hargrove and Dr. Tom Gibbons of ABB Power Plant Laboratories.

2.8 General Electric ATS Program Technical Review Phase 2 Activities

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Objectives

The Advanced Turbine Systems (ATS) Program Phase 2 objectives are to select a cycle, and to identify and resolve technical issues required to realize the ATS Program goals of 60% net combined cycle efficiency, single digit NOx, and a 10% electric power cost reduction, compared to current technology.

Background

In response to the industrial and utility objectives specified for the ATS, the GE Power Generation ATS Phase 2 Program consisted of a dual approach. These were 1) development of an Industrial ATS (aircraft engine based) led by GE Aircraft Engines, and 2) development of a Utility ATS which was already underway at GEPG. Both programs required the identification and resolution of critical technical issues. Both systems were studied in Tasks 3-7, and both have resulted in designs that meet all ATS goals. The Industrial ATS as defined (130 MW) did not meet projected market power size requirements, and emphasis has remained on the Utility ATS development. The design and testing effort has been focused on the MS7001H combined cycle gas turbine, as the next product evolution in GE Power Generation's product line. Common technology derived from the ATS Program is also being incorporated into the 50 Hz version of the ATS utility machine designated as the MS9001H.

Research sponsored by the U.S. Department of Energy, Morgantown Energy Technology Center, under contract DE-AC21-93MC30244 with G.E. Power Generation, 1 River Road, Schenectady, NY 12345

Program Status

The ATS Phase 2 Program consists of eight tasks, whose status is shown:

Task 1 - Project Plan - completed
Task 2 - NEPA Information - completed
Task 3 - Select Gas Fired ATS
  3A - Industrial GFATS - completed
  3B - Utility GFATS - completed
Task 4 - Conversion to Coal Fueled ATS
  4A Industrial CFATS - completed
  4B - Utility CFATS as part of IGCC analysis
Task 5 - Market Study - Draft Report completed
Task 6 - System Definition and Analysis

6A - Industrial System - completed
6B - Utility System - in progress
Task 7 - Integrated Program Plan
7A - Industrial GFATS - in progress
7B - Utility GFATS - not yet started
Task 8 - Design and Test of Critical Components
8A - Industrial Task 8.5 - completed
8B - Utility - all others in progress

Cycle Selection

Prior to the initiation of the ATS Phase 2 Program, GE Power Generation conducted a study of advanced combined cycles, and concluded that a significant net efficiency gain would be possible with a closed loop steam cooled turbine. This cycle, along with the new technologies required for its implementation, will meet the ATS program goals for net efficiency, emissions, and cost of electricity. Details of the cycle, hot section components, system integration and mechanical cross-section are given in Reference 1.

System Definition and Analysis

General Description

The MS7001H gas turbine has many of the basic heavy duty gas turbine features used on other GE gas turbines. The power output drive shaft is at the cold end. The gas turbine rotor is supported by two journal bearings. Axial thrust is contained by a single thrust bearing located at the compressor end. For ease of maintenance and inspection, the casings are horizontally split. The compressor/turbine rotor is removable as one piece. For each combustor, the liners and transition pieces can be individually replaced. Borescope holes are located in the compressor, combustion and turbine sections to facilitate visual inspections.

Overview

The original plan for the advanced machine product was to have the 7H (60 Hz) gas turbine scaled from the 9H (50 Hz). Based on a thorough analysis of cost, efficiency and market needs, a decision was reached to develop the 7H which was not a true scaled version of the 9H.

The ATS Phase 2 program focus has been on preliminary component design, and performing component detail design in preparation for long lead casting and forging releases. Components addressed include: compressor rotors and stators, combustors, turbine buckets and nozzles, casings, and thrust and journal bearings.

Compressor

The mechanical design of the ATS compressor was derived from GE's proven heavy duty gas turbine experience while the aerodynamics and aeromechanics were scaled from the proven CF6-80C2 aircraft engine. The compressor has 18 stages which provide a 23 to 1 pressure ratio and an air flow of 558 kg/sec (1230 lb/sec) at 60 Hz, and 685 kg/sec (1510 lb/sec) at 50 Hz.

Variable inlet guide vanes and four stages of variable stator vanes are used to control compressor air flow during part power operation and to optimize compressor efficiency and operational characteristics.

Combustor

The ATS machine combustion system is a can-annular lean premix Dry Low NOx (DLN) system. The design builds upon the GE DLN2 combustion technology. GE designed DLN systems are successfully operating in over 100 field installations. The ATS NOx goals are close to being demonstrated with these combustors at combustion temperatures approximating the ATS levels.

The combustor diameter is increased approximately 20% over the current 7FA DLN family in order to pass the higher flow levels. The can-annular combustors are common to both 50 Hz and 60 Hz machines, with a 14-can configuration in 50 Hz, and a 12-can configuration in 60 Hz applications.

Turbine Design

The ATS turbine incorporates high efficiency 3-D aerodynamics in a four stage design, which was selected to maintain optimum work loading and pressure ratio on each stage. With a 1426C (2600F) class firing temperature, the pressure ratio was increased to retain an exhaust temperature of approximately 593C (1100F) for good combined cycle performance.

The turbine employs closed loop steam cooling in the first and second stage nozzles and buckets plus the stage 1 shroud. The first two stages of airfoils are thermal barrier coated (TBC) for life improvement by reducing temperatures and stresses.

Power Plant Design

The ATS gas turbine is part of a combined cycle power plant. Exhaust steam from the high pressure steam turbine is split and a portion used to cool the ATS gas turbine hot section. After cooling, the hot gas path hardware, the steam temperature is increased to approximately reheat temperature. The gas turbine cooling steam is collected and returned to the steam cycle, where it is mixed with the reheated steam and introduced to the intermediate-pressure steam turbine for energy recovery.

Phase 2 Component Development Tasks

The definition of the cycle that meets ATS Program goals requires advancements in several areas of gas turbine technology. An extensive experimental program was initiated to develop these technologies. The results of these tasks are being utilized in the design of the ATS machine.

Coolant Fluid Contaminants. It is necessary to characterize any particles present in the steam flow path of a combined cycle steam loop in order to verify that the cooling steam quality is acceptable. Development programs were initiated to sample an existing combined cycle steam loop, to evaluate the use of filtration for particulate control, and to determine deposition characteristics of particulates in static and rotating coolant paths.

Thermal Barrier Coatings. Development of thermal barrier coatings (TBCs) with improved life and reliability will require a comprehensive understanding of the mechanisms of degradation that occur in a gas turbine. There are several ongoing TBC program elements.

The first is development and confirmation of methods to measure and predict TBC stress states as a function of thermal stress and mechanical strains to facilitate TBC design and life prediction methodologies. An additional objective is development of a practical, versatile laboratory-scale thermal gradient exposure facility capable of simulating the extreme thermal conditions anticipated for TBCs in the ATS machine. An atmospheric E-beam facility has been developed and is being used to evaluate TBC coated specimens in thermal and stress states expected in service.

Test specimens were designed to properly model the thermal and strain field present in critical regions (such as fillets) of a first-stage nozzle in the ATS gas turbine.

Improved instrumentation is being developed to measure the temperatures, fluxes and strains present in the E-beam specimens. Instrumentation types include: thin-film thermocouples, thin-film strain gages, IR pyrometers, surface profile monitors and laser fluoresence of the thermally grown alumina layer.

Advanced Seals Technology. The ATS gas turbine will require improved seals in order to withstand the increased pressures and temperatures, while reducing leakage compared to current seal designs. A static seal test rig was designed and built, and a variety of seal configurations were tested. Several seal designs were chosen that significantly reduce leakage in the turbine nozzle and shroud components.

An experimental facility is being fabricated to test the new seals at temperatures and pressures that simulate ATS conditions.

Rotational Heat Transfer - Bucket Cooling. Prediction of gas turbine bucket life requires accuracy in the prediction of both the local hot gas side and coolant side heat transfer coefficients present at the relevant bucket surfaces. A considerable database exists for the hot gas side coefficients, but the database for the rotating bucket coolant passages is very limited.

Experiments were performed in the Rotating Test Rig to determine the effects of rotation on local heat transfer coefficients in rotating cooling ducts. The results of these tests have been incorporated into the ATS bucket cooling passage design procedures.

Nozzle/Bucket Heat Transfer. It is necessary to determine the internal heat transfer coefficient distributions for critical regions of the ATS stage 1 nozzle and bucket. The closed-circuit cooling requires enhanced channel heat transfer to meet performance goals and part life.

Model fabrication of the nozzle and bucket airfoil cooling passages have been completed and some testing has been initiated.

High Mach Number Diffuser. The higher pressure ratio and flow of the ATS gas turbine result in higher compressor exit Mach numbers than have been previously experienced. The compressor exit diffuser must provide good pressure recovery and an even flow distribution to the combustors.

Flow visualization tests are being performed to evaluate the impact of higher compressor exit velocities and split diffuser designs. CFD will also be used to model the flow field within the compressor/diffuser wrapper volume to evaluate potential problems. Testing of an optimized exit diffuser is in progress.

Market Study

A market study was performed to assess the potential market in the U.S. for a gas fired ATS (GFATS). The study focused on the 1995-2004 time frame, and explored the competitive economics of GFATS, current technology gas-fired systems, and coal-fired utility power plants.

The study used NERC (North American Electric Reliability Council) supply and demand projections to establish future production requirements for all nine NERC regions. These regions vary in projected load growth, load profile, generation mix, reserve margin and fuel prices.

GE Power Generation's FASTPLAN utility generation resource planning program was used to model the electricity demand by region over the next decade, and the projected mix of capacity additions to be added. Additions are based on the least cost to provide the generating addition required.

The FASTPLAN analysis predicts a market penetration of 56% for capacity additions over the next decade, with a 10% reduction in the cost of electricity compared to current gas fueled turbine systems.

Conclusion

The ATS Program Phase 2 efforts have shown that the ATS Program goals are achievable. The GE Power Generation advanced gas turbine will utilize closed-loop steam cooling in the first two turbine stages and advanced coatings, seals and cooling designs to meet the ATS performance and cost of electricity goals.

Acknowledgment

The ATS Phase 2 Program is being performed under DOE Contract No. DE-AC21-93MC30244, period of performance 8/25/93 - 3/31/96. The DOE/METC COR is Ms. Abbie Layne.

References

1. J.C. Corman, 1995, "H Gas Turbine Combined Cycle", presented at DOE 1995 ATS Program Review and included in the proceedings.

2.9 Technical Review of Westinghouse's Advanced Turbine Systems Program

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Introduction

U. S. Department of Energy, Office of Fossil Energy Advanced Turbine Systems (ATS) Program is an ambitious program to develop the necessary technologies, which will result in a significant increase in natural gas-fired power generation plant efficiency, a decrease in cost of electricity and a decrease in harmful emissions. In Phase 1 of the ATS Program, preliminary investigations on different gas turbine cycles demonstrated that net plant efficiency greater than 60% could be achieved (Little et.al., 1993). The more promising cycles were evaluated in more detail in Phase 2 in order to select the one that would achieve all of the program goals (Briesh et.al., 1994). The closed-loop cooled combined cycle was selected because it offered the best solution with the least risk for exceeding the ATS Program goals of net plant efficiency, emissions, cost of electricity, reliability, availability, and maintainability (RAM), and commercialization in the year 2000.

Research sponsored by the U.S. Department of Energy's Morgantown Energy Technology Center, under Contract DE-AC21-93MC30247 with Westinghouse Electric Corp., 4400 Alafaya Trail, Orlando, Florida 32826-2399, telefax: 407-281-5633

The Westinghouse ATS plant is based on an advanced gas turbine design combined with an advanced steam turbine and a high efficiency generator. To enhance achievement of the challenging performance, emissions, and RAM goals, current technologies are being extended and new technologies developed. The attainment of ATS performance goal necessitates advancements in aerodynamics, sealing, cooling, coatings, and materials technologies. To reduce emissions to the required levels, demands a development effort in the following combustion technology areas: pre-mixed ultra low NOx combustion, catalytic combustion, combustion instabilities, and optical diagnostics. To achieve the RAM targets, requires the utilization of proven design features, with quantified risk analysis, and advanced materials, coatings, and cooling technologies. Phase 2 research and development projects currently in progress, as well as those planned for Phase 3, will result in advances in gas turbine technology and greatly contribute to ATS Program success.

The ATS engine will be the next frame in the series of successful utility turbines developed by Westinghouse over the last 50 years. During that time, Westinghouse engineers made significant contributions in advancing gas turbine technology as applied to heavy-duty industrial and utility engines (Scalzo et. al., 1994). Some of the innovations included single-shaft two-bearing engine design, cold-end drive, axial exhaust, first cooled turbine airfoils in an industrial engine, and tilting pad bearings, features which all major gas turbine manufactures are now incorporating in their designs. In the past, enhancements in Westinghouse gas turbine performance and mechanical reliability were made in continuous steps. The evolution of large gas turbines started with the introduction of the 45 MW 501A engine in 1968. Continuous enhancements in performance were made up to the 100 MW 501D5 introduced in 1981. The next engine was the 160 MW 501F introduced in 1991. The 230 MW 501G is the latest engine in the series and is the initial step in ATS engine development. Each successive engine design was based on the proven concepts used in the previous design (see Table 1).

Table 1. Proven Design Features

Feature	501D	501F	501G	ATS
2-Bearing Rotor	X	X	X	X
4-Stage Turbine	X	X	X	X
Ind. Combustors	X	X	X	X
Horiz. Split Casing	X	X	X	X
Cold End Drive	X	X	X	X
Single Row 1 Vanes	X	X	X	X
Cooling	AC	AC	AC/SC	AC/SC
Walk-in Enclosure	X	X	X	X

AC = Air Cooling SC = Steam Cooling

The 501F produces 160 MW at a simple cycle efficiency of 36%. Its combined cycle net efficiency is higher than 55%. This performance level was achieved by approximately 110°C (200°F) increase in firing temperature, compared to the previous engine, advanced compressor and turbine design, advanced airfoil cooling design, and improved materials.

The current production engine, 501G, introduced in the Spring of 1994, produces 230 MW. Its combined cycle net efficiency is 58%. This engine incorporates further advancements in materials, cooling technology, and component aerodynamic design. The 19:1 pressure ratio compressor uses advanced profile high efficiency airfoils. The combustion system incorporates 16 dry low NOx combustors. The combustor design is similar to 501F with the same flame temperature and hence the same low NOx emission. The four-stage turbine uses full 3-D design airfoils and proven aeroderivative materials and coatings.

Achieving the ATS Program's challenging goals will require breakthroughs in several key technologies as well as enhancements in a broad range of current technologies. At the ATS performance level, the key issues are turbine component cooling, coating systems, and emissions control. Of almost equal importance in achieving the ATS Program goals will be the advances in component aerodynamic performance, sealing technology, and materials. To mitigate the key technical issues and to bring about the necessary advances in the supporting technologies, several development programs were proposed for ATS Phase 2. These programs include developments in combustion, emissions, cooling, aerodynamics, sealing, coating, and materials technologies.

Westinghouse's strategy to achieve, and exceed, the ATS Program goals is to build on the proven technologies used in the successfully operating fleet of its utility gas turbines, such as the 501F, to extend the technologies developed for the 501G and to overcome the identified barrier issues through a concerted technology development effort in ATS Phases 2 and 3 (see Figure 1).

The gas turbine exhaust gases will pass through the three-pressure level heat recovery steam generator (HRSG) before being exhausted through the stack. The steam turbine will employ advanced 3-D aerodynamic design methods. The 60-Hz

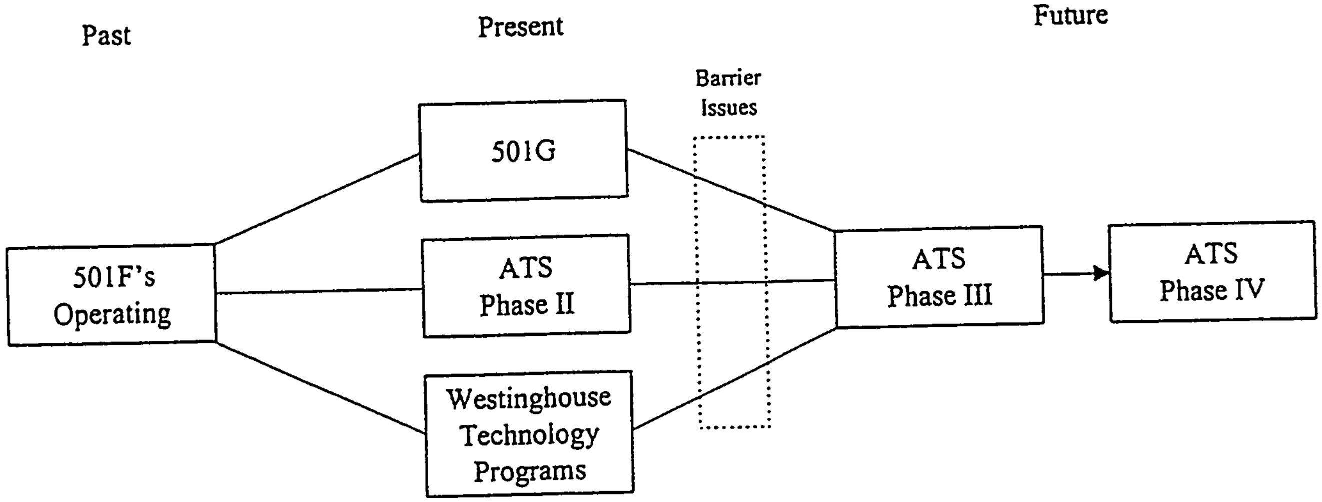

Figure 1. ATS Technology Development

two-pole generator will be an extension of the Westinghouse hydrogen-cooled modular design concept.

Objectives

The objectives of the ATS Program Phase 2 were to select the ATS cycle and to enhance or develop technologies required to achieve the ATS Program goals. This paper describes progress on the different technology development programs being conducted by Westinghouse in support of the ATS Program.

ATS Description

The ATS plant is based on the advanced combined cycle. The gas turbine, generator, and steam turbine will be connected together in an in-line arrangement with a clutch located between the generator and the steam turbine.

The ATS engine is an advanced 300 MW class design incorporating many proven design features used in previous Westinghouse gas turbines and new design features and technologies required to achieve the ATS Program goals. The compressor design philosophy is based on that used in the advanced 501G compressor. The aerodynamic design uses 3-D viscous codes, controlled diffusion airfoils and reduced airfoil thicknesses. Variable stators are incorporated in the front stages to improve starting and part-load operation.

The combustion system has 16 combustors of lean-premixed multistage design with catalytic components. To limit NOx emissions to less than 10 ppmv, nearly all of the compressor delivery air is premixed with the fuel. Therefore, closed-loop steam cooling is used to cool the combustors and transitions.

The four-stage turbine is an extension of the advanced 501G turbine design. The design is based on 3-D design philosophy and advanced viscous analysis codes. The airfoil loadings are optimized to enhance aerodynamic performance while minimizing airfoil solidity. The reduced solidity results in reduced cooling requirements and increased efficiency. To further enhance plant efficiency, the following features are included: turbine airfoil closed-loop cooling, active blade tip clearance control on the first two stages, improved rotor sealing, and optimum circumferential alignment of airfoils.

The ATS engine and plant conceptual designs have been completed and design reviews were held to verify these preliminary designs.

Phase 2 Component Development Projects

To resolve the identified barrier issues and achieve the ATS Program goals, an extensive R&D program is in progress in the fields of combustion, cooling, aerodynamics, leakage control, coatings, and materials.

Combustion

Due to the strict emissions requirements for the ATS engine, combustion development will be one of the critical areas requiring significant effort. To address this issue the following combustion development programs were initiated: combustor flow visualization, combustor cylinder flow mapping, optical diagnostics probe development, combustion instability/noise investigation, and catalytic combustion component development. In addition, several dry ultra low NOx combustor development programs are in progress.

Flow Visualization. Air flows inside the combustor cylinder and into the combustor baskets are very complicated. These flows have a significant effect on the losses, and hence on engine performance, and on the flow distribution inside the combustor baskets and hence on the combustion processes. The latter effect is especially critical in the dry ultra low NOx lean-premix combustors, which rely on the correct fuel/air ratios within a very narrow tolerance band, for low NOx production and operational flame stability. Flow tests are being carried out on plastic models of the ultra low NOx baskets in the single-can rig and the sector rig at Westinghouse Casselberry Labs. Flow visualization, detail flow mapping tests and effective flow area measurements are being performed. Hot wire anemometry, as well as other conventional measurement techniques, are employed.

Combustion Cylinder Flow Mapping. Flow mapping and flow visualization tests are in progress on a half-scale plastic model of a combustion cylinder at Clemson University. Higher order effects inside the combustor are being investigated. Detailed measurements of pressures, velocities and flow angles inside the combustion cylinder, and especially around the combustor baskets, are being obtained. Included in this investigation is the effect of struts, cooling air return pipes, top-hat length increase and cooling air extraction. In addition to studying and optimizing the flow around the combustor baskets, the objectives of these tests are to optimize the performance of the compressor exit diffuser, reduce the diffuser exit dump loss, and hence improve the ATS engine performance. In support of the experimental program, a CFD analysis of the combustion cylinder flow field was carried out.

Optical Diagnostics Probe Development. Optical diagnostics allow measurement of pertinent parameters, such as the composition and concentration of combustion products, in addition to velocities and flow angles, without disturbing the main flow. A laser-induced fluorescence fibre optic probe is being developed. Probe evaluation at high pressures and temperatures is in progress. This probe will be a very useful tool in enhancing combustion development productivity. It will be used in cold flow and fired tests.

Combustion Instability Investigation. Lean-premix combustion system will be employed to achieve the NOx emissions goals. The lean combustion with its inherent flame instability results in more combustion generated noise and hence in vibration problems in the combustion system as well as in the downstream components. A program to develop the theoretical background for combustion instabilities, to carry out experiments to aid in the understanding of the problem, develop a generalized analysis procedure, and to develop stability criteria is under way.

An active noise control system is being developed to eliminate combustion instabilities. It consists of a sensor to detect the combustion instabilities, signal processor, feedback algorithm generator and a fuel modulation valve and controller.

Ultra Low NOx and Catalytic Combustion Development. Westinghouse is developing several ultra low NOx combustors (Foss et. al., 1994). The ATS combustor will be based on the most successful candidate. Catalytic combustion will play an important role in achieving ultra low NOx emissions at the ATS engine firing temperature. The catalyst allows ultra lean-premix combustion without flame instability and flame outs. Therefore, NOx production is restricted to low single digits at ATS firing temperature with stable operation. Development is in progress to gain theoretical understanding of catalytic combustion, to design a catalytic combustion system using the "clean sheet approach" and to develop a practical catalytic combustor. Catalyst coated pilot has been tested in an ultra low NOx combustor with excellent results. A catalytic combustor with exhaust gas recirculation to preheat the catalyst to the required temperature is being designed.

Cooling

Closed-Loop Steam Cooling. The one new concept that will result in the greatest increase in the ATS plant cycle efficiency is closed-loop steam cooling. There are several challenges to a successful closed-loop steam cooling system. These include maintaining airfoil surface metal temperatures without outside film cooling, limiting wall temperature gradients, preventing corrosion and fouling of internal components over long periods of time, bringing coolant to and out of rotating components, leakage control, and cold start before steam from the downstream HRSG is available.

The major contributor to plant efficiency increase with closed-loop steam cooling is the elimination of cooling air injection into the turbine flow path. This results in an increase in gas temperature downstream of the first stage vane and hence an increase in gas energy level during the expansion process. A secondary contributor is the elimination of mixing losses associated with cooling air ejection. The combination of these effects results in a significant increase in ATS plant efficiency. In addition, NOx emissions will decrease because more air is available for the lean-premix combustor at the same burner outlet temperature. Achieving acceptable blade metal temperatures in a closed-loop cooling design is a challenge due to the absence of cooling air film to shield the turbine airfoil and shroud wall, and no shower-head or trailing edge ejection to provide enhanced cooling in the critical leading and trailing edge regions. To produce an optimized closed-loop cooling design, the following approaches are utilized: (1) airfoil aerodynamic design tailored to provide minimum gas side heat transfer coefficients, (2) minimum coolant inlet temperature, (3) thermal barrier coating applied on airfoil and end wall surfaces to reduce heat input, (4) maximized cold side surface area, (5) turbulators to enhance cold side heat transfer coefficients, and (6) minimum outside wall thicknesses to reduce wall temperature gradients and hence the internal heat transfer coefficients required to cool the airfoil.

Preliminary investigation was carried out on the following turbine airfoil closed-loop cooling concepts: thin wall shell/spar, thin wall casting, and peripheral spanwise cooling hole. More detailed calculations will be carried out to select the final ATS airfoil cooling design.

Shroud Cooling. The airfoil end walls or shrouds present a cooling challenge. The combination of flat burner outlet temperature profiles and uncertainty in the end wall heat transfer coefficients make it difficult to arrive at an optimized shroud cooling design analytically. To address this issue, plastic model tests are in progress to optimize first stage turbine vane shroud film cooling design. The thermochromic liquid crystal technique is being used to measure the surface temperatures and hence the heat transfer coefficients.

Serpentine Channel Cooling. To maintain low blade metal temperatures, complicated multipass serpentine cooling schemes are being developed. Plastic model tests are being conducted to verify and optimize the design prior to incorporation into the engine. Two models are being tested: one model simulating the multipass mid chord region of the blade and the second model representing the trailing edge portion of the blade. Tests are being carried out at different cooling air flow rates. The internal heat transfer coefficients and pressure losses are being measured. Tests on the trailing edge model have been completed, and testing on the mid chord model is in progress.

Integral Shroud Cooling. Turbine blades in the rear stages are designed with an integral interlocked tip shroud to enhance performance and to improve mechanical integrity by providing vibration damping. Metal temperatures and stress levels on these blades may necessitate cooling not only the airfoil, but also the tip shroud. A new approach is required in the cooling design, casting, and machining to cool the shrouds with cooling air, which will heat up through the blade before reaching the tip shroud. To effectively cool the tip shroud, alternative cooling schemes and manufacturing processes were investigated. An optimized shroud cooling design was developed. This cooling concept consists of a cast cavity in the bottom portion of the blade and a mid chord radial hole to supply tip shroud cooling air. The velocities and internal heat transfer coefficients in this hole are low. Therefore, the cooling air heat pick-up is minimized before the cooling air enters the cooling holes machined in the shroud.

Aerodynamics

High Efficiency Compressor. High efficiency compressor design is being developed for the ATS engine. The ATS compressor design philosophy is based on that used for the advanced 501G compressor. The aerodynamic design uses 3-D viscous codes, reduced number of stages, controlled diffusion airfoil design, reduced airfoil thicknesses and advanced sealing. An optimization study was carried out to optimize each stage efficiency individually so as to maximize the efficiency for the design pressure ratio with the minimum number of stages. Compressor performance at off-design conditions was investigated to ensure adequate surge margin over the entire operating range. Blade and stator profile definition is in aerodynamic/mechanical design iteration. All airfoils are custom shaped using controlled diffusion design process. The design objective is to satisfy all mechanical constraints with minimum airfoil thickness so as to optimize efficiency.

Leakage Control

Active Blade Tip Clearance Control. Turbine blade tip clearance has a significant effect on the performance of highly loaded front stages. For each one percent tip clearance increase (based on blade height), the stage efficiency may decrease by up to 2 percent. Even if the initial cold blade tip clearances are set at minimum values, during transients, such as rapid starts and emergency shutdowns, the blade tips are ground off. This results in increased hot running blade tip clearances, which get progressively worse with time. To optimize turbine efficiency, an active tip clearance control system is being developed. The objective of such a scheme is to maintain large tip clearances on start-up and to reduce them to minimum acceptable values when the engine has reached steady state operating condition. A conceptual design of an active tip clearance control system is in progress.

Brush Seals. To reduce air leakage, as well as hot gas ingestion into turbine disc cavities, brush seals, which have the potential to reduce leakage by up to 90%, will be incorporated in appropriate locations in the turbine and compressor. This will enhance engine efficiency as well as mechanical integrity of the turbine components. To incorporate an effective, reliable, and long-lasting brush seal system into a heavy-duty industrial gas turbine, a development program was initiated. Preliminary investigation was carried out to evaluate the benefits, potential seal locations, and validation testing required to apply brush seals to industrial gas turbine engines. Conceptual seal design at one engine location was carried out. Tribopair tests were carried out on five different bristle alloys, two rotor materials, and two rotor surface finishes to determine which tribopair results in minimum wear. The optimum tribopair was selected for seal leakage testing.

Coatings

TBC Field Testing. Ceramic thermal barrier coatings (TBC) are important to the success of the ATS program. TBC low thermal conductivity effectively insulates the metal substrate and provides approximately 11 to 14°C (20 to 25°F) metal temperature reduction per .025 mm (.001 in.) coating thickness. While TBC's have been used widely on stationary components, use on rotating components has been limited. Field testing of coated blades must be carried out to determine comparative coating longevity and effectiveness of air plasma spray (APS) and physical vapor deposition (PVD) thermal barrier coatings. Three batches of first stage turbine blades coated with APS TBC, PVD TBC, and with only the metallic coating were installed in an operating engine. At the next engine inspection, these blades will be removed and the coating performance will be evaluated.

Advanced Coating Development. The ATS engine turbine component coatings must be capable of operation for 24,000 hours. To ensure this, a program is in progress to develop an advanced bond coat/TBC system. Different bond coats are being evaluated under accelerated oxidation test conditions. New ceramic candidate materials are also undergoing testing. The objective of this program is to combine the optimum bond coat with the best performing TBC to provide a coating system with maximum service life at the ATS operating conditions.

Materials

Single Crystal Blade Development. To enhance performance and reliability, single crystal blades will be incorporated in the ATS engine. A casting development program was carried out to demonstrate castability of large industrial turbine blades in CMSX-4 material. Existing 501F engine tooling was used to cast single crystal blades. The castings were evaluated by grain etching, selected NDE methods and dimensional inspection methods to determine their metallurgical acceptability. After several trials, excellent results were obtained on a solid and a cored stage 3 shrouded blade. These results demonstrate that large single crystal blades are castable in CMSX-4 alloy, although further process development is still needed to improve the yield.

A development program is in progress to generate single crystal materials data for ATS turbine blade design. The program objectives are: (1) to optimize post-cast heat treatment, (2) to generate tensile, creep, and fatigue test data, and (3) to generate single crystal material design curves.

Ceramic Components. Ceramic components have potential for reducing cooling requirements, enhancing engine performance and improving turbine component reliability. Investigations are being carried out into the applicability of ceramic components, such as combustors, transitions, and ring segments into large industrial gas turbines. A conceptual design of turbine ring segments using ceramic matrix composite material is in progress.

Future Activities

The Phase 2 technology development efforts have progressed sufficiently to demonstrate that the ATS program goals are obtainable in the 5-year time frame. The Phase 2 technology developments currently under way and those planned for Phase 3 should resolve the identified technical barrier issues, so that the performance, emissions, and RAM objectives may be achieved. A concerted combustion development effort will be carried out to provide the ATS engine with an environmentally benign combustion system limiting NOx emissions to single digits while achieving stable, reliable, long service life operation. The cooling program will lead to optimized cooling designs which should result in enhanced performance, mechanical integrity, and reliability. The advanced coating systems and materials development programs will make a significant contribution to enhanced turbine component reliability as well as increased performance. The aerodynamics and advanced sealing developments are intended to ensure that the ATS program performance goal of greater than 60% net plant efficiency would be achieved with a substantial margin. Significant tehcnological advancements have already been achieved in Phase 2. The technology development programs planned for Phase 3 will build upon these successes and advance the gas turbine state-of-the-art thus making a major contribution to the success of the ATS Program.

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Session 3

ATS Related Activities

3.1 Advanced Combustion Turbines and Cycles: An EPRI Perspective

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Abstract

EPRI conducts a broad program of research in combustion turbine technology on behalf of its funders which is directed toward improving their competitive positions through lower cost of generation and risk mitigation. The major areas of EPRI interest are:

- Combustion Turbine Technology Development, Assessment, and Procurement Information and Products.
- Risk mitigation of emerging combustion turbines through durability surveillance.
- Existing Fleet Management and Improvement Technology.

In the context of the DOE ATS Review, the present paper will address new advanced turbines and cycles and durability surveillance, of emerging combustion turbines. It will touch on existing fleet management and improvement technology as appropriate.

Recent Heavy Frame Commercial Offerings: In 5 years combined cycle efficiencies have advanced nearly 5 percent-points, with installed F-Class combined cycle plants offered and being installed at approximately 55 percent efficiency with new G- and H-Class combined cycle plants now being offered in the 58 to 60 percent efficiency range. These machines incorporate innovative cycles as well as new materials, higher pressure ratios, and higher firing temperatures. ABB's GT24 employs sequential re-heat combustion, while the Westinghouse G and the GE H machines incorporate steam cooling. These advances result from market forces and from technology diffusion from the DOE ATS program and DOE aircraft engine programs.

Aeroderivative Engines: Aeroderivative engines have consistently provided higher simple cycle efficiency. They also have the advantage of light weight, allowing easy replacement of hot sections or even of whole engines rather than having to repair in place. Large numbers of older aeroderivatives are in use at EPRI member utilities. EPRI has sponsored programs to improve their availability and reliability, which have been found to essentially match those of heavy frames. EPRI studies of advanced aeroderivatives have indicated the operational flexibility promise of the advanced intercooled aeroderivatives, which would have low first cost with comparatively high efficiency for intermediate load utility service.

Collaborative Advanced Gas Turbine (CAGT) Consortium: The CAGT consortium is an international alliance of major utilities (gas, electric, and combined), generating companies, project developers, and research consortia. Originally organized (Phase I) to study long range generation options focused on exploiting aircraft engine technology for land-based generation, the consortium has moved (Phase II) into commercializing the most favorable of those alternatives, the intercooled aeroderivative (ICAD). As competition and mid-range generation emerges as a distinct market, the ICAD has the potential for lower cost advantages generation between capacity factors of approximately 20 to 70 percent. Further, this technology can be applied to the small sizes which are appropriate for distributed generation.

Cascaded Humidified Advanced Turbine (CHAT) Plants: The CHAT plant offers higher part-load efficiency and projected lower first cost than combined cycle plants. The original application included in previous papers was to a large turbine providing almost 300 MW. More recent work has concentrated on smaller plants in the 8 to 80 MW range. These applications result in full load efficiencies equal to combined cycle, while having superior first cost, part-load efficiency, hot-ambient performance, and shorter starting cycles. The CHAT cycle also lowers the first cost of gasification systems. The Cascaded Advanced Turbine (CAT) and the Cascaded Humidified Advanced Turbine (CHAT) were developed in cooperation between Energy Storage and Power Consultants, Polsky Energy Co., CAT Limited Partnership, and EPRI. CAT and CHAT are patented in the United States and many other countries.

Durability Surveillance of New Turbines: Durability surveillance (a comprehensive reliability, availability, and maintainability program) involves monitoring, diagnostics, and condition assessment, all aimed at anticipating, intercepting, and solving short and long term operating problems to achieve the lowest cost operation for the owner. This concept of proactive risk mitigation is tailored for a faster-moving market with rapidly advancing technology. Durability surveillance is equally applicable, with appropriate modifications, to all sizes of machines from large central station machines to small sub-megawatt microturbines. EPRI is participating with its funders in durability surveillance of fleet leaders of the F-Class technology. We are developing durability surveillance of G- and H-Class machines and anticipate programs for the DOE ATS demonstration projects. We are also developing projects for much smaller machines and for more complex cycles such as CHAT.

Conclusions: EPRI's collaborative research and product development serves its funders in a competitive environment. It is focused toward bottom-line goals: (1) developing and bringing to the market alternative cycle options, (2) providing information and products for technology assessment and procurement, (3) mitigating risks of introduction of new technology, and (4) maximizing return from existing installed resources. Working in complementary fashion with U.S. Government agencies such as DOE and the National Labs, with other institutions such as GRI, and with its funders remains an important goal.

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3.2

Advanced Turbine Systems Annual Program Review

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Abstract

Integrated High Performance Turbine Engine Technology (IHPTET) is a joint Air Force, Navy, Army, NASA, ARPA, and industry program focused on developing turbine engine technologies, with the goal of doubling propulsion capability by around the turn-of-the-century, and thus providing smaller, lighter, more durable, more affordable turbine engines in the future.

IHPTET's technology development plan for increasing propulsion capability with respect to time is divided into three phases. This phased approach reduces the technological risk of taking one giant leap, and also reduces the "political" risk of not delivering a product for an extended period of time, in that the phasing allows continuous transfer of IHPTET technologies to our warfighters and continuous transfer to the commercial sector (dual-use). The IHPTET program addresses the three major classes of engines: turbofan/turbojet, turboshaft/turboprop, and expendables.

Session 4

University/Industry Consortium Interactions

4.1 The AGTSR Consortium: An Update

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Abstract

The Advanced Gas Turbine Systems Research (AGTSR) program is a collaborative University-Industry 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 directly 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. The consortium is organized to enhance U.S. competitiveness through close collaboration with universities, government, and industry at the R&D level. AGTSR is just finishing its third year of operation and is sponsored by the U.S. DOE - Morgantown Energy Technology Center. The program is scheduled to continue past the year 2000. This update will serve to review the AGTSR triad, which consists of university/industry R&D activities, technology transfer programs, and trial student programs.

At present, there are 78 performing member universities representing 36 states, and six cost-sharing U.S. gas turbine corporations. Three RFP's have been announced and the fourth RFP is expected to be released in December, 1995. There are 31 research subcontracts underway at performing member universities. AGTSR has also organized three workshops, two in combustion and one in heat transfer. A materials workshop is in planning and is scheduled for February, 1996. An industrial internship program was initiated this past summer, with one intern positioned at each of the sponsoring companies. 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 strives to keep a prominent U.S. industry strong and on top well into the 21st century. This paper will present the objectives and benefits of the AGTSR program, progress achieved to date, and future planned activity in fiscal year 1996.

Introduction

Natural gas turbine systems are rapidly becoming one of the prime technologies for generating electricity. Within the next 20 years, natural gas turbines could produce at least half of the new power-generating capacity in the United States. Natural gas turbine power plants are also attractive in other parts of the world where the

The AGTSR research consortium is sponsored by the U.S. DOE - Morgantown Energy Technology Center, under cooperative agreement DE-FC21-92MC29061 with the South Carolina Energy R&D Center.

demand is even stronger, because they can be quickly fabricated and installed with relatively low capital costs. In addition, the use of industrial gas turbines as power generators in urban areas is growing as the concept of distributed or dispersed power is embraced by an increasing number of utilities and independent power producers. Generally, the installation costs of small-moderate gas turbine generator systems are less than those of large central power plants, which makes dispersed power very attractive in terms of dollars per kilowatt.

To ensure that the United States remains the world turbine leader, the Department of Energy is working with U.S. turbine manufacturers in an 8-year program to develop an advanced, ultra-high-efficiency, environmentally superior turbine system that will be less expensive than today's systems. Specifically, development of advanced turbine systems will lead to:

•Energy efficiencies well exceeding 60%, more than 15% higher than the best gas-fired turbine systems available today.

•Fuel flexibility - the capability of using natural gas today and clean gas from coal or biomass in the future.

•Significantly improved environmental performance, with nitrogen oxide emissions well under half of today's utility turbines.

•Reduction in the costs of electric power, resulting in savings to consumers.

•Increased competitiveness of the U.S. turbine industry, which already leads the world in turbine technology but faces increasing competition abroad.

•Increased competitiveness of U.S. manufacturers, particularly those whose product costs are significantly influenced by the cost of buying electricity.

High-efficiency turbine systems will also reduce U.S. fuel consumption by helping us become more energy-efficient. Introducing advanced turbine systems into the power market by the year 2000 could result in a savings of energy equivalent to more than 100 million barrels of oil annually by 2020.

The Advanced Gas Turbine Systems Research (AGTSR) program is considered a subset of the Advanced Turbine System (ATS) prototype program. The AGTSR consortium is closely tied to ATS technology needs and has the potential to strongly impact the future design of land-based gas turbine systems. AGTSR was established to pursue, in a concerted fashion, the research needs as defined by the ATS industry. AGTSR is a valuable resource that promotes collaborative R&D and multidisciplinary education in coordination with industry, university, and government gas turbine R&D activities.

AGTSR will contribute to the scientific foundation of the 21st century land-based gas turbine engine. The U.S. Department of Energy and the Nation's leading gas turbine manufacturers have embarked upon the ATS program to develop future power generation systems that utilize advanced gas turbines in the new century. Developing ultra clean, high-efficiency turbines will require substantial leaps forward in the following:

•The science of high-temperature corrosion-resistant coatings.

•The understanding of complex heat transfer, aerodynamic, and combustion phenomena.

•The integration and analysis of innovative thermodynamic cycles.

•The knowledge of how pollutants are formed when natural gas and other fuels are burned in a turbine, and how they may be prevented from forming.

The South Carolina Energy Research & Development Center is coordinating and managing a consortium of 78 universities in 36 states that is providing these technological advances and establishing this fundamental base of knowledge. Under the Department of Energy's oversight, the consortium brings together the engineering and science departments of the Nation's leading universities and the industrial turbine developers to ensure that the next generation of natural gas turbines is built on a solid base of knowledge. The consortium's projects will be critical to the U.S.'s continued world leadership in turbine technology for the 21st century. The consortium was formed in 1992 and will continue through 2000. There are 31 university research projects underway selected by the consortium's industrial members. Each focuses on obstacles applicable to the entire industry, and for which university research is most appropriate. Topic areas include: combustion to improve fuel utilization and minimize environmental impact; heat transfer and aerodynamics to improve turbine blade life and performance; and materials and coatings to permit higher operating temperatures for more efficient systems.

Program Objectives

The Advanced Gas Turbine Systems Research (AGTSR) program is a unique, industry-oriented university research program with several objectives in mind:

•contribute to the technology-research base to support the Advanced Turbine Systems (ATS) prototype program for both industrial and utility applications.

•actively seek industry collaboration and strive to transition research results to ATS and future growth power generation systems that utilize stationary gas turbines in a combined-cycle fashion.

•enhance gas turbine - power generation research activities at American universities and promote collaborative R&D with professors and their students developing projects focused on industry-defined issues.

•enhance and develop new power system course development as related to stationary gas turbines, combined cycle and cogeneration areas; and sponsor undergraduate and graduate internships at industry labs or government facilities.

•co-sponsor seminars, workshops, and specialty-topic meetings that directly contribute to the needs of the ATS and

AGTSR programs.

The AGTSR consortium is viewed as a synergistic program dedicated to interjecting fresh ideas and higher-risk research concepts from universities to industry's advanced gas turbine product line. The AGTSR central theme is to promote collaborative R&D and multidisciplinary engineering education. AGTSR encourages strong university-industry alliances in all of their research activities. These alliances will enable closer ties and interactions with respect to focused research activity and new educational opportunities to support the next frontier of land-based gas turbines, enhance U.S. competitiveness in the global market, and prepare us to meet 21st century demands for advanced electrical power generation systems. AGTSR believes that consortia are an effective way of doing R&D, especially in the new century where industry is becoming shorter-term oriented and focused on day-to-day engineering problems. If in the 21st century we adopt the "old" way of doing R&D, university and industry will again become separated and we will start to lose our competitive edge in the worldwide market.

Program Description

The AGTSR consortium is a new way of handling collaborative R&D. After only three years, AGTSR is still plowing new ground for industry and continually seeks ways to improve the effectiveness of university-industry interactions. AGTSR is viewed as a model program with universities working together and with industry and government to produce new research results, concepts, and predictive techniques dedicated to advancing stationary gas turbine designs. AGTSR is considered a cooperative venture for the betterment of the U.S. economy and for supporting a prominent U.S. industry to keep it strong and on top in the next century.

AGTSR Requests for Proposals are solicited on an annual basis with industry defining and prioritizing generic gas turbine research topics that are relevant to their needs and considered high payoff technology areas from the designer's perspective. The Industry Review Board (IRB) reviews the university proposals and selects superior ones for award. Proposal evaluation criteria consists of: technical merit and relevance to ATS goals; scope and value of R&D versus cost; leveraging of facilities; timeliness of results and transition plan; collaboration with industry; and qualifications and gas turbine related experience of research team.

The participating industrial members are AlliedSignal Engine Company, Allison Engine Company, General Electric, Pratt & Whitney of United Technologies, Solar Turbines, and Westinghouse Power Generation. All six of these IRB companies are cost-sharing AGTSR industrial members. Other members are the Electric Power Research Institute and the Gas Research Institute which represent the electric utility and industrial market segments that will purchase these advanced design gas turbines. The IRB is a very important facet of AGTSR, as it not only guides the technical thrust of the program but facilitates university-industry collaboration and ensures that university research studies make relevant technology contributions to the ATS program.

Research work by the university participants will be performed in existing or upgraded facilities, so program funding will be spent mainly on R&D activities. Universities must take the lead in any research proposal, however, they may subcontract with industry to support their research work. The work will generally be non-proprietary, with intellectual rights retained by the performing universities. All research results from the consortium are made available to the IRB, DOE and other AGTSR participants. Participation in the program is open to accredited engineering schools in the United States. Membership requires that the university administration indicates support for their faculty's involvement with the program. There are no membership fees for university performing members.

Results

As of September 1995, seventy-eight universities have been granted performing member status, representing 36 states and 6 major cost-sharing corporations. To date, there have been three RFP announcements with a total of 155 proposals submitted for competition. A total of 31 research projects are now underway: 11 projects are in combustion, 10 in heat transfer, 5 in aerodynamics, and 5 in materials. For the 1995 RFP, proposals were reviewed and evaluated not only by the Industry Review Board but also by technical experts representing DOD, NASA, and DOE-Oak-Ridge.

Figure 1. 1993 AGTSR Research Awards

Brigham Young	3D Combustion Model
UC/Berkeley	Catalytic combustion
Clarkson	Iceformation design method
Lehigh	Functionally Gradient Materials for TBC
LSU	Improved blade heat transfer
Penn State	Superalloy TMF analysis
Purdue	NOx submodels
Texas A&M	Aero and heat transfer improvements
Vanderbilt	NOx and CO submodels for LP flames
VPI	Innovative fuel/air flow control

DOD, NASA, and DOE do not vote or recommend proposals for funding, they only provided technical evaluation and advice to the IRB. Since the outcome of this evaluation was considered quite effective by the IRB, AGTSR will continue this type of collaborative review process for future RFP's.

Figures 1, 2, and 3 present the universities and associated research projects that were selected for award in 1993, 1994 and 1995, respectively. The trial educational portion of the AGTSR program motivates students and nurtures industrial internships to work more closely with companies and gain real-world engineering and design experience. At present, three trial programs are underway at the University of Minnesota, Clemson, and Clarkson University, dealing with undergraduate honors research projects. This program allows honor engineering students to be exposed to gas turbine R&D and work directly on a parent AGTSR research project. The AGTSR Industrial Intern program began during the summer of 1995. This program was highly recommended by the IRB. A total of thirteen applications were received and based on industries review and evaluation, six interns were selected to participate in the eight-week long program. Three interns from UC-Irvine were targeted for Solar Turbines, AlliedSignal, and P&W. An intern from Carnegie Mellon was positioned with GE-Corporate R&D, another from Central Florida joined Westinghouse - Orlando, and an intern from VPI joined Allison Engine Company in Indianapolis. All interns were graduate students and the intern from Carnegie Mellon was a post-doctorate student. The interns were paid a weekly stipend of $450 dollars per week. AGTSR received positive feedback from industry and interns, and plans are to at least double the number of interns in fiscal year 96 after AGTSR applies to DOE for this program expansion. Some constructive comments were to expand the program from 8-weeks to 10-weeks, distribute applications much earlier in the year, and provide an allowance of $1000 per intern to absorb dislocation expenses when traveling to the sponsoring company site. Depending on funding availability, the undergraduate research program may also be increased to 5-10 additional students next year. New program direction and initiatives are established by means of workshops and focused specialty meetings. In addition, long-range technology priorities and research issues for yearly RFP announcements are periodically reviewed and updated by the IRB.

Figure 2. 1994 AGTSR Research Awards

UC/Irvine	Mixedness effects in LP Combustors
Carnegie Mellon	Optical heat flux sensor
Central Florida	Steam effects on superalloys
Clemson	Film cooling computational tool
Cornell	PDF method for methane fuel
Georgia Tech	Combustion CVD for TBC
Maryland	Enhanced combustor pre-mixing
MIT	Rotational effects on heat transfer
Michigan State	Steam vs air for blade cooling
Minnesota	Film Cooling geometry effects
Oklahoma	Intercooler flow path analysis
Purdue	Multistage turbine aerodynamics
Wyoming	Turbulence effect on heat transfer

Research results from the AGTSR program are made available through semi-annual technical progress reports and two-page executive summaries which are distributed to the IRB members. Copies of the full report are kept on file at SCERDC and may be requested by the IRB on an as-needed basis. The executive summaries are very useful to the IRB, as they help it stay abreast of new ideas, accomplishments, capabilities and collaborations.

Figure 3. 1995 AGTSR Research Awards

Arizona State	Disk cooling effectiveness
Clemson University	Closed-loop mist cooling
Connecticut	Thermal barrier coatings
Connecticut	Heat pipe vane cooling
Georgia Tech	Active combustion control
Penn State	Modeling turbomachinery losses
Penn State	Combustion instability
Syracuse	Inverse design methodology
Vanderbilt /CalTech	Active combustion control framework

The third RFP was released in December, 1994, with proposals due in early March, 1995. Fifty-nine proposals were received under this RFP, and nine were recommended for funding by the IRB. This RFP focused on three main research areas: combustion instability, aerodynamics and heat transfer, and thermal barrier coatings. For the three AGTSR RFP's announced, an average of 20 percent of the proposals submitted were selected for award. In the future, this rate may drop to 10-15 percent as the number of proposals increase and the funding level remains fairly constant until the year 2000. It is anticipated that a research base of 30-35 projects will remain active in the AGTSR program. The average project length is three years.

AGTSR has sponsored three workshops, two in combustion and one in heat transfer. An ATS Materials Workshop is being planned for February, 1996, in Charleston, SC. The Materials Workshop will be co-hosted with DOE Headquarters and Oak-Ridge. The first AGTSR Combustion Workshop was held at Vanderbilt University in February, 1994. At this workshop, the combustion instability topic was identified as a high-payoff research area by industry, and as a result was included as one of the research topics in the 1995 RFP announcement.

The second AGTSR Combustion Workshop was hosted by Purdue University and Allison Engine Company and took place at Indianapolis, March 27-29, 1995. Over 85 people attended this workshop and an industry panel was also assembled to discuss industries' problems and concerns in the combustion instability area that required further research to enable lean, premixed combustion under realistic ATS operating conditions. Some of the important research issues highlighted at the workshop were the need for high pressure scaling, the justification of dual-fuel research, the coupling of swirl-acoustics influence, and NASA-Lewis' offering of a National Combustor Code by FY99 to industry and universities. We still plan to have combustion workshops on an annual basis. The third AGTSR Combustion Workshop will be held in March, 1996, at Lake Arrowhead, CA, hosted by UC-Irvine. This workshop will be organized in a more informal format -- AGTSR is considering a "Gordon-style" approach to review and discuss DOE sponsored combustion research activities.

AGTSR recently organized their first specialty technical retreat on combustion instability. This retreat was hosted by Penn State University. This first such retreat was motivated by the need to bring university and industry researchers closer together in certain subthrust topics of a technical discipline -- in this case, combustion instabilities in lean, premixed systems. The intent is to have a higher level of interaction focusing just on the specialty topic, in contrast to workshops which are wider-scoped in their review. Additional retreats covering other specialty topics within the heat transfer, aerodynamics, and materials areas will be considered on an as-needed basis. The specialty meeting at Penn State resulted in an important action item: industry experts in combustion instability agreed to review the experimental design, modeling, and prediction capability set forth in the new AGTSR proposals with the intent to mesh specific research/experimental deliverables with industry needs. This is a positive step in maintaining close collaboration with AGTSR combustion researchers on a regular basis.

AGTSR's first heat transfer workshop, hosted by Clemson University, took place March 1-3, 1995, at Hilton Head Island, SC. Over 70 people participated at the workshop with a strong attendance from industry and university researchers in the field. Heat transfer experts from NASA-Lewis and Air Force also attended the workshop. Tom Bechtel, the director of METC, gave the keynote dinner address where he stressed the importance of ATS and urged industry and universities to continually strive to work closer together -- especially at the R&D level. Some of the key conclusions identified at the workshop addressed the need for coupled aero-cooling optimization methods, doing more fundamental work in disk cooling and cavity flows, closed-loop air-mist cooling concepts and new advanced yet simple methods for internal cooling augmentation, new cooling concepts for the turbine gas path endwall regions, unsteady blade vane passing influence on heat transfer and film-cooling, and inviting software companies to our workshops to better understand the heat transfer modeling issues of industry and universities. Heat transfer workshops will probably continue on a bi-annual basis.

Daniel B. Fant and Lawrence P. Golan presented an AGTSR program update paper at the IGTI Turbo-Expo Conference in Houston, June,

1995. The paper was entitled "A Collaborative Venture: The Advanced Gas Turbine Systems Research Program." The paper was well attended in Houston and discussed the objectives and merits of the AGTSR research consortium, progress achieved to date, and future planned activity. The paper was presented in the session on industry, government, and university gas turbine consortia.

Based on a recent AGTSR Faculty/Student Inventory Summary, our FY93 and FY94 research subcontracts have placed AGTSR in contact with nearly 200 professors and students nationwide. It is this type of outreach that will keep our land-based gas turbine business competitive in the world-wide market. In addition, AGTSR will continue to grow and impact students, professors and industry as we initiate more research projects and continue to nurture the industrial internship and undergraduate fellowship programs within the AGTSR educational mission.

For the first two years of the AGTSR program, nearly $1.5 million dollars in cost-sharing has been achieved. This amount is essentially from three sources: Industry Review Board membership dues, cost-sharing from the 23 university research subcontracts, and industry time for proposal reviews and evaluations and program related travel expense and technical coordination meetings. Cost-sharing should continue, as AlliedSignal just recently became a new industrial member and 9 new research projects were started in September, 1995.

AGTSR recently became an affiliate member of the newly established Gas Turbine Association (GTA) that took over the charter of the American Gas Turbine Manufacturer's Association (AGTMA). The new chairman is Bill Day of United Technologies Turbo Power and the treasurer is Sy Ali of Allison. The executive director and spokesperson for GTA is Jeff Abboud. GTA is an advocate of gas turbine R&D and the ATS program. GTA had their first forum meeting in August, 1995, where they discussed gas turbine education and research needs, regulatory issues, and domestic and overseas marketing concerns.

AGTSR has also submitted two technology briefs for the 1995 and 1996 IGTI Technology Reports, which represents a great way to publicize the AGTSR program worldwide. Five AGTSR "Update" Newsletters have been published and distributed to all university and IRB members, METC and interested DOD and NASA personnel.

Status and Future Plans

The AGTSR program currently has 78 Performing Members, representing 36 states, and six gas turbine manufacturers as Industrial Members. Thirty-one research subcontracts are now underway. Substantial research is already in place in the combustion and heat transfer areas. Aerodynamics and materials research needs to be boosted and will likely become higher priority topics in future RFP's. New topics, as defined by the IRB, may also be added, such as dual-fuel issues and sensors and controls for land-based systems.

AGTSR continues to remain optimistic about maintaining funding for the outyears, even in light of DOE changes and consolidation. AGTSR contains some key ingredients for 21st century research consortia such as sound technical goals, close coordination with industry and universities, and economical and environmental attributes that have substantial benefit at the state and national level.

If the AGTSR budget remains fairly level, we plan on issuing yearly RFP's to address all the important technology and research barriers identified by the IRB. AGTSR anticipates that the 96RFP will be announced about the same time as last year, early December, with proposals due in late February. During the fall, AGTSR will be working with the IRB to finalize research topics and technology priorities. Proposals will continue to be evaluated, reviewed, and selected by the IRB with technical input and coordination from EPRI and GRI. We plan on maintaining a research base of between 30-35 research subcontracts out to the year 2000.

In FY96, AGTSR plans to expand the industrial internship program and possibly start a companion industrial summer faculty program. We will also continue with our Hotline program so that universities may highlight important research accomplishments for industry on a timely basis. We plan on expanding our industry base by targeting coating and utility companies. Recently, invitations have been extended to several firms to join the AGTSR consortium.

With METC, we are coordinating a technology matrix chart that will depict research program ties with university and industry partners. This matrix will be very useful in identifying research needs and facilitating the coordination and transition of research results and innovative design concepts to industry.

The AGTSR program is progressing well with focused, industry-oriented, university research goals coupled with a long-term educational mission. AGTSR is an exciting and timely consortium and is highly needed to complement industry's short-term R&D focus. Please let us know if you have any suggestions to make our consortium stronger, more in-tune with industry, and more effective.

Acknowledgements

The research support provided to the South Carolina Energy Research and Development Center is gratefully acknowledged. SCERDC acknowledges the assistance of the DOE Project Managers, Dr. Norman Holcombe and Mr. Charles Zeh. SCERDC sincerely appreciates the assistance provided by our Industrial Review Board Members; Dr. Sy Ali, Dr. William Day, Paul Bautista, Ihor Diakunchak, Dr. Arthur Cohn, Dr. James Corman, George Padgett and David Winstanley.

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Panel Overview of Allison/AGTSR Interactions

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Abstract

Introduction:

Morgantown Energy Technology Center's Tom Bechtel's perseverance resulted in the creation of the Advanced Gas Turbine Systems Research (AGTSR) initiative in 1992. His foresight resulted in establishing an advanced gas turbine research center. The center is supported by the Government and industry. The industry serves in an oversight role, and helps select the type of research projects to be conducted by universities. AGTSR now represents an effective university and industry partnership, and is recognized as a positive mechanism.

Allison Engine Company (Allison) continues to be an active participant and a strong supporter of the Advanced Gas Turbine Systems Research initiative at Clemson University. Allison took part in early formulation stages of this university/industry consortium. We have been a member of the consortium since its inception in 1992.

Allison's senior management is cognizant of the benefits of these jointly sponsored research programs. Over the years, Allison has promoted cooperative gas turbine research and advanced technology development at many universities. This activity is conducted through direct assignments at Allison for university students, and support of research projects at various universities, focused on different disciplines of gas turbine research.

Potential Benefits of AGTSR Consortium to Industry Members:

The benefits to industry members from participation in the consortium are directly proportional to the effort made by an industry member in guiding the initiative. The following observations on the benefits to industry and universities, represent the views of one industry member:

- With only nominal investment, the industry can direct high-risk gas turbine research, which is essential to long term U.S. leadership in world markets. Federal Government's financial support is essential to achieve this objective. Industry, with its priority on programs offering near term payoff, cannot underwrite long term research.

- The results of advanced gas turbine systems research are aimed to facilitate technological enhancements in the second generation advanced turbine systems. The output of this research will be available to all industry members

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for incorporation, with possible modifications, in their products.

- The single discipline oriented workshops, such as on combustion and heat transfer, offer major opportunities to key representatives of a member company to interact with respective universities personnel. These workshops should be expanded to include timely gas turbine research needs, and maintain certain frequency to encourage this productive information exchange.

- The coop student program, initiated by AGTSR in 1995, is mutually beneficial to universities and industry. This program should be expanded further.

  An industry member, who also participates in similar research initiatives at the Department of Defense (DoD), National Aeronautics and Space Administration (NASA), and National Institute of Standards and Technology (NIST), could likely gain more from participation in the AGTSR consortium.

  A major benefit of this initiative is the access to and direction of research at 78 universities in 36 states, with a nominal investment by industry members.

How to Enhance the AGTSR Consortium Output Product:

The following recommendations are presented to improve further the benefits to participants in the Consortium:

- Industry members should provide a prioritized listing of the latest pertinent research issues representing gas turbine research needs to AGTSR. This list should be available to AGTSR prior to the next solicitation for proposals.

- AGTSR should encourage university/ industry teams to make the research models more useful through proper experimental validation of the analytical data. This mechanism also enables utilization of existing experimental facilities at member companies, which otherwise would require a major capital investment.

- Solicitation for proposals documents should provide sufficient guidance to university respondents, in order to make their efforts worthwhile, and more responsive to AGTSR's needs. If possible, proposals evaluation criteria and weighting factors should be outlined in the solicitations.

- Stronger emphasis on advanced materials and coatings research is needed by AGTSR.

- The guidance from DoD and NASA in the proposals evaluation process should be continued to minimize duplication of research, or pursuing unproductive research.

- Analytical models developed at universities should be applied to at least one practical problem of a gas turbine manufacturer.

Session 5

ATS Supportive Projects

5.1 Design Factors for Stable Lean Premix Combustion

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Introduction

The Advanced Turbine Systems (ATS) program includes the development of low-emission combustors. Low emissions have already been achieved by premixing fuel and air to avoid the hot gas pockets produced by nozzles without premixing. While the advantages of premixed combustion have been widely recognized, turbine developers using premixed nozzles have experienced repeated problems with combustion oscillations. Left uncontrolled, these oscillations can lead to pressure fluctuations capable of damaging engine hardware. Elimination of such oscillations is often difficult and time consuming — particularly when oscillations are discovered in the last stages of engine development.

To address this issue, METC is studying oscillating combustion from lean premixing fuel nozzles. These tests are providing generic information on the mechanisms that contribute to oscillating behavior in gas turbines. METC is also investigating the use of so-called "active" control of combustion oscillations. This technique periodically injects fuel pulses into the combustor to disrupt the oscillating behavior. Recent results on active combustion control are presented in Gemmen et al. (1995) and Richards et al. (1995). This paper describes the status of METC efforts to avoid oscillations through simple design changes.

Approach

METC uses two experimental devices to study combustion oscillations. An atmospheric-pressure combustion duct (Figure 1) is used to study combustion oscillations produced by a premixing fuel nozzle. This combustor is used to screen various concepts for stable combustion, including changes to nozzle geometry and active control. Operation at atmospheric pressure allows relatively quick assessment of performance without the complications of pressurized operation. The fuel nozzle is mounted at the top of a 76-mm (3-in) refractory-lined duct. The fuel nozzle geometry is typical of current combustor designs, using swirl-vanes to generate a recirculation zone downstream of the nozzle exit. The 25-mm (1-in) annular swirl flow surrounds a 12.7-mm (0.5-in) pilot tube, which produces a pilot flame on the nozzle axis. The pilot flame is independent of the main lean premix flow exiting the nozzle annulus. The pilot allows flame-anchoring at conditions that would otherwise be too lean to support stable combustion. An optional extension leg at the bottom of the combustion duct allows changes to the acoustic frequencies that characterize the combustor. Tests results from this combustor are described below.

To complement tests conducted at one atmosphere pressure, METC uses a gas turbine

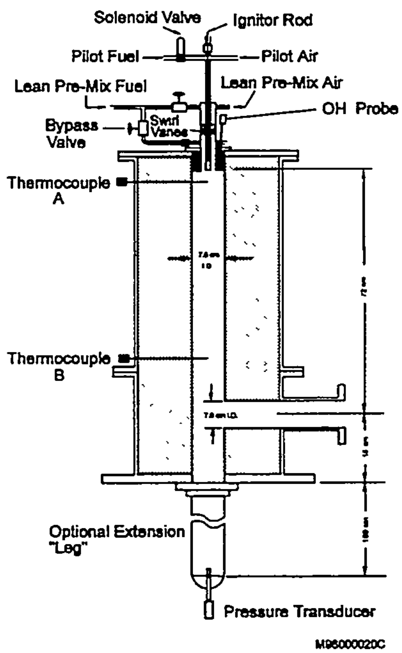

Figure 1. METC Atmospheric Pressure Combustor

style combustor (Figure 2). The combustion chamber is a water-cooled, cylindrical liner that has a diameter of 20 cm (7.9 in). To produce various acoustic modes, the liner is fitted with a removable refractory plug that is mounted on a seal ring as shown. The refractory is cast with a 7.5-cm (3.0-in) diameter passage on the central axis to form a cylindrical exhaust nozzle for the combustion region. The combination of the combustion chamber and the exhaust nozzle define a Helmholtz resonator with frequencies of interest to the gas-turbine designer (several hundred Hertz). The frequency can be adjusted by changing the dimension or location of the refractory plug. The combustor can operate at conditions typical of an industrial gas turbine, at pressures up to 11 atmospheres, and with the inlet air temperature preheated to 615 K (650 °F). The flow control valves are presently configured to meter combustion air up to 0.68 kg/sec (1.5 lbm/sec), but the facilities can supply combustion air up to 1.8 kg/sec (4 lbm/sec). Tests have already been conducted over the full range of operating conditions, demonstrating acoustic activity at the desired test points. As of this writing, test results showing the effects of operating pressure and inlet air temperature were preliminary, and will be presented in subsequent papers.

Results

Experiments in the atmospheric pressure combustor (Figure 1) have focused on establishing design methods to avoid oscillations from well understood instability mechanisms. Among the various mechanisms that contribute to instability, the variation in fuel or air flow rate may be most common. Reardon (1988) summarized more than 200 cases of combustion oscillations in dump combustors, and found that more than 70 percent of the oscillations were explained by variations in fuel or air flow-rate. Putnam (1971) reported on oscillations from dozens of commercial burners and attributed many of these cases to variations in fuel or air flow-rate. Because of their common occurrence in other burner designs, it is worthwhile to consider how these oscillations may be avoided in lean premix, gas-turbine fuel nozzles.

The processes occurring during fuel-feed variations are shown schematically in Figure 3. This figure considers just fuel-feed fluctuations; variations in the air flow are described by a similar behavior, but are not discussed here. Referring to Figure 3, air is swirled by vanes in the nozzle, which is upstream of the fuel injection point. The time average value of the fuel flow-rate is controlled by an orifice and control valve upstream of the fuel manifold, but the instantaneous value of the fuel flow, $\dot{m}_f(t)$, can vary in response to pressure fluctuations, P(t).

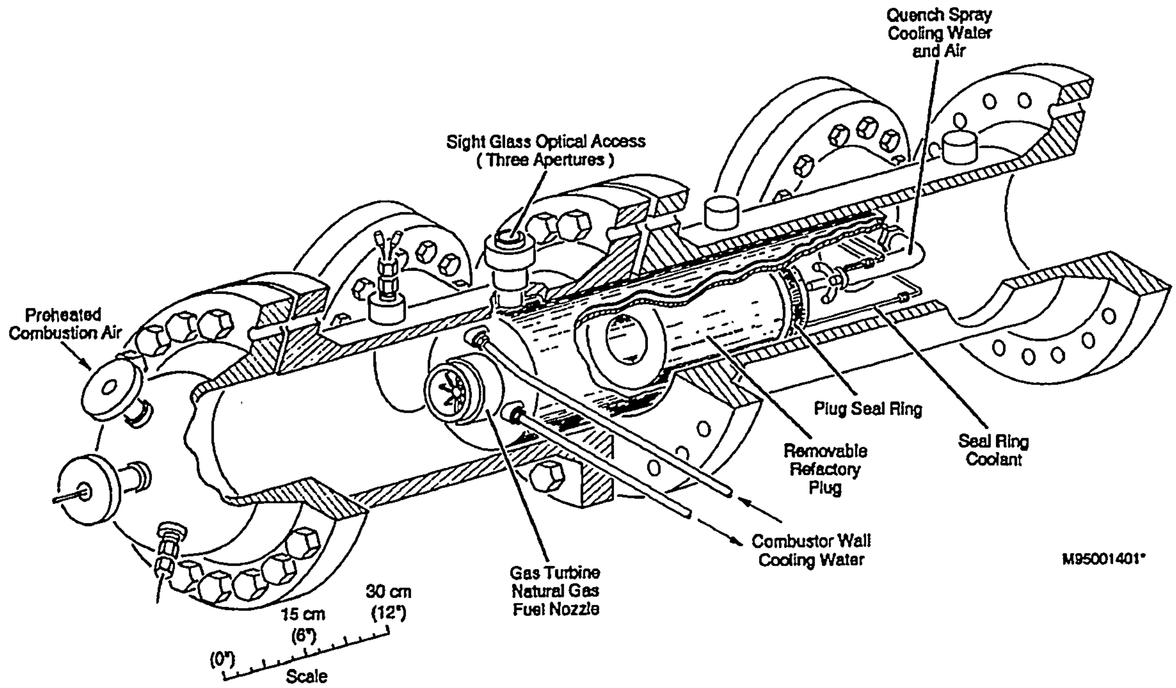

Figure 2. METC Unsteady Gas Turbine Combustor

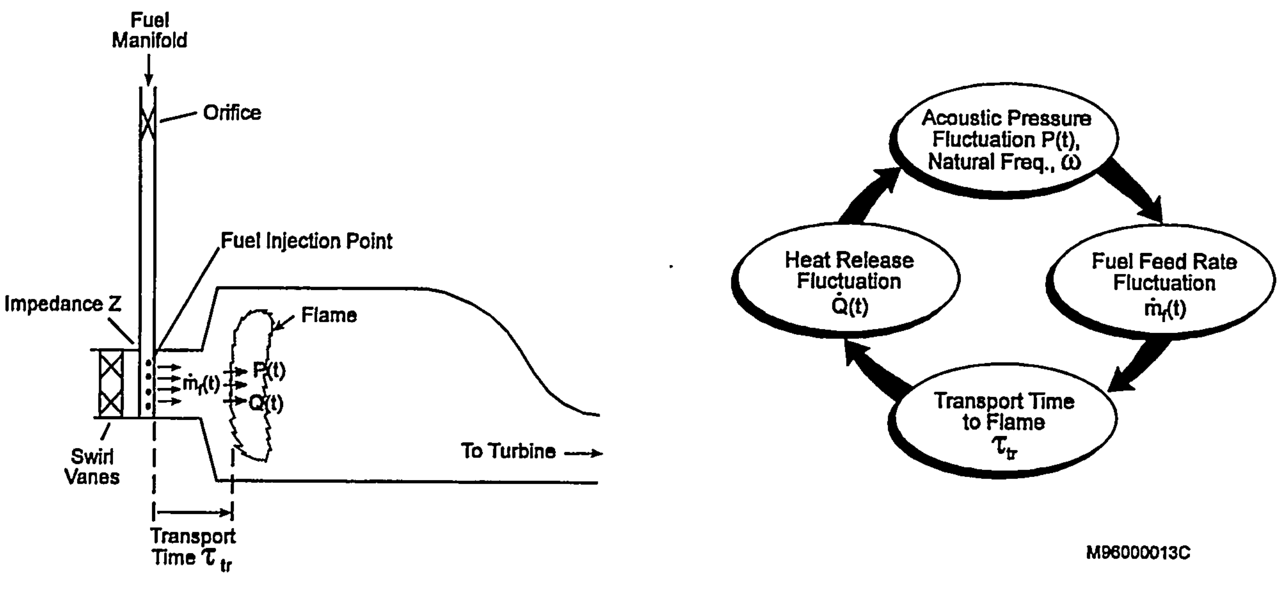

Figure 3. Schematic of Processes Occurring in a Fuel Nozzle/ Combustor During Fuel Feed Instability

For example, if acoustic waves in the combustor momentarily lower the pressure at the fuel injection point, the mass flow will briefly increase, producing a slightly richer fuel air ratio. This rich-mixture pocket will be transported to the premixed flame front in time, τ_{tr}, increasing the heat release rate, $\dot{Q}(t)$. If the accelerated heat release coincides with a high acoustic pressure (i.e., in phase), self-sustaining oscillations are very likely to occur. Conversely, if the heat release variations and the acoustic pressure disturbances are of opposite phase, the combustion should be stable.

These requirements are a statement of the well-known Rayleigh criterion for combustion oscillations. We note in passing that the easiest way to avoid these variations in fuel feed is to simply choke the supply of fuel at the point of fuel injection. A choked flow of fuel would not vary in response to changes in the downstream pressure, preventing the oscillations as described. This approach should be applied whenever possible, but an equal distribution of fuel on multi-nozzle gas turbines typically requires a carefully sized orifice *upstream* of the point of fuel injection, as shown in Figure 3. This limits the pressure drop available at the point of fuel injection. To avoid the penalty of excessively high fuel gas pressures, some tradeoff is necessary between the pressure drop at the fuel injection point and across the orifice. Even where relatively large pressure drops are feasible at the fuel injection point, operation at part load will suffer from reduced pressure drop.

In terms of the parameters shown on Figure 3, we showed in an earlier report (Richards and Yip 1995) how a criterion for oscillating combustion can be developed from the acoustic impedance, Z, of the fuel supply system. As in standard acoustic textbooks, the impedance is a ratio of the acoustic pressure to the change in volume flow of gas (i.e., fuel) flowing out of the fuel injection tube. Using a similar approach a criterion for stable combustion is

$$\textbf{phase angle} \left\{\frac{e^{-j\omega\tau_{tr}}}{Z}\right\} = \pi,\ 3\pi,\ 5\pi, \ldots \qquad (1)$$

Here, ω is the angular frequency in radians per second, and the transport time is estimated from the bulk flow velocity and the distance between the fuel injection point and the flame. The impedance, Z, is either known for simple geometries, or measured, and depends on the fuel system upstream of the fuel injection point.

In principle, combustion oscillations from fuel feed variations can be avoided by applying equation (1) during nozzle development. The transport time, τ_{tr}, and fuel system impedance, Z, should be designed to produce the requisite phase angle at combustor natural frequencies, ω. In practice, many of these parameters are difficult to estimate, making it difficult to apply equation (1) directly. Instead, it is suggested that equation (1) provides motivation to include some flexibility in nozzle design to allow subsequent changes to the relevant parameters.

As an example of how even slight changes to the fuel system impedance can play a significant role in combustion stability, METC's atmospheric pressure combustor was used to demonstrate certain features of equation (1). As described in Richards and Yip (1995), fuel feed oscillations were deliberately established in this experiment by supplying approximately 10 percent of the premix fuel through a "bypass" port, similar to the fuel injection point on Figure 3. The remaining 90 percent of the fuel was premixed with the air upstream of the fuel nozzle, entering the nozzle through choked orifices. The bypass arrangement allowed a select portion of the fuel to contribute to fuel feed oscillations, while the remainder of the fuel entered at a fixed rate.

To demonstrate the importance of the impedance, Z, the bypass port was manufactured from a variable length tube (Figure 4). The impedance of this tube is calculated from standard acoustic relations and is given by

$$Z = j*\text{constant}*\cot\left\{\frac{\omega L}{c}\right\}; \qquad j=\sqrt{-1}\ , \qquad (2)$$

where L is the length of the tube, and c is the speed of sound. Because the cotangent can change from a large positive to a large negative value at specific values of the length, L, equation (2) predicts that the phase angle in equation (1) can abruptly change with the length. This abrupt change may satisfy the requirements to either promote or silence oscillations. Figure 5 demonstrates this behavior from the METC experiment. The measured oscillating combustor pressure (root mean square, RMS) is plotted against the length of the bypass tube. As shown, a change of just 25mm (1 in) can activate the oscillation. This behavior is consistent with equations (1) and (2), and emphasizes the importance of understanding the role of the fuel system impedance before making changes to a fuel nozzle. From a design standpoint, it is suggested that allowance should be made for changes to the impedance should oscillation problems occur during combustor or engine testing.

Ongoing tests with the METC atmospheric pressure experiment have identified other oscillating mechanisms that may occur in turbine fuel nozzles. Figure 6 shows a plot of

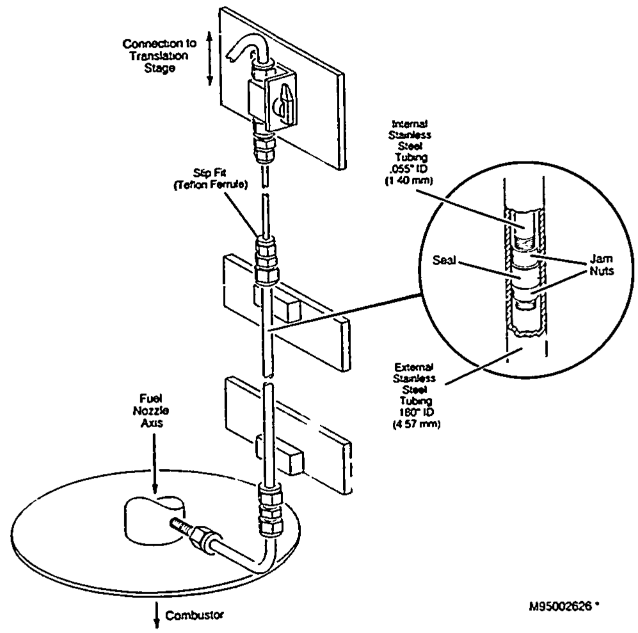

Figure 4. Variable Length Bypass Fuel Tube, Used on the Atmospheric Pressure Combustor (This tube corresponds to the fuel injection point in Figure 3.)

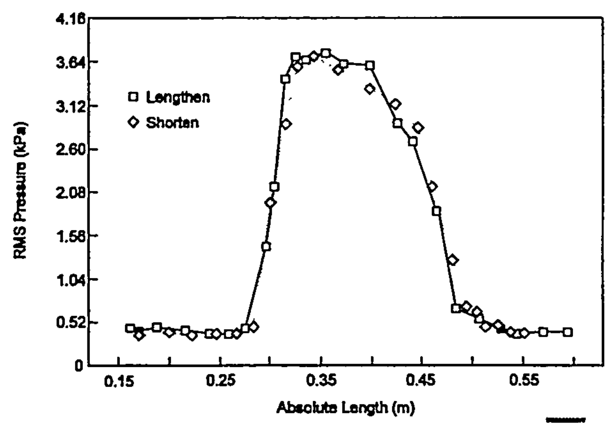

Figure 5. Oscillating Pressure Level (Root Mean Square) as a Function of the Bypass Tube Length

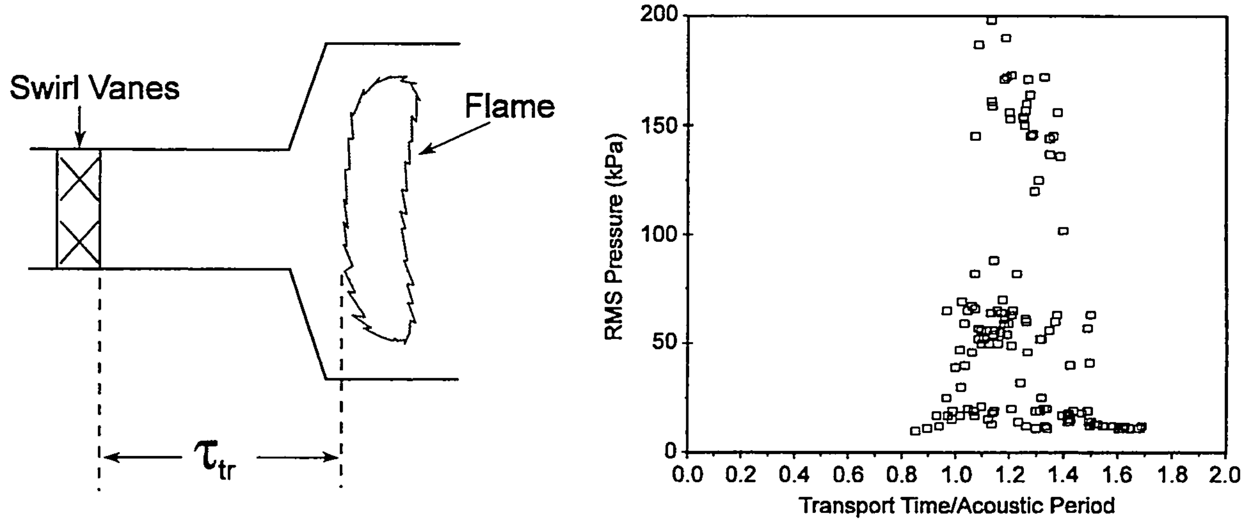

Figure 6. Oscillating Data Attributed to Changes in the Swirl Velocity. Note that transport time, τ_{tr}, is measured from the swirl vanes.

the recorded RMS pressure as a function of the ratio between the transport time, τ_{tr}, *measured from the swirl vanes, as shown,* and the acoustic period. In this nozzle, the fuel and air supply were choked so that fuel feed instability was not possible. The data in Figure 6 were gathered over a range of air flow rates, equivalence ratios, and oscillating frequencies. In spite of the changes in various operating parameters, oscillating behavior was confined to a specific range of time ratios between 1.0 and 1.5.

As described in more detail by Richards and Yip (1995), this behavior suggests that oscillations may result from a coupling between pressure fluctuations and changes in the axial velocity of fuel/air in the nozzle. If the axial velocity fluctuates, the fixed swirl vanes will produce changes in the tangential (or swirling) velocity. Such a change would altar the structure of the flame recirculation zone, and is thought to provide the mechanism needed to sustain oscillations. More data are being gathered to confirm this hypothesis. If this hypothesis is correct, such oscillations can be avoided by locating the swirl vanes along the nozzle axis to produce a time ratio greater than 1.5, or less than 1.0.

Future Work

Continuing tests in the atmospheric pressure combustor (Figure 1) are providing additional confirmation of the role of the swirl vane location in promoting stable combustion. In addition to the fuel feed instability described above, a criterion for avoiding fluctuations in the premixed air supply is being developed. METC is also testing various active control strategies (not discussed here) as an alternative to fuel nozzle design changes. METC's pressurized, unsteady, gas-turbine combustor (Figure 2) is being used to study the effect of operating pressure and inlet temperature on combustion stability. The pressurized combustor allows testing at a scale typical of industrial gas-turbine fuel nozzles.

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5.2 Ceramic Stationary Gas Turbine

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Introduction

The performance of current industrial gas turbines is limited by the temperature and strength capabilities of the metallic structural materials in the engine hot section. Because of their superior high-temperature strength and durability, ceramics can be used as structural materials for hot section components (blades, nozzles, combustor liners) in innovative designs at increased turbine firing temperatures. The benefits include the ability to increase the turbine inlet temperature (TIT) to about 1200°C (≈2200°F) or more with uncooled ceramics. It has been projected that fully optimized stationary gas turbines would have a ≈20 percent gain in thermal efficiency and ≈40 percent gain in output power in simple cycle compared to all metal-engines with air-cooled components (1). Annual fuel savings in cogeneration in the U.S. would be on the order of 0.2 Quad by 2010. Emissions reductions to under 10 ppmv NO_x are also forecast (2).

This paper describes the progress on a three-phase, 6-year program sponsored by the U.S. Department of Energy, Office of Industrial Technologies, to achieve significant performance improvements and emissions reductions in stationary gas turbines by replacing metallic hot section components with ceramic parts. Progress is being reported for the period September 1, 1994, through September 30, 1995.

Objectives

The overall objective of the DOE Ceramic Stationary Gas Turbine (CSGT) Development Program is to improve the performance of stationary gas turbines in cogeneration through the selective replacement (retrofit) of metallic hot section parts with uncooled ceramic components. The successful demonstration of ceramic gas turbine technology, and the systematic incorporation of ceramics in existing and future gas turbines will enable more efficient engine operation, resulting in significant fuel savings, increased output power, and reduced emissions.

Approach

The technology base for the CSGT program is provided by the advancements in ceramic component fabrication know-how developed under past ceramic turbine programs, such as the Advanced Gas Turbines (AGT) Program and the Advanced Turbine Technology Applications Program (ATTAP) of the U.S. Department of Energy, Office of Transportation Technologies. The program strategy provides a strong focus on near-term ceramic turbine technology demonstration and lowering barriers for its acceptance by the

[1] Research sponsored by U.S. Department of Energy's Office of Industrial Technologies, under contract DE-AC02-92CE40960 with Solar Turbines Incorporated, 2200 Pacific Highway, P.O. Box 85376, San Diego, CA 92186-5376; telefax: (619) 544-2830.

marketplace. Applications include retrofitting existing gas turbine installations and incorporating ceramic component technologies in future engine designs. The ceramic turbine technology to be developed under this program is also a key enabling technology to realize the performance and environmental goals of the Advanced Turbine Systems (ATS) program, a broad initiative of the U.S. Department of Energy, Office of Fossil Energy, and Office of Energy Efficiency and Renewable Energy, to develop the next generation of high performance gas turbines for utility and industrial applications (3).

Figure 1 is a schematic of the engine selected for ceramic insertion under the program, the Solar Centaur® 50S. The engine was formerly known as the Centaur Type 'H'. The baseline metal engine has a rated shaft thermal efficiency of 29.6 percent and an electrical output rating of 4144 kW and is fitted with a SoLoNOx™ dry, low-NO_x combustor. The gas producer turbine of the all-metal Centaur 50S has two stages and the power turbine has one stage. A single-shaft engine configuration was selected for the development engine.

The Centaur 50S is being retrofitted with first-stage ceramic blades and nozzles, and a ceramic combustor liner. The engine hot section is being redesigned to adapt the ceramic parts to the existing metallic support structure. Accompanying the ceramic insertion the Centaur 50S is being uprated from its current turbine rotor inlet temperature (TRIT) of 1010°C (1850°F) to a TRIT of 1121°C (2050°F). The performance improvements goals include a relative increase in the electrical thermal efficiency of 5.6 percent in simple cycle and 5.3 percent in cogeneration, and an increase in the electrical output from 4144 kW to 5217 kW, representing a relative increase of about 25.9 percent. Newer engines of the all-metal Centaur 50S engine model meet NO_x emissions levels of 25 ppmv over the 50-to-100 percent load range. Under the program NO_x emission levels of 25 ppmv or better must be demonstrated and the potential for much lower NO_x levels, 10 ppmv or better, must be indicated. Solar intends to demonstrate a NO_x level of 10 ppmv under the program. No CO level target was required for the program, but Solar has set a CO target of 25 ppmv. Predicted engine performance data have been reported previously (4).

Solar industrial gas turbines must be able to operate without interruptions, other than those resulting from scheduled maintenance for 30,000 to 40,000 hours, which is the typical time between overhaul (TBO). Ceramic components must therefore have design lives consistent with the expected TBO life. A 4,000-hour field test is planned for the program. To minimize the materials and design changes to the current metal engine, a design life target of 10,000 hours was selected for the engine and its components for the program.

Project Description

Project Team

Solar is the prime contractor on the program which includes participation of major ceramic component suppliers, nationally recognized test laboratories, a gas turbine manufacturer with expertise in life prediction, and an industrial cogeneration end user. The CSGT program team is summarized in Table 1.

Project Phases and Major Tasks

The program is conducted in three phases. Phase I of the program, started in September of 1992, involved concept and

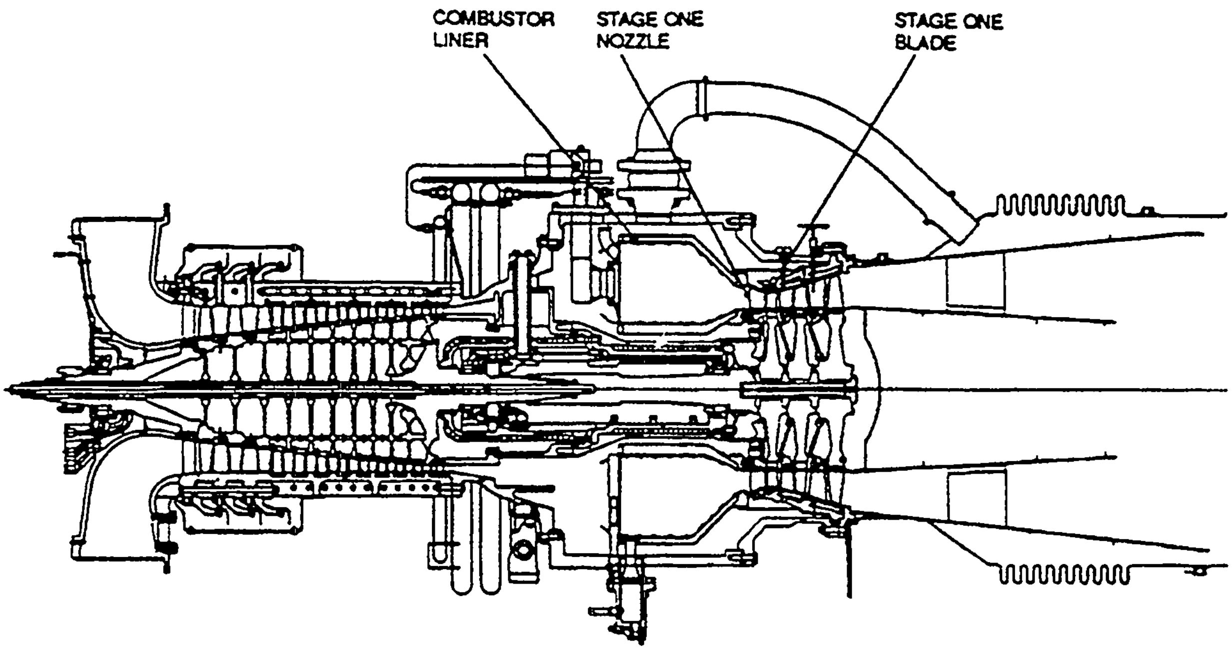


Figure 1. Solar Centaur 50S. Components for Ceramic Substitution are Indicated

preliminary engine and component design, ceramic materials selection, ceramic materials property assessment, and ceramic component fabrication planning, technical and economic evaluation, ceramic gas turbine concept assessment, and the development of a detailed work plan for Phases II and III of the program. The Phase I work has been presented at conferences (4-9) and has been fully documented in a final report (10).

The work in Phase II, started in April of 1993 and to be concluded in September of 1996, addresses detailed engine and component design (Task 7), ceramic specimen and component procurement and testing, including the testing of components in an engine rig (Task 9), low emissions combustor development (Task 10), and the development of a detailed plan for the Phase III 4,000-hour engine test (Task 11). Phase III of the program focuses on a 4,000-hour engine test at a cogeneration field site. Phase III major tasks include preparation and shakedown of the field test engine, the actual 4,000-hour field test, and ceramic component evaluation. A program management and reporting task (Task 16) accompanies the work in all phases of the program.

Figure 2 shows the program schedule. Major milestones for Phase II have been indicated.

Results

Phase II: Final Design, Material, and Component Testing

The program is currently in the third year of the 3.5-year Phase II scheduled performance period. First generation detail designs of the three ceramic components: the first-stage turbine blade, the first-stage nozzle, and the combustor liner have been completed. The starting point for the detail designs were the preliminary component designs developed

Table 1. CSGT Program Team

TEAM MEMBERS	RESPONSIBILITIES
GAS TURBINE MANUFACTURERS:	
Solar Turbines Incorporated (Solar)	* Program Management * Engine and Component Design * Materials Evaluation * Engine and Component Testing * Technical and Economic Evaluation * Technology Integration and Commercialization
Sundstrand Power Systems (SPS)	* Materials and Life Prediction Support
CERAMIC COMPONENT SUPPLIERS:	
Allied Signal Ceramic Components (CC)	* Rotor Blade (GN-10 Si_3N_4, AS-800 Si_3N_4)
Kyocera Industrial Ceramics Corporation (KICC)	* Rotor Blade (SN-253 Si_3N_4) * Nozzle (SN-281 Si_3N_4)
Norton Advanced Ceramics (NAC)	* Rotor Blade (NT164 Si_3N_4) * Combustor Liner (NT230 SiC)
NGK Insulators Ltd. (NGK)	* Nozzle (SN-88 Si_3N_4)
Carborundum	* Combustor Liner (Hexoloy® SA)
Babcock & Wilcox (B&W)	* Combustor Liner (Al_2O_3/Al_2O_3 CFCC)
DuPont Lanxide Composites (DLC)	* Combustor Liner (SiC/SiC CFCC)
B.F. Goodrich (BFG)	* Combustor Liner (SiC/SiC CFCC)
TEST LABORATORIES:	
Caterpillar Technical Center (CAT TC)	* Non-Destructive Evaluation (NDE)
Argonne National Laboratory (ANL)	
University of Dayton Research Institute (UDRI)	* Long-Term Testing of Ceramics
Oak Ridge National Laboratory (ORNL)#	
END USER:	
ARCO Oil & Gas	* End User Representation * Cogeneration Field Test Site
CONSULTANTS	Ceramic Materials, Design, Test

Support studies at ORNL were performed under a separate contract from the U.S. Department of Energy.

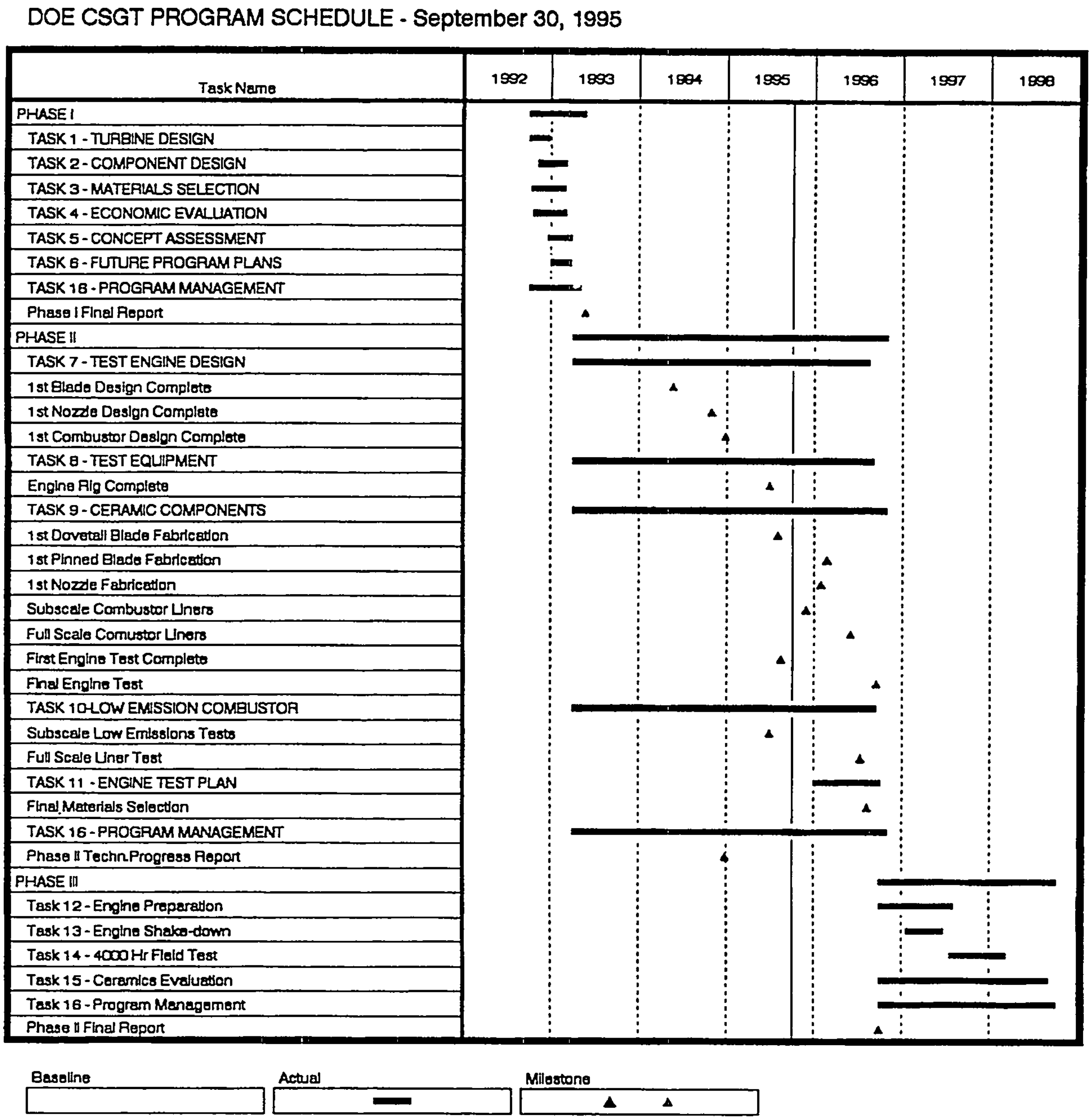


Figure 2. Program Schedule

in Phase I. In some cases significant changes had to be made to the Phase I preliminary designs to meet component life targets. For example, the attachment of one of the two blade designs, the pinned design, was modified to reduce design stress levels. In the case of the nozzle the airfoil design needed modification to reduce stress levels while retaining aerodynamic efficiency. The first generation combustor liner design is being modified after early subscale liner test results indicated the need for a more robust attachment configuration. First generation designs are nearly completed for most of the secondary hot section components adjacent to or in proximity of the ceramic parts.

Fabrication of ceramic components is in an advanced stage of completion. All first generation dovetail blades for engine testing have been delivered and first articles have been fabricated of the first generation nozzle design. Subscale combustor liner components have been fabricated by four suppliers and full-scale combustor liner components by one supplier. The ceramic components are being evaluated in rig and engine testing. Two engine tests involving ceramic blades were successfully completed during the reporting period. Combustor liner testing is in progress. Long-term testing of candidate ceramic materials in support of the design effort is continuing. NDE methodology has been fully developed for fiber-reinforced ceramic composites (CFCC) parts and is progressing for monolithic ceramics.

The Phase II work performed up until the end of 1994 has been reported in the literature (11-14). Detailed documentation of Phase II results until the end of October, 1994, can be found in a mid-phase Technical Progress Report (15). An account of program progress for the period September 1, 1994, through September 30, 1995, for each of the major tasks is given below.

Task 7: Engine and Component Design and Procurement

Figure 3 is an engine hot section layout showing broad aspects of the current design status of the three ceramic components: the annular combustor liner, the first-stage nozzle, and the first-stage blade as well as some detail of the secondary hot section components.

The critical steady-state temperatures and stresses for the ceramic components and selected candidate ceramic materials have been listed in Table 2. These design parameters will be further discussed under the narratives for the individual components.

Combustor Liner Design

The CSGT combustor is derived from the Centaur 50S SoLoNOx combustor. This is an all-metal, lean-premix, dry, low-NO_x combustor which provides NO_x levels of 25 ppmv and CO levels of 50 ppmv over the 50-to-100 percent load range for new engines. The emission levels are for operation with natural gas under conditions of 15 percent excess O_2. The combustor configuration is annular (see Figures 1 and 3). Ceramic insertion is targeted for the cylindrical sections of the outer and inner liners. The cylindrical sections are about 20 cm long. The diameters of the outer and inner liners are approximately 75 cm and 33 cm, respectively.

A key characteristic of lean-premix combustion is that as flame temperature, and consequently, NO_x emissions are lowered, CO emissions tend to increase. As a result, NO_x emissions are limited by the formation of unacceptably high CO levels. The benefit of ceramic insertion derives from the ability of a ceramic liner to operate uncooled at higher wall temperatures than a metal liner and thereby limit CO emissions. If CO emissions can be kept low by using a ceramic liner, then the flame temperature can be lowered, resulting in lower NO_x formation.

Under the CSGT program, both monolithic ceramics as well as continuous fiber-reinforced ceramic composites (CFCCs) are being considered as candidate materials for a "hot wall" combustor design. Although, in general, monolithic ceramics have greater strength than CFCCs their relatively low fracture toughness prevents their use as integral

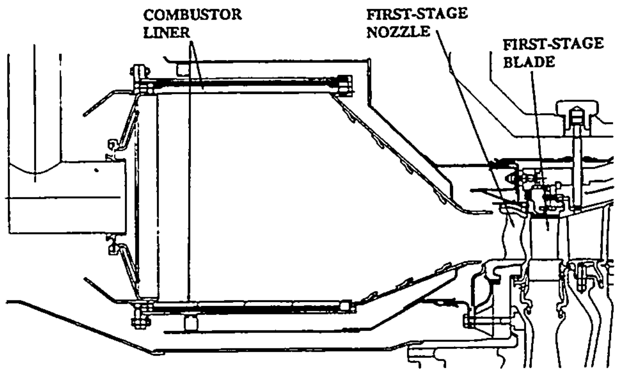


Figure 3. Schematic of CSGT Engine Hot Section

shapes for combustor liners of the size of the Centaur 50S SoLoNOx combustor. The combustor designs developed under the CSGT program incorporate monolithic ceramics in segmented (ring, tile) configurations while the much tougher CFCCs are used as integral cylinders.

The design shown in Figure 3 is a second-generation design for monolithics, showing inner rings and outer tiles. At present the tile design is only considered for the outer liner and the ring design for the inner liner. Tiles were not considered for the first generation inner liner design because the combustor pressure drop tended to disengage the tiles in that design. Rings are considered for the inner liner only, in part because of lack of supplier furnace capability, and in part because of the potential for critical defects in large outer liner rings. The other impediment is the projected cost of 75 cm diameter outer liner rings.

The rings and tiles are piloted through zirconia end elements and insulated from the metal housing using Nextel felt. Though insulated, the liner will operate below its 1204°C (2200°F) maximum design temperature limit. A metallic wave spring is used to control the axial load. The wave spring is cooled to a temperature lower than 538°C (1000°F) to prevent permanent deformation. The cooling air is exhausted into the combustion chamber. The flow is thereby minimized which prevents a detrimental effect on emissions due to flame quenching. The second generation design was

Table 2. Critical Steady-State Component Temperatures and Stresses

Component	Ceramic	Peak Temperature	Peak Stress
Blade (Airfoil)	NT164 Si_3N_4	1116°C (2041°F)	186 MPa (27 ksi)
Blade (Dovetail)	NT164 Si_3N_4	682°C (1260°F)	214 MPa (31 ksi)
Blade (Pinned Root)	SN-253 Si_3N_4	682°C (1260°F)	283 MPa (41 ksi)
Nozzle	SN-88 Si_3N_4	1297°C (1260°F)	179 MPa (26 ksi)
Combustor Tile	Hexoloy® SiC	1204°C (2200°F)	190 MPa (28 ksi)*
Combustor Ring	Hexoloy® SiC	1204°C (2200°F)	75 MPa (11 ksi)*
Combustor CFCC	SiC/SiC	1150°C (2100°F)	78 MPa (11 ksi)
Combustor CFCC	Al_2O_3/Al_2O_3	1150°C (2100°F)	163 MPa (24 ksi)

* Maximum principal stress levels established for a maximum liner wall temperature of 1366°C (2490°F) during preliminary design analyses.

developed because subscale combustor liner testing of the first generation tile design indicated an undesirable loading condition between the tiles and interfacing support structure. The second-generation design is mechanically simpler than the first-generation design and also avoids air leakage paths that would make emissions control more difficult. The interfaces between adjacent rings have an angled edge geometry. Direct contact between adjacent tiles is minimized. The detail design is presently at the stress and thermal analysis stage. The CFCC design is very similar.

Silicon carbide rather than silicon nitride ceramics were selected for the monolithic combustor liners at the preliminary design stage because of the high steady-state liner maximum design temperature, about 1366°C (2490°F). Steady-state stresses calculated for Hexoloy® SA SiC, the primary design material at this temperature, are listed in Table 2. The calculated maximum stress for the ring design was 75 MPa (11 ksi), significantly less than for the tile design which was estimated at 190 MPa (28 ksi). The reliability of the monolithic combustor designs were evaluated using the NASA CARES/LIFE and Sundstrand's SPSLIFE computer programs for life assessment (16,17). Details of the life assessment have been presented elsewhere (9). It was established that slow crack growth was the life-limiting failure mode. Probability of survival (POS) for Hexoloy® SA SiC rings was higher than for tiles. The combined fast fracture and slow crack growth POS consistent with 30,000 hours operating life at 1366°C (2490°F) was estimated at 0.9759 for one tile and at 1.0000 for one ring. To improve the POS for the tiles and to prevent sticking between adjacent tiles or rings, it was decided to lower the design liner temperature to 1204°C (2200°F) as shown in Table 2.

Because of the lowering of the design temperature, silicon nitride materials are also currently under consideration for second generation subscale and full-scale liner fabrication. Factors to be considered include estimated component stress levels in steady-state and transient operation, thermal shock resistance, estimated component life based on materials properties and predicted stress/temperature levels, and cost of fabricating prototype and commercial quantities of liner components.

CFCC's have the advantage over monolithic ceramics that they can be used as large integral shapes because of their superior fracture toughness. A disadvantage of CFCCs compared to monolithics is their relatively low strength. SiC/SiC CFCCs are limited by the first matrix cracking strength which is typically on the order of 80 MPa (12 ksi) at temperatures in excess of 500°C (932°F). The Al_2O_3/Al_2O_3 CFCC for this program is limited by the yield strength which is about 210 MPa (30 ksi). Because of the lower thermal conductivity design stresses in the Al_2O_3/Al_2O_3, CFCC are about twice those in the SiC/SiC CFCC (see Table 2). The design stresses are only slightly below the limits for the CFCC material. Efforts are underway to lower the design stresses in the integral CFCC liner designs.

Nozzle Design

The nozzle design started with the cooled two-airfoil metallic nozzle. There are 15 cooled Pt-aluminide coated two-vane FS-414 nozzles with attached tipshoes in the all-metal Centaur 50 engine. For fabrication simplicity, a single-vane ceramic nozzle concept was selected and the current integral tipshoe was decoupled from the nozzle.

Maximum steady-state stresses in the airfoil trailing edge of the initial ceramic nozzle design were high, 380-480 MPa (55-70 ksi), because of the temperature gradient set up by the combustor exit profile under "hot spot" conditions. Several alternative design solutions aimed at lowering these stresses were considered, including nozzle segmentation and airfoil cooling. Segmented designs may experience leakage and contact stress problems while materials degradation may occur as a result of surface flaws near the cooling apertures in a cooled design. These design approaches were considered but subsequently abandoned for these reasons.

Acceptable stress levels were achieved by reducing the airfoil axial chord from 3.88 cm to 1.78 cm and by reducing the vane stiffness by introducing a combination of axial and tangential curvature (bowed nozzle). Trailing edge thickness was reduced by 40 percent. The steady-state stress was lowered to 179 MPa (26 ksi) at the hot spot trailing edge where the maximum temperature was estimated at 1288°C (2350°F) (see Table 2). A solid model of the bowed nozzle which has a hook attachment is shown in Figure 4. ANSYS finite element temperature and stress maps for the bowed nozzle design are shown in Figure 5.

Long-term testing combined with life prediction using CARES/LIFE and SPSLIFE have guided the selection of the nozzle materials (9,12,13). Data from specimen testing and available ceramic materials properties were used as input to the NASA CARES/LIFE life assessment program for four candidate nozzle materials. Combined surface/volume reliability for fast fracture and slow crack growth for the four candidate materials for 10,000-hour service life was 0.2155 (NT164 Si_3N_4), 0.9999 (SN-253 Si_3N_4), 0.8831 (Hexoloy® SA SiC), and 0.9940 (SN-88 Si_3N_4). On the basis of these results, SN-88 and SN-253 Si_3N_4 ceramics were initially

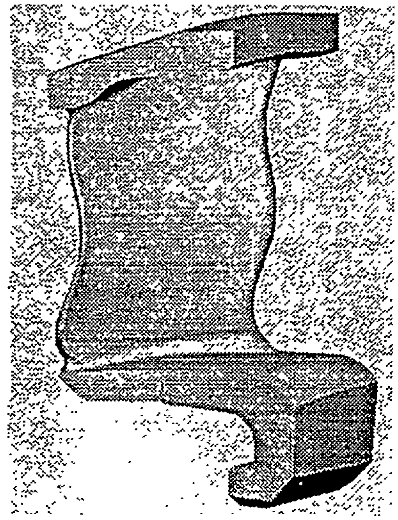
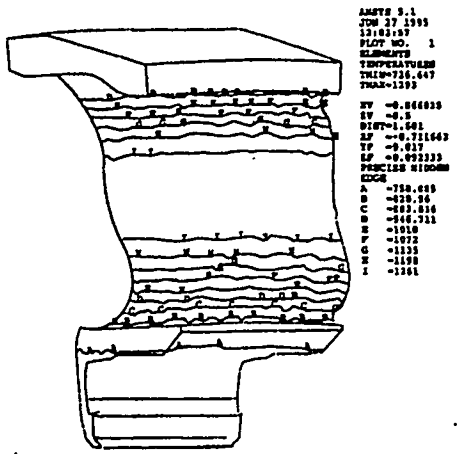


Figure 4. Bowed Nozzle Design

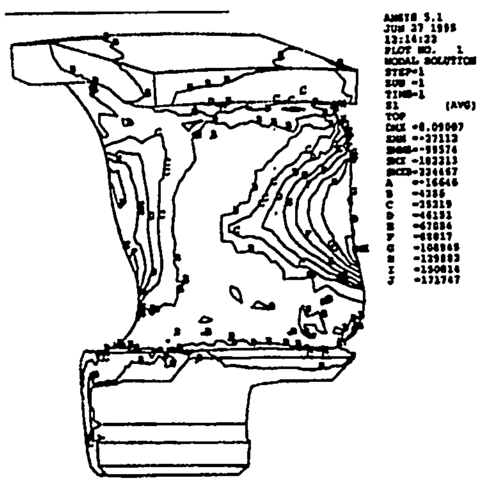
selected for nozzle development. Recently, SN-253 showed inadequate life and significant residual fast fracture strength degration during 1000-hour creep testing at 1288°C (2350°F) and 207 MPa (30 ksi). A program decision was made to continue evaluation of SN-253 in extended 5000 hours creep testing but to substitute Kyocera's SN-281 for SN-253 for nozzle fabrication on a demonstration basis. SN-281 is believed to have superior long-term properties compared to SN-253. SN-281 test specimens are being fabricated for comparison testing with other nozzle materials. SN-88 is currently the only material selected for full-scale nozzle fabrication.

Blade Designs

The current Centaur 50 engine has 62 cooled Pt-aluminide coated first-stage MAR-M-247 (equiaxed) blades. The blade airfoil shape has been largely retained in the ceramic blades with a slight modification to circumvent a predicted vibrational interference. The firtree root attachment of the current Centaur 50S metallic first-stage blade has been modified to accommodate the ceramic root to metal disk interface. Two uncooled ceramic



(A) Temperature Map (°C)

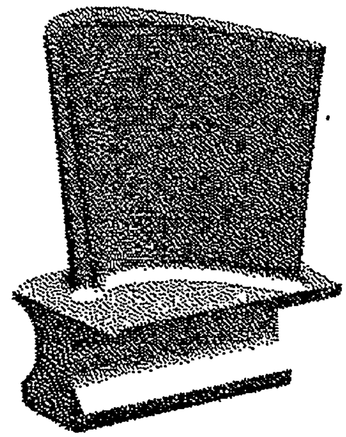


(B) Stress Map (kPa)

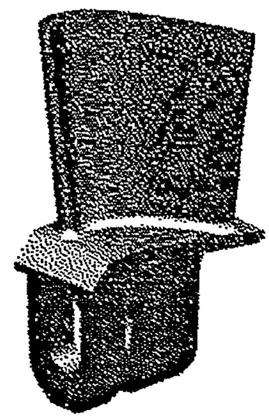
Figure 6. ANSYS Finite Element Temperature and Stress Maps for Bowed Nozzle

blade designs have been developed. One is based on a "dovetail" type root attachment (55° angle) using a compliant layer. The second design is based on a modified pinned root attachment. The two designs are shown as solid models in Figure 6.

Table 2 summarizes critical stresses and temperatures for the blade designs. The maximum steady-state stress for the dovetail blade design is 214 MPa (31 ksi). This level is predicted for the critical neck region in the dovetail root. The critical stress in the life limiting region on the airfoil is about 186 MPa (27 ksi). The materials selected for prototype dovetail blade fabrication were GN-10 silicon nitride from Allied Signal Ceramic Components and NT164 silicon nitride from Norton Advanced Ceramics.



(a)



(b)

Figure 6. Solid Models of Dovetail (a) and Pinned Blade (b)

The second ceramic blade design has a "pinned" type root attachment wherein a single pin retains the blade in the disk. The initial integral pinned root concept had a simple round hole and cylindrical retaining pin (11). However, steady-state stresses in this design were on the order of 550 MPa (80 ksi). These high stresses were unacceptable and the design was subsequently modified to a two-tang root with oval hole and pin to lower stresses and resolve cooling problems. The ANSYS finite element steady-state stress map for the pinned blade attachment design is shown in Figure 7. The maximum stress in the critical neck region for the pinned blade is estimated at 283 MPa (41 ksi). The critical stress is in the airfoil region at about 186 MPa (27 ksi), similar to that for the dovetail blade. The material selected for pinned blade fabrication is SN-253 silicon nitride from Kyocera Industrial Ceramic Corporation.

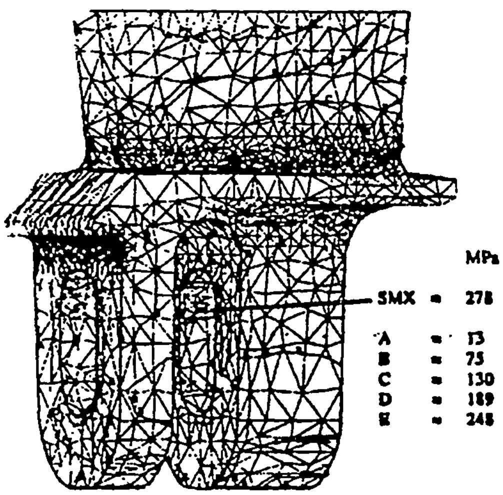


Figure 7. ANSYS Finite Element Stress Map for Pinned Blade Design

The materials properties were incorporated in CARES/LIFE life prediction for the blade designs. POS values for 30,000 hours were estimated to be about 0.98 for the HIP-sintered materials, GN-10 and NT164, based on an extrapolation of earlier data for NT154 Si_3N_4, a predecessor material for NT164 (9). Slow crack growth is the life limiting mode. The estimated POS values for these materials are too low for service applications. Review of materials selection and/or blade redesign will be required to obtain acceptable POS values. Service life for SN-253 is believed to be adequate based on dynamic fatigue data. Creep is not believed to be life limiting for the temperature range of the blade.

Secondary Component Design

Redesign of the components interfacing with the ceramics is an important effort under the program. Redesign is required to ensure thermal matching of adjacent ceramic and metal parts. Several design changes were also made to accommodate the heat management in view of the increase in TRIT from 1010°C (1850°F) to 1121°C (2050°F) and elimination of cooling in the first stage blade and nozzle. At the writing of this report, the secondary component designs are nearly completed. Extensive changes were made in the designs of the support structure of the combustor liner, in the designs of the support structures interfacing with the inner and outer nozzle shrouds, and in the first stage disk. Some of the materials changes for the secondary components have been summarized in Table 3. The primary design of the secondary components in the area adjacent to the ceramic parts are shown in Figure 3.

The changes to the secondary components have been backed up by extensive mechanical design and analysis and heat transfer analyses to establish potential interferences, overstress conditions, and localized overheating. The interested reader is referred to the Phase II Technical Progress Report for a detailed account of the concepts behind the secondary component redesign (15).

Table 3. Materials Changes for Secondary Components

Component	Current Material	New Material
Stage 1 Disk	V-57	Waspalloy
Front and Aft Rim Seals	Not in Current Centaur 50	Waspalloy
Stage 2 Disk	V-57	Waspalloy
Stage 2 Blade	IN-738LC	DS MAR-M247
Stage 1 Diaphragm	N-155	IN-903
Stage 2 Diaphragm	N-155 To Accommodate Aft Rim Seal	Waspalloy
Outer Shroud Sealing	New Design to Accommodate Ceramic Nozzle	IN-718, Haynes A230

Because monolithic ceramics are characterized by their low fracture toughness and low impact resistance, a basic design philosophy in this program has been to avoid a blade rub at all times under engine operating conditions. As a prerequisite it is mandatory to predict accurately the turbine blade axial and radial clearances for the whole operating cycle. Therefore, a model was developed to predict temperatures and displacements of ceramic and interfacing metal engine components during steady-state and transient engine operation. The results of these analyses are being used to set cold assembly clearances and control blade closures.

Task 8: Design and Procurement of Test Facilities

The work in this task involves setting up the test facilities to evaluate the ceramic stationary gas turbine components. Existing test facilities for materials property testing, spin testing, and combustor liner testing were modified if needed for the testing envisioned. A standard Centaur 50 engine was procured and modified to accept the ceramic hardware as detailed under Task 7.

Ceramic Materials Testing

Solar has extensive test equipment for materials property characterization including metallographic equipment, SEM/EDX, and various SATEC, MTS, and ATS test equipment for flexure, tensile, creep, and fatigue testing. Flexure, tensile, and creep testing can be performed up to 1700°C (3092°F). Special Waspalloy grips were fabricated for the testing of various blade root configurations. Waspalloy was selected since it is the first stage disk design material.

Cold Spin Rig

The CSGT program requires the use of a vacuum spin pit to test and evaluate various candidate monolithic ceramic inserted turbine blade attachment geometries along with candidate compliant layer materials. The rig must be capable of providing a centrifugal load on blades to at least 150 percent of the engine design load without introducing any loading conditions or forcing functions on the blades that would not be experienced in the actual engine environment. Prior spin pit experience has shown that the required spin pit partial pressure must be controlled in the range of 200 to 300 milli-torr to ensure stable test rotor operation.

Based on the recommendations of Test Devices, Inc. of Hudson, MA, a number of modifications were made to the existing spin rig equipment including incorporating high strength cover bolts and lid retention dogs with limit switches (to prevent drive operation until the lid is closed), installation of a non-contact vibration monitor (to measure the vibration of the spindle and shut down the drive if vibration exceeds a threshold), upgrading of the lubrication equipment (to prevent failure of the turbine bearing and consequent loss of the test article), upgrading of the vacuum system, and the installation of an automatic control system using an industrial programmable logic controller (PLC).

The upgraded cold spin rig during the proof testing of two NT164 first stage blades are shown in Figure 8. The blades are held in disk slots at a 180° spacial separation.

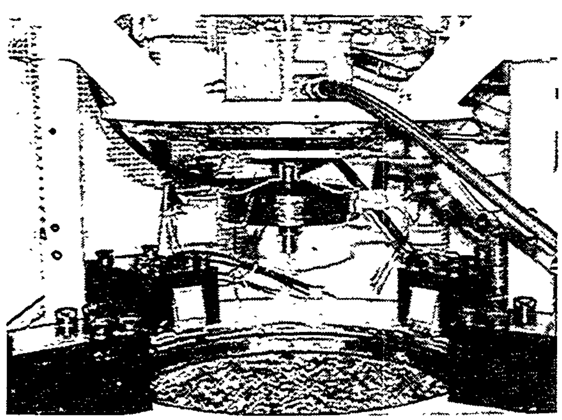


Figure 8. The Upgraded Cold Spin Rig With Two NT164 Blades During Proof Testing

Hot Spin Rig Testing

Solar's blade spin rigs are currently not set up to conduct hot spin testing. Although the current upgraded cold spin rig can be further modified for hot spin testing, a program decision was made to use the services of Test Devices, Inc. for any hot spin testing required under the program.

Mechanical Nozzle Attachment Rig

The aerodynamic load on the airfoil produces analytically predicted stresses in the ceramic to metallic attachment region (surface contact) and in the trailing edge inner airfoil root fillet. The purpose of the mechanical nozzle attachment rig is to assess the design contact loads and resulting stresses. The rig which was specifically designed and fabricated for the CSGT nozzle testing imposes the aerodynamic loads analytically predicted for the nozzle segment on the attachment region through the use of a mechanical loading device (air cylinder). The rig has been designed with the option for mounting to a shaker table for vibratory testing.

Thermal Nozzle Test Rig

A second nozzle rig is being designed to produce a thermal gradient in excess of that expected in "hot spot" locations during engine operation. Application of the temperature gradient will produce stress conditions intended to proof test the nozzle durability prior to installation in an engine. The test will be used to eliminate nozzles that exhibit unacceptable materials flaws.

Subscale Combustor Rig

Solar's subscale test facility has the capacity to achieve engine rated temperatures and pressures while maintaining a single injector's mass flow into the rig. All subscale testing of the monolithic and CFCC subscale combustor liners will be conducted with a production Centaur 50S SoLoNOx fuel injector. The facility is instrumented for temperature, pressure, and flow measurements. Exhaust emissions are monitored using a state-of-the-art Rosemount analytical continuous emission monitoring system (CEMS). To prevent the ceramic liners from exceeding a wall temperature of 1204°C (2200°F), a fuel shutoff system has been installed. The system is integrated with 15 Type K thermocouples that are instrumented on the liner wall.

Atmospheric Combustion Rig

Full-scale combustor liners will first be tested in an atmospheric combustor facility. This rig will provide a preliminary indication of the performance of the full-scale combustor hardware. The facility which can accommodate three combustor modules provides hot air to the rig at atmospheric pressure. A complete set of 12 Centaur 50 SoLoNOx fuel injectors is used to run the rig, and the flow function is matched to the engine design point. A thermocouple rake system provides temperature data for pattern factor and radial profile calculations. Exhaust emissions are monitored by a CEMS, and data is captured by a Daytronics and VAX RETS data acquisition system. TRIT conditions and liner wall temperatures expected in the engine can be closely simulated. The rig is being used without extensive modification for ceramic combustor liner testing.

High-Pressure Combustion Rig

The high-pressure test facility (loop rig) is a recuperated Centaur T4000 (early version of the Solar Centaur 40 engine) which provides an appropriate test vehicle for the full-scale ceramic combustor liner hardware. Full air flow (~16 kg/s) can be obtained with a maximum pressure of approximately 724 kPa (105 psig). The engine is fully instrumented with an Allen-Bradley controls system and has a complete data acquisition system, including Kessler type pressure oscillation sensors for monitoring the combustor harmonic frequencies. Pattern factor and radial profiles are measured with a Type K thermocouple rake assembly. Emissions can be taken at the exit of the combustor plane or at the exhaust stack by a CEMS. Load transients and fast shutdowns can be performed on this engine. These will provide data for the heat transfer and stress models. This rig is being used on the CSGT program without modification.

Engine Rig

The engine test rig is the test bed apparatus for the CSGT program to demonstrate the use of advanced ceramic components for the first stage rotor blade, first stage nozzle, and the combustor liner. The rig consists of a production Centaur 50 turbine engine, standard cold end drive gearbox, standard engine/generator mounting skid, and a (non-standard) 7000 hp Hoffman water-brake dynamometer. The engine rig will be operated to a maximum (TRIT) of 1121°C (2050°F) at 100 percent (14,950 rpm) engine speed which equates to a tip speed of approximately 407 m/s. The engine rig will evaluate ceramic hot section components in a typical Solar Turbines generator-set operating environment.

Prior DOE-sponsored ceramic engine programs have shown that ceramic components are evaluated most accurately in the actual engine environment for which the components have been designed. Smaller subassembly test rigs can typically only partially reproduce the engine operating environment, and therefore cannot completely be relied upon to expose ceramic components to all engine induced temperature and stress conditions prior to actual engine testing. The engine test bed engine thus serves the CSGT program as the final qualification test for all ceramic components before they are installed in the 4,000-hour field test engine.

The CSGT rig engine (S/N 442H) is a new sales order engine with all hardware dedicated to the CSGT program. The engine was assembled in the Solar Kearny Mesa facility and was acceptance tested at the Harbor Drive facility in the cold end drive test cell. The acceptance test was performed to production test standards for the Centaur 50 engine, and the engine was accepted after having achieved the required performance within the vibration limitations specified in the standard test specification. The Centaur 50S CSGT engine rig is shown in the test cell in Figure 9.

Task 9: Ceramic Component Iterative Design, Manufacturing, and Testing

Work under Task 9 includes fabrication of specimens, subscale and full-scale components, testing of specimens, blade attachment specimens, and prototype blades and nozzles. Testing of subscale combustor liners and of full-scale combustor liners prior to engine testing is performed under Task 10.

Full-Scale and Subscale Ceramic Component Fabrication

During the reporting period a number of first generation full-scale and subscale components were received from the suppliers. Components received to-date have been listed in Table 4.

During the reporting period Norton Advanced Ceramics made a business decision to abandon high-temperature ceramic gas turbine development work and to focus more fully on automotive component and ball-bearing activities. This decision affects the CSGT program in the sense that NAC has stated its preference not to fabricate second generation components. Solar is not considering NAC in the selection process for second generation component fabrication, for this reason.

Examples of silicon nitride blade and nozzle components delivered to-date are shown in Figure 10. Full-scale SiC/SiC CFCC combustor liners from B.F. Goodrich are shown in Figure 11.

Receiving/Inspection

A detailed procedure has been implemented at Solar to control receipt and inspection of all CSGT ceramic parts. This procedure is described in some detail in the mid-term Phase II Technical Progress Report (15). The procedure involves tracking of all contract property, inspection practices, and corrective action. Guidelines for visual inspection, part identification, dimensional inspection, and fluorescent dye penetrant inspection have been outlined in appropriate Solar specifications. Solar's requirements for supplier inspection have been detailed in supplier materials specifications. Action on discrepant parts is taken by a Materials Review Board (MRB).

Eighty-five (85) NT164 blades were received from NAC and 94 GN-10 blades from CC. All of these parts have been inspected visually, dimensionally, and by fluorescent dye penetrant inspection (FPI) using improved methodology developed by ANL. Based on these inspection techniques, 15 NT164 blades were rejected for the first engine build. Three NT164 blades were forwarded to ANL for NDE. Of the 94 GN-10

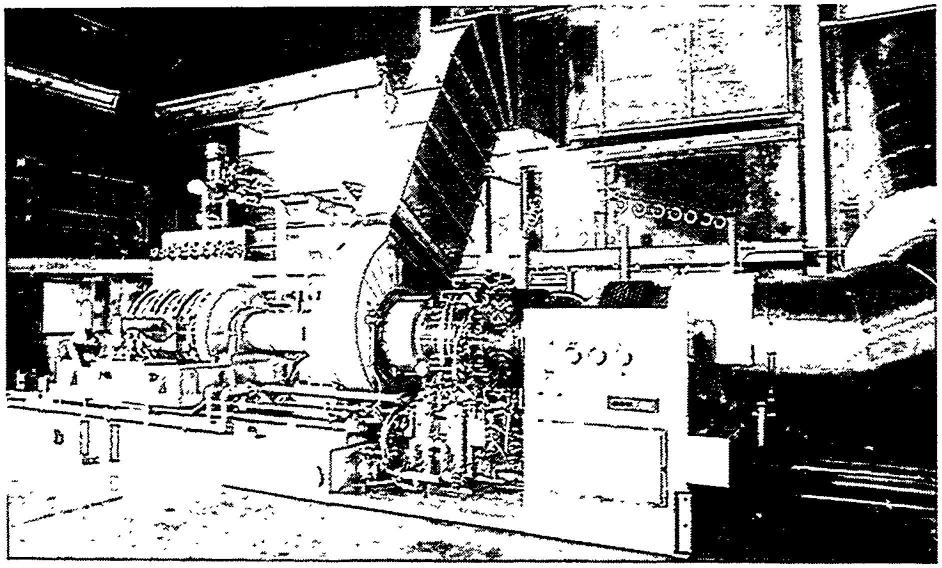


Figure 9. CSGT Centaur 50S Engine Rig

blades received from CC, only one blade was rejected. Following visual inspection 70 NT164 blades were frequency inspected and the data taken as a whole indicate a very consistent set of frequencies for the first three important modes. The standard deviation for all modes was approximately 10 to 12 percent of the frequency being measured. This scatter is somewhat greater than for the metal nozzles, but it is probably indicative of frequency variations brought about by inconsistent dimensional control of the airfoil shape in the fabrication process. Frequency scatter for the GN-10 blades was appreciably better than for the NT164 blades, the standard deviation being approximately 7 percent.

Two first article nozzles from NGK were visually inspected. Their general appearance appeared to be in very good condition. A sudden transition in thickness near the trailing edge is due to the mode of machining in the green state and will be corrected by NGK. Some additional machining will also be required for the outer shroud slash angles to more accurately match drawing requirements.

Blade Attachment Testing

Testing of ceramic inserted blade attachment concepts to a metallic disk involves a matrix of both static and dynamic tests. Since ceramic blade to metallic disk attachments typically degrade due to the combination of (1) centrifugal (CF) blade loads on a ceramic to metallic interface and (2) relative motion (tangential sliding) at the loaded interface due to thermal expansion of the disk rim, all CSGT blade attachment testing focuses on these two primary conditions.

Attachment tensile testing for the dovetail design and an early version of the pinned root blade design have been reported previously (11,14). Testing for the dovetail blade design has been conducted with appropriate compliant layer systems designed to

Table 4. First Generation Full-Scale and Subscale Components Received To-Date

Supplier	Material	(Subscale) Component	Delivery Status
AlliedSignal Ceramic Components (CC)	GN-10 Si_3N_4	94 Dovetail Blades (+ Co-Proc. Flexure Bars)	6 AS-800 Si_3N_4 Dovetail Blades Due
Norton Advanced Ceramics (NAC)	NT164 Si_3N_4	85 Dovetail Blades (+ Co-Proc. Flexure Bars)	Complete
Kyocera Industrial Ceramics Corporation (KICC)	SN-253 Si_3N_4	2 Pinned Blade Pre-Prototypes	80 SN-253 Si_3N_4 Pinned Blades Due
NGK Insulators, Ltd. (NGK)	SN-88 Si_3N_4	2 First Article Nozzles, 1 Pre-Prototype Nozzle	100 SN-88 Si_3N_4 Nozzles Due
Carborundum	Hexoloy® SA SiC	3 Sets (5/Set) Subscale Combustor Liner Tiles	Complete
Norton Advanced Ceramics (NAC)	NT230 SiC	6 Combustor Liner Rings	Complete
Babcock & Wilcox (B&W)	Al_2O_3/Al_2O_3 CFCC	4 Subscale Combustor Cylinders (+ Co-Processed Test Specimen)	Complete
DuPont Lanxide Composites (DLC)	SiC/SiC CFCC	4 Subscale Combustor Liners (+ Co-Processed Test Specimens)	Complete
B.F. Goodrich (BFG)	SiC/SiC CFCC	2 Sets of Full-Scale Liners (2/set) (+ Co-Processed Test Specimens)	Complete

accommodate the relative motion of the ceramic blade and disk under conditions of temperature cycling.

The results of the testing to-date show the following trends:

1. Dovetail attachment specimens tested at room temperature fail at typically 3-4X the nominal design stress.

2. At temperatures typical for the blade root in service (about 682°C, 1260°F) dovetail attachment specimens fail at lower loads but, still, the failures occur at 2-3X the design stress. Some pinching of the dovetail blade in the grip side that had not failed was observed for this test.

3. Reducing the dovetail angle from 60 percent to 55 percent appeared to have had a beneficial effect. Following attachment testing to 100 percent of design load at the approximate blade root service temperature, the attachment was found to be free in the bottom grip and mildly wedged in the top grip.

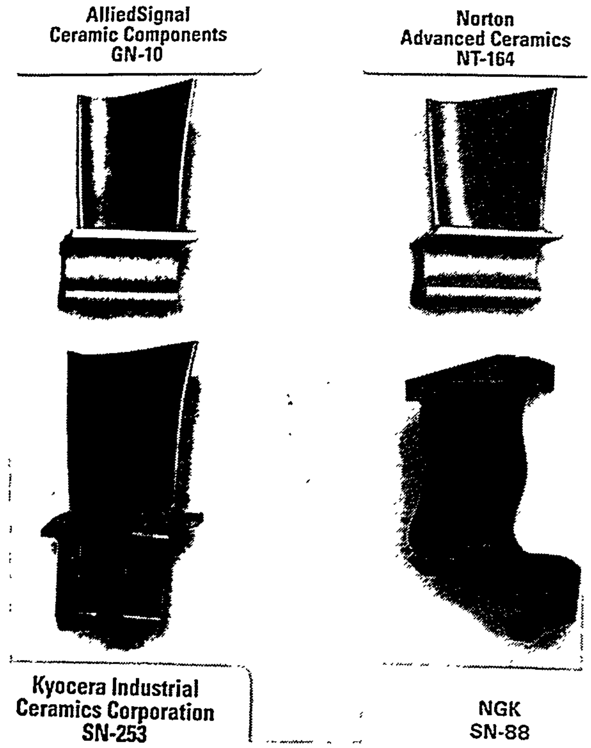


Figure 10. Fabricated Dovetail and Pinned Root Blades and Bowed Nozzle

Only slight heating was required to loosen the specimen.

4. The incorporation of a friction-reducing additive or surface appears to reduce the incidence of sticking in cyclic testing at the approximate blade root design service temperature.

5. Testing with attachment specimens representative of the current pinned blade design indicated failure at approximately 183 percent of design load at room temperature. No compliant layer system was used in these tests.

6. Attachment testing on the new pinned blade root design at a root service temperature of about 682°C (1260°F) resulted in failure at approximately 155 percent of design load.

In summary, dovetail blades appear to present a more comfortable design margin than pinned blades based on attachment test data to-date.

Cold Spin Testing

Blades are being subjected to spin testing to evaluate the blade root attachment and ceramic materials performance. Initial cold spin testing was conducted on simulated blades which were machined from attachment specimens. The design rotational speed of the first stage dovetail blades is 21,625 rpm (the rpm is higher than for the actual engine disk because of the smaller size of the spin disk). Cold spin testing has been conducted on simulated dovetail blades of the three candidate blade materials at rotational speeds corresponding to up to 35,989 rpm (200 percent of design load). All simulated blades survived the spin tests.

All first stage blades that had passed visual and dimensional inspection from NAC (75) and CC (93) thus far have been cold spin proof tested at 125 percent design CF load (112 percent speed). A random blade from each of these suppliers has been taken to 200 percent CF load (141 percent speed) successfully. Figure 8 shows two of the NT164 blades following a cold spin proof test.

Hot Spin Testing

Following the cold spin proof tests, a series of hot spin tests was conducted at Test Devices, Inc. of Hudson, MA. Test objectives were to confirm the integrity of the compliant layer system after thermal and CF load cycling. It was felt that successful results from this series of tests must be obtained prior

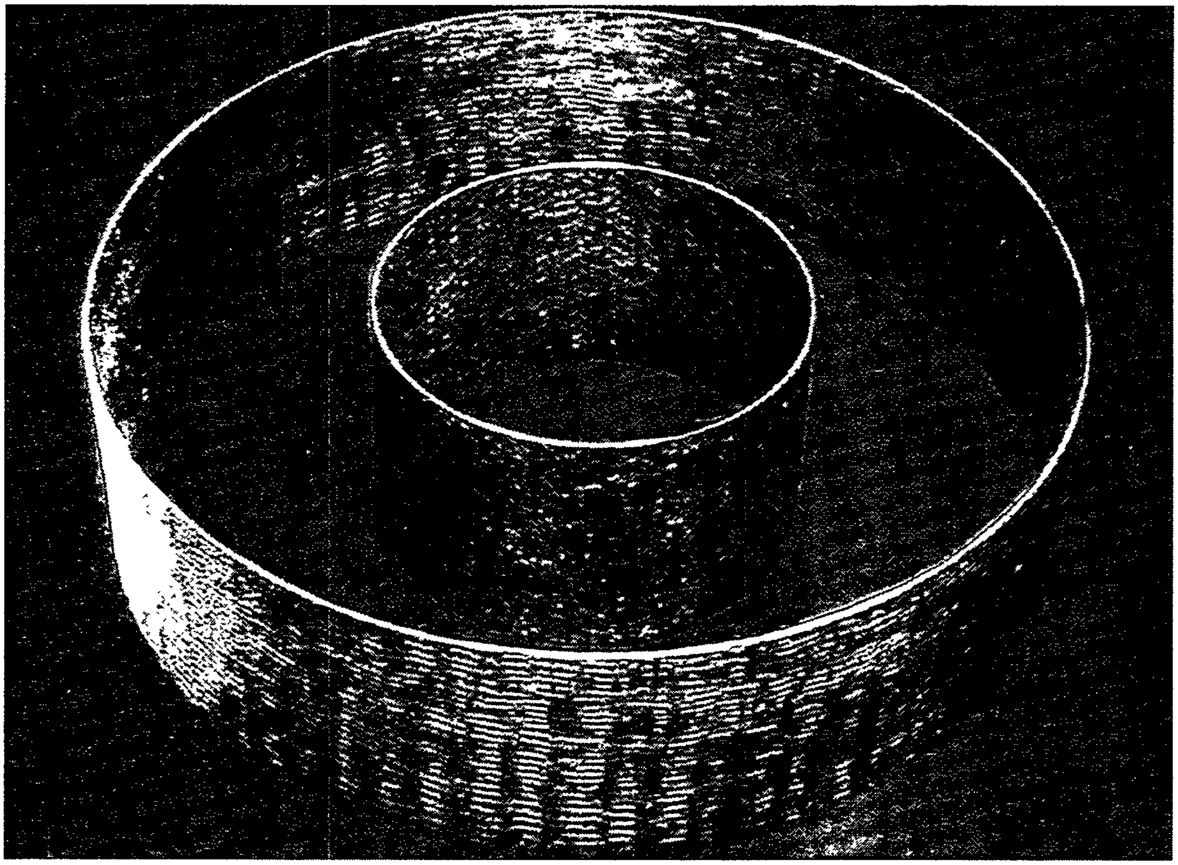


Figure 11. Set of B.F. Goodrich Full-Scale Combustor Liners

to conducting the first engine test with ceramic dovetail blades.

Three dovetail blades of each of NT164 and GN-10 were hot spin tested at 125 percent design load at 682°C (1260°F). Good results were obtained for each material in three separate tests with a maximum of 25 load cycles (0 to 125 percent load) with the current standard compliant layer system of a Ni-base alloy with friction-reducing surface. No sticking was observed for any of the tests performed. A detailed analysis of the compliant layer systems after the hot spin tests is under way in order to assess long-term behavior.

Engine Testing

In the engine test planning for the CSGT gasifier test rig, a strategy was defined in which each individual ceramic component is fully evaluated by initially testing it with the remaining flowpath components fabricated from metallics. This methodology will help prevent secondary damage to downstream ceramic components. The engine is to be tested at the standard operating TRIT of 1010°C (1850°F) for each ceramic component system prior to testing these components in combination. In subsequent testing, ceramic components will be combined and installed and the engine will again be operated at the standard TRIT. The final test at a TRIT of 1010°C (1850°F) will be conducted with an engine build incorporating one of the two ceramic blade designs (to be decided), the ceramic nozzle, and a ceramic combustor liner system.

Once all three components have been combined in a build and satisfactorily evaluated at a TRIT of 1010°C (1850°F), an increase in TRIT to 1121°C (2050°F) will be incrementally imposed until a steady-state operating condition at the final temperature regime is achieved. This test strategy was determined to be the lowest risk approach to evaluating the ceramic components in an engine test bed and was used as the basis for all subsequent planning decisions and scheduling of the engine tests. The current test plan is summarized in Table 5.

The first engine test was performed on August 18, 1995. The test which lasted for 1 hour at a nominal TRIT of 1010°C (1850°F) and 100 percent load was performed with the CSGT Centaur 50S test engine incorporating a full first stage disk of NT164 dovetail blades (62 blades). To avoid any chance of a tip rub the blades were run with wide open cold clearances. The target clearance was 1.27 mm, which is 0.76 mm wider than in the metal Centaur 50S in which a tip rub is normally incurred during the initial start-up of the engine. The engine was run with a SoLoNOx combustor modified to generate a non-standard combustor exit temperature profile defined by the design heat balances for the ceramic blade and (future) nozzle with adjacent support structure.

Upon disassembly the NT164 blades showed no evidence of degradation. Some of the compliant layers showed evidence of impact, but the compliant layer system overall performed as expected. Some design changes have been incorporated into the compliant layer system to eliminate impact in future runs. The NT164 blades will be used in future runs, the first one of which is a cyclic test (Build No. 4 in Table 5).

The second engine test was performed with GN-10 dovetail blades in the first stage. The test was very similar to the first test except that the engine was initially operated at 95 percent speed to avoid a possible vibrational interference estimated to be present at about 105 percent speed. After successful operation for 1 hour at 95 percent speed, the engine speed was carefully increased to 100 percent speed and operated at full load for an additional hour under conditions nominally identical to those of the NT164 blade engine test. Table 6 lists performance parameters for the first two engine tests and for a comparable run with the all-metal engine. GN-10 blades are currently being examined. Data analysis for both runs is in progress.

Figure 12 shows the first stage disk with NT164 dovetail blades during engine assembly. The disk was thermally painted to obtain an indication of its temperature profile during operation. Figure 13 shows the disk following completion of the first engine test.

Long-Term Data Base

Work is ongoing at Solar and the University of Dayton Research Institute (UDRI) to generate a long-term data base. Testing involves baseline fast fracture tensile and flexure testing, tensile and flexure dynamic fatigue testing to assess evidence of slow crack growth, and short-term and extended creep testing. A sizable data base has been generated to-date for the program blade and nozzle materials (11,14). Support work is also ongoing at Oak Ridge National Laboratory and UDRI under a separate support contract.

Table 5. Engine Test Schedule

Build No.	TRIT (°C, °F)	Description	Status
1	1010, 1850	NT164 Dovetail Blades, Metal Nozzle	Completed
2	1010, 1850	GN-10 Dovetail Blades, Metal Nozzle	Completed
3	1010, 1850	BFG CFCC Combustor, Metal Blades, and Nozzles	
4	1010, 1850	BFG CFCC Combustor, NT164 Blades, Metal Nozzle, Cyclic Test	
5	1010, 1850	Instrumented Engine Test - All Metallic - Generate Boundary Conditions	
6	1010, 1850	KICC Pinned Blades, Metal Nozzle	
7	1010, 1850	NGK Nozzles, Metal Blades	
8	1010, 1850	BFG CFCC Combustor, Ceramic Blades (To Be Selected), NGK Nozzle	
8a	1010 --> 1121 1850 --> 2050	BFG CFCC Combustor, Ceramic Blades (To Be Selected), NGK Nozzle (Continue Test of Build No. 8)	
8b	1121, 2050	BFG CFCC Combustor, Ceramic Blades (To Be Selected), NGK Nozzle, 10 Hours (Continue Test of Build No. 8a)	
9	1010, 1850	2nd Gen. Ceramic Combustor, Ceramic Blades, Metal Nozzles	
10	1010 --> 1121 1850 --> 2050	2nd Gen. Ceramic Combustor, Ceramic Blades, Ceramic Nozzles, 10 Hours	
10a	1010 --> 1121 1850 --> 2050	2nd Gen. Ceramic Combustor, Ceramic Blades, Ceramic Nozzles, 50 Hours	

Four candidate nozzle materials were subjected to fast fracture and dynamic fatigue testing at UDRI and Solar. These materials were NT164, SN-88, and SN-253 Si_3N_4 and Hexoloy® SA SiC. Based on the UDRI and Solar data and on life prediction assessment using the NASA CARES/LIFE program, SN-88 and SN-253 were subsequently selected for short-term (1000 hours) and long-term (5000, 10,000 hours) tensile creep testing at UDRI. Short-term creep testing was also performed for Hexoloy® SA SiC. Data for the creep tests performed to-date have been listed in Table 7.

During the 1000 hours creep screening tests, SN-88 was the only material for which all tensile specimens survived. The residual tensile strength values measured at 1288°C (2350°F) ranged from 367 to 387 MPa (53 to 56 ksi). This compares well with an average fast fracture strength of the material prior to testing of 461 MPa (67 ksi). The one SN-253 specimen that did not fail in the 1000-hour

Table 6. Performance of the First Two Ceramic Engine Tests and All-Metal Engine Baseline

	All-Metal Engine	NT164 Blade Test - Build No. 1	GN-10 Blade Test - Build No. 2	GN-10 Blade Test - Build No. 2
Date	7/19/95	8/18/95	9/21/95	9/21/95
Shaft Speed	100.0%	100.6%	95.2%	100.6%
TRIT °C (°F)	1007 (1845)	1022 (1872)	1017 (1863)	1019 (1867)
Thermal Efficiency	28.8	27.9	25.7	28.1
Shaft Horse Power	5257	5246	4370	5225

* Corrected to 27°C/80°F, sea level, rel. hum.: 60%, zero inlet, and exhaust losses.

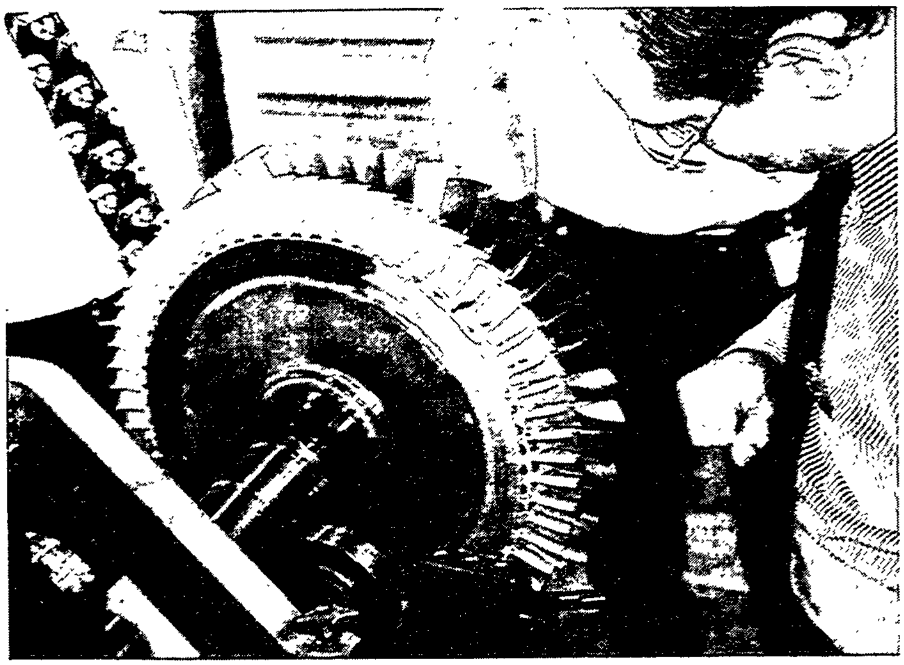


Figure 12. First Stage Disk with NT164 Dovetail Blades During Engine Assembly

creep test had a residual tensile strength at 1288°C (2350°F) of 205 MPa (30 ksi), a significant drop from the 590 MPa (86 ksi) tensile strength before exposure. One of the two Hexoloy® SA specimens which did not fail had a residual tensile strength at 1288°C (2350°F) of 467 MPa (68 ksi), similar to the pre-exposure fast fracture tensile strength of 453 MPa (66 ksi). The second surviving specimen showed a dramatic drop in strength. The data confirm earlier observations about Hexoloy® SA. The material exhibits either

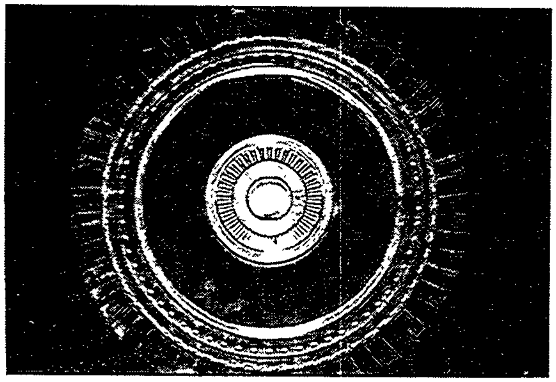


Figure 13. First Stage Disk with NT164 Dovetail Blades After Engine Disassembly

little slow crack growth or creep, or the strength degrades rapidly because of intrinsic flaws in the specimen.

Since SN-253 was selected as one of the two nozzle materials, a decision was made to continue long-term testing of this material. However, the two specimens slated for the 10,000-hour creep test at the design stress of 186 MPa (27 ksi) and a temperature of 1288°C (2350°F) failed after 1343 hours and 764 hours, respectively. It was subsequently decided to eliminate SN-253 as a nozzle material and discontinue planned further long-term creep testing. A new KICC material, SN-281 Si_3N_4, which reportedly has improved properties is being considered as a back-up material and tensile specimen procurement is in progress. SN-281 specimens will be tested in fast fracture and dynamic fatigue tensile tests and in short-term (1000 hours) creep testing at UDRI.

The long-term test data indicates that SN-88 is currently the only nozzle material that has the potential of meeting the design life criteria of the nozzle under the critical hot spot conditions. Continued long-term creep testing will indicate to what extent SN-88 will survive over the planned 5,000 to 10,000 hours duration of the test plan.

Nondestructive Evaluation

Development of appropriate nondestructive evaluation (NDE) methodology is performed in a collaborative effort by the Caterpillar Technical Center (CAT TC) and Argonne National Laboratory (ANL). The initial methodology development work and component evaluations are the responsibility of ANL while CAT TC has responsibility for the coordination of the NDE effort and for technology transfer to Solar.

NDE techniques considered for monolithic ceramics are principally visual inspection, density measurements, microfocus X-ray radiography, fluorescent dye penetrant inspection (FPI), laser scatter, and acoustic resonance. ANL has successfully improved the detection limit of the FPI technique by incorporating an optical magnification (> 25X) procedure. Surface flaws can be detected down to 0.5 mm with the improved technique compared to a limit of about 1.2 mm with conventional FPI. ANL also incorporated a boroscope extension to view visually inaccessible areas such as the internal surfaces of the pin contact area of the pinned blade root.

ANL is able to perform state-of-the-art microfocus X-ray radiography on the CSGT monolithic hot section components with acceptable resolution, but the penetrating power of the current 120 kVp X-ray head does not allow comprehensive 3-D scanning of critical sections of the ceramic blade and nozzle components. ANL is considering upgrading its equipment to include a 225 kVp or 320 kVp X-ray head for improved resolution.

Table 7. Creep Test Data for Three Candidate Nozzle Materials

Ceramic (No. of Specimens)	Stress (MPa, ksi)/ Temperature (°C, °F)	Planned Test Time	Time Until Failure	Residual Tensile Strength (MPa, ksi)
SN-88 Si_3N_4 (3)	207 MPa/1288°C 30 ksi/2350°F	1000 Hours	No Failure at 1000 Hours (3)	387 MPa/56 ksi 367 MPa/53 ksi 379 MPa/55 ksi
SN-253 Si_3N_4 (3)	207 MPa/1288°C 30 ksi/2350°F	1000 Hours	997 Hours 658 Hours No Failure at 1000 Hours	205 MPa/30 ksi
Hexoloy® SA SiC (3)	207 MPa/1288°C 30 ksi/2350°F	1000 Hours	367 Hours No Failure at 1000 Hours (2)	250 MPa/36 ksi 467 MPa/68 ksi
SN-88 Si_3N_4 (2)	186 MPa/1288°C 27 ksi/2350°F	10,000 Hours	Time as of 9/21/95: 2706 Hours, 2446 Hours	
SN-88 Si_3N_4 (4)	186 MPa/1288°C 27 ksi/2350°F	5000 Hours	Time as of 9/18/95: 1196 Hours, 1220 Hours	
SN-253 Si_3N_4 (2)	186 MPa/1288°C 27 ksi/2350°F	10,000 Hours	1343 Hours 764 Hours	
SN-253 Si_3N_4 (4)	186 MPa/1288°C 27 ksi/2350°F	5,000 Hours	Not Started Because of Early Failures in 10,000-Hour Test	
SN-88 Si_3N_4 (1)	172 MPa/1288°C 25 ksi/2350°F	10,000 Hours	Time as of 9/21/95: 860 Hours	

The predominant techniques used for the CFCC materials are infrared imaging and selected area computed tomography (CT). Sub-scale combustor liners have been examined in the as-received state and following combustor rig testing. Pre-existing defects such as low-density regions and delaminations have been detected. Figure 14 shows infrared imaging scans of DLC SiC/SiC CFCC combustor liners before and after a 10-hour subscale liner test. It can be seen that a region of low density or possibly minor delamination extended during the test.

Task 10: Low Emission Combustor

This task involves the subscale and full-scale combustor liner testing of the designs developed under Task 7.

Subscale Testing

The objective of subscale testing is to demonstrate key attributes of the full-scale liners in a cost-effective but representative geometry. These key attributes include liner design features such as attachment to the metallic support structure, materials durability, and emissions potential. The test articles for subscale combustor liner testing are 20 cm

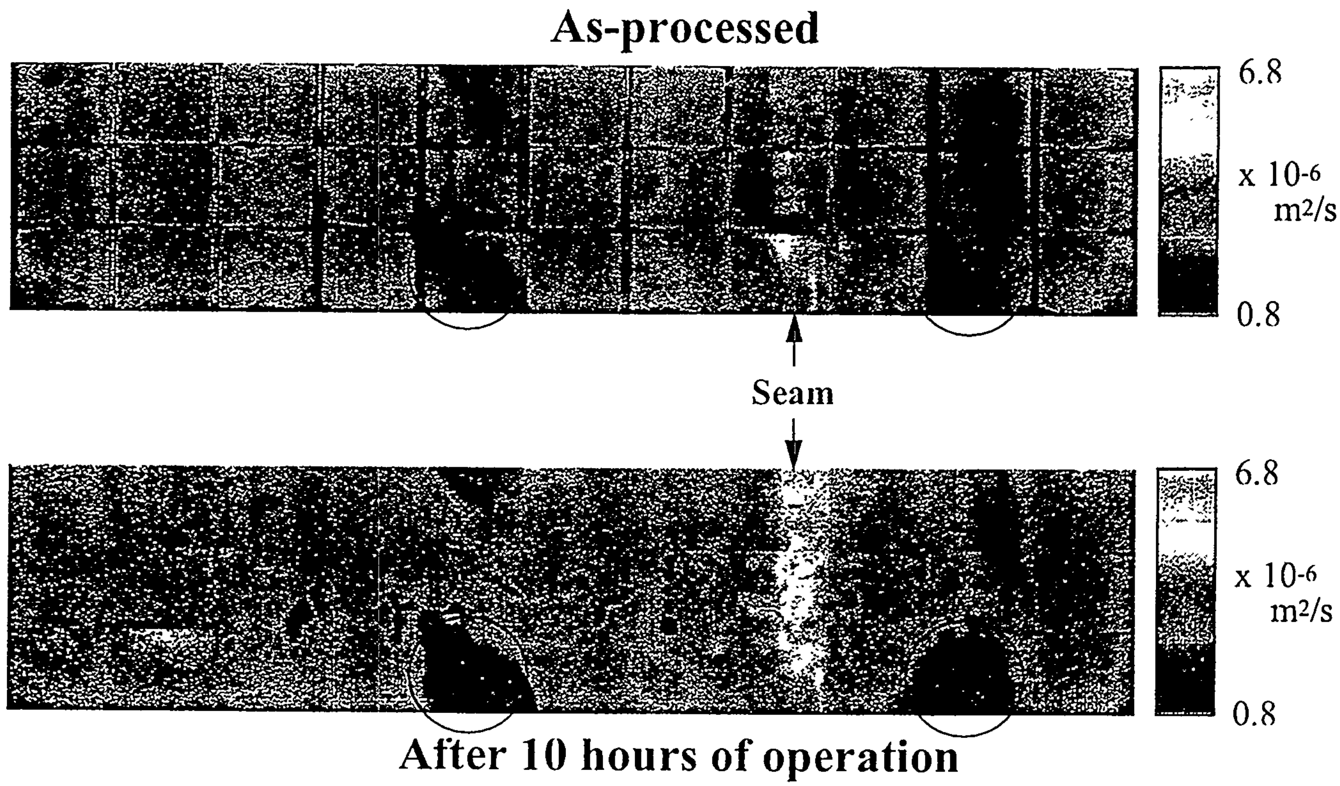


Figure 14. Infrared Imaging Scans of DLC SiC/SiC Subscale CFCC Combustor Liner Before and After 10 Hours Combustor Rig Test

diameter by 20 cm long cylinders fabricated by candidate monolithic and CFCC combustor suppliers. Two subscale combustor rigs are being used for the testing. Both systems are based on a simple can type geometry with a single production SoLoNOx fuel injector. The first rig has been used primarily to assess the low emissions potential of the ceramic liners and the testing to-date has been done exclusively with CFCC materials. This rig will also be used for durability testing. The CFCC liner is contained within a metallic cylinder and is held in position with a Nextel 440 insulating blanket. The ceramic liner is freed from any mechanical loads in this configuration. The second rig simulates the attachment mechanism and metallic support structure of the combustor. It has been used both for CFCC liner and monolithic tile testing. The container can consists of metallic strips held together by two clamping rings in a barrel-and-stave arrangement. In the monolithic tile and ring configurations, the liners are loaded by three external tie bolts. The loads are transferred by small ceramic balls positioned in radial grooves at the edges of the liner assemblies. Table 8 summarizes the subscale liner tests planned and the status of the testing to-date.

Attachment/Durability Testing

The only monolithic test completed to-date involved Hexoloy® SA tiles in a subscale combustor configuration which was a miniature version of the full-scale configuration. Following completion of the tests, the tiles showed cracks which were initiated from the edges at the contact areas with the metal support structure and at the interfaces between the tiles. Although thermal shock was not

Table 8. Subscale Liner Tests Status

Test Configuration	Material	Purpose	Nominal Condition	Duration	Results
2-D CFCC	DLC SiC/SiC	Attachment/ Durability	1177°C (2150°F)	1 Hour	Pre-Existing Delamination Can Intact
2-D CFCC	DLC SiC/SiC	Attachment/ Durability	1177°C (2150°F)	10 Hours	Pre-Existing Delamination Extended Can Intact
2-D CFCC	DLC SiC/SiC	Attachment/ Durability	1177°C (2150°F)	100 Hours	TBD
2-D CFCC	DLC SiC/SiC	Emissions	871°-1177°C (1600°-2150°F)	2x 2 Hours	<10 ppmv NO_x, CO Can Intact
Fil.-Wound CFCC	B&W Al_2O_3/Al_2O_3	Attachment/ Durability	1038°C (1900°F)	1 Hour	Pre-Existing Delamination Extended
3-D CFCC (Nextel 610)	B&W Al_2O_3/Al_2O_3	Attachment/ Durability	1177°C (2150°F)	1 Hour	Possible Low-Density Region, Can Intact
3-D CFCC (Nextel 610)	B&W Al_2O_3/Al_2O_3	Attachment/ Durability	1177°C (2150°F)	10 Hours	Three Axial Cracks, Can Maintain Integrity
3-D CFCC (Nextel 720)	B&W Al_2O_3/Al_2O_3	Attachment/ Durability	1177°C (2150°F)	100 Hours	TBD
Tiles (Shiplapped)	Carborundum Hexoloy® SA	Attachment/ Durability	1204°C (2200°F)	1 Hour	Tiles Cracked, Interference
Tiles (Bevelled)	Carborundum Hexoloy® SA	Attachment/ Durability	1204°C (2200°F)	1 Hour	TBD
Tiles (Bevelled)	Carborundum Hexoloy® SA	Attachment/ Durability	1204°C (2200°F)	10 Hours	TBD
Rings	NAC NT230 SiC	Attachment/ Durability	1204°C (2200°F)	1 Hour	TBD
Rings	Carborundum Hexoloy® SA	Attachment/ Durability	1204°C (2200°F)	1 Hour	TBD
Rings	Carborundum Hexoloy® SA	Attachment/ Durability	1204°C (2200°F)	10 Hours	TBD

excluded as a contributor to the tile failure, it was concluded that the design of the metallic support structure was deficient in preventing undesirable levels of load transfer to the tiles. Design changes to the combustor liner were therefore implemented. Future testing will establish more clearly the durability of the monolithics once an improved design is implemented in the subscale tests.

The CFCC subscale testing indicated that notwithstanding materials imperfections as evidenced by localized low density regions and/or delaminations the CFCC liners generally retained their integrity during the testing. These tests were generally conducted in the first rig configuration which has minimal loading on the liners.

Emissions Testing

The purpose of the emissions testing was two-fold. The DOE SOW requires demonstrating NO_x levels < 25 ppmv and showing the potential of NO_x levels < 10 ppmv with a ceramic "hot wall" combustor. Solar's own goal was to demonstrate NO_x levels < 10 ppmv on the CSGT engine. The initial development was performed on a single-fuel injector can type geometry because (1) its simple geometry, (2) common test configuration with the subscale testing for attachment/durability, and (3) its easy scale up to an off-line can type combustor in case an annular combustor system cannot meet the target NO_x levels.

Two tests were conducted to establish the low emissions reduction potential of the ceramics. A DLC SiC/SiC CFCC can liner was used in these tests. The results of the test are shown in Figure 15.

In these tests the CFCC liner was used as a generic ceramic substrate and compared with a conventional metallic louvre-cooled liner (which is the common configuration for the Solar engine combustors) and a metallic effusion-cooled liner which represents an advanced liner cooling technique. As can be seen in Figure 15, the NO_x levels of the louvre- and effusion-cooled liner are typically > 20 ppmv over the fuel:air ratio range investigated for all three combustor liner systems. The level of CO increases sharply

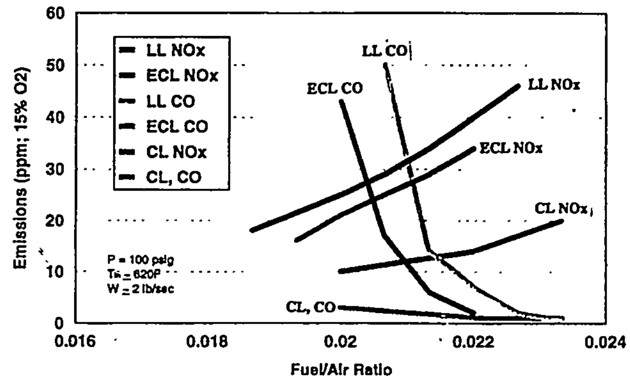


Figure 15. Emission Levels of NO_x and CO as a Function of Fuel:Air Ratio for Metallic and CFCC Liners

with decreasing fuel:air ratio. In generally, the levels of NO_x and CO are somewhat lower for the effusion-cooled liner compared with the louvre-cooled liner.

The CFCC liner shows significantly lower values of NO_x and CO compared with the metal liners. NO_x levels of about 10 ppmv were established for the CFCC liner compared to NO_x levels of 20 to 30 ppmv for the metal liners. CO levels were < 5 ppmv over the fuel:air ratio range investigated. The low CO levels present an opportunity to further lean out the flame to lower fuel:air ratios with reduced risk of a flame-out. This is expected to further reduce the level of NO_x in the combustor.

The tests have shown the potential of a "hot wall" combustor for reducing NO_x and CO levels significantly below those of metallic systems. Further development of the emissions potential will be conducted on full-scale systems.

Full-Scale Combustor Testing

Initially full-scale combustor testing was not envisioned till the end of Phase II. It was moved forward to enable time for sufficient iterative combustor emissions development to achieve the target NO_x level under the program. Also, the availability of a full-scale combustor at an earlier stage in Phase II was deemed desirable to enable simultaneous testing of multiple components. For this reason full-scale SiC/SiC CFCC liners were procured on a part supply basis from B.F. Goodrich because of their ability to meet the schedule for delivery. The BFG liners are considered a generic ceramic substrate useful for demonstrating the "hot wall" effect for the reduction of NO_x and CO, for emissions reduction development, and for development of the required radial profile and pattern factor essential for delivering the design heat flows to the critical nozzle vane and shroud areas.

To-date the testing of full-scale combustor liners has included an atmospheric and a high-pressure evaluation in combustor rigs. The atmospheric rig enables establishment of initial component temperatures while the high-pressure rig more accurately simulates engine combustor conditions. The latter rig enables emissions measurements, for example. To-date one set of BFG liners has been tested in both rigs. Test data have been summarized in Table 9.

The liners performed satisfactorily in the full-scale rig tests. No obvious signs of degradation were noticed upon inspection of the components following the testing. The liners will subsequently be tested in the engine rig (Table 6, Build No. 3).

Application and Benefits

The objective of the CSGT program is to demonstrate ceramic gas turbine technology with the aim at eventual commercialization and ensuing national energy savings and emissions reduction. The economic and technical potential of the ceramic gas turbine technology has been analyzed and described in the Phase I Final Report for the CSGT program (10).

Performance Benefits

The benefits of the technology derive (1) from the incremental value associated with the fuel savings and output power increase resulting from replacing cooled metal hot section components with uncooled or minimally cooled ceramic parts coupled with the increase in firing temperature these parts allow, and (2) from the value represented by the reduction in emissions of NO_x, CO, and UHC (unburned hydrocarbons) in ceramic engines compared to all-metal baseline engines. The added value can be estimated at the level of individual engine installations and can be extrapolated to the aggregate of installed power-generating capacity making assumptions about the level of market penetration of the ceramic technology.

The incorporation of ceramic hot section components in existing gas turbine installations in the context of a TRIT uprate in a retrofit scenario similar to that for the CSGT engine is expected to result in a moderate improvement in fuel efficiency of about 5 to 6 percent and a significant increase in output power of as much as 25 percent. These gains represent added value to the turbomachinery equipment which can be quantified. The interested reader is referred to the Phase I final report for a quantitative estimation of value added to gas turbines from ceramic insertion (10). When ceramic insertion is integrated in a comprehensive redesign of the engine hot section its value to the gas turbine is further enhanced. Improvements in fuel efficiency of about 20 percent and increases in output power of about 40 percent are

Table 9. Data from Atmospheric and High-Pressure Rig Testing for B.F. Goodrich Full-Scale Liners

Test (Duration)	Pressure	Max. Combustor Outlet Temp.	Max. Inner/ Outer Wall Temp.	Full Load Emissions	Liner Condition
Atmospheric (1 Hour, 2 Cycles)	1 atm	1049°C (1920°F)	950°C (1742°F) 1022°C (1872°F)	Not Evaluated	No Visible Degradation
High Pressure (3 Hours, 1 Cycle)	120 psia	1071°C (1959°F)	1120°C (2048°F) 1107°C (2025°F)	50 ppmv NO_x 6 ppmv CO	Liner Intact Some Degradation of Surface Coating

achievable. The greatest potential for ceramic gas turbine technology can be expected when used as one of a number of design tools in truly "clean sheet" designs such as those of the Advanced Turbine System program. There the benefits of reduced cooling and higher firing temperature can be combined with heat recovery, and possibly, at more advanced stages, with intercooling and chemical recuperation.

Emissions Reduction

In addition to improvements derived from enhanced fuel efficiency and increased output power significant benefits are anticipated because of the ability of ceramic "hot wall" combustors to lower emissions of NO_x, CO, and UHC. The true value is represented by the actual reduction in the gas turbine exhaust emissions burden on the environment and the potential for significant cost savings to the end user of gas turbine equipment by eliminating the need for water injection or expensive post-exhaust cleanup equipment such as selective catalytic reduction (SCR).

Application of Ceramics

The application of ceramic components is beneficial because it enables a higher component temperature in a simpler and therefore, less costly, design and/or it reduces the need for part cooling and the use of protective coatings. When considering the cost associated with utilizing ceramic blades and nozzles, one can assume that ceramics will be (1) more expensive than uncooled parts of conventional superalloys, (2) are of comparable cost as cooled conventional superalloy parts, and (3) can be significantly less expensive than parts fabricated of cooled and coated advanced superalloys.

Where the design temperature allows the use of uncooled superalloy components, there is no advantage in using ceramic parts unless other benefits are sought (e.g., a reduction in stress on a disk by using lighter ceramic blades). As a result, there is no benefit in considering ceramic blades for engines with a TRIT under ~900°C (~1650°F) or ceramic nozzles for engines with a TRIT under ~850°C (~1560°F). The lower temperature limit for the nozzle is attributable to the need to design for "hot spot" conditions. Under these temperature limits uncooled metal parts function satisfactorily and they can be fabricated at a fraction of the cost of ceramic parts assuming aerospace quantities of components (i.e., 10,000s/year).

When cooled superalloy components are replaced, the cost of ceramic and metal parts are expected to be of similar magnitude and the benefits of eliminating cooling favor the use of ceramics. The replacement of expensive cooled and coated advanced superalloy components with uncooled ceramic parts is particularly attractive since a component cost reduction is accompanied by a performance improvement derived from the elimination of cooling.

An interesting scenario is presented by an engine uprate as is represented by the CSGT engine. Here the scenario involves a significant performance improvement because of the increase in TRIT. But the TRIT increase also necessitates an upgrade in component structural materials from affordable conventionally cooled and metal parts to advanced cooled and coated superalloy parts. Here ceramics provide the double advantage of enabling the improved engine performance at a potential cost reduction.

The application of ceramic combustor liners needs to be viewed somewhat differently than the application of ceramic blades and vanes. The benefits associated with emissions control are substantial and the potential to meet regulatory emission standards without the need for expensive add-ons represents a substantial value to the end user. Therefore, broadly speaking, the cost of a ceramic combustor liner can be higher than the cost of a comparable metal part. Also, because of the potential emissions benefits ceramic combustors are expected to find applications in many engine models over a wide range of TRIT values.

Special consideration must be given to small engines. These engines often compete with diesel and/or gas engines and the allowable incremental cost is constrained by the package cost of these competing prime movers. The allowable cost range will be less elastic than for larger engines. Overall package cost targets will put restrictions on the cost of the combustor liner components.

A somewhat similar situation may arise in the case of a retrofit of a small engine. There is a limit to what an established end user is willing to pay for a retrofit package even if emissions benefits are substantial. Unless the end user is forced to meet tighter emissions regulations, it is unlikely a substantial increase in the cost of an overhaul is acceptable and, again, the increase in the cost of a combustor liner will be limited.

Timeframe for Commercialization

It is not possible at this point to present a firm target date for commercialization of the ceramic engine, since many factors are involved, but a likely scenario can be delineated, based on the timeline for the CSGT program. The commercialization timeframe can be represented as follows:

- 1992-1995: Ceramic component development.
- 1995-1996: Engine testing and design validation.
- 1996-1999: Ceramic engine field testing.
    - 1997/1998: 4,000-hour CSGT engine field test.

- Multiple engine field tests.

- 1998-2000: Ceramic engine product development.

- 2000: Earliest introduction of ceramic engine components in commercial engine.

  - Combustor liners first.

  - Nozzles next.

  - Rotating components last.

- 2005: Significant penetration of retrofit markets.

- 2010: Established mature market for ceramic engines.

The above time schedule assumes demonstration of technical feasibility through successful field testing, favorable economic conditions (fuel and electricity prices), and market acceptance.

National Energy Conservation and Environmental Benefits

Estimates of potential national energy savings and emissions reductions as a result of implementing ceramic gas turbine technologies in industrial engines (0.5-25 MW output) have been made as part of the Phase I work. Potential annual national energy savings have been estimated to range from 0.076-0.28 quads (1 quad = 10^{15} Btus) by 2010. The lower end of this range assumes a modest penetration of the projected engine fleet with first generation retrofits. The higher end of the range assumes that the entire installed fleet will consist of second generation ceramic engines.

An estimate has also been made of the emissions benefits of the ceramic gas turbine. Assuming an across the fleet reduction of NO_x to 10 ppmv, the total NO_x savings for the U.S. industrial engine fleet are estimated to be about 4.5 x 10^5 tonnes of NO_x.

Future Activities

Phase II work to-date has essentially involved completion of the first generation ceramic component designs and the design of the interfacing metallic support structures, fabrication of subscale components and full-scale prototypes, set-up and modification of test rig facilities, testing of specimens and subscale components, the generation of a long-term data base, and the development of supporting technologies such as NDE. Testing of full-scale prototype components in rigs and in the program engine was started at the end of the reporting period.

The work for the remainder of Phase II involves the following activities:

- Completion of the fabrication of all first generation ceramic components and testing of these components in proof rigs and in the engine rig. The final demonstration of the designs evolved during Phases I and II will be a successful 50-hour engine test at a TRIT of 1121°C (2050°F) incorporating all conditions typically expected during operation of an engine in the field.

- Modification of ceramic component and secondary component designs based on the results of testing of the first generation hardware. The modifications should eliminate any materials and design imperfections identified in the rig and engine testing.

- The selection of the designs, materials, and suppliers for the components to be tested in the final Phase II engine tests and in the 4,000-hour Phase III field test.
- Fabrication of the second generation components for final engine testing and field testing.
- Establishment of long-term test data base for the critical failure modes (fatigue, creep, oxidation) expected to affect the performance of the ceramic parts in the field testing. Creep data for up to 10,000 hours of exposure will be generated.
- The establishment of NDE methodology for monolithic ceramic and CFCC gas turbine components that will enable assessment of component integrity in the as-received state and following service in an engine.
- Development of a detailed plan for the Phase III 4,000-hour engine test at the ARCO Oil & Gas Bakersfield site.

Acknowledgements

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5.3 DOE/Allison Ceramic Vane Effort

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Introduction

An objective of the Advanced Turbine Systems (ATS) program is to develop ultra-high efficiency gas turbine systems. Rotor inlet temperatures several hundred degrees greater than for the highest temperature current industrial engines will be required to meet the ATS objectives. Consequently, new technologies need to be developed and demonstrated to achieve the required ultra-high ATS efficiencies.

Objectives

Other than combustor-related components, the highest temperature parts in a turbine are the first-stage stator vanes. Ceramic vanes are being considered to enable the increased turbine inlet temperatures needed to meet the ATS program efficiency goals. However, ceramic vanes have not been proven for industrial turbines, even at current inlet temperatures. The Allison Phase 2 ATS program was modified to prove ceramic vanes at current industrial turbine conditions. The objectives of the task described in this paper are to design, evaluate, and demonstrate first-stage ceramic vanes in an industrial turbine operated at a current inlet temperature in the vicinity of 1100°C (2000°F). This could provide a stepping stone to the introduction of ceramic vanes into ATS turbines with very high inlet temperatures in excess of 1427°C (2600°F).

This research is sponsored by the U.S. Department of Energy's Morgantown Energy Technology Center, under contract DE-AC21-93MC 29257 with Allison Engine Co., P.O. Box 420, 46206; telefax 317-230-3691.

Approach

The program objectives will be accomplished by the following approach:

- design and analyses of first-stage ceramic vanes and mounting hardware
- ceramic vane procurement
- thermal shock proof tests of the ceramic vanes
- proof tests of the vanes and mounting hardware in a test engine
- demonstration of the ceramic vanes and mounting hardware in a long term Allison 501 turbine run at a commercial site

Project Description

Design/Analyses of Ceramic Vanes and Mounting Hardware

Ceramic vanes and mounting hardware will be specified and designed for retrofit into an Allison 501 turbine. For that engine, the first-stage vanes are exposed to an average combustor outlet temperature up to the vicinity of 1100°C (2000°F) with hot spots several hundred degrees higher. The intended vane life is 30,000 hr, comparable to the current design life of metallic vanes.

The initial mechanical design of the vanes and their mounting hardware will be based on Allison's extensive experience in the design and testing of smaller experimental automotive turbines that use ceramics. Computerized heat transfer and stress analyses will be used to evaluate the initial design and refine it, as needed. Typical ceramic properties of the vendor materials will be used in the initial analyses. The stress analyses will be later refined using materials data obtained from flexure and tensile test of vendor specimens formed from the same batches used to form the purchased vanes.

A probabilistic design methodology has been developed by Allison that addresses the statistical nature of a ceramic's strength distribution and the reliability requirement for the component in service. The material surface and volume strength is characterized by a two-parameter Weibull statistical treatment of the four-point bend modulus of rupture strength of test bars. The component reliability service life goal is apportioned for required reliability in customer service. Additionally, the engine operating environment is input to the sophisticated finite element modeling of the component to analytically assess the fast fracture reliability. Both steady-state and transient (startup and shut down) thermal and mechanical loads for engine operation will be considered in design analyses.

The results of the design and analyses activities will be used to specify the ceramic vane configuration to ceramic vendors. These activities will also be used to produce mounting hardware drawings for fabrication or procurement by Allison under this task.

Procurement of Ceramic Vanes

The ceramics suppliers will be involved in the definition of vane and mount designs. The purpose of interaction with the ceramics suppliers is to assure that the vane design is engineered not only for long life but also for acceptable production costs. Procurement of the ceramic vanes will be based on the specifications and drawings resulting from the iterative design, analyses, and supplier interactions.

Thermal Shock Proof Tests

Proof tests will be conducted for all ceramic vanes that are expected to operate in later engine tests. The proof tests will simulate temperatures corresponding to at least one engine startup from room temperature to full load (vicinity of 1100°C [2000°F]), a period of exposure at that temperature, and an abrupt drop in temperature to represent a generator trip in service which results in an immediate shutdown of fuel to a turbine. The purpose of this test is to screen out any vanes with undetected flaws that could initiate cracks and failure due to thermal shock in an operating turbine. After the proof test, each vane will be visually inspected and analyzed by nondestructive techniques such as fluorescent penetrant and microfocus X-ray.

Vane/Mount Proof Test in Engine

A full set of first-stage ceramic vanes and their mounting hardware will be operated in a 501 turbine at Allison. The purpose is a proof test of both ceramic vanes and metallic mounting components in an operating test engine prior to installation at a commercial site. The test will verify that the metallic mounting hardware does not transmit excessive contact stresses or excessive mechanical loads to the ceramic vanes due to distortions caused by the combustor temperature patterns. The test will probably consist of a normal startup of the turbine, operation for up to 50 hr at load, and a normal shutdown.

Ceramic Vane Field Demonstration

Since the field demonstration depends on a final agreement with the end-user, the following test plans are preliminary.

Vanes that had been screened in the thermal shock proof test and the engine proof test will be installed with mounting hardware in an Allison 501 turbine that has been taken out of commercial service for maintenance.

The turbine will reenter service at its commercial site for up to 8000 hr under its normal operating conditions. The commercial site will most likely be a cogeneration plant, at which operation is essentially continuous at full load, except for unanticipated shutdowns (such as generator trips) and scheduled maintenance (probably 6 month intervals). Inspection frequency for the ceramic vanes and their mounts will depend on the agreement with the end-user, since any additional inspection outages result in loss of plant revenues. At the end of the test, ceramic vanes will be removed from the engine and analyzed to assess their condition and expected additional life.

Results

Vane Screening Analyses

The highest stresses for the ceramic vane are expected to result from emergency shutdowns to prevent the turbine from overspinning due to loss of generator load. The fuel to the combustors is instantly shut off and the gas entering the first stator passages immediately drops in temperature by as much as 720°C (1300°F). The thin trailing edges of the hot vanes cool faster than the thicker leading edges to produce high thermal transient stresses.

Probability of survival (POS) analyses were conducted to calculate thermal transient stresses in ceramic vanes with the same profile shape as the metallic vanes in a commercial Allison 501 turbine. Materials properties of three candidate ceramics were used for the POS evaluations. Vane platform effects were neglected in these initial screening analyses.

The POS during an emergency shutdown of a full set of 60 solid ceramic vanes was calculated at about 99 percent for the best of the three ceramics. Calculations for hollow ceramic vanes indicated a reduction in thermal shock stresses. However, discussions with ceramic suppliers indicated that hollow vane production costs in commercial quantities increase significantly for vanes of the scale used in the Allison 501 turbine.

To alleviate thermal shock stresses, a new vane shape was designed by the Allison aerodynamics group. This new vane design (Figure 1) has less thickness variation over its chord to result in more uniform cooling and about 24% lower thermal shock stresses than a ceramic vane with the shape now in the 501 turbine. The calculated POS for the full set of stator vanes with the new profile approaches 100 percent. Also, the new vane shape has improved aerodynamic performance due to advances in aerodynamic computational techniques since the original design of the 501 turbine vanes.

Vane/Mount Design

In addition to long lifetimes at steady state conditions and probabilities of survival approaching 100% during startup and shutdown thermal shocks, two design goals for the ceramic vanes are:

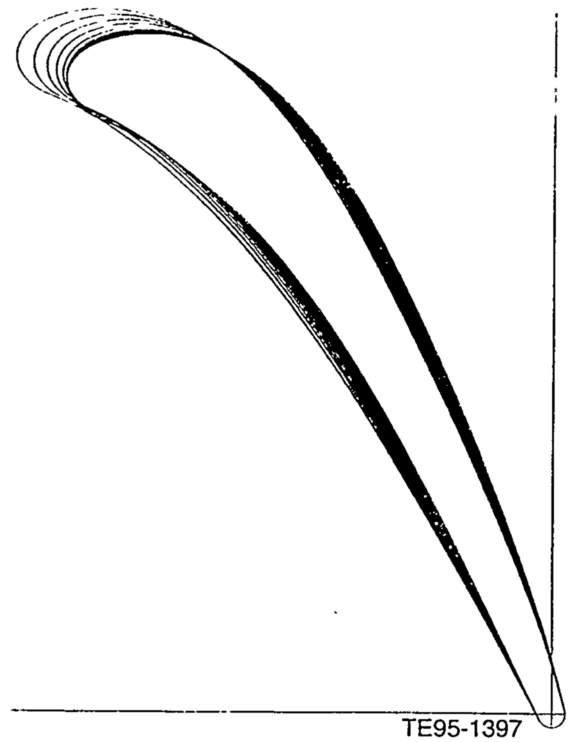

Figure 1. Redesigned Ceramic Vane.

- production costs competitive with current metallic vanes
- reduction of contact stresses between the ceramic vanes and their metallic mounts

Various design options have been discussed with ceramics suppliers and an initial design has been chosen for 3-D thermal and stress analyses. For this design, the ceramic vane is not hard mounted and the contact area at metallic interfaces is minimal. These features alleviate contact stresses and the amount of expensive diamond machining required at ceramic surfaces in contact with metallic mounts.

Vane/Mount Analyses

The 3-D stress analyses for steady state and emergency shutdown probabilities of survival (POS) of the ceramic vanes are in progress. Figure 2 shows the finite element mesh networks for both the vane and its metallic mounts. The properties of candidate ceramics from three suppliers are being used in these evaluations. Two of the ceramics are monolithic silicon nitride materials and the third is a relatively low cost ceramic matrix composite of silicon carbide particles in a matrix of alumina.

Ceramic Vane Thermal Shock Tests

The layout design and drawings have been completed for the thermal shock test equipment to be used for proof tests of every ceramic vane expected to operate in later engine tests. The detailed design and drawings are in process.

Application

Technology advancements in metallic cooling techniques and materials will be needed if alloys are to be used for the airfoils that experience the highest gas temperatures in ATS turbines. An alternate approach is the development of structural ceramics which would need little or no cooling of the high temperature airfoils.

There are several potential benefits for ceramic airfoils over cooled metallic airfoils. Since compressed cooling air bypasses the combustor, the resulting turbine performance penalty for cooled metallic airfoils is reduced for ceramic airfoils. NOx emissions goals are more easily met if ceramic, rather than metallic, first-stage vanes are used. Since the drop in gas stream temperature between the combustor and the first rotor blades is less for ceramic vanes, a lower combustor temperature (which produces less thermal NOx) can be used to achieve a given rotor inlet temperature.

Future Activities

Upon completion of the ceramic vane 3-D thermal and stress analyses, the design will be modified, if needed, for improved POS and life. The vanes will be ordered from the ceramic suppliers upon verification of the design by these analyses. The vanes will then be proof tested in the thermal shocks rig prior to operation in engine tests.

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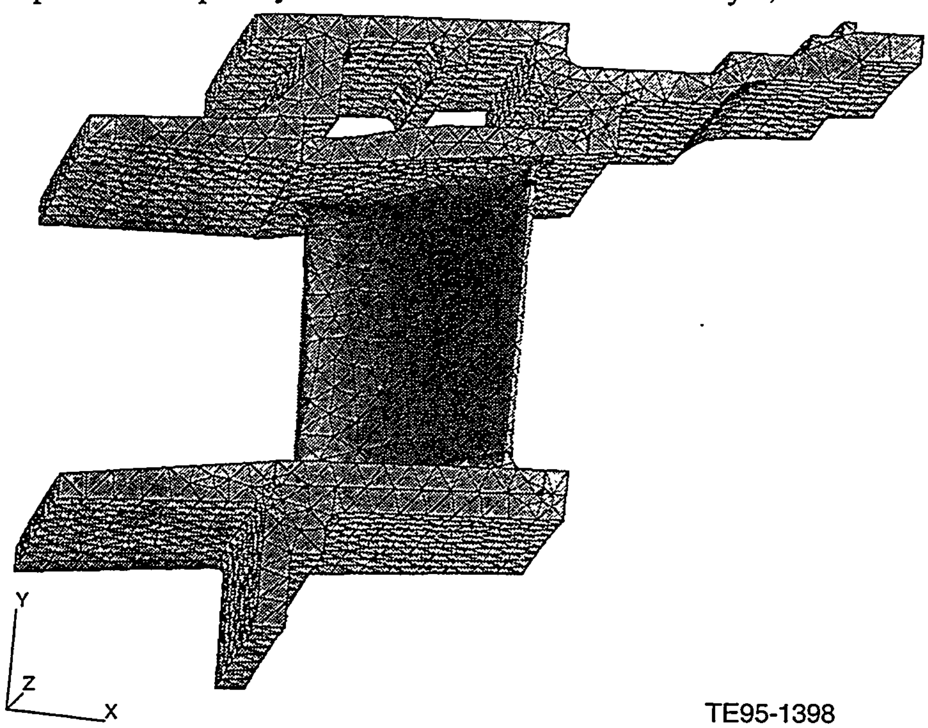

Figure 2. Finite Element Mesh for Ceramic Vane and Mounts.

5.4 Materials/Manufacturing Element of the Advanced Turbine Systems Program

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Abstract

The technology based portion of the Advanced Turbine Systems Program (ATS) contains several subelements which address generic technology issues for land-based gas-turbine systems. One subelement is the Materials/Manufacturing Technology Program which is coordinated by DOE-Oak Ridge Operations and Oak Ridge National Laboratory (ORNL). The work in this subelement is being performed predominantly by industry with assistance from universities and the national laboratories. Projects in this subelement are aimed toward hastening the incorporation of new materials and components in gas turbines.

A materials/manufacturing plan was developed in FY 1994 with input from gas turbine manufacturers, materials suppliers, universities, and government laboratories. The plan outlines seven major subelements which focus on materials issues and manufacturing processes. Work is currently under way in four of the seven major subelements. There are now major projects on coatings and process development, scale-up of single crystal airfoil manufacturing technology, materials characterization, and technology information exchange.

Introduction

The Department of Energy, in cooperation with the Gas Turbine Industry, initiated a program in 1992 to develop Advanced Turbine Systems (ATS) for land-based power generation. The objective of the ATS Program is to develop ultra-high efficiency gas turbine systems for base-load utility and industrial markets. The ATS Program is jointly sponsored and managed by DOE Fossil Energy and DOE Energy Efficiency and Renewable Energy. The program plan (Ref. 1) outlines an eight-year program which involves turbine

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manufacturers, utilities, industrial end-users, national laboratories, and universities.

One of the major supporting elements of the ATS Program is the materials/manufacturing task. The purpose of this element is to address key materials issues for both utility and industrial gas turbines. This paper is a status report on the ATS Materials/Manufacturing Element.

Objective

The ATS Materials/Manufacturing Plan was completed in April 1994 (Ref. 2). This plan was developed in coordination with the turbine manufacturers. In developing the plan, the turbine manufacturers stated a need for turbine inlet temperatures as high as 2600°F to achieve the efficiency goals. To achieve these temperatures for extended operating periods, there is a need to utilize new materials developments. The turbine manufacturers also indicated a need for effective interactions among themselves, material suppliers, national laboratories, and others.

The primary objective of the Materials/Manufacturing Element is to provide materials and materials-related manufacturing technology support to meet the ATS goals. The ATS prime contractors are responsible for the technologies necessary for the demonstration projects. The materials manufacturing support is intended to compliment the ATS team efforts and provide expertise not available to any one single contractor.

Approach

The technical program for the Materials/Manufacturing Element focuses on generic materials issues, components, and manufacturing processes. The subelements for the program are divided into seven categories (Figure 1).

- Coatings and Process Development.
- Single Crystal Airfoil Manufacturing Technology.
- Materials Characterization.
- Turbine Airfoil Development.
- Ceramics Development.
- Catalytic Combustor Materials.
- Technology Information Exchange.

Currently, efforts are under way in four of the seven subelements. There are now projects ongoing on coatings and process development, scale-up of single crystal airfoil manufacturing, materials characterization, and technology information exchange. The remainder of the paper will summarize the status of the ongoing activities.

Description of Coating Projects

The coatings and process development program effort is focused on thermal barrier coatings (TBCs) systems which, for current systems, involves a ceramic outer layer that provides thermal protection, and an inner metallic layer, or bond coat. Proposals for Research and Development of Thermal Barrier Coatings Technology were received in late 1994. As of late September 1995, contracts had been signed between DOE-Oak Ridge Operations and Westinghouse Power Generation Business Unit of Orlando, Florida, and Pratt & Whitney, East Hartford, Connecticut. The goal of these programs is the development of dependable thermal barrier coatings (TBCs)

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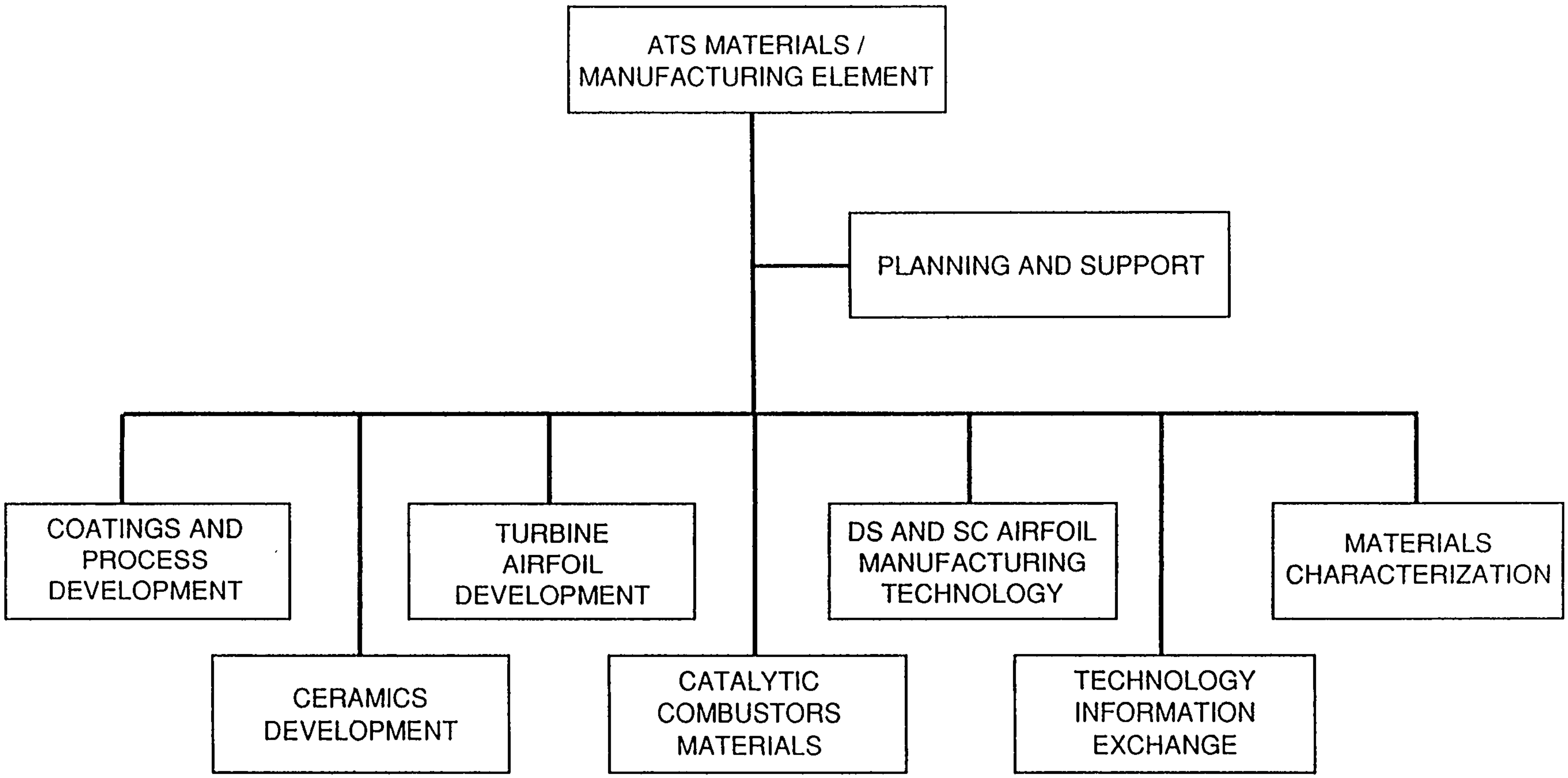

Figure 1. Work Breakdown Structure of the Research Tasks in the ATS Materials/Manufacturing Element

that enable increased turbine inlet temperatures while maintaining airfoil substrate temperatures at levels to meet ATS life goals. Each of these projects involves three phases, which address:

a. TBC process development
b. Bench tests, and
c. Product-line gas-turbine testing.

The main issues being addressed by these TBC contracts and by limited supporting studies at national laboratories and universities include:

(i) The development of bond coats with improved ability to reliably form a slow-growing and adherent alumina scale. The relative performance of several candidate bond coat systems, such as diffusion aluminides and overlay MCrAl-type compositions will be evaluated. Bond coat composition that promote the formation of adherent, thermally-grown alumina scales by exploiting the effects of reactive element additions such as yttrium, or by having very low tramp sulfur levels are included. In addition to different coating compositions, an evaluation will be made of the influence of surface pretreatments such as controlled preoxidation on the performance of TBC systems in screening exposure tests.

(ii) The ability to reproducible apply TBCs based on yttria-stabilized zirconia (YSZ) to all the surfaces of large, cooled vane and blade shapes while maintaining the desired coating composition, microstructure, and thickness. The effects of changing the operating parameters of available coating processes (electron beam-assisted physical vapor deposition, and plasma spray processes) will be correlated with the microstructure of the ceramic layer. The ability to maintain the structure and thermal resistance of the ceramic layer as a function of thickness also will be explored. The performance of the coatings systems 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, using test pin specimens and conventional burner rig-type testing.

(iii) The feasibility of alternative or new materials or coating structures to achieve improved strain tolerance, improved phase stability, slower rate of sintering, decreased thermal conductivity, and/or increased resistance to spallation compared to the YSZ+bond coat concept will be explored. This effort will rely mainly on analysis of available physical and mechanical property data, but a limited number of experimental systems also will be produced and examined. One approach is the use of a ceramic layer that exhibits decreased oxygen transport compared to zirconia, and so could possibly lead to a slower rate of growth of the alumina scale formed on the metallic bond coat and longer time before spallation occurs.

Each program also includes efforts to measure relevant mechanical and physical properties of the TBC systems, and to use this information in mathematical models being developed to relate coating deposition/processing parameters to coating performance and expected lifetime. In addition to the adaptation of nondestructive examination (NDE) techniques for inspection of these coatings, some innovative concepts for observing coating performance and for measuring properties in situ will be tested. If successful, some of these approaches will be incorporated in the bench test specimens, and into engine hardware to be used in the product line engine test phase.

The most promising candidate TBC systems that emerge from the process development phase will be applied to airfoils which will be used in the bench testing phase. This effort will involve tests designed to simulate more closely the expected service conditions, particularly the thermal gradient through the coating system. The contractors are developing specialized test methods that use cooled specimens and reproduce the essential features of the environment experienced by the first stage vanes and blades in their particular engine design.

The TBC system(s) that achieve the performance goals of the bench testing phase will be applied to components that will be installed and run in a product line engine, provided that this optional phase is pursued. The duration of the engine test will be up to 12 months. The coated components will be fully characterized using the appropriate NDE technologies before installation, and their performance will be monitored during the test by means of built-in sensors. Post-test destructive analysis on selected samples will be used to verify the NDE/sensor indications. The data generated will be used to calibrate the life prediction models.

Description of Manufacturing Technology for Scale-Up of Single Crystal Turbine Airfoils

A solicitation was issued in 1994 to extend the capability of single crystal complex-cored airfoil technology to larger sizes so that higher turbine inlet temperatures could be attained in land-based turbines in a cost-effective manner. Two selections were made and contracts have been signed with Howmet Corporation in Whitehall, Michigan, and PCC Airfoils in Cleveland, Ohio.

Howmet Project

The project led by Howmet is supported by a team including ABB, Pratt & Whitney, Solar, Westinghouse, Aracor, and Purdue University. The project is scheduled over a period of 34 months with completion in April 1998. This project includes four technology thrust areas:

- Low-sulfur alloys.
- Casting process development and understanding.
- Postcast process development and improvement.
- Casting defect tolerance level.

The effort on low-sulfur alloys includes producing low-sulfur heats of four alloys, casting single crystal test specimens of each, and conducting cyclic oxidation tests on the specimens to evaluate the effects of sulfur content on oxidation resistance.

Casting process development and understanding encompasses developing the single crystal casting process for two alloys in utility size airfoils and for one alloy in industrial size airfoils, developing improved wax, developing improved molds, and producing improved cores to reduce the occurrence of grain defects and improve dimensional control.

Postcast process development and improvement includes investigation of varying heat treatment and hot isostatic pressing treatment on large test specimens, conducting metallographic examinations, performing mechanical property tests to determine effects of varying treatments, and developing inspection techniques for detection of porosity and internal defects.

The area of casting defect tolerance level entails conducting tests to characterize the effects of defects such as freckles, low-angle boundaries, splaying, and of varying size and severity on mechanical properties.

The program plan for the project was completed in early September 1995, and work was begun on the development effort.

PCC Airfoils Project

The project team is led by PCC Airfoils and they are supported by GE Power Generation. The effort is scheduled over a period of 29 months with completion in July 1997. This project includes four major tasks: alloy melt practice, modification/improvement of single crystal casting process, core materials and design, and grain orientation control.

The task on alloy melt practice involves producing heats of a single crystal alloy with a very low-sulfur level, casting single crystal test specimens, and conducting cyclic oxidation and hot corrosion tests on the low-sulfur specimens and baseline sulfur-level specimens to determine the effects of sulfur level on oxidation and hot corrosion resistance.

The single crystal casting modification/improvement task entails developing the casting process for one single crystal alloy for utility turbine size airfoils in both cored and solid configurations. This will be done by making a series of castings in which a number of important casting parameters are varied and their effects on the quality of the casting evaluated. To guide the selection of the process parameters, the casting process will also be modeled on a computer program where the casting parameters will be varied. Once the optimum values of the process parameters have been determined, a few additional molds will be made to verify the quality of the airfoils made by the final casting process.

The task on core materials and design will address the issues associated with producing cores that will have the required characteristics to consistently form complex cooling passages and maintain tight wall thickness tolerances in large airfoils. A number of core material compositions will be investigated and evaluated for shrinkage, strength, stability, and porosity. Cores exhibiting superior strength and stability will be selected for the first casting trials. These cores will be evaluated during the casting trials for their performance relative to dimensional control, metal interaction reactions, and core removal characteristics.

The objective of the task on grain orientation control is to evaluate the effects of defects such as grain boundaries and freckles on the fatigue strength of the material. Test specimens will be cut from areas containing specific defects in the airfoils produced in the early casting trials. The specimens will be subjected to low-cycle fatigue testing at typical operating conditions for the airfoil root section. The test results will be evaluated for the effects of each type of defect to help establish criteria for defect tolerance levels in large airfoils.

The Program Plan for the project was completed in April 1995, and the tasks on alloy-melt practice and single-crystal casting are under way.

Description of Materials Characterization

Long-Term Testing of Ceramics for Gas Turbines

The Department of Energy's Office of Industrial Technologies (OIT) has initiated a program to develop ceramic components for use in industrial gas turbines. The program was designed to bring ceramic technology to the point where short-term reliability and engine performance have been demonstrated.

DOE-OIT selected Solar Turbines Incorporated for the development of ceramic gas turbine components. Solar Turbines started work in late FY 1992. One of the critical areas outlined in their program was a long-term materials testing program. Long-term materials tests are needed to determine the survivability of the materials for land-based applications. This section outlines the long-term testing conducted at Oak Ridge National Laboratory (ORNL) and University of Dayton Research Institute (UDRI) in support of the program with Solar Turbines.

Research activities on this project focus on the evaluation of the static tensile creep and stress rupture (SR) behavior of three commercially available structural ceramics which have been identified by the gas turbine manufacturers as leading candidates for use in industrial gas turbines. Tensile creep data are being generated in air by measuring creep strain as a function of time, applied stress, and temperature. The SR resistance is being evaluated by continuing each creep test until the specimen fails. For each material investigated, a minimum of three temperatures and four stresses are being used to establish the stress and temperature sensitivities of the creep and SR behavior. The test matrix utilized in this program is intended to extend the test conditions investigated by the engine component manufacturers. Because existing data for many candidate structural ceramics are limited to testing times less than 2,000 h, this program is focused on extending these data to times on the order of 10,000 h, which represents the lower limit of operating time anticipated for ceramic blades and vanes in gas turbine engines.

TBC Characterization

The primary goal of this research is to develop and apply state-of-the-art characterization techniques to the evaluation of the mechanical and thermal reliability of thermal barrier coatings. In Phase I of this program, an extensive review of the characterization techniques previously applied to the study of TBC failure will be performed. Results of this study will be used to select the most promising characterization techniques for further evaluation. It is anticipated that specific emphasis will be placed upon methods appropriate for the measurement of residual stress, thermal conductivity, damage in the form of micro- and macrocracks, and oxidation. In Phase II, the effectiveness of these various methods to the evaluation of cyclic-dependent failure of TBCs will be addressed by measuring these properties both in the as-fabricated state and after various amounts of thermal cycling. In Phase III, data generated from the Phase II effort will be used to extend existing life prediction models describing the time (cyclic)-dependent failure of TBCs.

Description of Technology Information Exchange Task

The objective of this element is to provide a mechanism to transfer information on materials issues developed at other agencies such as NASA, DoD, and other DOE materials programs to the ATS program. Some of these material efforts can have significant impacts on the ATS program.

The main effort that occurred in this area was a Thermal Barrier Coatings Workshop that was held jointly with NASA and NIST in Cleveland, Ohio, on March 27-29, 1995. The objective of the workshop was to assess the state of TBC knowledge and identify critical gaps in the knowledge that hinder the use in advanced applications. These goals were achieved through presentations on topics ranging from defining the needs of TBCs to the design of future coatings, through extensive discussions on the issues facing TBC use. There had not been a major TBC Workshop in over ten years, and it is now anticipated that there will be a workshop similar to the one held in 1995 every other year.

Summary

The technology-based development portion of the ATS Program contains elements which address generic technology issues for advanced gas turbine systems. One element is the materials/manufacturing element which is directed by Oak Ridge with work performed by industry with assistance from national laboratories and universities. A Materials/Manufacturing Plan was completed in April 1994 in coordination with the gas turbine manufacturers. The plan outlines seven major subelements which focus on materials issues and materials-related manufacturing technology issues. The seven major subelements are: (1) Coatings and Process Development; (2) Turbine Airfoil Development; (3) Ceramic Development; (4) Single Crystal Airfoil Manufacturing Technology; (5) Materials Characterization; (6) Catalytic Combustor Materials; and (7) Technology Information Exchange.

Work is currently under way for the four major subelements. There are now major projects on Coating and Process Development, Scale-Up of Single Crystal Airfoil Manufacturing, Materials Characterization, and Technology Information Exchange.

The coating projects include major efforts on TBCs. There are two major industrial projects, one with Westinghouse, the other with Pratt & Whitney, and the goal of these is the development of dependable TBCs that enable increased turbine inlet temperatures while maintaining airfoil substrate temperatures. Each of these projects involves three phases which address TBC process development, benchmark testing, and a product-line gas turbine testing. There are also supporting studies at national laboratories and universities that include development of bond coats and TBC characterization.

Other major ongoing projects include a turbine airfoil manufacturing program that extends the capability of single crystal complex airfoil technology to larger sizes, so that higher turbine inlet temperatures can be obtained in land-based gas turbines. The specific purpose of these efforts is to define manufacturing methods that will allow single crystal technology to be applied to power generation turbines in a cost-effective manner. Currently, projects are under way with Howmet Corporation and PCC Airfoils.

Long-term testing of ceramic materials is under way at ORNL and UDRI. This is in support of Solar Turbines' Ceramics for Stationary Gas Turbines Project. The objective of that program is the development of ceramic gas turbines components, and one of the critical areas outlined by the program was a long-term materials test program. The primary goal of this research is to determine the long-term survivability of ceramic materials for industrial gas turbine applications.

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5.5 Land-Based Turbine Casting Initiative

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Introduction

The Advanced Turbine Systems (ATS) program has set goals which include a large-scale utility turbine efficiency that exceeds 60 percent (LHV) on natural gas and an industrial turbine system heat rate improvement of 15 percent. To meet these goals, technological advances developed for aircraft gas turbine engines need to be applied to land based gas turbines. These technological advances include: directionally solidified and single crystal castings, alloys tailored to exploit these microstructures, complex internal cooling schemes, and coatings.

Equiaxed and directionally solidified castings are employed in current land based power generation equipment. These castings do not possess the ability to meet the efficiency targets as outlined above. The production use of premium single crystal components with complex internal cooling schemes in the latest generation of alloys is necessary to meet the ATS goals. However, at present, the use of single crystal components with complex internal cooling schemes is restricted to industrial sized or aeroderivative engines, and prototype utility sized components.

Research Sponsored by the U.S. Department of Energy's Office of Fossil Energy (Morgantown Energy Technology Center) and Office of Energy Efficiency and Renewable Energy (Office of Industrial Technology), through Oak Ridge National Laboratory, under Contract DE-AC05-84OR21400 with Howmet Corporation, 1500 S. Warner St., Whitehall, MI 49461-1895; FAX 616-894-7826.

Objective

While the processes, measurements and specification of controls are in place for components currently used in aircraft gas turbine engines, a re-examination of the practice is necessary, primarily because of 2X to 3X increase in size of single crystal castings for land based turbines. As the casting size increases, it would seem inevitable that the total number of defects and variation in properties with increasing surface area and volume of material would increase also. These property variations may be expected to impart additional cost and performance penalties. Furthermore, these issues must be addressed in the context of an altered operating scenario in which the long-term, steady state durability is more critical than the number of start-up and shut-down cycles.

Specific developments have been identified which are required to scale aircraft single crystal casting technology up to land based turbine size components. The objective of the proposed program is:

- Develop and implement the technology necessary to scale single crystal aircraft gas turbine investment casting technology up to utility land based turbine sized components.
- Enhance the performance of industrial land based turbines through the application of next generation single crystal superalloys.
- Develop and implement improved casting and inspection practices.

Approach

The United States aircraft gas turbine industry has developed, implemented, and successfully utilized state-of-the-art crystal growth technologies, such as directional and single crystal solidification, to achieve a world dominant market position. This world dominant market position has contributed significantly to the U.S. balance of trade. The proposed program will extend and apply this technological preeminence to the land based power generation industry to develop high efficiency, environmentally superior, and cost competitive gas turbine systems for application in utility and industrial land based power generation equipment. The proposed program includes all aspects of investment cast hardware for land based power generation equipment including alloy chemistry, investment casting process development and understanding, post-casting processing, and characterizing the detrimental effect of defects common to large directionally solidified or single crystal components. The team assembled to conduct the proposed program includes expertise in the areas of alloy production, investment casting, and OEM end users.

The proposed program to scale aircraft gas turbine casting technology up to land based gas turbine size components is based on four technology thrust areas. These four technology thrust areas, while pursuing different disciplines and discrete innovations, constitute a coherent system which encompasses the entire process to reliably produce high quality, cost effective investment casting for land based gas turbines. The four thrust areas are: low sulfur alloys, casting process development/understanding, post-cast process development/improvement, and establishing casting defect tolerance levels. The program technology thrust areas are shown schematically in Figure 1.

To scale investment casting technology up to land based gas turbine engines will require advances in each of the thrust areas. Within the low sulfur activities, previously developed melt processing treatments which lower the bulk alloy sulfur content will be examined. Casting process activities will focus on developing a fundamental understanding of the relationship between defect formation and cast part geometry, casting process parameters, and mold and core design and materials. The post-cast process improvement efforts will address the need of enhancing mold, core, and gating removal, and heat treatment and HIP cycles to produce optimum properties in large section sized components. In addition, improved nondestructive inspection systems need to be developed for large land based components. The fourth thrust area examines the effect of casting defects; such as freckles, primary misorientation, low angle grain boundaries, and recrystallized grains, on mechanical performance. While improvements in any one of these thrust areas will improve land based turbine performance, by working each of these technologies concurrently, the developments will be coordinated and synergize to produce the highest quality, most cost effective castings.

The proposed program will be conducted by a team comprised of utility and industrial gas turbine OEM's, an investment casting supplier, and an inspection system developer. This team addresses the entire supply chain to produce land based gas turbine castings including: alloy production, investment casting and end users. The team members include:

- ABB: producer of utility power generation gas turbines.
- ARACOR: developer of industrial non-destructive evaluation systems based on computed tomography and digital radiography.
- General Electric: producer of power generation gas turbines, aircraft gas turbines,

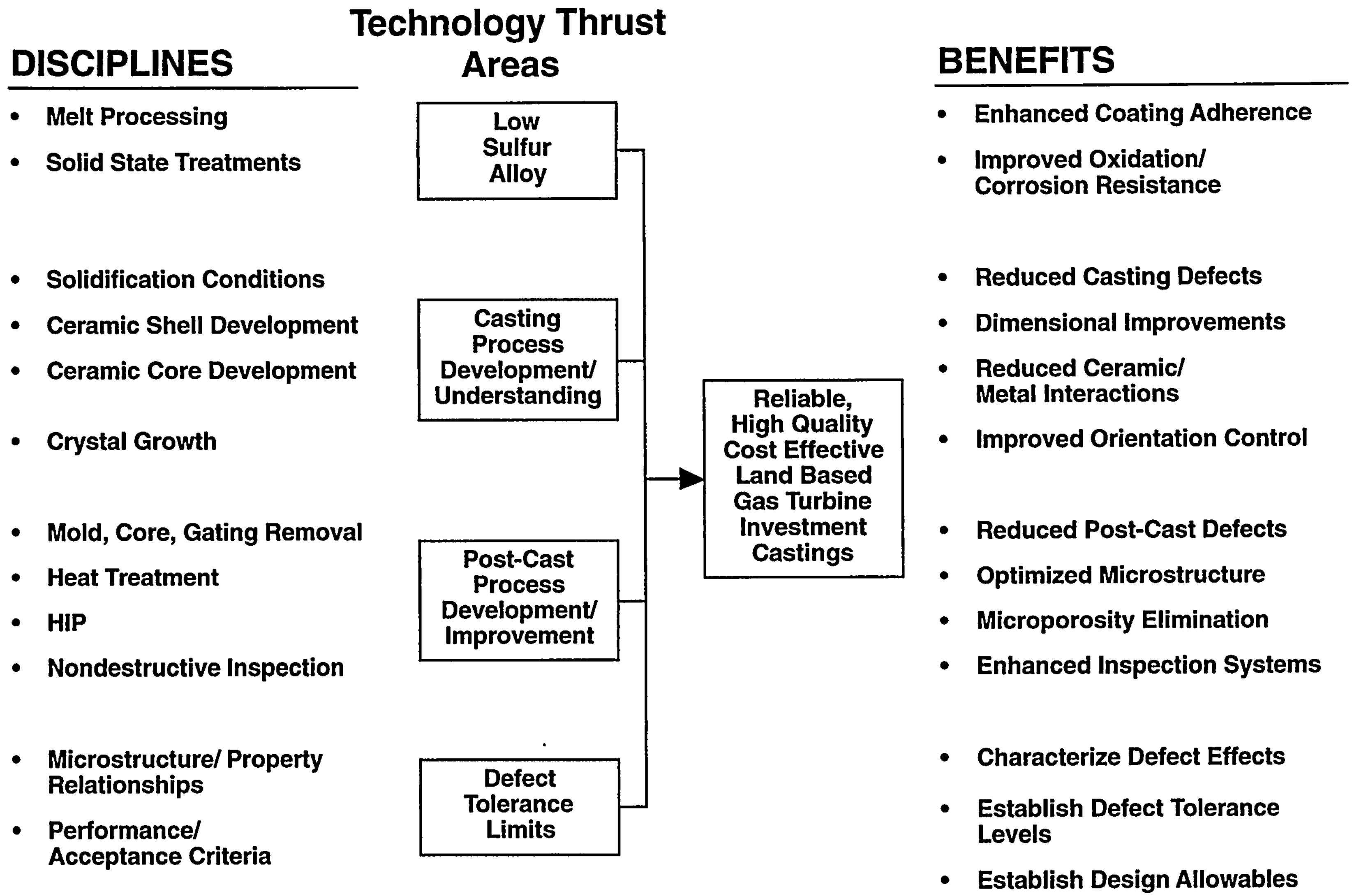

Figure 1. Land-Based Turbine Casting Initiative Technology Thrust Areas

and power generation and aircraft gas turbine superalloy developer.

- Howmet: superalloy supplier and superalloy investment casting company.

- Pratt & Whitney: producer of aero-derivative power generation gas turbines, and a superalloy developer for aircraft and power generation gas turbine applications.

- Solar: producer of industrial power generation gas turbines.

- Westinghouse: producer of utility power generation gas turbines.

Project Description

The program to develop and implement the technology necessary to cast large single crystal components was initiated in June, 1995. The detailed program planning phase has been completed. Technical efforts began in September, 1995. The discussion that follows overviews the program plan and highlights the technical activities to be conducted during the course of this program.

Low Sulfur Alloy Castings

An objective of the proposed program is to produce nickel-based superalloy castings with superior environmental resistance through the use of low sulfur alloys. Since it is well established that lower sulfur content in castings results in improved oxidation performance, Howmet has developed a process to reduce sulfur content in the master alloy. Low sulfur alloy, in the range of less than 1.0 wppm sulfur, has been produced at Howmet. For this program, special low sulfur heats of GTD 111, PWA 1484 and Rene' N5 will be prepared. The target sulfur level for these heats will be less than 1.0 wppm. Throughout the course of this program, Howmet will continue to improve its low sulfur melt capabilities beyond the limits currently attained and will work to scale the heat sizes from development to production sizes. Cannon-Muskegon will produce low sulfur CMSX-4 and CMSX-10 heats. Possible differences in the sulfur levels attained in the various alloys will be characterized.

Low sulfur components will be cast. One goal during casting is to prevent the bulk pick-up of sulfur. The sulfur content of the ingot will be compared to that of the cast components. Low sulfur solid test panels will be cast to provide test material for process scale-up. Flat panels (0.080" thick) will be cast in CMSX-4, PWA 1484, GTD 111 and Rene' N5 current production and low sulfur materials. Cyclic oxidation benchmark testing of the panels with low and current production sulfur levels will be conducted to assess the beneficial effect of low sulfur.

Production scale-up of the low sulfur alloy formulation process will be guided by measurement of residual sulfur contents, cyclic oxidation testing and microstructure characterization. Sulfur analysis will be performed using a LECO model 444-LS sulfur and carbon analyzer. This instrument can measure sulfur contents as low as 0.1 wppm in an inexpensive and timely fashion. Results of experimental work will be used to provide direction in the identification of beneficial process modifications.

DS/SC Casting Parameter Development

Most DS/SC casting processes originated with aircraft applications and evolved to other configurations. Some process attributes can be scaled up or down based on configuration. Other process attributes cannot be readily scaled due to size limitations. This task will examine the effect of scaling casting parameters on both metallurgical and dimensional casting quality.

The current DS/SC process for land based turbines will be benchmarked relative to aircraft blade and vane DS/SC processes. Benchmarking will include: alloy, application (stage and/or configuration), part sophistication (machined or as-cast features), and sophistication of cooling (solid, radial hole impingement, film). The benchmarking includes documenting shrinkage, dross, inclusion, dimensional distortion, wall deviations, and single crystal grain defects. The different types of single crystal grain defects include: primary misorientation, bicrystals, low angle boundaries (LAB), slivers, freckles, and zebras. The grain defects are shown schematically in Figure 2.

Based on the benchmark analysis, designed experiments will be conducted to generate the process knowledge necessary to make true process improvement on large land based single crystal blade configurations. The designed experiments will be conducted on current generation single crystal alloy compositions, Rene N5' and CMSX-4, and a third generation single crystal alloy, CMSX-10. These experiments will examine not only the effects of geometry, alloy composition, and casting parameters on metallurgical and dimensional quality; but also will include mold and core factors as well. The objective of these experiments is to identify the critical factors affecting quality and interactions between different factors. With this knowledge, it will be possible to optimize the most critical factors identified in the designed experiments. The knowledge gained from this series of designed experiments will be captured in process models so that it can be transferred and applied to other component geometries and alloys.

Mold Materials and Design

The mold must fulfill the dual role of maintaining casting shape while allowing for adequate heat transfer. These requirements are often conflicting in that a thicker shell improves dimensional repeatability, but reduces heat transfer which can increase the likelihood of metallurgical grain defects. The response of current mold systems and designs will be benchmarked, and explored in the casting parameter designed experiments. Based on the results of the benchmarking and designed experiments, mold development activities will be conducted.

To quantify the capability of current mold systems, statistical data on thermophysical properties will be determined as a function of temperature on molds produced over a 3 month period. The results of these tests will be compared to dimensional data on production wax patterns, molds, and castings collected over the related period of time. Also, the test results will be compared to grain inspection results on castings produced over the related period of time. Where technically justified, the data will be examined for correlations between shell properties and shell performance through casting. Key relationships between shell properties and casting quality will be noted.

Mold development will be conducted to evaluate new concepts to improve those aspects of mold performance identified as most in need of improvement. Such concepts could include use of advanced forms of slurry powders, binders, stuccos, and reinforcements, and various processing modifications. These changes will be evaluated on test specimens and compared to the benchmarking results. Modifications showing promise will be evaluated in integrated casting experiments.

In addition to examining mold performance, the behavior of the waxes that form the patterns will also be investigated. The results of the current program to develop new wax systems for aircraft turbine engine hardware will be examined for application to large utility sized blades. These evaluations will assess the dimensional performance of the new waxes, their compatibility with the mold materials, and the resultant casting surface quality.

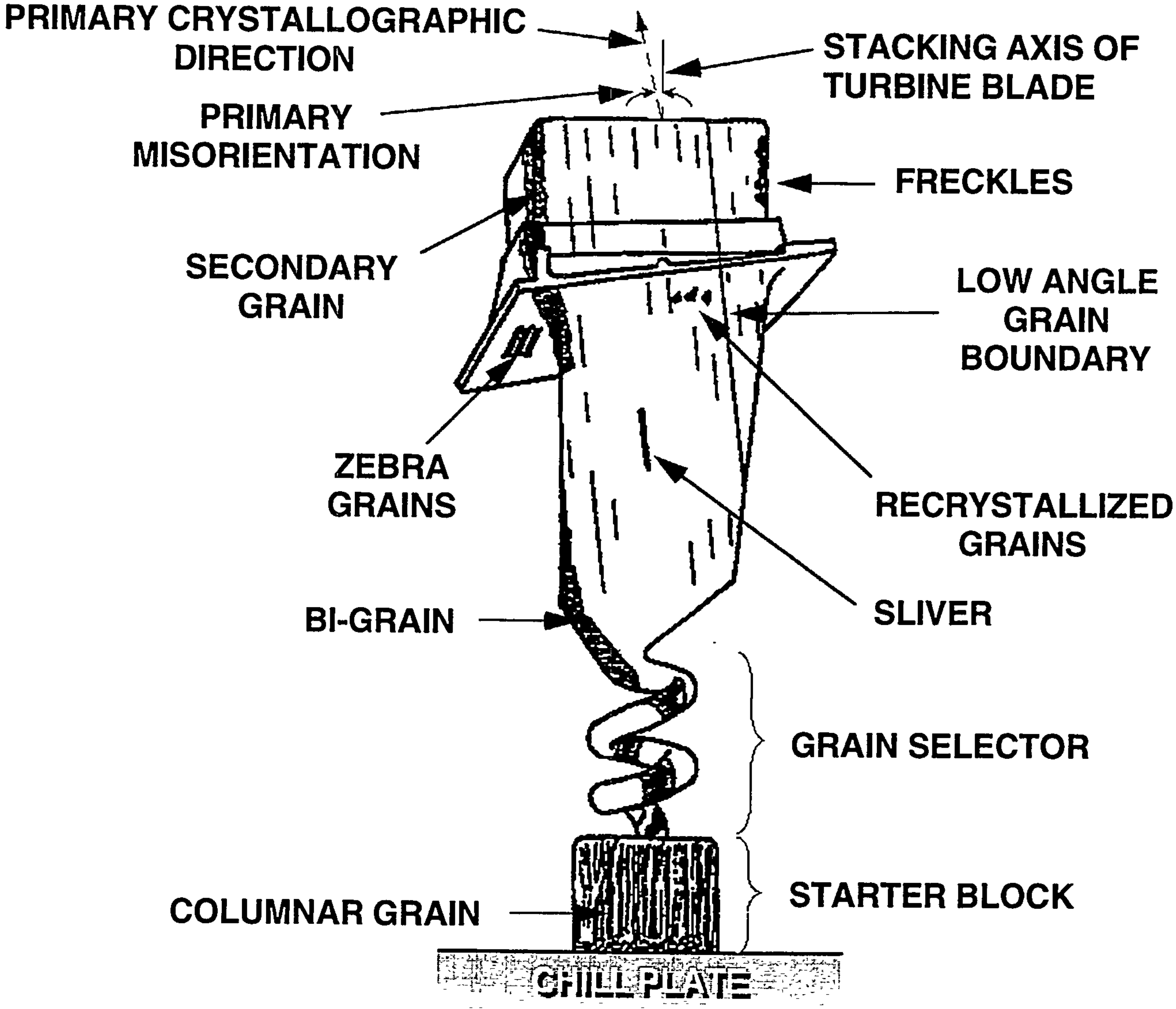

Figure 2. Grain Defects in Single Crystal Turbine Blades

Core Materials and Design

The core produces the internal passages in cooled blades and vanes. As such, the core must be dimensionally stable, not react with the molten metal, but yet needs to be removed from the casting without degrading casting quality. The response of current core systems and designs will be benchmarked, and explored in the casting parameter designed experiments. Based on the results of the benchmarking and designed experiments, core development activities will be conducted.

To quantify the capability of current core systems, current production data will be analyzed to assess the defects attributed to cores. These defects will be related to specific core thermophysical and thermomechanical properties. In addition, alternative core positioning techniques will be investigated for dimensional and microstructural casting effects within the casting parameter designed experiments.

Alternate cores are currently being developed for DS/SC aircraft turbine investment castings to reduce cost and improve core and casting quality. Small trials have indicated that these new cores have potential for the production of the large cores required for utility turbines. This task will extend and modify current developments to examine their feasibility for blade and vane cores. The cores will be evaluated for dimensional, mechanical and visual quality and then integrated into casting portions of the program to evaluate applicability.

Grain Orientation Control

Single crystal castings are used to exploit the anisotropy in superalloy mechanical properties with different crystallographic orientations. As such, control about the desired orientation becomes critical. In this task the procedures for controlling orientation, which were developed on aircraft turbine size components, will be evaluated for applicability to land based sized components. In addition, the phenomena of splaying, the fanning out and rotation of orientations as the crystal grows, will be investigated.

The current orientation control procedures will be benchmarked through visual inspections, X-ray, Laue orientation determinations, and limited investigation of sub-structure using techniques such as electron channeling patterns (ECP). Components cast with several combinations of alloy, component design, mold design and other casting parameters will be characterized to identify the problems associated with scale up of single crystal casting technology. A principle activity in the benchmarking will be to define the extent of orientation splaying. Splaying will be assessed using Laue techniques and ECP at different locations along and normal to the primary axis of the casting.

Based on the results of the benchmarking analysis, new procedures to achieve better orientation control or to reduce splaying will be evaluated. Factors to be considered include different starter configurations, different selector configurations, and modified casting parameters. Modifications showing promise will be evaluated in integrated casting experiments.

Mold and Core Removal

After casting, the ceramic mold and core must be removed from the casting without degrading the casting quality. The current ceramic mold and core removal systems, which were derived from those used on aircraft turbine castings, will be benchmarked for applicability on large, land based turbine castings. Specifically, the benchmarking will examine the levels of scrap or rework caused by poor procedures. The benchmarking will also examine the time required for core removal in large components, and determine its impact on overall casting cost.

Based on the benchmarking analysis, deficiencies in mold and core removal procedures will be assessed, and new procedures developed and tested to evaluated their effect on part quality and cost.

Airfoil Cleanup Techniques

Gating removal and airfoil cleanup techniques may be very different for land based components as compared to aircraft turbine components due to their very different sizes. For example, aircraft turbine components are typical small enough to handle manually. For land based turbine components, manual handling may not be acceptable. The current systems used to remove the gating and clean the airfoils will be benchmarked to determine the levels of scrap or rework caused by the current procedures, and to assess the relative cost of the current procedures. Based on the results of the benchmarking analysis, new techniques will be developed and evaluated.

Post Cast Processing

Post cast processing operations include heat treatment, HIP and quality inspections. The current heat treatment and HIP operations, which have been developed for aircraft turbine size components and limited section sizes, will be benchmarked for applicability to large land based components which may exhibit coarser dendritic structures, and more severe levels of macrosegregation and porosity formation. New techniques will be developed and tested based on the results of the benchmarking analysis.

Two principal aspects of post cast processing of large single crystal castings will be evaluated; these relate to gamma prime morphology and secondary microstructural features. With reference to the gamma prime morphology, the focus will be on cooling rates attainable from the solution heat treatment temperature in large single crystal components. The study of secondary features will address the presence of casting porosity and microstructural inhomogeneity, and the feasibility of their reduction via homogenization heat treatment and HIP. To address heat treatment and HIP of large land based components, test bars will cast and used to simulate casting and cooling rate conditions attained in large components. Using the specimens with intentionally simulated microstructures, mechanical properties such as creep and fatigue will be evaluated. For power generation operation, long time creep behavior is most relevant and it is important to establish if this is altered by the starting gamma prime size, given that gamma prime coarsens during long-term service operation. In addition, the thick root sections of large components will be evaluated for segregation and porosity, and then given heat treatment and HIP cycle to verify the above results. The goal here will be to establish the sensitivity of different alloys to gamma prime size variations and to determine if the HIP response in land based turbine components is similar to aircraft turbine hardware.

Based on the results of the above analyses, alterations in the heat treatment and HIP procedures developed for aircraft sized components will be evaluated. These investigations will most likely include gradient bar tests to establish the solutioning and incipient melting behavior of materials with different levels of segregation. These analyses may indicate the need to slow the solutioning heat up rates or extend the solution temperature hold times. The heat treatment studies will also be coupled with HIP studies to ensure closure of microporosity. The objective will be to define optimized processes to produce the appropriate microstructure.

Defect Tolerance Limits

The complete elimination of single crystal grain defects may be very difficult in large component sizes for some alloy compositions. This subtask will assess the performance loss associated with having defects present. Test material with freckles and recrystallized grains will be cast, heat treated, and machined for mechanical testing. To evaluate the effect of LAB misorientation, seeded bicrystal slabs with varying LAB misorientation will be cast. LAB's in these slabs will be characterized by visual macroetch and X-ray Laue techniques. Specimens will be machined with the LAB normal to the stress axis or located in a highly stressed notch area. The types of testing to be conducted include: creep, fatigue, and tensile testing.

Primary orientation control within the specification range defined for aircraft turbine engine components may be difficult for land based components due to the increased size. This effort will assess the performance loss as a function of primary axis misorientation. Creep and fatigue data will be generated as a function of primary misorientation, so that primary grain orientation control specifications can be better defined.

Inspection System Development

Investment casting designs, particularly high performance turbine blades and vanes, are rapidly evolving in complexity. In order to reduce the development cycle for a new design, it is necessary to monitor and control the critical dimensions of the casting and associated cores and molds. In addition, detailed knowledge of the casting geometry is necessary to plan the drilling of cooling holes during airfoil manufacturing. A new approach to dimensional control of castings and casting machining operations based on X-ray metrology has been developed called 2.5D reconstruction. The approach uses multiple 2D X-ray views of the casting to reconstruct the 3D geometry of selected features.

The complete reconstruction of an electronic data file requires three major steps. First, the accurate position and shape of 2D features in each view is determined by model-directed image feature extraction. The model is a deformable template based on the CAD file of the component. The template adapts to the local X-ray intensity pattern of the feature and is able to locate the feature to sub-pixel accuracy. The use of a deformable model also provides the necessary integration to achieve accurate geometry in the presence of high quantum and sensor noise levels. This last point is particularly important in the case of power generation turbine castings since these castings can exhibit long X-ray path lengths which results in poor contrast images and a low signal-to-noise ratio.

Next, a set of correspondences is established between feature projections in each X-ray image where the features are visible or relatively unoccluded by other internal geometric boundaries. From two or more correspondences the 3D geometry of a feature can be reconstructed by stereo triangulation. The accuracy of the 3D reconstruction is directly related to the accuracy by which the position and shape of the feature in each 2D X-ray image projection can be determined. In this phase of computation, the reconstructed 3D geometry is reprojected into each X-ray image and a global optimization is performed to minimize the error of reconstruction. Also in this phase, the identification of secondary features such as porosity occurs.

Thirdly, it is necessary to correlate the measurement of the external dimensions of the part with the internal feature geometry. This integration of data provides a uniform description of the part dimensions and can improve the accuracy of the X-ray dimensional measurements by providing local coordinate datum refinement. This refinement requires an optimum global solution which minimizes the difference between feature position and shape, as determined by 2.5D reconstruction, and determined by external gauging.

Future Activities

The activities described, as contained in the detailed program plan, will be executed over the next 30 months. The activities have just commenced and will be reported in future meetings.

Acknowledgment

Research sponsored by the U.S. Department of Energy's Office of Fossil Energy (Morgantown Energy Technology Center) and Office of Energy Efficiency and Renewable Energy (Office of Industrial Technology) through Oak Ridge National Laboratory, under contract DE-AC05-84OR21400 with Howmet Corporation, 1500 S. Warner Street, Whitehall, MI 49461-1895; FAX: 616-894-7826. Period of Performance: June, 1995 to March, 1998

5.6 Turbine Airfoil Manufacturing Technology

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Introduction[1]

The efficiency and effectiveness of the gas turbine engine is directly related to the turbine inlet temperatures. The ability to increase these temperatures has occurred as a result of improvements in materials, design, and processing techniques. A generic sequence indicating the relationship of these factors to temperature capability is schematically shown in Figure 1 for aircraft engine and land based engine materials. A basic contribution that is not captured by the Figure is the significant improvement in process and manufacturing capability that has accompanied each of these innovations. It is this capability that has allowed the designs and innovations to be applied on a high volume, cost effective scale in the aircraft gas turbine market.

Examples of these processing developments are:

- Vacuum melting for the nickel-base superalloys.
- Ceramic technology that produces complex, dimensionally reliable, stable cores that can be readily removed.
- Casting methods and furnace designs that allow both directionally solidified (DS) and single crystal (SX) produce to be produced in aircraft airfoils at yields approaching 90%.
- Advanced nickel-base alloy compositions, which utilize hafnium, rhenium, and in some cases small quantities of yttrium to improve the required DS and SX properties.
- Coatings that protect the airfoils from oxidation and provide thermal barriers.

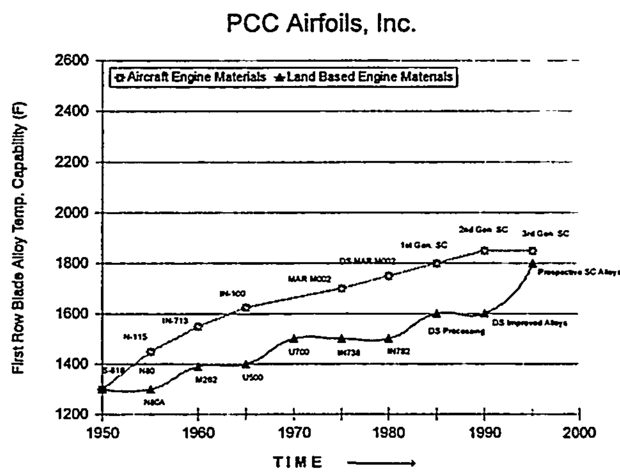

Figure 1. Development History of Aircraft and Land Base Engine Materials

Future efforts are being directed toward further reducing manufacturing variation so that

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yields will approach 95% and costs will come down accordingly, more advanced and challenging thin-wall cooling schemes, and lighter weight materials (intermetallics and high temperature composites).

Although land based turbines can make use of the technology developed by the aircraft engines, some very real challenges and differences are present. Land base turbines operate under different duty cycles. Therefore designs have different creep and low-cycle fatigue criteria. In addition, alloy compositions are often aimed at greater sulfidation resistance (higher chromium content).

The major limiting factor, however, in directly transferring aircraft engine technology to land base designs is increased size and weight. The largest SX complex-cooled part for a military engine is approximately 10" in length. DS parts in this range are routinely produced at high yields. Both of these applications have relatively small root sections and pour weights compared to industrial gas turbine applications.

A need exists to shift the capability of the complex-cored airfoil technology to larger sizes so that higher turbine inlet temperatures can be attained in land base hardware in a cost effective manner. The Department of Energy has recognized this need as part of the planning effort for the Advanced Turbine Systems (ATS) Program to develop advanced gas turbines for power generation in utility and industrial applications. It was assessed that a need exists to extend the capability of SX complex-cored airfoil technology to larger sizes so that higher turbine inlet temperatures can be attained in land base hardware in a cost effective manner.

In response to this need the Turbine Airfoil Manufacturing Technology Program has been initiated at PCC Airfoils, Inc./General Electric Power Generation Group which envisions using the available methods for producing SX airfoils and scaling them up to much larger land base components.

Objectives

The specific goal of this effort is to define manufacturing methods that will allow SX technology to be applied to complex-cored airfoil components for power generation applications. A number of specific technical issues are being addressed and these form the task structure of the program and include the following:

- Alloy melt practice to reduce sulfur content in alloys.
- Modification/improvement of SX casting process.
- Core materials and design.
- Grain orientation control.

Within the task structure represented by these technical issues specific objectives have been identified, the achievement of which will produce a resultant process that is cost effective. The specific objectives for these tasks are listed as follows:

Alloy Melt Practice

The objective of this task is to establish a process to reduce sulfur in castings to a sufficiently low level to promote the adhesion of a protective oxide scale. Activity will focus on N5 alloy (containing no yttrium) evaluated in GE burner rig oxidation/corrosion tests.

SX Casting Process

The objective of this task is to define manufacturing methods that will allow SX technology to be applied to complex-cored and solid airfoils for land based turbine applications. The results will define process details that can be successfully used to determine a cost effective production process.

Core Materials

The objective of this task is to provide ceramic cores for the SX casting process for the complex cored component which can control wall thickness to tight requirements over long spans. The results will be a definition of the capability of the core bodies with respect to their ability to produce complex serpentine cores for SX applications.

Grain Orientation Control

The objective of this task is to provide data to enable decisions to be made concerning the establishment of grain limit defect criteria. It is anticipated that the information will reduce the risks associated with liberalizing the defect criteria.

Approach

The technical approach to define manufacturing methods that will allow SX technology to be applied to complex-cored airfoils for land base turbine applications was developed by a program team consisting of PCC Airfoils, Inc. and GE Power Generation. The program philosophy is to expand and modify as required the existing, well-established techniques for aircraft engine airfoils to larger size components. This approach will confirm the ability to use the extensive and competent industrial base, which has been used for military and commercial aircraft applications for the expanding markets available to land base turbines. The technical approaches to meet the task objectives are described below.

Alloy Melt Practice

To reduce sulfur in the N5 alloy, activity will include evaluating desulfurization methods in the melt with the principles demonstrated by applying them to the remelt operation. Four conditions will be studied - a baseline composition with no desulfurization, and desulfurized condition using the PCC alloy desulfurization method, and both of these conditions to which hydrogen anneals will be applied. Each of these conditions will be tested on specimens in GE Power Generation cyclic oxidation and corrosion test rigs.

SX Casting Process

To define SX manufacturing methods a number of casting variables will be examined through experimental designs used for the production of cored as well as solid blade configurations in several iterations. This iterative approach will result in a fixed casting process which will be verified by a series of molds specifically cast for this purpose.

Core Materials

To provide ceramic cores for the SX process the low pressure core manufacturing method will be applied to meet the wall thickness dimensional requirements. Core injection does not require large equipment and the core materials used tend to be more stable during core firing and casting. Without the need to fill very fine features, coarser and therefore more stable ceramic mixes can be used.

Grain Orientation Control

To provide data to enable decisions to be made relative to grain defect criteria, the planned approach will include testing of cast specimens containing grain defects which will be tested at conditions critical to root sections where fatigue life margin can be reduced. Testing will include low cycle fatigue (LCF) types of tests which will also incorporate a hold time, which more closely simulates a part cycle where there is a period of steady state operation between startup or shutdown.

Project Description

The Turbine Airfoil Manufacturing Technology effort is comprised of five tasks which include a planning task (Task 1) and four tasks (2-5) of technical effort. The Program Schedule is shown in Figure 2. The following sections describe the planning and technical effort to be conducted during the program.

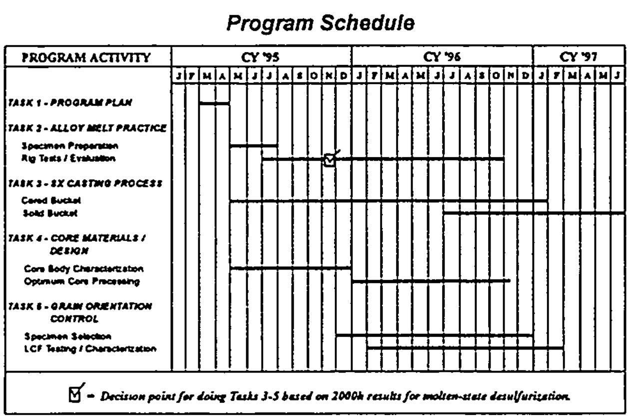

Figure 2. Program / Task Schedules for TAMT Program

Task 1 - Program Plan

Program planning activity involved the creation of an exact work breakdown structure that will allow close coordination between program elements and provide a clear blueprint for program review and management. The Program Schedule was also finalized during this planning activity.

Task 2 - Alloy Melt Practice

Alloy Melt Practice activity is shown in Figure 3 and includes ingot preparation, mold preparation/casting, hydrogen heat treatment and GE burner rig testing.

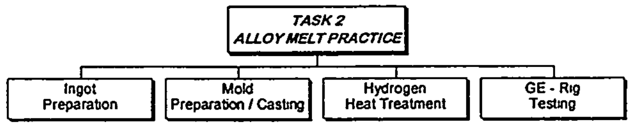

Figure 3. Work Breakdown Structure for Task 2 - Alloy Melt Practice

Ingot preparation includes making the vacuum induction melted (VIM) master metal which will be cast into the test pin configuration for rig testing. An ingot of standard N5 as well as a desulfurized ingot will be produced. The desulfurization will be accomplished in the melting operation with the sulfur aim being less than 0.5 parts per million (ppm).

Mold preparation and casting will follow procedures established for the production of SX castings. The molds will be configured such that 24 pins each 0.180 inch in diameter by 6 inches long will be produced and these pins can then be cropped to the desired length for the GE tests. The cast pins will be solution heat treated to homogenize the structure and one half the pins will be given a hydrogen heat treatment to further reduce sulfur levels.

Rig testing including oxidation and hot corrosion tests will be conducted as per the test matrix shown in Table 1. A decision point occurs after the testing has reached 2000 hours in that surface degradation will be evaluated at this point and if the molten desulfurization results are not better or equal to the hydrogen annealed results, the remaining task of the program will not be conducted.

Table 1. Test Plan for Evaluating Desulfurization

Condition	N5 Baseline	N5 De-S Alloy	N5 H_2Anneal	N5 De-S Alloy H_2Anneal
1900°F Oxidation	3 @ 2,000 hrs. 2 @ 4,000 hrs. 2 @ 8,000 hrs.	3 @ 2,000 hrs. 2 @ 4,000 hrs. 2 @ 8,000 hrs.	3 @ 2,000 hrs. 2 @ 4,000 hrs. 2 @ 8,000 hrs.	3 @ 2,000 hrs. 2 @ 4,000 hrs. 2 @ 8,000 hrs.
2000°F Oxidation	3 @ 2,000 hrs 2 @ 4,000 hrs. 2 @ 8,000 hrs	3 @ 2,000 hrs. 2 @ 4,000 hrs. 2 @ 8,000 hrs.	3 @ 2,000 hrs. 2 @ 4,000 hrs. 2 @ 8,000 hrs.	3 @ 2,000 hrs. 2 @ 4,000 hrs. 2 @ 8,000 hrs.
1700°F 40 ppm Na, 1% S Corrosion	3 @ 1,000 hrs 2 @ 2,000 hrs 2 @ 4,000 hrs.	3 @ 1,000 hrs. 2 @ 2,000 hrs. 2 @ 4,000 hrs.	3 @ 1,000 hrs. 2 @ 2,000 hrs. 2 @ 4,000 hrs.	3 @ 1,000 hrs. 2 @ 2,000 hrs. 2 @ 4,000 hrs.

Task 3 - SX Casting Process

SX Casting Process activity is shown in Figure 4 and includes a series of iterative casting trials for a cored part and a solid part. The cored part, a GE Power Generation Prototype Bucket, features complex cooling and is approximately 15 inches long while the solid part (another prototype) will be approximately 24 inches long.

Efforts for the cored configuration will encompass a total of 6 mold trials totaling 20 molds in an iterative manner. Thermal simulation modeling will be conducted in conjunction with the trials to establish the effects of important casting variables. The initial trial will address mold structural integrity including survivability during the casting process. Subsequent trials will address process optimization with variables being selected as a result of earlier trial activity. The final trial addresses process verification and will act to provide statistical significance to the existing data as well as determine the possible extent of process variability associated with casting procedures.

Efforts for the solid configuration will encompass a total of 3 mold trials totaling 10 molds in an iterative manner. The activity is directed towards mold structural integrity and process refinement.

The castings resulting from the trials for both configurations will be subjected to thorough evaluations including NDT, chemistry, microstructural characterizations and mechanical property testing.

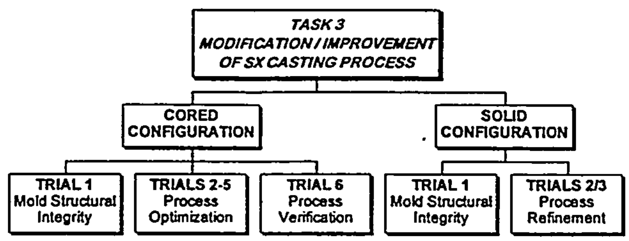

Figure 4. Work Breakdown Structure for Task 3 - Modification / Improvement of SX Casting Process

Task 4 - Core Materials

Core Material activity is shown in Figure 5 and includes core body characterization and optimized core processing. Core body characterization involves an evaluation of a number of silica based core compositions available for application to the SX casting process. Raw materials characterization will include purity, particle size distribution and specific surface area measurements on all raw materials associated with the core body compositions. Cores will be processed and evaluated for a number of characteristics including shrinkage, modulus of rupture, stability and porosity. The characterization data on the various core bodies will be analyzed and a downselection will be made for the initial casting trials. As part of the casting trials, evaluations of core performance will be conducted including resistance to core/metal reactions, stability, additional shrinkage during the casting process and core removal kinetics. Assessments of this core performance will be made for the selection of cores required for the subsequent casting trials.

Optimized core processing will include the manufacture of cores for the subsequent casting trials and will be evaluated for the same characteristics established during core body characterization. The purpose of these evaluations is to ensure that the cores selected for subsequent casting trials are representative of those evaluated during the first trial.

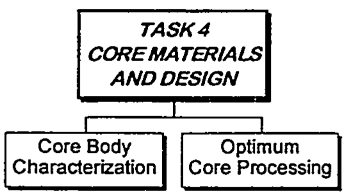

Figure 5. Work Breakdown Structure for Task 4 - Core Materials and Design

Task 5 - Grain Orientation Control

Grain Orientation Control activity is shown in Figure 6 and includes LCF testing of cast specimens containing defects. Defects will include high angle boundaries, freckles, and porosity. Specimens with no defects will provide baseline information. The LCF test plan is shown in Table 2.

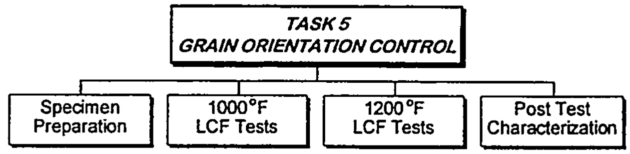

Figure 6. Work Breakdown Structure for Task 5 - Grain Orientation Control

It is planned that the castings produced as part of the casting trials will be examined to select regions which would be appropriate for machining into specimens for the LCF tests. Defects located on relatively flat portions of the casting surfaces would be most appropriate for specimen machining whereas defects located in regions of high curvature would not.

For the testing, cycles to crack initiation will be reported for each test. Comparisons will be made to the baseline material containing no obvious surface defects. Post test characterization will consist of light metallography as well as Scanning Electron Microscopy of selected areas to aid in interpreting the LCF data.

Table 2. Planned Test Matrix for Evaluation of Casting Defects

Defect Type		Rene N5	
		1000°F	1200°F
High Angle Boundary (HAB):			
	0.050" - DIA.	3	4
	0.100" - DIA.	3	4
Freckles:	0.125"L x 0.060"W	--	4
	0 250"L x 0 060"W	--	4
Porosity:	0.015" - DIA.	--	4
	0.030" - DIA.	--	4
Baseline:	Defect-Free (001)	3	4
Low Cycle Fatigue (LCF), Strain-Controlled, 2-Minute Hold Time			

Results

Task 2 - Alloy Melt Practice

Specimen Preparation. Work was initiated on the alloy melt practice activity described in the plan of Figure 3. Test pins have been produced, given the appropriate thermal exposures and burner rig testing has been initiated at GE.

Initial activity included preparing the master metal for subsequent remelting into the test pin configuration. An ingot of standard N5 alloy was obtained to serve as the baseline and its sulfur level was 2.5 ppm. The desulfurized ingot was produced using the practice of reducing sulfur during the melting operation and its sulfur content was 0.4 ppm.

Molds were prepared following procedures established for the production of molds used for SX castings. This included wax injection, mold assembly and dipping. Dipping the assembled wax pattern was done sequentially in ceramic slurries to build a mold of the required thickness.

Casting involved remelting the alloy ingots and pouring the molten metal into the molds to produce the SX pins for GE rig testing. This included vacuum melting using the mold preheat conditions of 30 minutes at 2650°F and a pour temperature of 2850°F. The mold withdrawal solidification cycle was programmed for a withdrawal speed of 6 inches/hour for the first 30 minutes of solidification followed by a 8 inch/hour withdrawal speed for 50 minutes.

The appearance of a typical 6-pin candelabra grouping after the casting knock-out operation is shown in Figure 7. Each pin within the candelabra solidified from the same single crystal starter geometry. Each mold was comprised of four such candelabras. The pints can be cropped to the desired length to accommodate the GE burner rig.

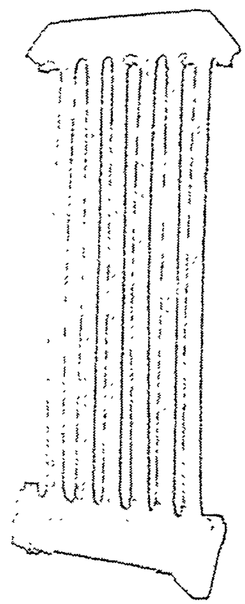

Figure 7. Test Pin Candelabra Casting After Mold Knock Out

Heat treatments including homogenization cycles and hydrogen desulfurization cycles were applied after the casting operation. All of the pins received the standard N5 heat treatment to homogenize the structure by minimizing any chemistry gradients resulting from the casting operation. Hydrogen heat treatments were applied to one half of the pin specimens intended for rig testing. These treatments were conducted in a production facility with a standard 50 hour cycle under a partial pressure of 7 mm of hydrogen. Both the standard N5 alloy and the desulfurized alloy were similarly heat treated. Sulfur levels were measured for materials of the various conditions making up the test matrix shown in Table 1. It has been experienced that sulfur pick-up can occur during the remelting operation and in these instances repeat measurements are taken. The following summarizes the sulfur levels for the various materials/conditions planned for the GE burner rig tests:

Condition	*Sulfur Level (ppm)*
N5 Baseline	2.5
N5 De-S Alloy	0.4
N5 H_2Anneal	0.7
N5 H_2 Anneal	0.3

Burner Rig Testing. Burner rig testing was initiated for all specimen conditions shown in the testing plan of Table 1. Testing was initiated with the 1900 and 2000°F oxidation tests and the 2000 hour exposure times for these tests are scheduled to be completed by the end of October.

A schematic illustration of a burner rig unit is shown in Figure 8. Each rig consists of a tube inside a tube furnace, with an atomizing fuel nozzle at one end and an exhaust at the other. Atomized fuel is combined with air in the combustion chamber and burned, resulting in hot gases which flow past a double beam fixture suspending test samples in the hot gas stream. Up to 21 pin or disk samples can be housed in a sample fixture.

Upon completion of the designated exposure times, the pins will be examined metallographically and the thickness of the remaining metal and the depth of internal attack will be measured as an indication of resistance to the oxidizing environment.

Task 3 - SX Casting Process

Work was initiated on planned Task 3 activities related to the cored configuration and

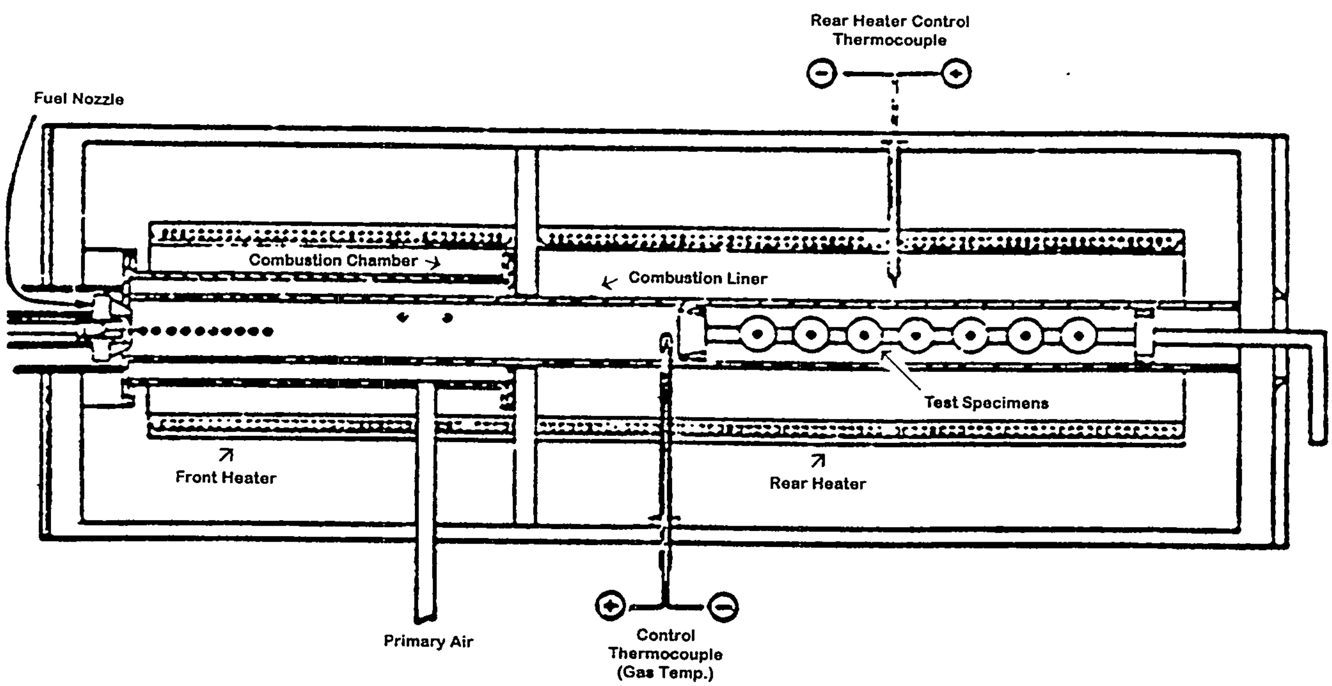

Figure 8. Schematic Illustration of GE Burner Rig Unit

included preparations for the first trial and involved tooling procurement and modeling.

Tooling involves modification effort directed at the current tooling available for the cored component. This component is currently produced with a columnar grained directionally solidified structure. In order to make the current wax tooling amenable to the SX casting process, certain feature additions are required including a ramp die, downpole tool and assembly plate. With these feature additions the current tooling can be used interchangeably to make a columnar grained or a SX version of the cored component. Design and build of the feature additions was initiated.

Modeling activity encompasses two areas including the construction of electronic models and simulation of the envisioned casting processes. Electronic models have to be complete before simulation modeling can take place. The modeling involves the construction of a three dimensional geometric model for subsequent CMM and layout measurements and an electronic file for the simulation activities. Modeling has progressed to the extent that both the external geometric model as well as the internal core configuration model have been completed and activity is now focusing on combining the external and internal models with the ramp die configuration.

Task 4 - Core Materials

Work was initiated on planned Task 4 activities and included core body characterization. The preferred manufacturing method for the large cores needed for the prototype configuration is the low pressure method as practiced by PCC Airfoils, Inc. A flowchart of the low pressure injection molding process is shown in Figure 9. The low pressure process differs from high pressure injection molding processes typically used in the manufacture of ceramic cores for investment casting applications in several aspects, the most significant being the use of gravity to fill the die cavity with a ceramic slurry. Low pressure is applied to the core mix to displace entrapped air only after the cavity is filled, as opposed to processes where high pressure is used to fill a die cavity.

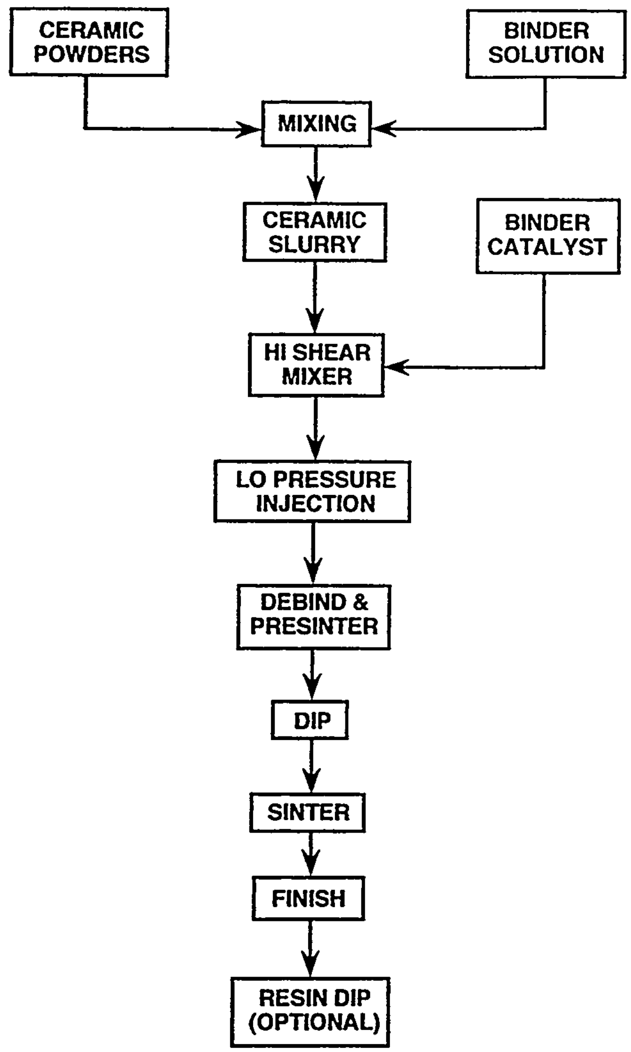

Figure 9. Flow Chart of the Low Pressure Core Injection Molding Process

The process begins with the mixing of a silica slurry which is then blended with a binder catalyst in a high shear mixer. The core die cavity is then filled by low pressure injection and once the core body is hardened sufficiently to handle, the die is opened and the core body removed. Once the core body is shaped, it is fired to remove binder and presinter the part. The core is then fired a second time to induce shrink and generate strength through the formation of necks between adjacent ceramic particles. After firing, the core body is finished to remove the die flash and patch any surface defects, if required. Owing to the porous nature of the core body, a fired core can be dipped in resin or other organic material to increase strength through the wax injection process step at the foundry.

Core body characterization has been completed and the downselection made to produce cores for the first casting trial. The core body characterization included the evaluation of silica based core compositions for applicability to the SX casting process to produce the GE prototype bucket. For these evaluations ten (10) cores each were made from several core body compositions. A typical core is shown in Figure 10.

Important considerations in the downselection process included fine particle size to allow filling of the finely detailed core features particularly in the trailing edge regions. In addition, reasonable strength as represented by room temperature modulus of rupture (MOR) in a three-point binding type of test is required to survive handling and wax injection without core breakage. Finally, some level of porosity is required to accommodate some crushing during the cool down during solidification (to avoid generating high residual stresses in the castings) and create some degree of access into the internal regions of the core by core leach media. This access acts to facilitate the core removal operation.

On the basis of these considerations the PCC SRI 200-SXA core composition was downselected for the initial casting trial. The average properties exhibited by the cores made for the evaluations included the following: *(Modulus of Rupture: 1850 psi, Porosity: 30%, Posi-Resin MOR: 2700 psi).*

It can be seen that resin dipping had a significant impact upon increasing the core body MOR. The SRI 200-SXA downselection was made on the basis that these types of strength and porosity values are representative of cores currently in production for aircraft SX applications. It was reasoned that, as a first approximation, these levels warranted evaluation in the initial casting trials for the larger prototype bucket.

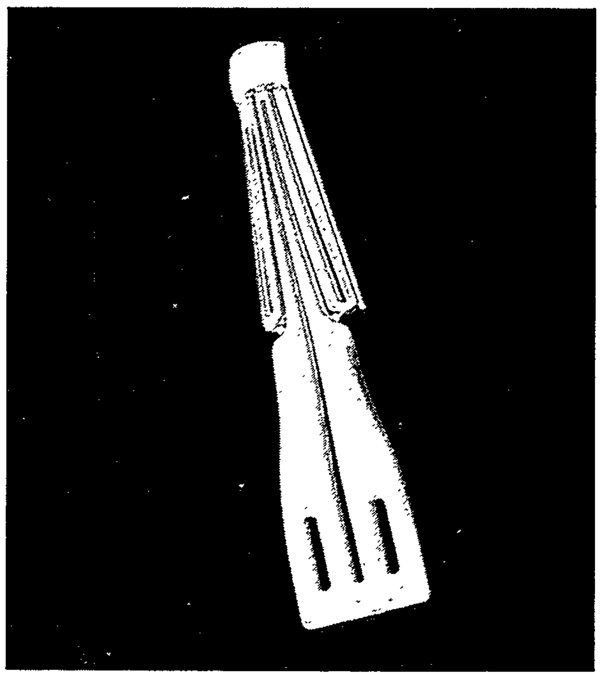

Figure 10. Ceramic Core for GE Power Generation Prototype Bucket

Benefits

This program provides a very focused approach aimed at solving the basic casting scale-up problems that currently limit the use of SX casting methods in land base turbine applications.

The specific benefits anticipated from the program include:

- Utilization of SX manufacturing methods to produce land base turbine airfoils in the 24 inch range for solid and simple-cored components and 14 inch range for complex-cored airfoils.
- Definition of cost effective casting methods to produce large land base airfoils.
- Correlation of mechanical properties to critical process characteristics (e.g., grain defects and orientation).
- Capability to produce large, easily removed complex cores with close dimensional control and high stability during casting.
- Ability to use the large and competent industrial base, which has been used for military and commercial aircraft airfoil applications for the expanding markets available to land base turbines.

Future Activities

Future activities can be identified in the Program Schedule shown in Figure 1. During the up-coming year of effort the alloy melt practice activity will be completed. Development work in the SX casting process area will have progressed to the end of process optimization for the complex-cored part and efforts will have initiated on the solid configuration. All core material work will have been completed and testing will be underway involving LCF testing of specimens containing grain defects.

Acknowledgement

The Contracting Officer's Representative (COR) for the Project is Robert S. Holcomb, Oak Ridge National Laboratory. The period of performance is February 20, 1995 through June 30, 1997. The major subcontractor to PCC Airfoils, Inc. is the General Electric Power Generation Group.

5.7 Pratt & Whitney Thermal Barrier Coatings

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Introduction

The objective of the Advanced Turbine Systems (ATS) Program is to develop ultra-high efficient, environmentally superior, and cost competitive gas turbine systems. The operating profiles of these industrial gas turbines are long, -less cyclic with fewer transients- compared with those for aircraft gas turbine engines. Therefore, creep rather than thermal fatigue, becomes primary life-limiting for hot section components.

Thermal barrier coatings (TBCs) will be used to achieve the objectives of the program. TBCs allow surface temperatures to increase without compromising the structural properties of the alloy. TBCs typically consist of a ceramic insulating layer, deposited onto the substrate with an intervening metallic layer, which imparts oxidation protection to the substrate and provides a surface to which the ceramic layer can adhere.

Research sponsored by the U.S. Department of Energy's Oak Ridge Operations Office, under Contract DE-AC05-950R22426 with Pratt & Whitney Aircraft, 400 Main Street, East Hartford, CT 06118

Project Description

The maturation of the iron, nickel, and cobalt base superalloys and the gas turbine engines used in propulsion, transportation, and power generation are intertwined. The increases in power and thermal efficacy is directly related to the increase in turbine inlet temperature. The prevention of structural failures related to melting, creep , oxidation, and thermal fatigue is accomplished in part through compositional and processing changes combined with improved and novel cooling schemes.

The remarkable growth of superalloys and the design of airfoils over the past 30 years is summarized in Figure 1. The early alloys were based on the performance of the Ni-Cr system. In a relatively short period the strength of the alloys was sufficiently increased to transition from wrought to cast. Within two decades , the polycrystalline structure gave way to the columnar grain structure, which within a decade, transitioned to the single crystal technology of today. Thus, within three decades the temperature capability of the alloys increased by more than 200 °F. At the same time significant improvements in casting technology and design further extended the operational envelope. The design evolution and the associated benefits of advanced cooling concepts are shown in Figure 2.

Further increases in efficiency and power requires additional cooling air and the use of improved thermal barrier coatings. TBCs provide insulation equivalent to about 300 °F (167 °C) from a typical 10 mil (0.254 mm) ceramic layer. The FT-4000 intercooled industrial engine high pressure turbine (HPT) blades are designed to achieve a 25,000-hour life while operating continuously at turbine inlet temperatures of 2700 °F (1480 °C). This is achieved with innovative advanced cooling methods, outstanding coatings and the insulation obtained with the use of TBCs. The morphology of a typical TBC is shown in Figure 2, and the beneficial increase in equivalent metal temperature is shown in Figure 3.

The majority of TBCs currently used on turbine components is based on the yttria stabilized zirconia system. They are applied by plasma spraying or EB-PVD; two distinctly different processes, Figure 4. Plasma deposition is essentially an adaptation of the flame spray process. Particulate matter introduced into the plasma is heated to a semiplastic state and accelerated toward the workpiece. Upon impact, the hot particles deform to produce a complex interlocked structure, which is tightly bonded to the substrate.

The EB-PVD process is an extension of the metallic NiCoCrAlY overlay technique, pioneered and developed by P&W over 3 decades ago. The unique ceramic microstructure achieved through this process offers a significant improvement in strain tolerance of the ceramic insulating layer, as the failure location for EB-PVD TBCs is distinctly different from that of plasma TBC. In the plasma system, failure generally occurs as a result of cracking in the ceramic layer parallel and adjacent to, but not coincident with the metallic ceramic interface, Figure 5a. A driving force for failure is the cumulative cyclic mechanical strain superimposed on that induced by oxide growth on the bond coat.

The EB-PVD ceramic system exhibits enhanced durability. It is fundamentally different from that of the plasma sprayed ceramic. Its microstructure confers a high degree of strain tolerance. It is characterized by columnar growth, with little bonding between adjacent columns but strong bonding with the substrate. When failure does occur the location is distinctly different from that of plasma sprayed TBC. It fails by cracking at the thermally grown aluminum oxide layer (TGO) that develops on the bond coat at the ceramic-bond coat interface Figure 5b.

The operational envelope of the industrial gas turbine differs significantly from that of the aircraft engine. The former operates primarily at sea level where the air is often burdened with industrial and agricultural dusts as well as sea salt crystals. The latter are generated at the air sea interface and travel inland more than a hundred miles. The industrial gas turbine utilizes fuels which can contain significantly higher concentrations of known corrodents and can also contain elements and compounds that adversely affect combustion characteristics. Equally important, the industrial gas turbine operates for prolonged durations at baseload conditions whereas the cyclic duration for the aircraft engine is significantly shorter. Lastly, the aircraft gas turbine generally experiences a series of temperature changes during each cycle; a behavior not generally true for the industrial engine. For these and additional reasons, the role of corrosion in the industrial gas turbine presses to the forefront.

The corrosion community has exposed TBCs to the same tests employed to study and rank metallic coatings and aircraft superalloys, and more often than not the findings from the laboratory are not consistent with field results. We have conducted in-depth analyses of the nature and concentration of deposits from operational industrial gas turbines located worldwide. A model that describes the passage, accumulation, and deposition of industrial oxides and salts, and correlates site location, air and fuel quality with deposition and corrosion behavior has been constructed. For example, it is well established that the principle constituents of the corrosive salts associated with hot corrosion of gas turbine components are the sulfates of sodium, magnesium, and calcium. However, the corrosive salts removed from industrial hardware also contain significant concentrations of potassium. The ratio of potassium to sodium in the deposits is more than an order of magnitude greater than that in sea salt. Analyses of the ratios of potassium to sodium in sea salt, and in deposits removed from compressor and turbine components have shed much light on understanding the deposition mechanism for airborne corrodents. Any deposition mechanism which does not take account of the selective increase in potassium, would not simulate what occurs in practice. The significant differences in composition of sea salt, a primary source of the hot corrosion corrodents and the typical chemistry of the salts associated with hot corrosion, is shown in Figure 6.

Industrial gas turbines are continually subjected not only to sea borne, agricultural, and industrial salts, but also to industrial dusts. The various salts and dusts accumulate onto compressor components and adversely affect gas turbine efficiency. Equally important the industrial dusts are composed of known oxides that can behave as sintering agents to the TBC ceramics. These oxides are captured on the surfaces of the sophisticated filters specifically developed for industrial and marine gas turbines. However, by their very nature, the filters must pass some of the accumulated matter. The nature of this matter is shown in Figure 7, a typical analyses of filter matter from an industrial site. Based upon the available phase equilibria supported from in-house studies, the oxides of both iron and silicon are active sintering aides.

It is a materials challenge to negate the combination of active sintering aids and corrosive salts. The former can significantly alter both the mechanical and thermal properties of the ceramic, significantly affecting mechanical integrity; allowing the corrosive salts to interact with the metallic substrates. This behavior is illustrated in Figure 8, a view of a ceramic coated combustor component. The salts identified on the surface consist of both the metallic corrosion products and the corrodent.

The corrosive salts on the surface of the TBC can, without physical contact, influence the chemistry of the metallic bond coat. It is well established that many oxides are relatively transparent to the passage of oxygen. Oxygen is readily transported through zirconia. At the salt-ceramic interface, the partial pressures of sulfur and oxygen are established by salt chemistry. The presence of sulfide precipitates are observed in the vicinity of the bond coat ceramic interface without any discernible path for the flow of corrodent. This is shown in Figure 9. Thus, unlike the aircraft environment, the industrial TBC must establish inherent resistance to many fused salts.

Approach

An overview of the program is shown in Figure 10. The program is divided into the originally suggested four phases. The benchmarking ceramic candidates include (a) air plasma sprayed ceramic on APS bond coat, (b) APS ceramic on LPPS bond coat, and (c) EB-PVD ceramic on LPPS bond coat. Of the benchmarking systems (a) has experienced the most exposure in industrial gas turbines, (b) has accumulated the most time in flight engines, and (c) is the outstanding blade system which has demonstrated excellent performance in revenue service with approximately a 10X increase in durability over plasma sprayed systems.

The compositions of the candidate ceramics were selected based upon the chemical knowledge and experience obtained from the industrial field combined with the thermomechanical behavior derived from millions of flight hours. The ceramic systems include enrichment of the yttria level in the ceramic in recognition of the depletion of this element that occurs in the industrial environment. It also includes the evaluation of ceria stabilized ceramic. In addition to the differences in chemical behavior, ceria imparts additional toughness. Further improvements in fracture toughness and chemical stability as well as superior resistance to heat flow are among the benefits to be realized by the interlaying of ceria and yttria stabilized zirconia. Additional systems rely on the chemical inertness of the candidate to dissolution by molten alkali rich salts and the chemical attack by oxides that tend to promote sintering. Lastly, attention is also focused on increasing the strength of the ceramic-bond coat interface and the reduction of the stresses related to the growth of oxide at this critical junction.

The bond coat not only unites the ceramic to the substrate but also imparts oxidation and corrosion resistance. Evidence from the field clearly shows the presence of sulfur-bearing species in the TBC system. The candidate bond systems take advantage of the recent knowledge, first discovered under Government sponsored UTC programs, that relates premature oxide scale spallation to indigenous sulfur present in all superalloys and coatings. The candidate materials include compositions that have inherent resistance to the movement of sulfur that travels inbound through the ceramic or outbound from the substrate alloy. Other candidate materials have inherent resistance to sulfidation corrosion as well as improved mechanical properties, and ease of application.

The approach taken for the TBC Life Model Development is a combination of the analytical studies and empirical/mechanistic investigations previously developed and later expanded under NASA's HOST program. In that study the inelastic behavior of the ceramic was identified as a critical parameter. In the case of the EB-PVD ceramic which behaves predominantly elastic, the critical parameter was identified to be the response of the thermally-grown oxide (TGO) layer. This program focuses upon generic modeling of the TBC failure processes/mechanisms. The intent is to sort out the dominant TBC failure mechanism(s), develop sensitivity relationships, and define a operable TBC life prediction application method.

The Manufacturing Process Development as well as Maintenance, Repair, and Inspection are equally important tasks. Even though many of the processing aspects of TBCs currently in use are proprietary, a generic approach must be developed to list processing steps. The interchangeability of spray and aluminizing processes as well as EB-PVD to plasma spray need be addressed. An aim, for example, is to transfer TBCs developed for blades to the combustor or vise versa. Other concerns address post ceramic processing such as hole drilling.

With respect to Maintenance, Repair, and Inspection, attention is focused on full ceramic repair which encompasses complete stripping and recoating of both the ceramic and the bond coat. Laser holography and acoustic emission are primary procedures to be evaluated to assess TBC damage. These sensing methods focus on the detection of incipient defects and processing damages long before they become visible to the naked eye.

Lastly, the heart of any corrosion-related undertaking is the test program that generates the necessary information that promotes knowledge and understanding in a meaningful time frame without actually performing full-scale long-term tests. In this program, the gradient test burner rig which generates surface temperatures in excess of 2600 °F with 300 °F gradients across the TBC coated air cooled test specimens shown schematically in Figure 11, is used in addition to the state-of-the-art burner rigs. Also employed is a unique controlled environment rig in which the partial pressures of oxygen and sulfur are controlled in order to simulate the oxygen and sulfur activities associated with the presence of condensed salts on the surface of industrial TBCs. This data aids in the evaluation and response of the material chemistry with respect to sulfide formation.

Summary

TBCs will be used to achieve the objectives of the ATS program. They are used in aircraft engines and have accumulated millions upon millions of reliable hours. The differences in the duty cycles of the aircraft and the industrial gas turbine are recognized as is the marked differences in environmental operational envelope. At the completion of this program the TBCs best suited to meet the needs of the ATS program will have been identified, tested, and confirmed.

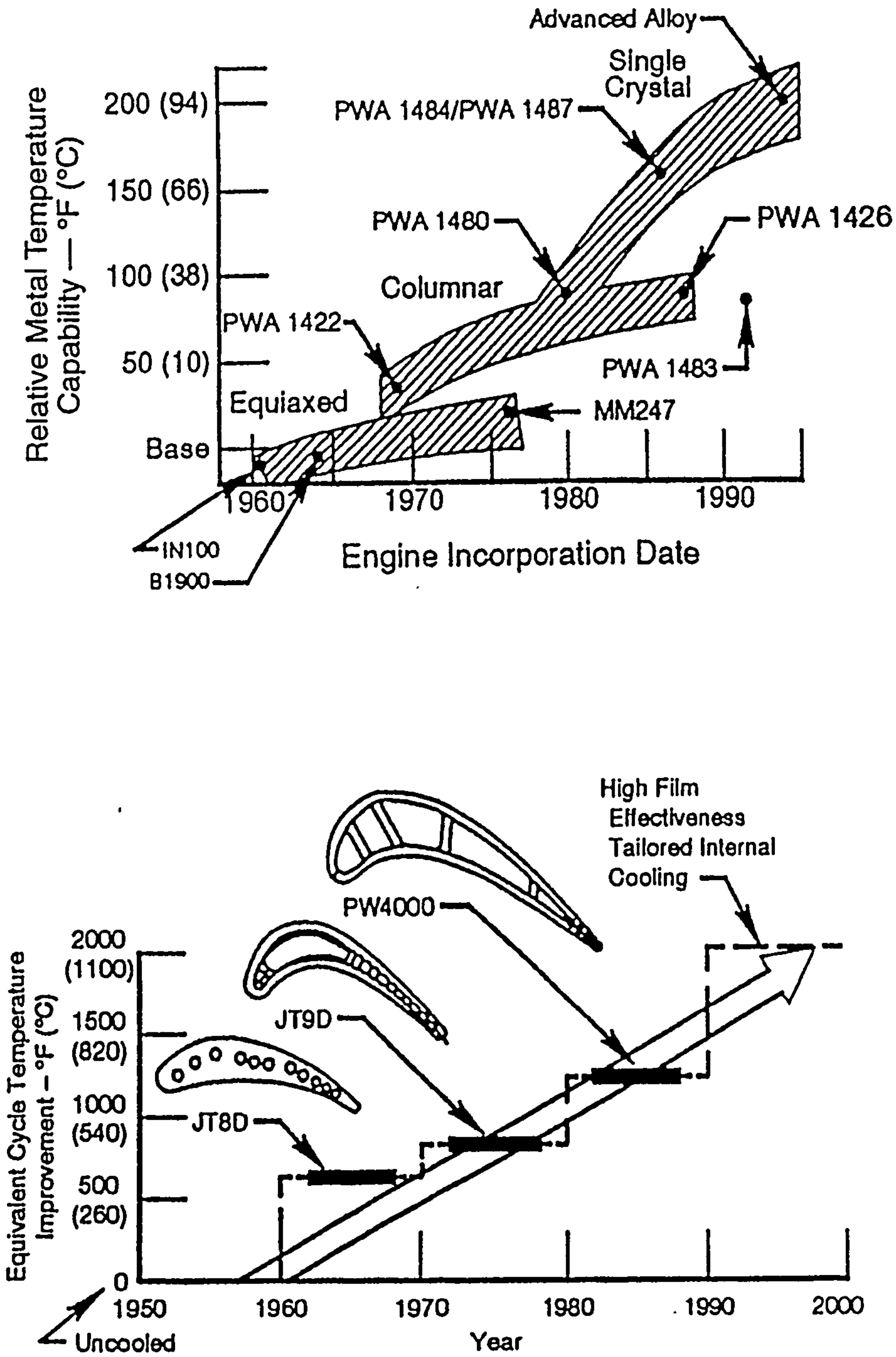


Figure 1. Advances in Turbine Blade Materials and Processes

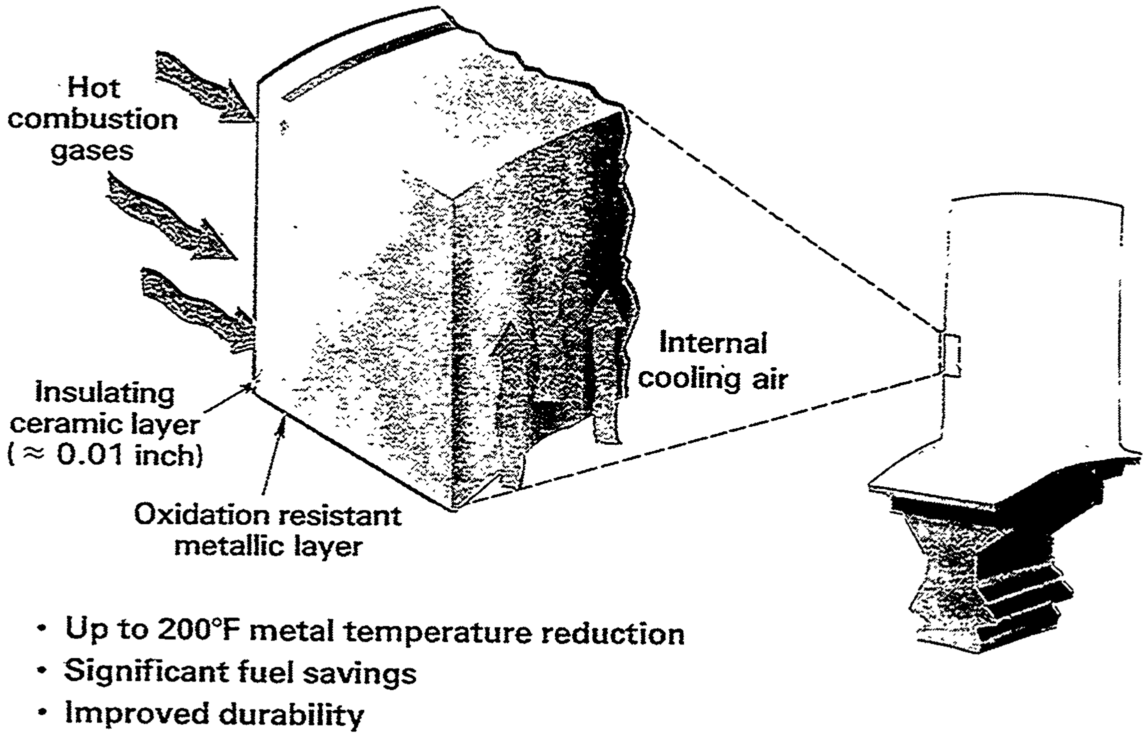


Figure 2. Thermal Barrier Coating

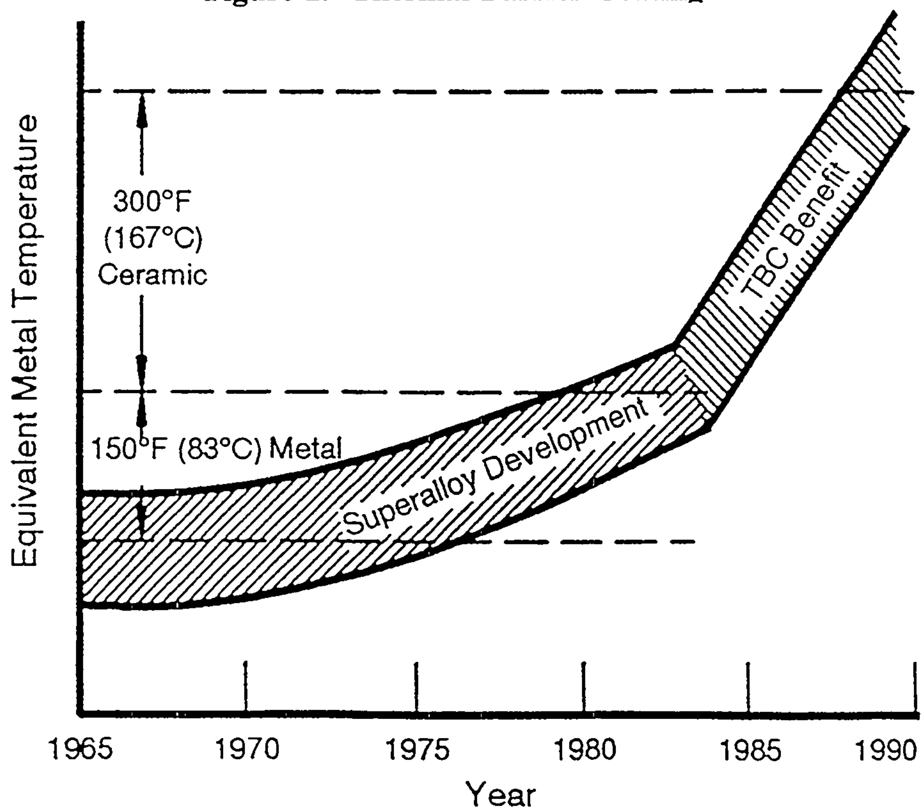


Figure 3. Benefits of Advanced Superalloys and TBCs

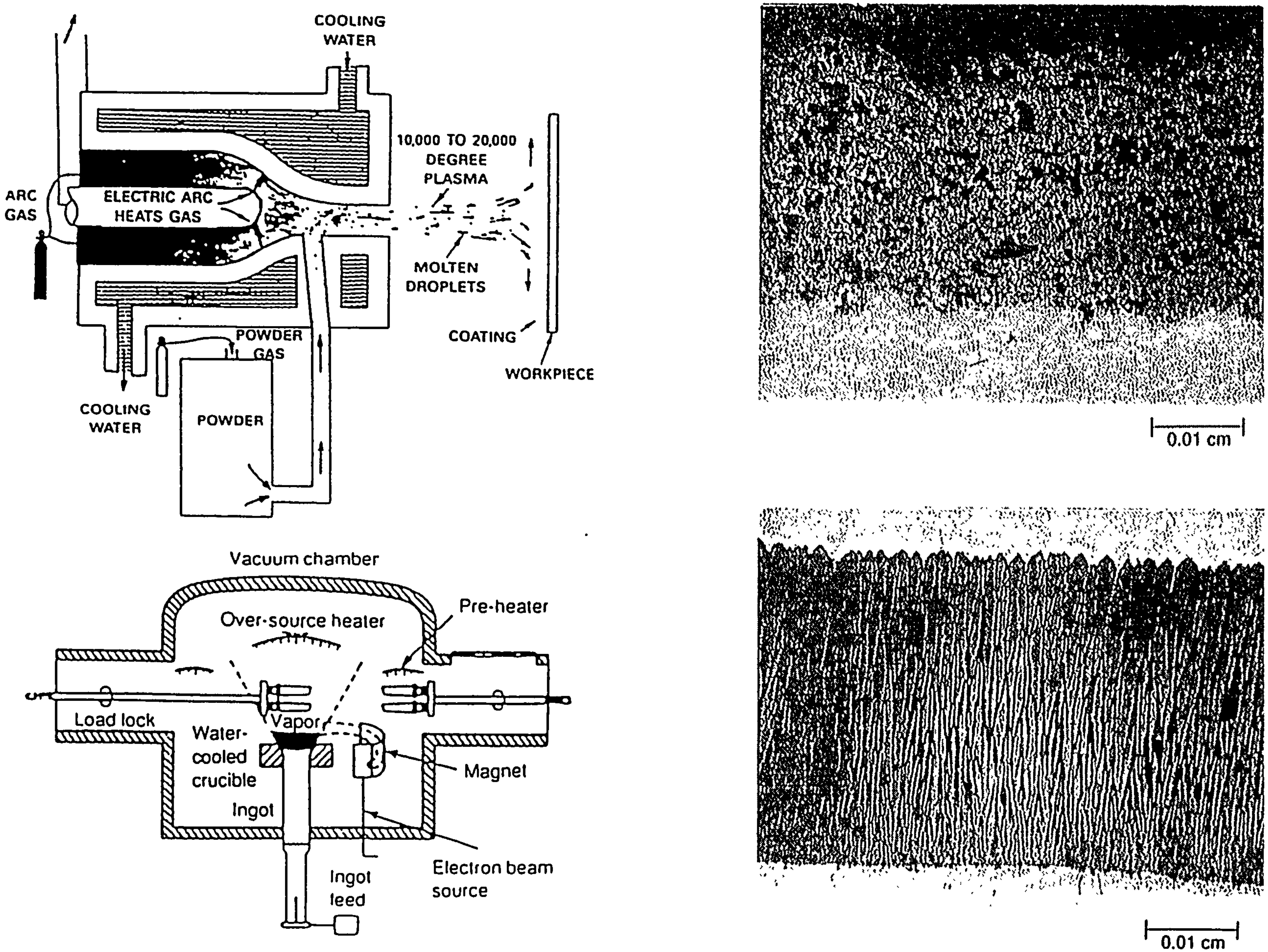
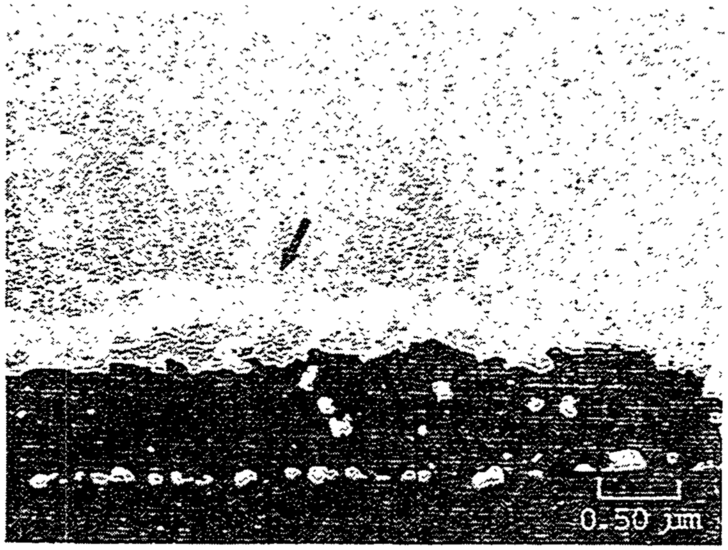
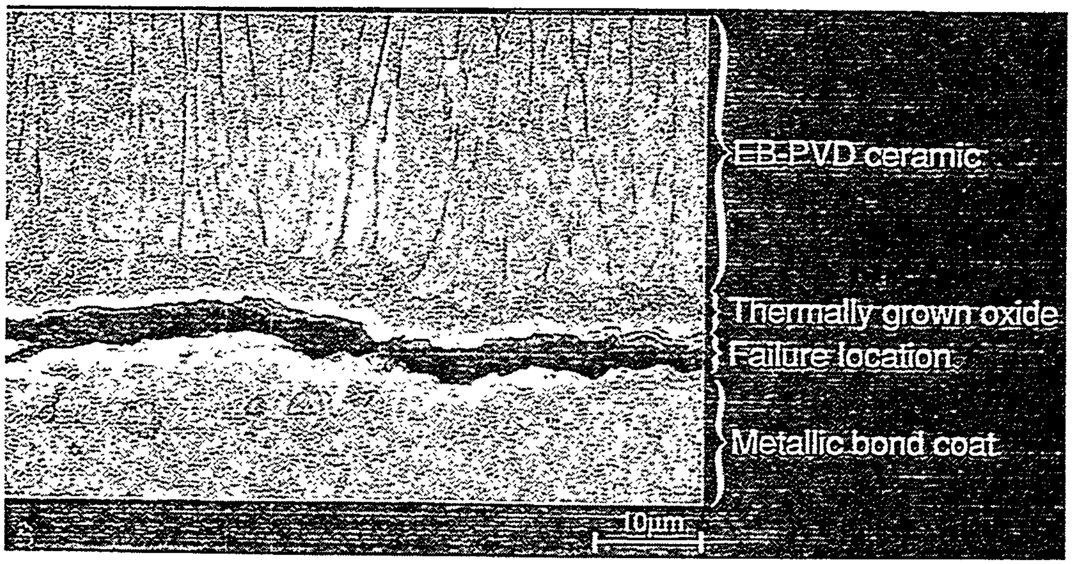


Figure 4. TBC Processes



PWA 264

delamination occurs primarily within ceramic phase



PWA 266

delamination occurs primarily within Thermally Grown Oxide

Figure 5. Failure Modes

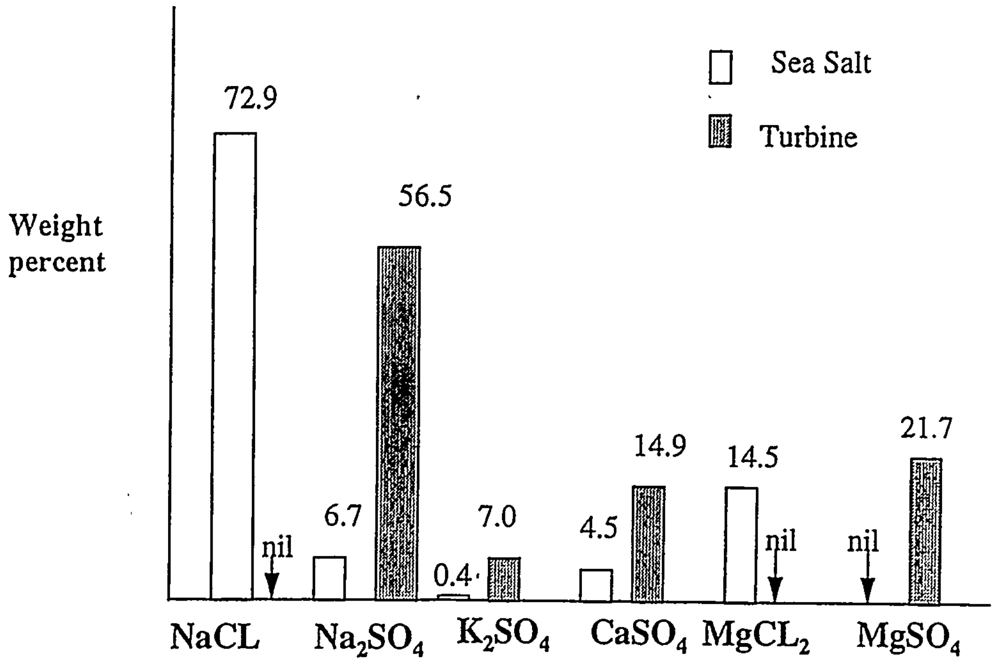


Figure 6. Comparison of Salt Chemistries

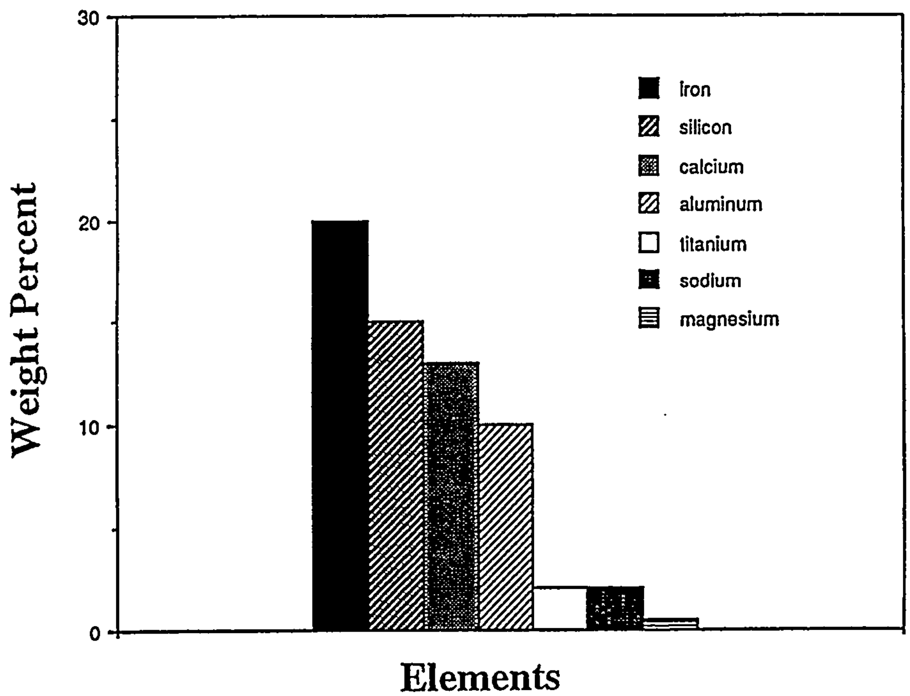


Figure 7. Filter Insolubles

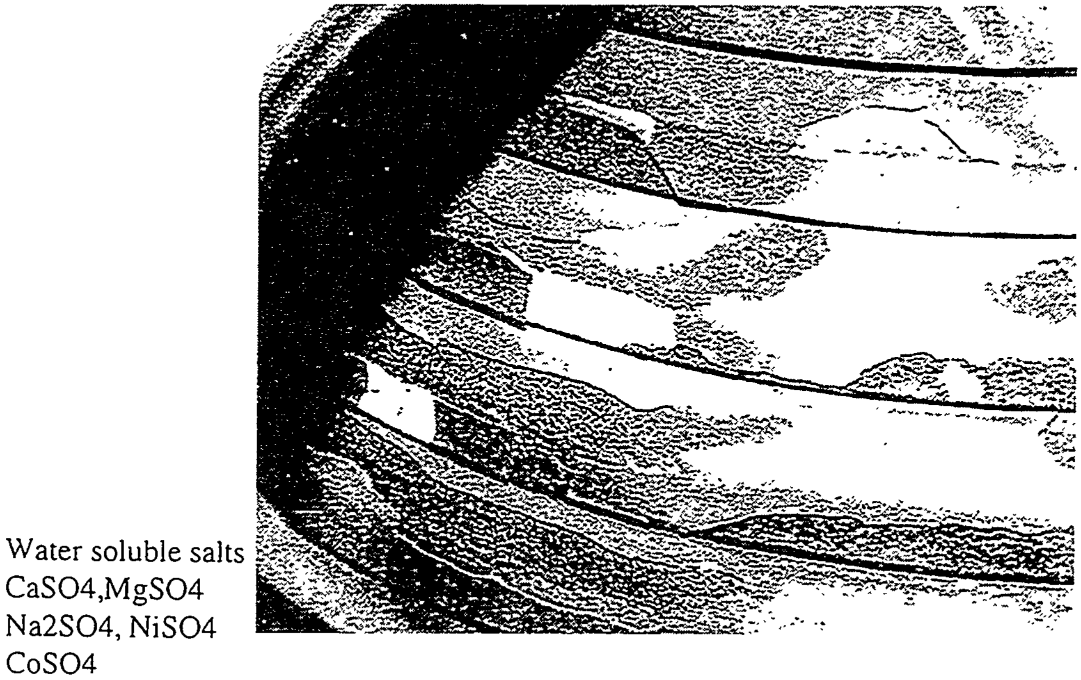


Figure 8. Industrial and Marine Deposits Acerbate Delamination

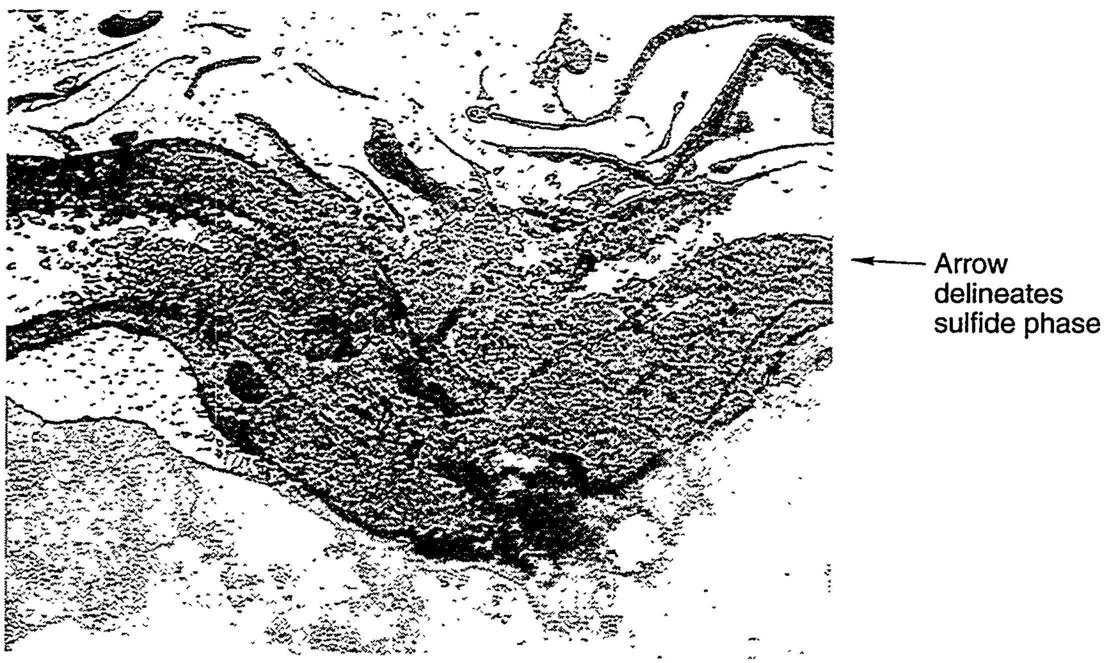


Figure 9. Sulfides Present at TBC/Bond Coat Interface

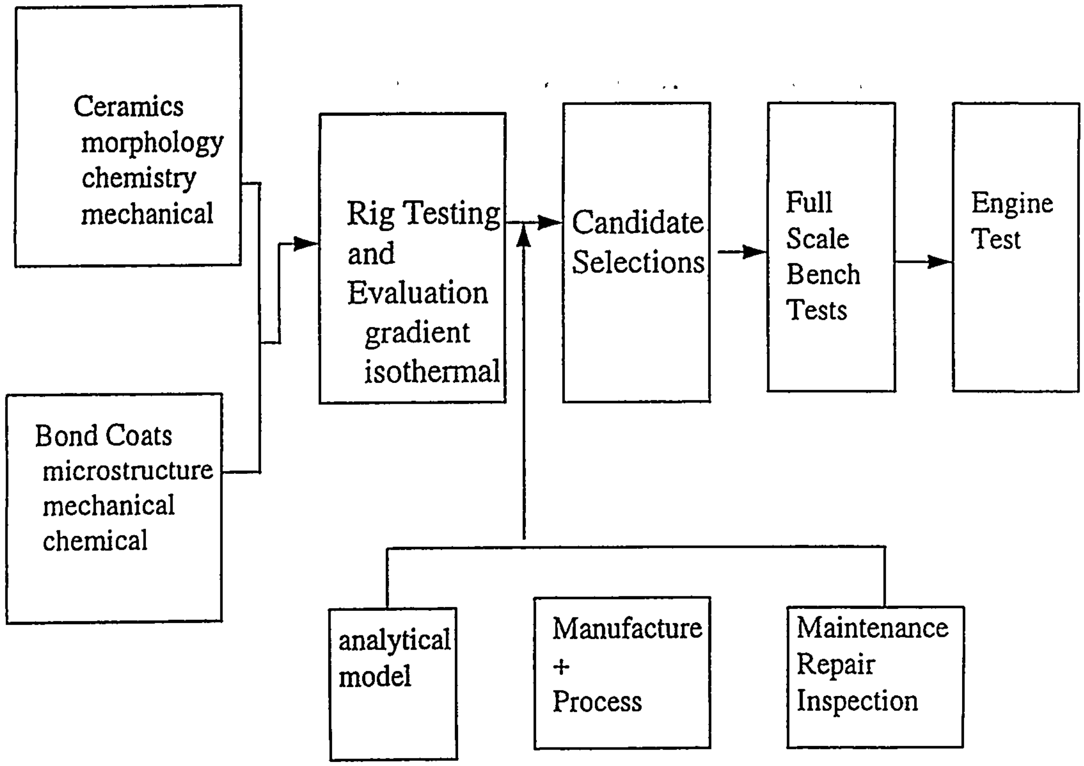


Figure 10. Program Overview

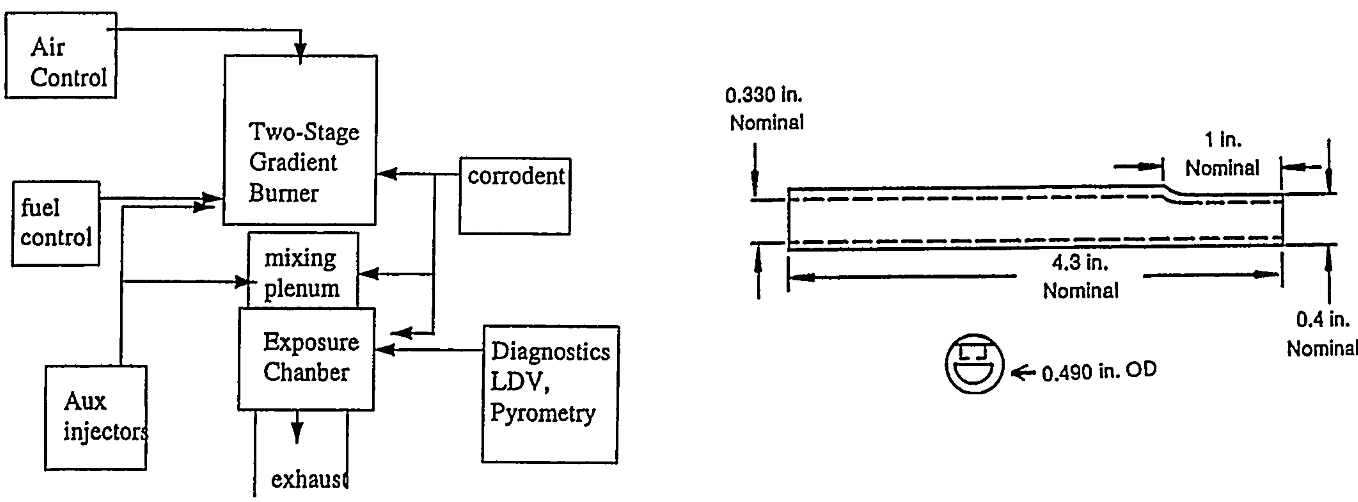


Figure 11. Schematic of Gradient Test Rig and Speicmen Configuration

5.8 Westinghouse Thermal Barrier Coatings Development

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Introduction

Westinghouse, in conjunction with the Department of Energy and Oak Ridge National Laboratory, has embarked upon a program for the development of advanced thermal barrier coatings for industrial gas turbines. Development of thermal barrier coatings (TBC's) for industrial gas turbines has relied heavily on the transfer of technology from the aerospace industry. Significant differences in the time/temperature/stress duty cycles exist between these two coating applications. Coating systems which perform well in aerospace applications may not been optimized to meet power generation performance requirements. This program will focus on development of TBC's to meet the specific needs of power generation applications.

The program is directed at developing a state-of-the-art coating system with a minimum coating life of 25,000 hours at service temperatures required to meet increasing operating efficiency goals. Westinghouse has assembled a team of university and industry leaders to accomplish this goal. Westinghouse will coordinate the efforts of all program participants. Chromalloy Turbine Technologies, Inc. and Sermatech International, Inc. will be responsible for bond coat and TBC deposition technology. Praxair Specialty Powders, Inc. will be responsible for the fabrication of all bond coat and ceramic powders for the program. Southwest Research Institute will head the life prediction modelling effort; they will also be involved in coordinating nondestructive evaluation (NDE) efforts. Process modelling will be provided by the University of Arizona.

A complete coating life cycle approach has been established for this effort. It begins with an evaluation of new ceramic and bond coat chemistries and the processing methods used to deposit coatings. Off-line inspection techniques, optimized specifically for coatings, will be used to insure coating quality and integrity at the factory floor, before service begins. Once in service, on-line inspection techniques developed under this program will be used to monitor coated component performance. Life prediction models will be developed to establish the anticipated service life for coating systems. As service hours increase, maintenance and repair techniques established under this effort will be implemented to insure the service life and reliability of coated components.

Research sponsored by the U.S. Department of Energy's Morgantown Energy Technology Center, under contract DE-AC05-95OR22242 with Westinghouse Electric Corporation, 4400 Alafaya Trail, Orlando, FL 32826.

Program Description

The approach begins with new bond coat materials. Currently, oxidation of the bond coat is the life-limiting failure mechanism of the TBC system; for this reason a significant effort will focus on developing oxidation resistant bond coat materials. Oxidation resistance, while important, cannot be the sole consideration, chemical stability, bond coat compatibility with the substrate, physical and mechanical properties are also concerns. Chemical diffusion between the bond coat, substrate, and TBC can have deleterious effects on the properties of the system. Physical properties, such as thermal expansion, and mechanical properties, such as creep relaxation and fatigue endurance, also impact coating durability. Each substrate, bond coat and TBC composition will have unique interactions which influence coating system life. The investigation will place a large emphasis on elucidating these interactions using analytical techniques. The approach follows from the assumption that no single bond coat composition will provide optimal coating life for every substrate alloy.

The bond coat deposition process also plays an important role in obtaining optimal coating durability. Low Pressure Plasma Spray (LPPS) is the predominant industry standard for depositing reliable, durable bond coats. The superior quality of LPPS bond coats is a direct result of depositing the coating in a low pressure, reduced oxygen environment. Obtaining such an environment requires large, expensive vacuum systems which directly impact the process cost. As part of the TBC development program, Westinghouse will evaluate the High Velocity Oxygen-Fuel (HVOF) and Gator-Gard processes as cost effective alternatives to the LPPS process. HVOF is a fuel combustion technique, Gator-Gard is a high velocity plasma spray technique. These techniques do not require use of expensive vacuum systems; both approaches provide high powder velocities which minimize the dwell time of the powder in the gas stream, thus minimizing oxidation. The high particle impact velocity produces a high density coating with high bond strength. Bond coat materials deposited using optimized HVOF and Gator-Gard processes will be compared to those deposited by LPPS to establish the viability of these processes as cost effective means of producing quality, durable bond coats.

Chemical Vapor Deposition (CVD) and Physical Vapor Deposition (PVD) of bond coat materials are more costly than HVOF and Gator-Gard; however, the processes can produce bond coat materials with unique, beneficial properties which may provide increased coating system life. Bond coat materials deposited using these techniques will also be evaluated.

Process variables, such as bond coat surface finish and bond coat pre-oxidation will be evaluated. The adhesion of an Air Plasma Sprayed (APS) bond coat relies, in part, on the mechanical interlock between the TBC and bond coat surface. The bond coat surface is intentionally roughened to achieve the required mechanical interlock. This rough, interlocked interface is characterized by hills and valleys which act to increase the local stresses at the interface. These stresses contribute to the eventual failure of the coatings system. A balance between the surface roughness required to obtain TBC adherence, and the increase in deleterious stresses associated with a rough interface, must be achieved to optimize coating life.

An integral part of the Electron Beam - Physical Vapor Deposition (EB-PVD) process is pre-oxidation of the bond coat within the coating chamber to form an oxide interface onto which the EB-PVD TBC is deposited. Growth of the oxide in this manner is believed to promote the formation of a compact, slower growing oxide than that found on APS coatings. The merits of pre-oxidation of the bond coat for APS coating systems will be assessed.

A systems approach to improving coating performance must also consider the ceramic thermal barrier. The use of 8% yttria stabilized zirconia has demonstrated performance in the aerospace industry. It has many desirable properties, thermal stability at high temperature, high thermal expansion and low thermal conductivity. The life-limiting failure mechanism remains oxidation of the bond coat; it can be argued that improvements in the ceramic TBC performance under these circumstances is of secondary importance. As bond coat developments provide increased oxidation resistance, the influence of ceramic TBC properties on coating durability will increase. Given this, gains can be made through further development of the ceramic TBC.

Improvements may be made through use of alternate compositions, or through processing to increase coating compliance or decrease thermal conductivity. With this perspective, Westinghouse will evaluate new ceramics compositions which may provide improvements over yttria stabilized zirconia. Microstructural modifications, such as microcracked, segmented, and columnar plasma sprayed structures, offer the promise of improving coating compliance while reducing thermal conductivity. The merits of such structural modifications will also be assessed.

Obtaining improvements in coating properties through microstructural manipulation will require an increased analytical understanding of the process variables. While many of the processing "rules of thumb" are known, implementation on a production basis often involves a trial and error approach. Such an approach becomes particularly cumbersome and expensive when considering large industrial gas turbine components. A process modelling effort, operating on a macrostructural and microstructural level, will be conducted to support manufacturing needs.

The process models being developed within the program will provide an analytical means of predicting coating thickness and microstructure to guide process control parameters. Individual models will be developed for the plasma spray and EB-PVD processes.

The plasma spray models will follow a splat build-up approach based on an empirical description of the powder size, distribution and trajectory as it leaves the plasma spray gun. Process variables which determine the microstructure will be an integral component of the model. Component geometry and spray-gun trajectory will also be incorporated into the model, providing an analytical approach to depositing a uniform coating on complex components in a cost effective manner.

A similar model for EB-PVD processing will be based on a first principles understanding of the deposition process. Analytical descriptions of material evaporation and condensation will be used to characterize coating rate, thickness and microstructure. Component geometry and position within the coating chamber will be an integral part of the model. Westinghouse and the University of Arizona will work cooperatively with Sermatech International, Inc. and Chromalloy Turbine Technologies, Inc. to utilize the process model results in production facilities to obtain coated engine hardware with improved performance.

Given program time constraints, the 25,000 hr. durability requirement can only be established using predictive models. To this end, an analytical model will be developed to provide a predictive assessment of coating durability. In addition, the model will provide an analytical tool to identify those properties which can be controlled to increase coating system life. This effort will be conducted through a cooperative effort between Westinghouse and the Southwest Research Institute. Southwest Research Institute has extensive experience with life prediction modelling.

The model will follow a mechanistic approach which considers bond coat oxidation, thermal stress, geometric factors and time dependent mechanical properties of the bond coat and TBC. Each of these factors impact the stress state of the coating system and contribute to the accumulated coating damage. The stress state of the coating is directly related to the time-temperature-stress duty cycle of the component, this information will be integrated into the model. The model will be used to develop life prediction curves based on the calculated stress state and the inherent coating strength.

Validation of any life prediction model is critical to its success. An evaluation of the predictive capability of the model must rely on accelerated laboratory tests if it is to be accomplished within the time scope of the program. The test conditions will be carefully selected to evaluate the contribution of each damage mechanism to the overall coating life. The validation effort will focus on new, developmental coating systems, as well as established systems for which long-term field service data are available. Extensive properties data on strength, elastic modulus, stress relaxation behavior, fatigue properties and thermal expansion will also be obtained to support the model effort.

Once the efficacy of the model is established, it can be exercised to establish service inspection times, and ultimately, coating life. The mechanistic approach being followed will also allow parametric studies to direct selection of material properties to improve coating durability.

Control of component temperature will most likely be accomplished by a combination of TBC's and thin film cooling. The use of these complimentary approaches introduces the manufacturing challenge of depositing a coating without disrupting the integrity of cooling holes. To this end, a manufacturing initiative will be conducted to establish techniques for masking cooling holes during the coating process. The feasibility of alternative practices, such as re-drilling of obstructed cooling holes, will also be investigated. From these studies, manufacturing recommendations will be established.

The NDE, maintenance and repair efforts of this program span the complete coating life cycle, from quality control of new components to field service inspection and repair of service exposed coatings. The effort involves use of established technology and the development and application of new technology for use on TBC systems. Westinghouse will work with university and commercial concerns to demonstrate these technologies for industrial gas turbine applications.

Conventional, off-line NDE techniques such as radiography, eddy current and ultrasound will be evaluated to assess there application to TBC systems. These techniques are well established for use on conventional metallic components and could be applied to coatings. In addition to these conventional techniques, two innovative, off-line NDE techniques, thermal wave imaging and inductive-capacitive arrays, will be evaluated.

Thermal wave imaging is a sophisticated time-lapse infrared imaging technique which allows a non-destructive means of identifying hidden flaws, such as debonding, within the coating. High energy flash lamp sources and infrared sensitive cameras are used to build a time-lapse image of the energy transfer within the coated component. Areas of debonding within the coating act as insulators, radiating energy to the camera and appearing as hot-spots; thereby, providing an image of the hidden defects within the coating. A beneficial aspect of the technique is the ability to evaluate a large coated component surface area in real time. This makes the technique attractive for manufacturing quality control and field service evaluations of coated components.

Inductive-capacitive techniques are well established for use on conventional metallic components, however, experience on TBC systems is limited. In addition, standard inductive-capacitive sensors can only be used for point contact measurements, allowing only limited component areas to be evaluated. Advances in this technology have led to the development of sensor arrays that can be used to scan the entire component, thus making the technique more desirable for quality control and field service evaluations.

These NDE techniques will be supported by mathematical modelling to establish the unique relationships associated with the application of a ceramic coating onto a metallic component. The models will provide the theoretical knowledge to optimize these techniques for use on TBC systems. This understanding will also assist in designing appropriate NDE calibration standards and establishing theoretical detection limits relevant to TBC systems.

This program will also pursue development of innovative on-line NDE techniques to bridge the gap between off-line inspection periods. Relying on established infrared optical fiber thermometry (IR-OFT) technology, a system will be investigated for monitoring component temperatures during engine operation. Such information would provide a powerful means of monitoring component integrity and engine performance. The theoretical understanding and hardware for optical fiber thermometry measurements is well established. The application of this technology to measure component temperatures within the turbine environment, however, provides new challenges. The focus of this effort will be to demonstrate that IR-OFT can be used to measure component temperatures during engine operation.

Such a demonstration of fiber optics technology would open new avenues for on-line monitoring of the engine. The use of fiber optics, once demonstrated, could be extended to obtain addition spectral information. With this perspective, a feasibility study will be conducted on Rayleigh, Raman and Brillouin scattering phenomenon to establish their utility in an on-line engine monitoring system. Each of these scattering phenomenon could provide additional on-line information on the properties and condition of engine components during service.

The use of coatings also requires establishment of maintenance and repair capabilities. Repair and maintenance techniques will be investigated to insure the ongoing reliability of coated components once they are introduced into the engine, supporting the complete life cycle approach to coatings development. Issues such as degradation of the substrate and compatibility of the repair with the existing coating will be considered.

The most promising technological advancements established in this effort will be brought to test in the bench test phase (Phase III) of the program. In the bench test, full-scale coated sections of engine components will be tested under high temperature, high pressure conditions. The bench test will bring together all components of the development effort. New bond coats, new ceramics and optimized processing methods will be incorporated into the coating systems. Test conditions will be designed to support verification of the life model. NDE techniques, both off-line and on-line, will be brought to practice for the bench test.

The successful completion of this program will be marked by the development of a reliable, cost effective coating system which enables gains in the efficiency and reliability of industrial gas turbines. This can be achieved through the cooperative efforts between industry, university and government concerns that have been established for this program.

Acknowledgments

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5.9 High Performance Steam Development

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OBJECTIVES

- Increase industrial and electric utility efficiency through the development of high temperature steam technology.
- Increase steam temperature to 1500°F at 1500 psig for applications for small combined cycles for industrial cogeneration using supplementary firing in the gas turbine exhaust.
- Design, fabricate and test for 500 hours a full tube length steam generator test module at 1500°F and 1500 psig.
- Develop production cold drawn final superheater tubes to meet all of the ASME Section I Fired Boiler Code requirements and the economic goals of high performance industrial steam generators.
- Design and fabricate an industrial sized 1500°F heat recovery steam generator matched to a supplementary fired 5 MWe industrial gas turbine.
- Design and fabricate a back pressure steam turbine (BPST) to operate at 1500°F and 1500 psia and produce 4 MWe.
- Develop a high temperature valve to control the system as a combination throttle, bypass, and stop valve.
- Design a 1500°F piping system to minimize thermal stress and costs in a high temperature system.
- Incorporate a low emissions burner.
- Test the High Performance Steam System (HPSS) in a factory proof development test for 100 hours prior to placing in a site cogeneration system.
- Install HESS at a permanent site in cogen-eration and monitor it for the first 1000 hours.

BACKGROUND INFORMATION

Over 30 years ago U.S. industry introduced the world's highest temperature (1200°F at 5000 psig) and most efficient power plant, the Eddystone coal-burning steam plant. The highest alloy material used in the plant was 316 stainless steel. Problems during the first few years of operation caused a reduction in operating temperature to 1100°F which has generally become the highest temperature used in plants around the

[1] Research sponsored by the U.S. Department of Energy, Chicago Operations Office, under contract DE-AC02-87CD40812 with Solar Turbines Incorporated, P.O. Box 85376, San Diego, California 92185-5375; telefax: 619-544-5500.

world. Leadership in high temperature steam has moved to Japan and Europe over the last 30 years.

Because the majority of the U.S. electricity production and much of its industrial heat depends upon steam, the DOE has launched this development to make a step change in technology to 1500°F steam. The previous 100 years of industrial and utility developments have only averaged about 7°F per year. Gas turbine technology, advancements in high temperature superalloys, manufacturing technology advancements, and a new class of once-through steam generators (OTSG) provided the technology base to start this ambitious program.

Thermodynamic analysis show that the overall cycle efficiency of a Rankine cycle increases as temperature and pressure increase. The highest possible performance gains can be achieved in a 1500°F steam system when using a topping turbine in a back pressure steam turbine configuration (BPST) for cogeneration. Figure 1 shows the thermodynamics of expanding

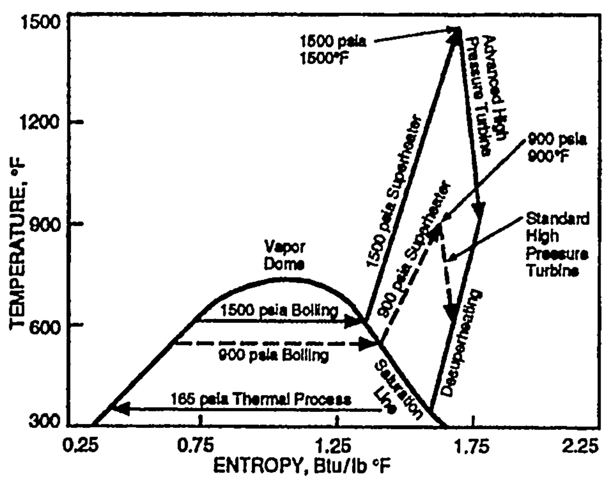

Figure 1. Temperature-Entropy of 1500°F Steam Cycle Compared to 900°F Steam in an Industrial Backpressure Steam Turbine Cogeneration System

from 1500°F and 1500 psia compared to typical cycle conditions for small industrial cogeneration (900°F and 900 psia). When expanding steam to 165 psia more than twice the energy is available in the 1500°F case to be converted to electricity (an enthalphy drop of 304 compared to 150/Btu per pound of steam). Because this configuration has the highest thermodynamic advantages with the best economics and many practical development advantages it was selected for the development program Natural gas was selected as the fuel to minimize costs and emissions although other fuels have been studied in detail (Ref. 1).

Development costs and potential payback to industry of the program also established the small size for the cogeneration system. On natural gas, small combustion turbines with process boilers have been the most cost competitive. In large systems combined cycles are standard. In small systems combined cycles are not as competitive and need innovative technologies to bring the performance and economic advantages of combined cycles to smaller industrial and commercial plants. Developments of the OTSG has greatly simplified the steam generation and systems complexity for small combined cycles. Supplementary firing in combined cycles with BPST arrangements are normally the best economic solution, because they can provide fuel utilization efficiencies of over 90 percent.

Figure 2 schematically shows this simple arrangement for a BPST combined cycle. In this arrangement, the maximum amount of electricity is produced per unit of steam to the process, at an incremental fuel efficiency, to produce electricity of over 90 percent when supplementary fired to 2500°F in the exhaust of the gas turbine. Other combined-cycle systems can be configured by adding a condensing low pressure turbine to produce much more electricity, but the overall fuel utilization efficiency decreases as the heat of vaporization is lost in the condenser.

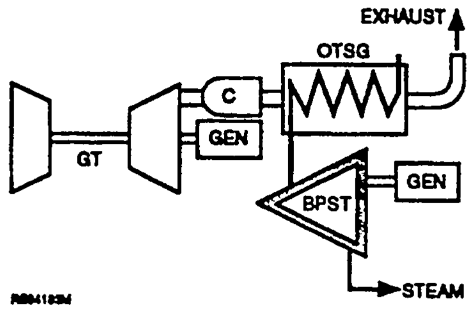

Figure 2. HPS Combined Cycle With Exhaust Firing and Backpressure Steam Turbine for Cogeneration

A high production family of gas turbines, Solar' Centaur, of 4 to 5 MWe was selected to size the steam generator system. Although some combined cycles based on the Centaur have been installed, the large majority of Centaur cogeneration systems use only a process steam generator, using supplementary firing. This decision is based upon current economic conditions. With traditional technology, the ability to "put-the steam-to-work" on its way to process heating is only marginal due to low power recovery and consequential costs. High performance steam can be used to essentially double the electrical output of the system and improve its economics.

An exhaust firing temperature of 2500°F was selected on the basis of maximizing performance in cogeneration while maintaining ultra-low emissions capabilities in a lean premixed combustion system. At a gas turbine exhaust flow of 38 pounds per second, 56,000 pounds per hour of steam is produced at 1500°F and 1540 psig. In the combined-cycle configuration (Figure 2) the BPST will produce 4 MWe and the gas turbine will produce 5 MWe for a total of 9 MWe combined cycle with 74,000 pounds of desuperheated steam to the process The use of 1500°F steam in cogeneration in addition to producing more electricity from the topping expansion has two additional benefits. Because the BPST exhaust is at 990°F (to match traditional steam turbines) it can provide superheated process steam for many industrial processes requiring high temperature steam, such as steam reforming. The high exhaust superheat temperature also provides a greater amount of electricity from a low pressure condensing steam turbine if incorporated in the system. An additional 6 MWe from the low pressure turbine produces more electricity efficiently when process steam is not required, for a total of 15 MWe with a 5 MWe gas turbine.

In cogeneration with biomass-produced gas and low-Btu landfill fuels, the HPSS can be configured as a 4 MWe steam plant for cogeneration without the gas turbine or a 10 MWe condensing steam power plant.

In coal plants the BPSS technology has been studied in a separate program (co-funded by EPRI) for repowering old coal steam plants and for new advanced steam power plants. By operating at higher pressures (to 5000 psig) and lowering the temperature to 1300°F, heat rate reductions of 12 percent can be achieved using the same tubes developed by the DOE cogeneration program and many HPSS technology developments. Reference 1 details the materials, manufacturing, design and corrosion issues that have directly supported scale-up to utility systems using HPSS technology for repowering 100 to 300 MWe plants with topping turbines of 25 to 50 MWe. It also discusses the application to topping the steam plant of large combined cycles. Table 1 summarizes the positive impact the HPSS technology can have on utility ATS combined cycles, utility repowering, new steam plants and industrial cogeneration.

PROJECT DESCRIPTION

Phase II — 500 Hour Proof-of-Concept Test

Based upon results of the Phase I study (Reference 2) a 500-hour proof-of-concept test module was designed, fabricated and successfully

Table 1. The Effect of HPSS on Cycle Performance

	Combined Cycle (LHV)		Repowering (HHV)		New Steam (HHV)		Cogeneration (LHV)	
Fuel	1.00	1.14	1.00	1.10	1.00	1.11	1.00	2.5
Gas Turbine	0.45	0.45					0.31	0.31
HPSS Turbine		0.12		0.09		0.08		0.29
Base Turbines	0.12	0.12	0.35	0.35	0.38	0.38		
Efficiency	57%	61%	35%	40%	38%	42%	78%	90%
Output	0.57	0.69	0.35	0.44	0.38	0.46	0.31	0.60
Heat Rate, Btu/kwh	5,988	5,595	9,714	8,674	8,981	8,126	4,376	3,792

tested. Figure 3 shows the module being erected in the test facility. It had four once-through steam generator (OTSG) circuits. It was based upon OTSG patents and designs used in Solar's small combined cycles at traditional steam temperature. Approximately 20 of the low temperature OTSG's are used in combined cycles with plant size from 8 to 70 MWe using multiple units. They are the ultimate in design simplicity and well matched to small combined cycles. The OTSG is also ideally configured for high temperature and pressure steam systems. All tubing in the installed OTSGs is made of alloy 800 super stainless steel. For traditional temperatures, carbon steel fins are used and supply 90 percent of the heat transfer surface. For the HPSS-OTSG the final superheater is made from Inconel 617. As fin temperatures go above 950°F the material is changed to stainless steel alloy 321. Above 1400°F the fins are made from stainless steel alloy 310. A unique manufacturing process is used to bond the fins to different tube materials. The bonding process is rated for operation to 1800°F.

A natural gas combustion system supplied combustion gases to the module at 2500°F. A total of 517 hours of operation at 1500°F and 1500 psig was completed in the module development tests. Transients were investigated and a total of 38 starts and a shutdowns were accomplished. Relatively good control of metal temperature in each of the final superheater tubes was maintained within ±50°F of 1500°F. Tests also indicated that a higher radiation heat flux to the screen tubes occurred than was estimated analytically.

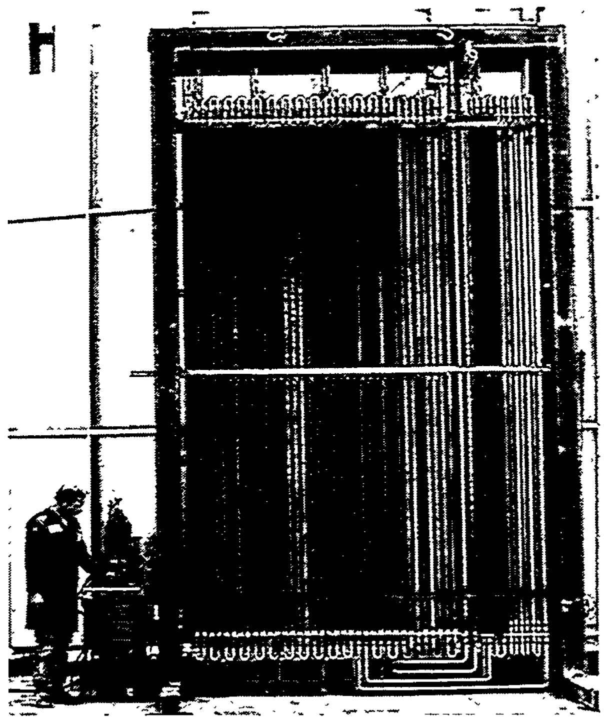

Figure 3. Once-Through Steam Generator Module Prior to 500 Hour Proof-of-Concept Test

Post test examination of the final superheater after 500 hours showed an adherent thin chrome-based oxide film, a few microns thick, on both the steam side and air side of the tubes. No evidence of steam oxide scaling or spallation was present. This correlated well with 4000 hour bench loop test results on corrosion of superalloys in steam over 1500°F at 1500 psig. In both tests surface oxide penetration on the steam side was slightly less than on the air side of the tubes.

Phase III - Industrial Prototype HPSS Development

Phase III was initiated when the critical technology 500 hour OTSG module test was successfully completed in 1991. In phase III, the primary tasks were to analyze, design, build, and test a complete HPSS power plant for 100 hours at 1500°F and 1500 psig. Figure 4 shows the complete HPS system in the final test phase with the OTSG at the right and the 4 MWe BPST on a skid using a gear box-driven water brake dynamometer to measure performance in the foreground. Tests have been successfully completed. Over 102 hours of factory proof tests were completed on the system that included the following key components:

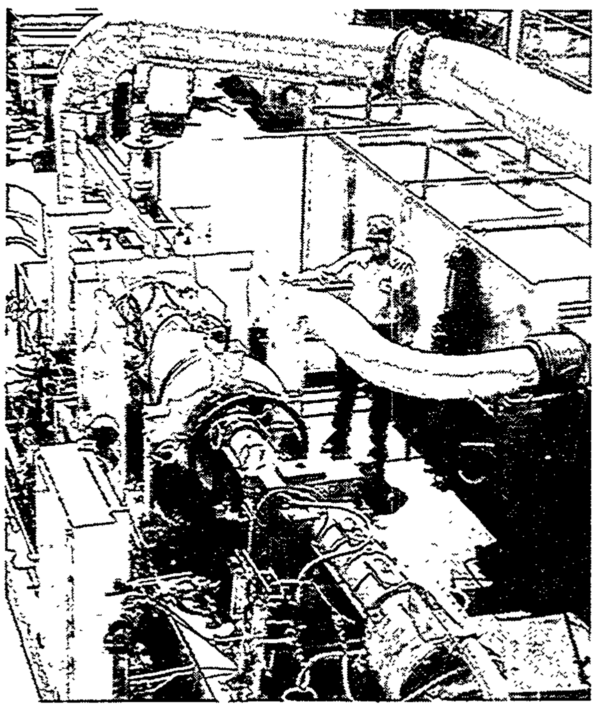

Figure 4. 1500°F HPS in Final Test With OTSG on Right and BPST on Left Driving Reduction Gear to a 6000 HP Water Brake Dynamometer

- Topping steam turbine
- OTSG steam generator
- Control valve
- Low Emissions combustor
- Piping system
- Electronic control system

To minimize cost, fresh air firing was used with exhaust gas recirculation providing a similar combustion system input to operating with a gas turbine.

Low Emissions Combustion System

A natural gas, low-emissions combustion system was specially matched to the design criteria of the OTSG. Figure 4 shows a top view of the 1 10 million Btu per hour combustion system on the top right of the photograph. A 16-foot long reaction zone, six feet wide and sixteen feet high is lined with refractory material The hot wall configuration prevents wall quenching, and consequent CO formation common in water wall boilers. It allows lean operation with exhaust gas recirculation, at theoretical flame temperatures of 2500°F. High rates of exhaust gas recirculation are used to keep emissions low and steam generator efficiency high when not using the exhaust of a gas turbine. The exhaust gas recirculation can also be adjusted to simulate exhaust conditions into the burner from a gas turbine. Figure 5 shows the burner assembly with stabilizer and fuel injection nozzles for lean premixing. Air is supplied to the windbox from a fan connected directly to the windbox. Figure 6 shows the fan and the location of the exhaust recirculation connection directly downstream of the fan inlet air vortex vane control

Figure 5. Lean Premixed Coen Low Emissions Burner (33 inch diameter, 110 million Btu/hr)

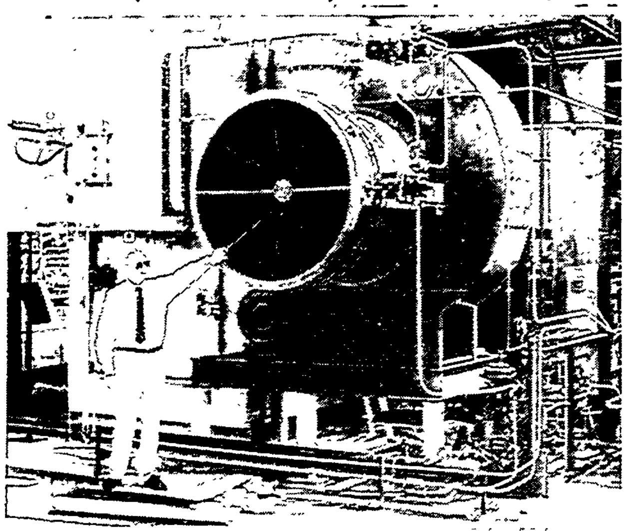

Figure 6. Air Supply Fan With Exhaust Gas Recirculation Connection

valve. The pressure drop across the valve supplies the pressure differential to circulate about 22 percent of the OTSG exhaust into the combustion air supply.

In a combined cycle configuration, the fan would be replaced by the exhaust flow of the gas turbine and no exhaust gas recirculation would be incorporated because the O_2, CO_2, and H_2O levels would be about the same.

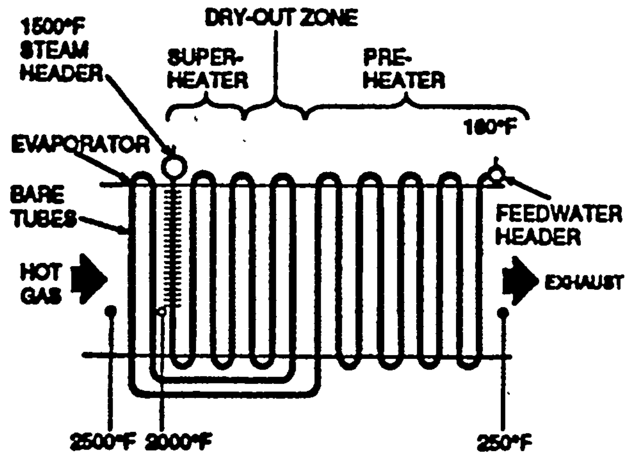

Figure 7. Prototype Once-Through Steam Generator Flow Schematic

Steam Generator

The steam generator has a once-through water-steam flow path with horizontal gas flow path. Figure 7 schematically illustrates the flow configuration. A total of 26 circuits are assembled to complete the OTSG heat transfer module. Based upon test results obtained in the 500 hour proof-of-concept-test of Phase II, a number of improvements in the design were incorporated in the industrial prototype OTSG circuits. Simplification of the design was obtained by eliminating an intermediate header and the number of radiation screening bare tubes were reduced. Simplification of seals and supporting structure was also accomplished to improve mechanical design for production. Figure 8 shows one of the 26 circuits used in the prototype unit. Six fins per inch of 0.5 inch high carbon steel are used for over 66 percent of the heat transfer. The last 22 rows use carbon steel fins and show as dark tubes in Figure 8. At the inlet gas side the tubes are bare in the first four rows. The initial superheater uses 321 SS fins and the final superheater has 310 SS fins. Final superheater tubes are made of seamless cold drawn

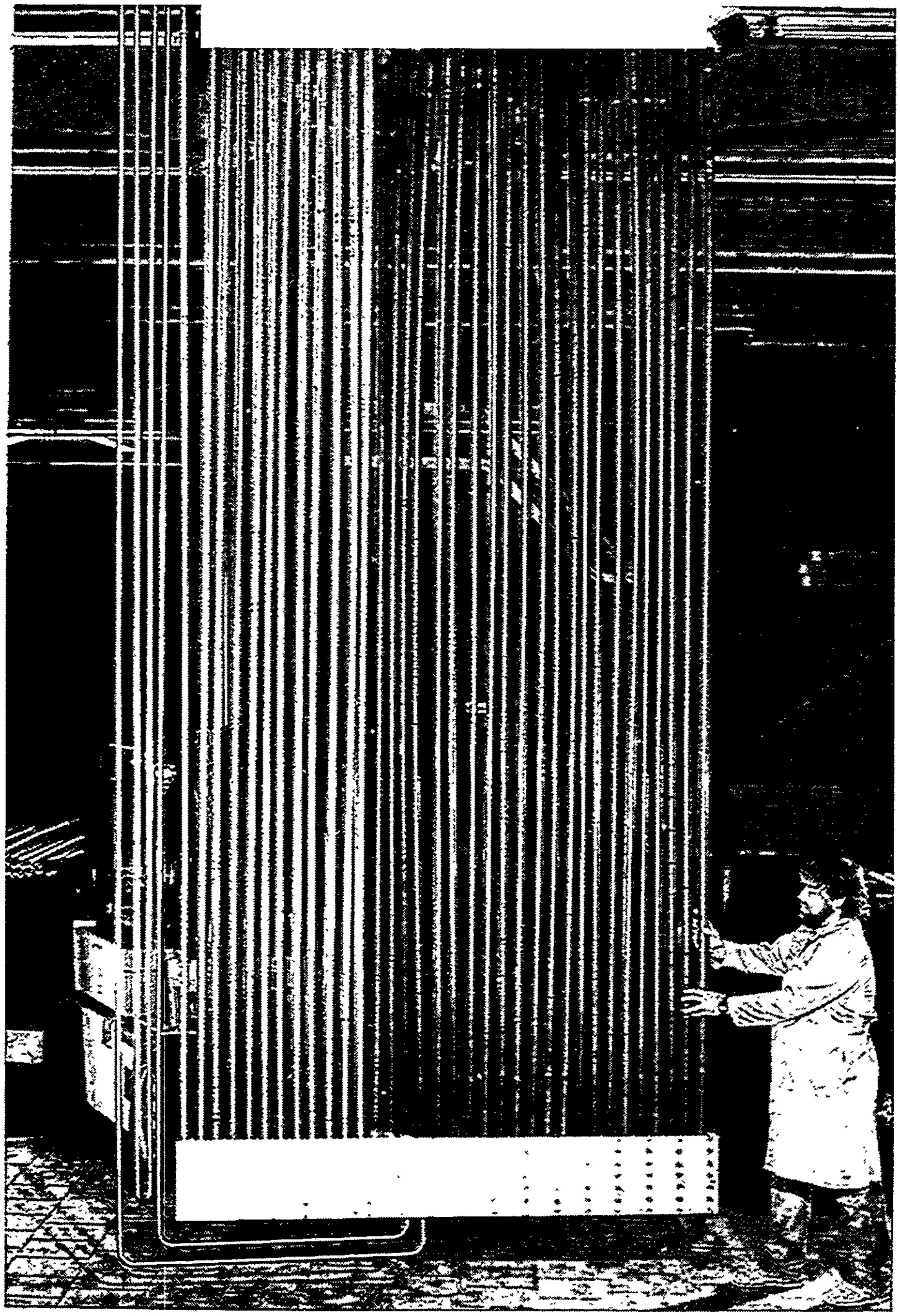

Figure 8. Configuration of a OTSG Circuit Feedwater in at Top Right and Superheated Steam Out at Top Left

Inconel 617, 1.0 inch outside diameter tubes. The last row is 0.28 inch thick with one row of 0.20 and one row of 0.12 wall thickness Inconel 617 in each of the upstream rows. The remainder of the unit is made of Alloy 800H and Alloy 800 tubing. The majority of the tubing is thin wall 0.083 inch seamless alloy 800 in 26 of the 38 rows in the OTSG. Thin wall alloy 800 is standard in all OTSGs currently installed in combined cycles at traditional temperature and pressure steam conditions.

All of the different wall thickness tubes of Inconel 617 were specially developed for this prototype unit. A high production type process had to be developed because the 500 hour module used bar stock-machined tubes in the final superheater. Final optimization of the tube diameter and wall thickness versus production costs was done by the OTSG designers working with Inco' International's tube manufacturing process engineers. Extensive process development produced the tubes to the ASME specification requirements of the Boiler Code. Cold-drawn seamless tubes of this size and high strength material are an important technology developed to cost effectively advance HPSS for commercialization.

Each circuit was hydrostatically tested to the ASME Section I Fired Boiler Code, and assembled into the prototype module consisting of 26 circuits (Figure 9). Each circuit inlet and outlet are connected by headers to form a complete steam generator. All outlet tubes are instrumented with two thermocouples. Two circuits, one in the center and one at a wall are instrumented throughout their flow path. The finned area of tubes is 14 feet long and the 26 circuits are about five feet wide. Because each circuit is an individual steam generator, the design can match a 10 MWe gas turbine by doubling the number circuits. A square frontal area, 14 by 15 feet using 78 circuits, would match approximately a 15 MWe gas turbine and produce a 45 MWe HPSS combined cycle with condensing turbine. No further development would be necessary for this replication approach to scale up the OTSG prototype design.

Piping and Valve to Turbine

Because of the step increase in temperature, all of the high temperature steam components needed innovation, special design, and development. Circuits are connected to a 5.25 inch diameter 1.1 inch thick hot extruded seamless tube header with two 90 degree bends connecting to the

Figure 9. OTSG Module for Prototype HPSS Showing 25 Circuits for a 56,000 pph System

control valve. Figure 4 is an overview, and Figure 10 a more detailed view showing the control valve. The header is allowed to slide away from the turbine. The turbine is fixed and the valve is allowed to slide in line with the turbine axis with its weight carried on spring hangers. Inconel 617 rods support the Hastelloy X valve. By placing the turbine at the plane of the header and sliding all components on low friction bearings, pipe bending loads are eliminated (except for friction). Total pipe length is less than 10 feet, thus minimizing cost and stress with a single design approach of allowing all flexing to occur in the long, 1.0 inch diameter final superheater tubes.

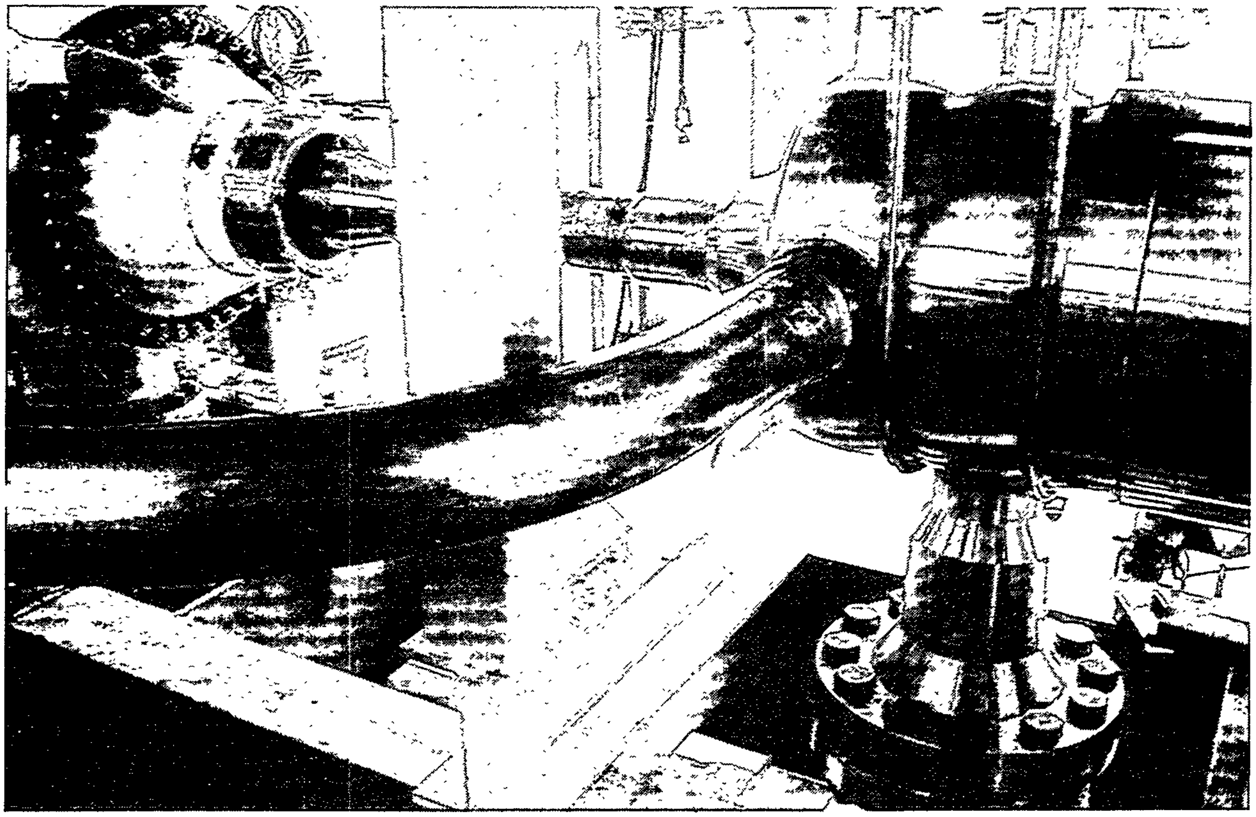

Figure 10. OTSG's Outlet Header Connection to Control Valve with Steam Turbine Connection in Background

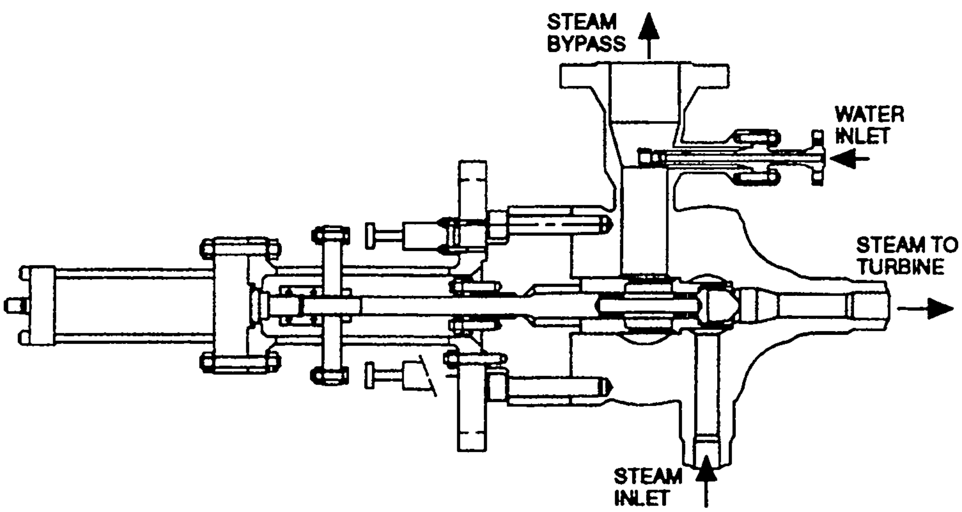

Figure 11. High Performance Steam Control Valve Cross-Section

The valve has a triple function using a single moving plug that throttles, shuts off, and by-passes steam as required by the electronic controls. Figure 11 is a cross section of the valve showing the desuperheater function built into the low pressure bypass line (vertically down line in Figure 10). A line in Figure 10). A 2000 psi hydraulic system controls the valve with failsafe features to always shut the steam to the turbine. It has a 0.15 second fast trip capability with or without the hydraulic pump operating, by using accumulators. A mechanical spring is also capable of shutting steam to the turbine in the event of accumulator malfunction. The valve bypass arrangement has the same flow restriction as the turbine nozzle and is designed so that the OTSG always has the same flow area venting to the low pressure exhaust steam system regardless of valve position. Fisher Valve Company has specially developed this valve for the BPSS program and it is designated a special ASME/ANSI B16.34, Section 8 special 9000# Special Class valve.

Steam Turbine

To make a major step advance in steam turbine inlet temperatures, several key design concepts were adapted from industrial gas turbine design criteria. It is critical to costs and technical success that the turbine be as small as possible. Small dimensions reduce pressure stresses, wall thickness and thermal stresses. Complete symmetry is also important to reduce thermal stresses and distortions during transients. The design must also allow the use of gas turbine superalloy materials in the nozzle and superalloy manufacturing process proven for gas turbines.

Figure 12 is a schematic section of the turbine flow path and Figure 13 is computer aided design (CAD) layout of the turbine assembly. They illustrate how the critical design criteria were achieved. A high-speed (30,000 rpm) single-stage impulse turbine with a small diameter overhung rotor, a vertically split case and centered inlet line flow arrangement is an optimum configuration- for compactness and symmetry. A turbine efficiency of 68 percent when expanding from 1500°F and 1500 psia to 165 psia back pressure yields a 995°F exhaust temperature. This traditional steam system temperature becomes the cooling for the rotor

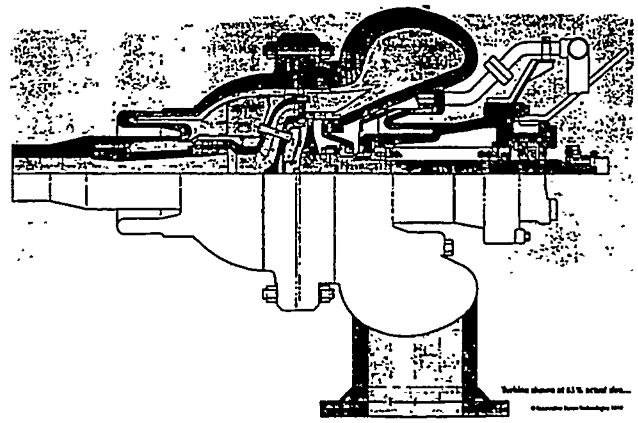

Figure 12. Backpressure Steam Turbine Flow Schematic

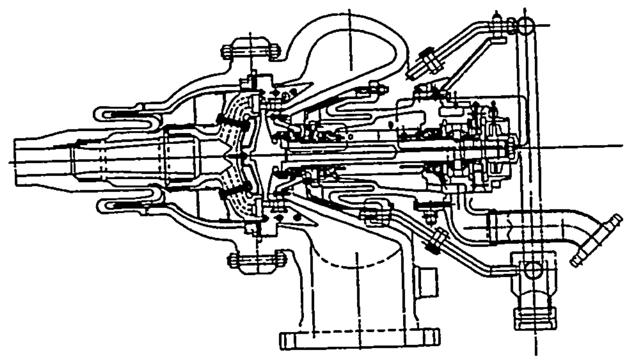

Figure 13. Backpressure Steam Turbine Detail Layout

and outer case. An overhung rotor allows an inner case design that can be fabricated using gas turbine nozzle superalloy Inconel 939 manufacturing technology.

Steam from the valve enters the turbine through a 5.25 inch diameter line with a 1.1 inch wall thick-ness made of Inconel 617. An electron beam weld joint connects the hot extruded seamless pipe to a thermal isolation series of three ring forgings welded to, form convolutions and to the cast steel outer case made of low alloy steel WC-9.

The outer casing is cooled by exhaust steam to operate at 1000°F. It contains exhaust pressure at 165 psia. A floating sleeve connects the outer case to the inner case and is sealed by ten close fitting seal rings to minimize leakage psia and 1500°F. Steam flows through a total of 12 passages in the investment casting that forms the inner case to direct steam to the nozzle ring. The sleeve inner case and nozzle ring are all made from cast Inconel 939, which is used in gas turbine nozzles at metal operating temperatures in the 1500°F range.

The inner casing and nozzle ring is the most critical component in the turbine. They and the inlet sleeve and inlet-to-case transition are the only components that must operate at 1500°F. Design of the 1500°F inner casing was based on a maximum allowable stress value to not exceed 67 percent of the average stress for rupture in 100,000 hours as guided by Section VIII Division I of the ASME Boiler and Pressure Vessel Code. For hot isostatic pressured castings of Inconel 939 this value is 18 ksi. Because statistical data was lacking, the design allowable stress value was set at 10 ksi, corresponding to 55 percent of the rupture value from the master curve which includes an 85 percent casting allowance. The design and the casting process were iterated with a total of three castings made before the final design was obtained. Figure 14 shows the casting with test bars cast for laboratory evaluation. Extensive finite element modeling was made of the design to ensure acceptable stress levels for casting process modifications required for production. A total of 24 structural vanes are used in the casting to support the inner and outer walls of the casing. The inner and outer walls and struts are typically 0.38 inch thick. The maximum Von-Mises stress was calculated to be 8,630 psi at the trailing edge of the strut to wall transitions and thus satisfied the allowable stress value with a relatively thin wall design.

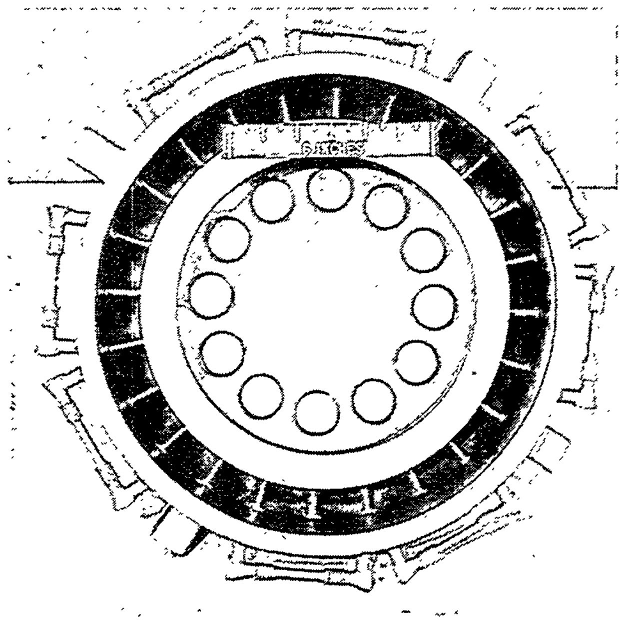

Figure 14. Inner Turbine Case Casting

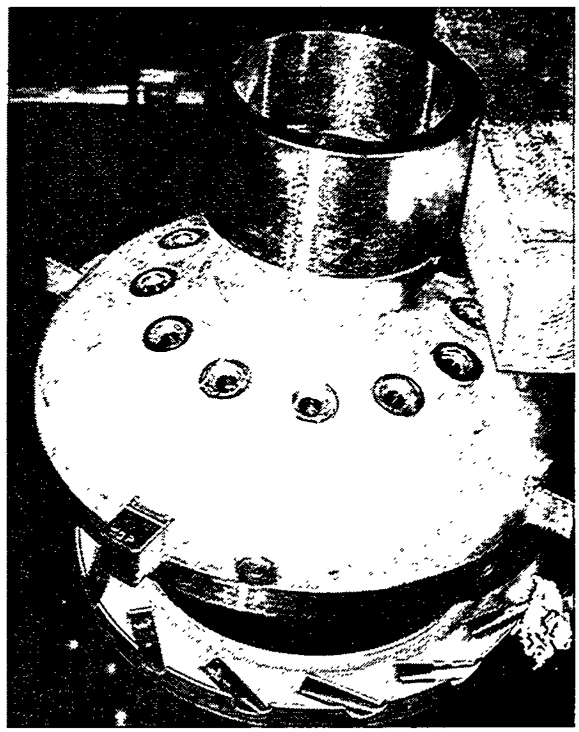

Figure 15. Inner Casing Assembly With Nozzle Ring Showing Cooling Holes in Cast Struts

Figure 15 is a photograph of the finish machined inner casing showing the 12 cooling holes that go through struts in the casing. Four radial lugs on the inner casing periphery hold the horizonal and vertical centerline of the inner to outer case. Thermal barrier coatings reduce the amount of cooling steam necessary to keep the outer case at acceptable temperatures. Radiation shielding and cooling steam maintained the temperature of the outer casing less than 1000°F by ducting cooling exhaust steam around the inner wall of the outer case before flowing through the tubes in the inner casing holes and then across the inlet face of the turbine disc to cool the disc surface with exhaust steam. During the 100 hour test the turbine cooling steam at the front of the rotor measured about 70°F above the exhaust steam. This steam cooled the rotor disc to an estimated temperature of about 1040°F.

Figure 16 is the completed inner casing assembled with the nozzle ring. Fourteen convergent-divergent nozzles have a spouting velocity of Mach 2, or 4000 feet per second. This nozzle is mechanically attached to the casing and the mechanical connections are sealed with a high temperature braze. Extensive manufacturing process development efforts were used in obtaining a nozzle exit angle near 11 degrees to the face of the nozzle in the extremely tough Inconel 939 material.

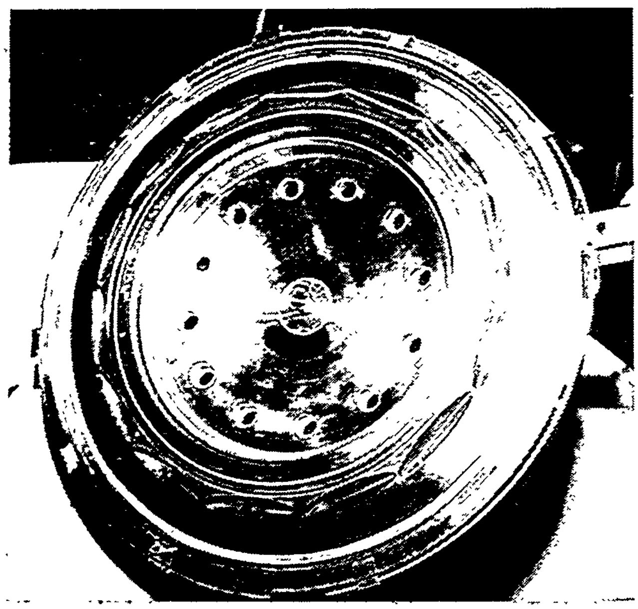

Figure 16. Supersonic Convergent-Divergent Nozzle Assembly

A rotor with 62 inserted blades was (Figure 17) used in the 100 hour test to replace the original bladed disc. The bladed disc had 91 blades. Because of limitations on the space needed for blade attachment only 62 blades could be inserted into the disc. This produced an efficiency loss as did the larger diameter radius used for leading and trailing edges of the redesigned turbine. Two to three percentage point of loss were analytically predicted and were verified in the performance tests. Impulse blading is used and is followed by a vaned diffuser. Tandem exit guide vanes raise the static pressure by recovering the high swirl energy in the turbine exhaust. Additional static pressure is recovered by the diffuser downstream of the vanes. The flow then dumps into the exhaust hood collector producing additional static pressure rise. The velocity of the machine exhaust is a modest velocity of 150 feet per second. Because of the diffuser, the static pressure between the nozzle exit and bucket inlet is significantly less than the exhaust back pressure. This makes possible a cooling steam flow to cool the case and the inlet side of the rotor disc via cooling tubes isolated from the inner case in holes drilled in 12 vanes (Figures 13 and 15). The downstream side of the disc is cooled by exhaust steam leaking to the labyrinth seals on the output shaft.

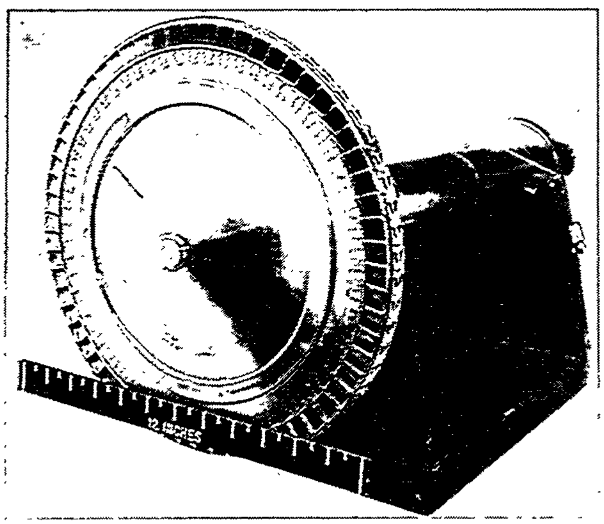

Figure 17. Turbine Rotor Bladed Disc (11.5 Inch Pitch Diameter)

The exhaust collector and outer case are made from a single low alloy steel casting designed to the ASME Pressure Vessel Code design intent. This is the heaviest component of the turbine assembly and weighs about 2,500 pounds with mounting plates. Less than 10 percent of total weight of the machine is made with super alloys while the remainder is of conventional steam turbine materials.

The bearing housing is made from cast low-alloy steel. It is nested under the hot exhaust collector. Thermal isolation is achieved through the use of a radiation shield with cooling air between the housing and shielding. Air admitted to the bearing housing is also used as a buffer in the honeycomb labyrinth steam/oil seal adjacent to the front bearing.

Figure 18 shows the completed steam turbine assembly installed in the HPSS prior to initial testing. A centerline trunnion flexible plate mount to the rails of the skid is shown. This point is the only fixed point in the system with the valve and steam generator header designed to slide in the horizontal plane to accommodate thermal expansions. Rigid vertical and horizontal slide guides on the valve support system are designed to react friction forces caused by sliding the system. This configuration eliminates pipe bending loads and minimizes nionients around the turbine. A slide key on the bottom of the turbine case allows moments caused by friction to be reacted between the valve guide ways and the turbine case.

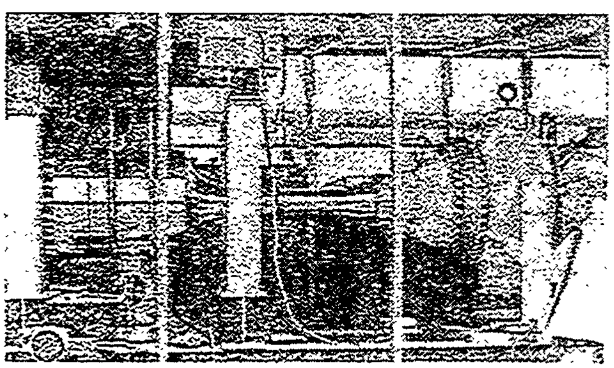

Figure 18. BPST Installed in HPSS Prior to Initial Tests

RESULTS - PHASE I AND II

Phase I Study

Results of the program to date include the completion and publishing of the Phase I study that defined optimum configurations of the HPSS for 4 to 50 MWe industrial cogeneration (Ref. 2). It identified design criteria for cogeneration that would meet the maximum number of industrial sites in the U.S. This study identified combined cycles with a BPST as the highest performance configuration in industrial cogeneration.

Phase II - Proof-of-Concept 500 Hour Test of OTSG Module

In Phase II a proof-of-concept 500 hour test was designed and tested to develop the basic technology needed to generate 1500°F and 1500 psig steam in a steam generator matched to supplementary fired gas turbine combined cycles. A total of 517 hours of operation at rated conditions were successfully completed on the module (Figure 3). A total of 38 starts and stops were monitored during the test. Several important design and manufacturing improvements to reduce cost and improve temperature distribution were discovered in the course of testing the highly instrumented test module. These features were incorporated in the design and manufacture of the OTSG prototype built in and tested in Phase III.

Phase III - 100 Hour Endurance Test Results

The complete HPSS (Figure 6) was tested at above 1500°F and 1500 psig for over 102 hours at full power with a water brake dynamometer. Full power at the output shaft of the turbine was typically greater than 5500 HP. The steam generator operated typically at 1540 psig and an

At the inlet to the turbine, the temperature averaged about 1502°F for the 100 hour test. Pressure inlet to the turbine was averaged at 1500 psia (or 1485 psig). The back pressure on the turbine for the 100 hour test ranged from 155 psia to 165 psia (140 to 150 psig). The design pressure ratio of the machine is 10 to 1. Twenty-one starts to 150°F were made with the complete system in operation. Additional starts and shutdowns were performed on the steam generator and control valve for preliminary tests and emissions test prior to completion of the turbine.

The 100 hour test was successful from all aspects evaluated to date. No significant problem with the HPSS caused any delays. Some instrumentation (about 300 channels) problems, some electronic control and auxiliary equipment such as test facility pumps caused the system to trip a few times. However, the 20 system trips during the 100 hour test were normally scheduled or part of the test. Several full power trips to test the control valve trip speed were performed. The longest con-tinuous run was about 20 hours during the endur-ance test. Full power trips were the normal shut-down when the days testing was completed. This mode was used since it was observed that it proved the simplest, fastest shutdowns with the minimum of temperature cycling of any of the steam components. Figure 20 shows a typical full power trip from 30,000 rpm and 1500°F and 1500 psia.

Based upon the excellent results of this 100 hour endurance test, I believe the system is ready to go into a field site as a standalone cogeneration system for at least 1000 hours operation at 1500°F and 1500 psig. A tear down and inspection has not yet been performed and is also a requirement and scheduled prior to the next phase.

Phase III results are listed below:

- Production Tubes Developed and Tested for Final Superheater. Production tube manufacturing processes were developed for the final superheater tubes. The 500 hour test module used 15 foot long tubes in the final superheater that were manufactured from bar stock with a machining process which was not suitable for production units or ASME Code requirements. In the Phase III tests recently completed, cold drawn ss tubes were developed and installed from INCO 617.

- ASME Design Approval for 1500°F Generator. The prototype design based upon the 500 hour test module was approved by the Authorized Inspector for operation at 1535°F and 1536 psig in industrial or commercial sites to the requirements of the ASME Section I Fired Boiler Code.

- Prototype, Steam Generator Tested for 110 Hours. An OTSG production prototype producing 56,000 pounds per hour steam from natural gas was fabricated and tested (Figure 8). It has accumulated about 200 hours with about 110 hours above 1500°F and 1500 psig. Its performance was as calculated. With a filing temperature of 2500°F and an exhaust of 190°F, it had an efficiency of 95 percent (LHV). Development work on balancing flow within the OTSG resulted in excellent superheater temperature distribution of about ±25°F, about an average outlet temperature of 1523°F. Figure 19 shows an actual calibration and temperature distribution on each of the 26 circuits. Note good correlation between all circuits that had both thermo-couples functional. Circuit number 5 thermo-couples were not correlating well but the temperature was adjusted to keep the high reading thermocouple within acceptable limits of the design.

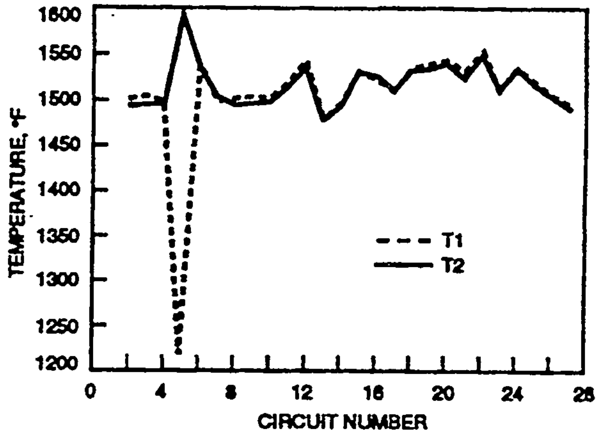

Figure 19. Twenty-Six Superheater Outlet Circuit Temperatures

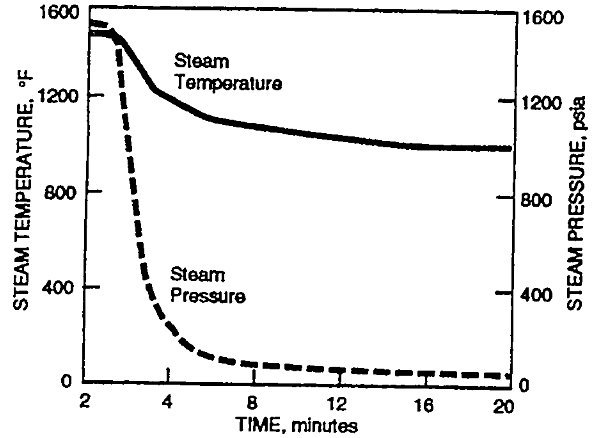

Figure 20. Maximum Steam System Transient - Pressure and Temperature Transients

- HPSS Controls. Excellent outlet temperature and pressure control was maintained by the automatic control system. At 1500°F and 1500 psig, temperature control was within a ±5°F band and pressure did not vary more than ±10 psi. Excellent transient control of the system pressure was obtained with less than a 30 psi pressure transient observed during steam turbine trips at full steam generator operating conditions. When the entire system is shut down from full firing conditions, the steam pressure drops very rapidly (Figure 20) when fuel, water, and air flows are stopped (as in a loss of electrical power turbine trip). Figure 20 shows a turbine trip from 1500 psig and 1500°F with all systems shut down. Steam temperature shows only a 300°F temperature drop due to swell associated with the rapid pressure drop as the full steam flow is bypassed through the control valve. It maintains high superheat for many hours as it slowly cools and most of the water is boiled out of the OTSG. Automatic starts and warm-up of system was performed over 21 times to full conditions. The unit was successfully dry started each time with very low pressure superheated steam exiting the superheater and flowing through the bypass port of the valve to warm these components and dry out the piping. As soon as superheated steam was sensed above 500°F, the turbine valve was opened and the turbine warm-up started with an automatic ramp.

- Control Valve. The steam control valve had problems initially with tolerances, causing binding during warm up procedures. A design modification to the internal parts allowed operation with differential temper-ature of up to 1200°F. A new static seal design was incorporated to control internal leakage with large internal clearances. In addition, electric heating pads were used to preheat the valve to about 800°F prior to system startup. The flow control performance of the valve was excellent. It was tested to 1500°F and 1500 psig and cycled a number of times including about 15 full power turbine trips. It could maintain accurate closed loop speed control of the turbine from warm-up speed of a few thousand rpm to the full design speed of 30,000 rpm.

- Piping System. The design for controlling thermal expansion of the piping, valve and turbine by allowing the OTSG final superheater tubes to flex was successfully demonstrated.

- Steam Turbine 100 Hour Endurance Test. The turbine was operated at 29,900 rpm 100% speed and 100% power for over 102 hours of testing. Steam inlet condition at the inlet connection to the turbine immediately downstream of the triple function valve averaged 1502°F and 1500 psia. Steam flow averaged about 55000 pph for the test. The output shaft power was 5500 HP when the backpressure was maintained at 160 psia. This performance is about 1 percent below the analytical predictions for the tested rotor with 62 inserted blades.

  The inserted blade design replaced a bladed disc that failed in high cycle fatigue in the first test. The bladed disc failure occurred in less than 30 minutes. At the blade passing frequency to nozzles cycles are accumulated at 7000 cycles per second. The unshrouded bladed disc did not have sufficient damping to limit resonant response. By using inserted blades it was possible to add integral shrouds with internal damping bands and reduce the cyclic stresses below the endurance limit. Tests at full power and temperature have imposed over 2.57 billion cycles on each blade in the test just completed. The high accumulation rate of cycles and the good success of the test provides confidence that the damping system has accomplished its goals.

  The four shoe tilt pad journal bearings also performed well. The rotor operates between the second and third rotor criticals. It had to operate through the first and second criticals under significant loads because of the water dynamometer characteristics. Shaft amplitudes were below 1 mil while operating in the critical speed ranges and the measured amplitudes showed no increase at the first and second critical. At full power the loaded bearing had an amplitude of about 0.5 mils while the unloaded bearing was at 0.7 mils characteristic of overhung turbine designs. Rotor cooling performed well with an estimate one percent of the exhaust flow aspirated through the cooling passages, effectively cooling the outer case and front face of the rotor disc.

- Low Emission Combustion System Tests. Low emissions from the combustion system on the OTSG were certified by three one-hour steady state tests while operating at 50 percent and 100 percent power. NOx levels were averaged to 27 ppm and CO was 21 ppm, both referenced to three percent oxygen (used for steam generators). At the gas turbine reference level of 15 percent oxygen these are equivalent to nine ppm NOx and seven ppm CO.

Phase IV — HPSS Cogeneration Site Installation and Test

With the successful completion of Phase III, a long term commercial installation of the tested HPSS is planned for a cogeneration (or power generation site). It is planned that the DOE project will monitor the first 1000 hours of operation at 1500°F and 1500 psig. Site visits and evaluation by DOE and industry representatives will be part of this demonstration. The same arrangement of components shown in Figure 4 will be used at the site to eliminate then need for piping system redesign. The turbine skid will be redesigned to accommodate an electric generator package (Figure 21), replacing the water brake dynamometer and its gear box with an electric generator matched to the site voltage, and a new reduction gear.

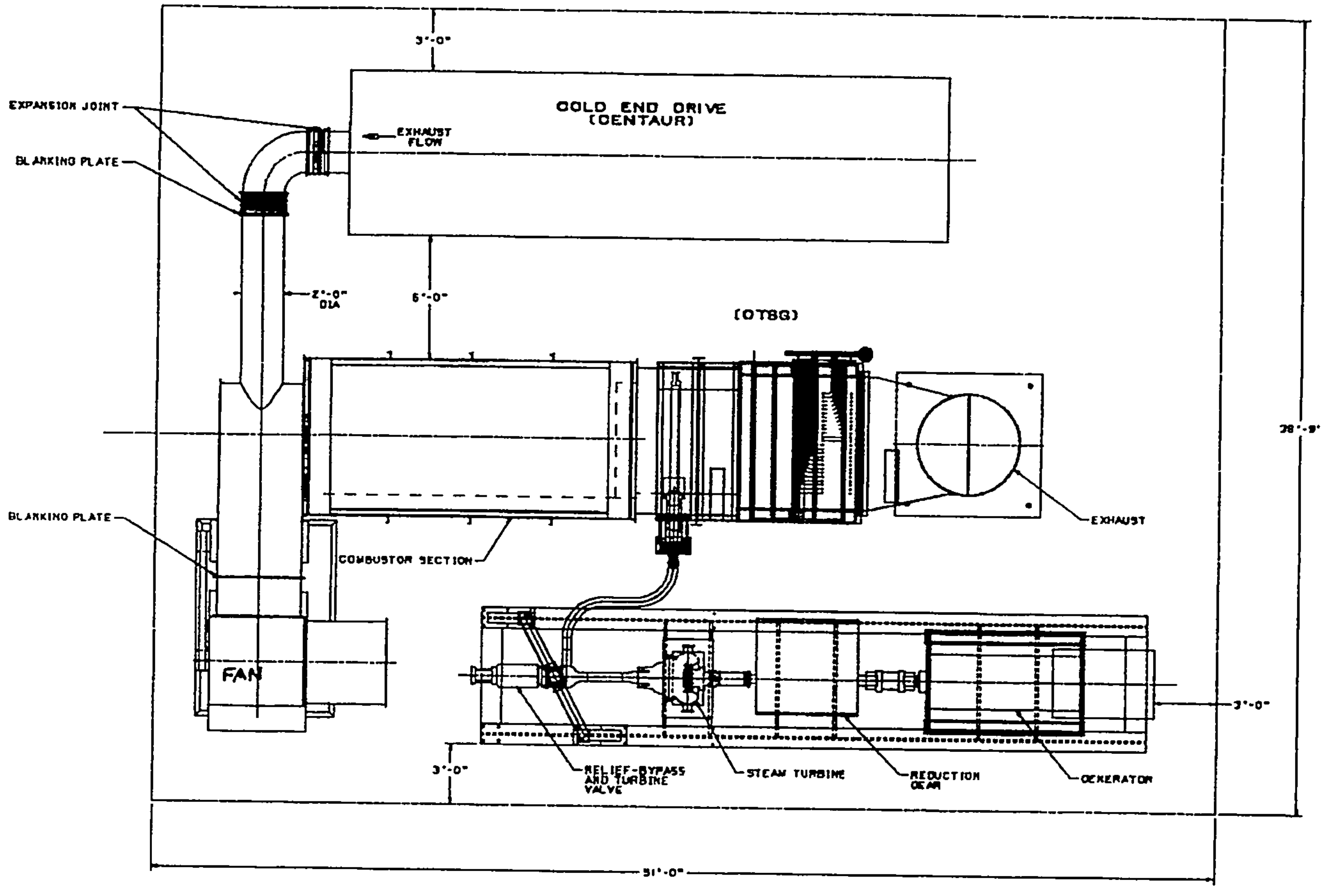

Figure 21. HPSS With Centaur H (optional) or Fresh Air Fan (optional)

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1. "High-Temperature Steam Topping Cycle Study," Final Report on Project 1403-44, EPRI TR-102059 (1993).

2. "Advanced High Performance Steam Systems for Industrial Cogeneration," Final Report on DOE Contract No. AC02-85CE40746, DOE/CE/40746-T1 (1987).

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