2002 Peer Review

of the U.S. Department of Energy

Microturbine and Industrial Gas Turbine Programs

U.S. Department of Energy
Microturbine and Industrial Gas Turbine Program
2002 Peer Review Report

EXECUTIVE SUMMARY

The U.S. Department of Energy's (DOE) Office of Energy Efficiency and Renewable Energy leads the Federal role in developing electric power applications of advanced microturbines. The Microturbine and Industrial Gas Turbine Program conducted a rigorous, performance-based Peer Review on March 12-14, 2002. The agenda can be found in Appendix A. Presentations from the review can be downloaded at www.eren.doe.gov/der. This Peer Review was undertaken to respond both to a National Academy of Science recommendation for a strategic peer review of programs under the Assistant Secretary for Energy Efficiency and Renewable Energy as well as to a Department-wide strategic review to bring programs into alignment with the National Energy Policy. The Peer Review will play an important role in the program's success. Approximately 100 people attended the peer review, and 6 experts participated as reviewers. Reviewer comments were compiled, scores were analyzed, and project rankings were determined. Results were reported to the Program Managers at DOE. This report includes the reviewer comments on the entire program. The contractors each received comments and scores related to their project and an average score of the combined projects.

The peer review process will result in the following:

- Continuous improvement of program quality
- Accountability and responsible use of public funds
- Evaluation of researchers' performance in a public forum and allowing an active exchange and sharing of information and data
- Management tool for good decision making
- Expert, external inputs that assist managers to effectively and efficiently allocate resources, establish program priorities, scope, direction, and spend plans for subsequent fiscal years

Reviewers were asked to comment on the program's strengths, weaknesses, and to give their general impressions and recommendations concerning mission and goals, productivity and accomplishments, R&D plans, and research coordination and technology transfer.

This peer review structure yields Program evaluation results in realistic and readily understandable terms and outcomes that respond to the evaluation requirements of the Government Performance and Results Act of 1993 (GPRA). GPRA is fundamentally a budgetary instrument requiring performance evaluation results which must be of the highest quality. Performance evaluation results from program peer reviews and supplementary quantitative performance measures are required.

Overall program evaluations made by reviewers during the peer review are well characterized by the following comments:

Microturbine Program

- Overall the program was thought to be well managed.
- It is quite early in the program to assess productivity…the next two years will tell a more complete story.
- The program's strategy is sound. It is attempting to address technology advances important to the success of small scale distributed generation as a viable option to consumers and end users.
- Generally "very good," but could be strengthened by university involvement and continuing to push advanced materials work.

Industrial Gas Turbine Program

- This is an excellent extension of the Advanced Turbine Systems Program efforts.
- Program scores ranged from "very good" to "excellent", but would be strengthened by more emphasis on research and generic, long range technology.
- There should be a companion academic research program.
- The contractors are enthusiastic about their work and are progressing and meeting milestones.
- This is a well managed overall program with an appropriate mix of industry and national labs.
- The projects are at a critical point and should be continued.

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1 BACKGROUND

The proposed activities of the Department of Energy, Office of Energy Efficiency and Renewable Energy are to develop advanced microturbine systems and advanced materials and low emissions technologies for distributed energy resource applications.

Since 1994, hundreds of executives from various industries have met in dozens of vision and roadmap workshops to discuss the elements critical to success in the global marketplace over the next twenty years. Cleaner and more efficient, affordable, and reliable heat and power systems is one of the most prominent needs raised during these sessions. The rapidly changing marketplace for utility energy services is opening new opportunities for the nation's heat and power users to reduce energy costs, increase power quality and reliability, and reduce environmental emissions. In addition, over the next twenty years, a significant portion of the nation's aging stock of boiler and power generation equipment will reach the end of its useful life and need to be replaced.

One opportunity is investment in smaller-scale distributed energy resources that can be integrated into overall manufacturing plant or building operations. These technologies can be controlled locally to optimize performance and satisfy needs for both electricity and thermal energy. Energy managers and building operators want to have heat and power services for less cost, less emissions, better reliability, and greater control than what they can get from the utility grid.

MICROTURBINES

Because of their compact size, modularity, and potential for relatively low cost, efficient, and clean operations, microturbines are emerging as a leading candidate for meeting these needs for electricity and thermal energy. The mission of this program is to lead a national effort to design, develop, test, and demonstrate a new generation of microturbine systems that will be cleaner, more fuel efficient, more fuel-flexible, more reliable and durable, and lower cost than the first generation products that are just entering the market today.

The projected funding requirement for the program is $63 million in appropriations from the U.S. Congress and at least $63 million of additional funding is expected in cost sharing. More information can be found in the Advanced Microturbine Systems Program Plan for Fiscal Years 2000-2006 www.eren.doe.gov/der/microturbines/docs_resources.html. The program's planned activities are aimed at achieving the following performance targets for the next generation of advanced microturbine systems:

- ***High Efficiency*** – The target for fuel-to-electricity conversion efficiency is at least 40 percent.
- ***Environmental Superiority*** – The NOx target for emissions is less than seven parts per million in practical operating ranges.
- ***Durable*** – The goal is 11,000 hours of operation between major overhauls and a service life of at least 45,000 hours.
- ***Cost of Power*** – The target is achieving installed cost lower than $500 per kilowatt, a cost of electricity competitive with current technologies.

- ***Fuel Flexibility***-- The next generation of microturbine products should be capable of using different kinds of fuels, including natural gas, diesel, ethanol, landfill gas, and other biomass-derived liquids and gases.

Industrial Gas Turbines

Industrial gas turbines are used in many industrial and commercial applications ranging from 1MW to 20MW. A key effort in the Industrial Gas Turbine Program has been to enhance the performance of gas turbines for applications up to 20MW. The focus of this effort is on advanced materials research, such as composite ceramics and thermal barrier coatings, which will continue to improve performance. In addition, low emissions technology research and development will improve the combustion system by greatly reducing the NOx and CO produced without negatively impacting turbine performance.

Planned activities for this program focus on the following performance targets:

- ***High efficiency and performance***—increase the fuel-to-electricity conversion and improve the overall performance of turbines through the use of advanced materials. New emissions systems and materials should have no negative impact on turbine performance and no more the 10 percent cost add-on.
- ***Environment*****—**the emissions targets is less than five ppm NOx and 25 ppm CO with no post combustion controls.
- ***Durability*****—**the goal is 8,000 hours of operation between major overhauls.
- ***Fuel Flexibility*****—**Should be capable of using alternative/options fuels, including natural gas, diesel, ethanol, landfill gas, and other biomass-derived liquids and gases.

2 The 2002 Peer Review Process

The peer review panel included six distinguished experts representing associations, academia, and the private sector.

Peer Review Panel

Name	Affiliation
Roy Allen	Consultant
Tom Bechtel	Consultant
Richard Drake	NYSERDA
Eric Larson	Princeton Environmental Institute
Walter O'Brien	Virginia Tech
Dave Richerson	Consultant

The peer reviewers provided a quantitative score for the overall program evaluation based on the following rating scale:

Excellent	9-10
Very Good	7-8
Good	5-6
Fair	3-4
Not Adequate	1-2

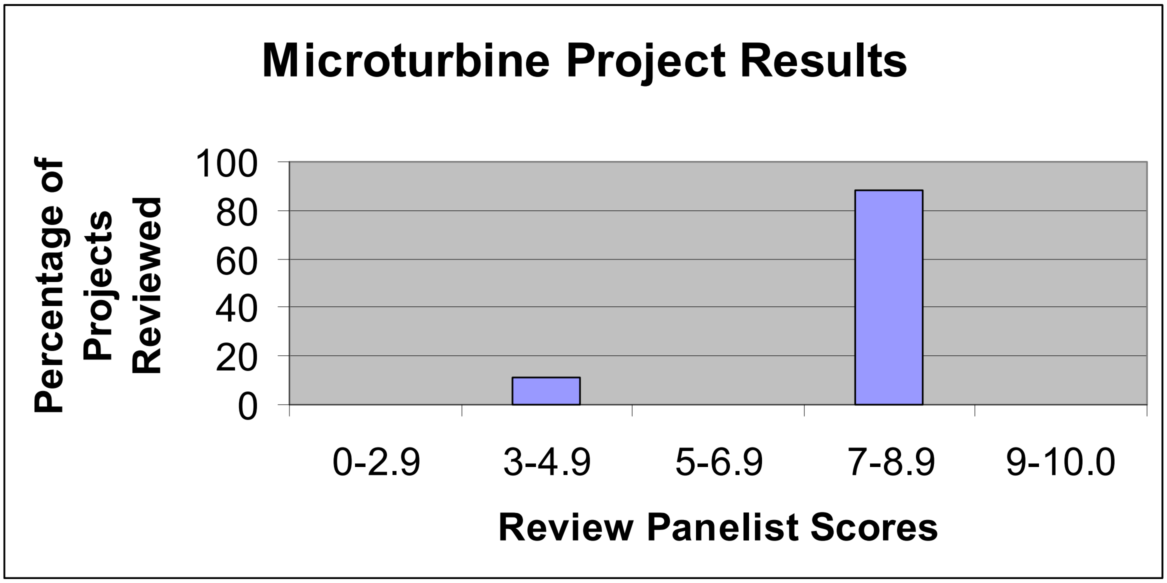
Each individual project was scored on the following weighted criteria:

- Relevance to overall program objectives; 20 points
- Approach to performing the research and development; 20 points
- Technical accomplishments and progress toward project and DOE goals; 30 points
- Approach to and relevance of proposed future research; 20 points
- Leverage of funds/collaborations with industry/universities/government laboratories/states/end-users; 10 points

3 PROJECT REVIEWS

MICROTURBINE PROGRAM

The following figure shows that approximately 89% of the projects received scores of 7-8.9, which corresponds to a “very good” rating. Only 11% of the projects fell in the category of “fair”. Seven of the projects fell above the average of 75 and two fell below.



On July 25, 2000 an award of $40 million to six industrial partners for research, development and testing of "next generation" microturbine systems was announced. The industrial partners will share 40% of the total cost of DOE funds awarded. Beyond the department's contribution, each individual partner will contribute approximately 30-50% of the cost.

Industry Projects

There were six industry projects reviewed; overall comments ranged from fair to very good. The projects are in the early stages and the following year will show a clearer picture of progress made to the overall program’s goals. Overall the projects scored the highest on the relevance to overall program objectives criteria.

The following summaries of the microturbine projects give the scope of work being conducted.

General Electric

GE’s technical focus is on advancing microturbine component performance and systems design. The process is working to improve the specific components, optimize the system layout, and verify this level of technology. The second step on the path to a 40% electrical efficient (LHV) unit will be to increase the operating temperature through use of advanced materials. In FY01, the GE team completed the market study and the conceptual design of the advanced systems in addition to kicking off all major component design tasks. A key milestone for FY02 is the demonstration of the first unit.

Capstone Turbine Corp.

The project work includes cycle studies, preliminary design, rig development and ceramic material testing and feasibility. It also focuses on recuperator and high temperature materials process development. The project is also devoted to controller development and its integration to the three evolutionary stages of the engine (simple cycle, metallic development, and high efficiency) and the development of the remainder of the unit. Partners in the project include Goodrich, COIC, Honeywell, Saint Gobain, Haynes, Elgiloy, J.H. Benedict, PCC, ORNL, and UC Irvine. FY01 accomplishments included a preliminary design, rigs development and ceramic material testing and feasibility. In FY02, the project will focus on the development of an all metallic engine.

Ingersoll-Rand

Ingersoll-Rand's PowerWorks™ program combines a novel application of industrial turbocharger equipment, an advanced recuperator, and proven industrial gas turbine design practices. The program will perform a comprehensive analysis of ceramics suitable for the turbine section and recommend the most suitable PowerWorks™ platform. It will also design the turbine section, test, and ultimately commercialize the product. Partners in this project include ORNL and various ceramic suppliers and developers.

United Technologies Research Center

The strategy is to utilize affordable, advanced technology to increase the electrical efficiency of the DTE Energy Technologies ENT400 microturbine system. The targeted technologies include ceramics, advanced recuperator materials, Organic Rankine cycle (ORC) systems, low-emission combustion, and electrical power generation/conversion systems. UTRC is working with ORNL to characterize advanced materials. In FY01, system analyses identified a configuration that would affordably achieve 40% electrical efficiency. In FY02, the project plans to demonstrate a 5 point gain in electrical efficiency.

Solar Turbines, Inc.

Solar is proposing to improve the recuperation aspect of the turbine systems by development work aimed at improvement in affordable foil alloys that will allow higher system temperatures (higher cycle efficiencies). The proposed scope of work focuses on the development of a new, economical stainless derivative recuperator material that will allow operation at higher temperatures. Allegheny Lundlum is partnering with Solar on this effort. In FY01, a series of materials were identified and testing was initiated; testing will be completed in FY02, and recommendations will be made for recuperator endurance tests.

Los Alamos National Laboratory

The LANL microturbine engine design is a unique and new configuration that has high potential for enhanced operational efficiency, lower manufacturing costs, superior turbine-section cooling and a more compact footprint. The overall objective is to study this new configuration for viability, explore the design operational space and verify the promise for enhanced efficiency, compactness, and likelihood for lower manufacturing costs.

Advanced Materials Projects

There were three advanced materials for microturbines projects. Reviewers felt that these projects were an important part of the overall program and scores were high for relevance to overall program objectives and approach to performing the RD&D. It was thought that a university component should be added to this effort.

Honeywell

The Honeywell project has three components 1) testing advanced materials with and without environmental barrier coatings, 2) development of a high-temperature burner test rig, and 3) development of a low-cost near-net-shape fabrication process. Honeywell is working with ORNL on these efforts.

ORNL Ceramics

One objective of this project is to develop test facilities for evaluating the influence of high-pressure and high-temperature water vapor the long-term mechanical behavior of monolithic ceramics with environmental barrier coatings. The second objective is to evaluate and document the long-term mechanical properties of very small specimens machined from ceramic components (e.g., blades, nozzles, vanes, and rotors) in as processed and after engine testing at ambient and elevated temperatures under various controlled environments.

ORNL Alloys

This project is working closely with many different microturbine OEM's to identify and tailor advanced alloys appropriate to their particular improved recuperator technology needs. Analysis of as-fabricated and engine-tested recuperator components will establish current performance benchmarks and help estimate the gains in performance and lifetime achieved from making the same components from advanced alloys. The goal is to obtain commercially produced foils and sheets of several cost-effective advanced austenitic stainless alloys that microturbine OEM's can then use to make higher performance recuperator components for evaluation and engine testing.

Microturbine Application Projects

The reviewers gave comments for these two projects, but they were not scored. These projects were thought to be very beneficial to the overall program and were providing useful results given the level of funding.

NRECA

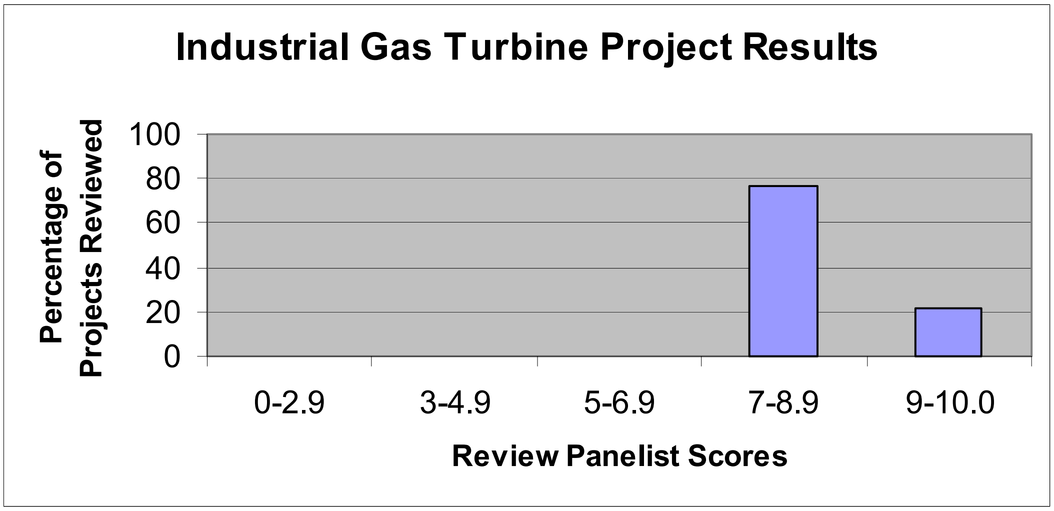
NRECA is demonstrating and field testing a comprehensive set of microturbine generators at a broad spectrum of participating cooperative sites across the nation in order to measure the performance, reliability, and maintainability of microturbine generators in actual real-world operation; determine representative economics including the impact of operational and thermal recovery factors; identify any major permitting, interconnection, and code compliance issues needing attention; benchmark the current technology and identify any crucial remaining developmental needs; identify promising types of applications and related electrical production modes; assess the prospect for future microturbine use by co-ops and by their customers. NRECA plans to collect operating data from new installations in 2002.

Southern California Edison

Southern California Edison's Microturbine Generator Testing Program envisions supporting the commercialization of microturbines by providing performance testing results against each microturbine manufacturer's specifications and industry or other standards such as power quality and emissions. Also assessed is ease of installation, operability, and maintainability. Each manufacturer is provided with individual feedback on suggested product development and improvements.

INDUSTRIAL GAS TURBINE PROGRAM

The following figure shows that approximately 78% of the projects received scores of 7-8.9, which corresponds to a "very good" rating. 22% of the projects fell in the category of "excellent". Five of the projects fell above the average of 83% and four fell below.



On July 3, 2000, DOE awarded $13 million to nine industrial partnerships for research and development on durable and cost-effective low emission technologies for turbines used in distributed power generation. Five projects were awarded $6 million over the next two years for research in low-emission gas turbines; industrial partners will share nearly 40% of the cost. Four projects will receive $7 million for research and development in advanced materials for industrial gas turbines with industry cost sharing of nearly 50%. The awards will focus on research and development intended to be commercialized for use

LOW EMISSIONS

Catalytica Combustion Systems, Inc.

Catalytica is commercializing catalytic combustion technology for gas turbines to achieve NOx concentrations in the turbine exhaust of 2.5 ppm or lower. This technology, incorporated in the Xonon Combustion System, is operating in a 1.5 MW industrial gas turbine engine connected to the electric power grid at Silicon Valley Power in Santa Clara, California. Solar Turbines and UC Irvine are part of this effort. FY01 accomplishments include catalyst life extension and cost reduction.

Precision Combustion, Inc.

Precision is developing a superior catalytic combustor technology for industrial gas turbines applications that offers ultra-low NOx (<3ppm), low temperature catalytic reactor lightoff, high firing temperature operation, high resistance to pre-ignition or flashback, tolerance to fuel/air unmixedness, wide turndown, more durable catalyst and fuel-flexible operation. Solar Turbines is a partner in this activity. A 1000 hour durability demonstration was successfully completed in FY01 and a follow-on full-scale engine test program is being pursued in FY02.

Alzeta Corporation

Alzeta is demonstrating that surface stabilized combustion can achieve ultra-low emission in industrial gas turbines. The demonstration is to be on a test engine in the four to seven megawatt range. Solar Turbines and the California Energy Commission are partnering with Alzeta. FY01 accomplishments include cast injector development and testing with the Tarus and Saturn engines. A full annular engine test with the Centaur unit is planned.

Honeywell International

The objective of this program is to reduce risks in the provision of a catalytic combustion system design aimed at reducing NOx and CO emissions from industrial gas turbines. It is intended that natural gas NOx levels will be below 5 ppm and that the catalyst system be capable of running on Diesel fuel. The catalytic combustion system will be based on the Honeywell ASE50DLE 3.9 MW industrial engine. Partners in this effort are Precision Combustion Inc., Texas A&M University, and Vericor Power Systems. The project has demonstrated NOx levels below 5 ppm on natural gas and capability of running on diesel and natural gas.

Solar Turbines Incorporated, Precision Combustion Inc.

This project assesses a unique catalytic combustion concept that has the potential of reducing gas turbine NOx emissions to < 3ppm on natural gas. Solar and sub-contractor Precision Combustion (PCI) are conducting rig tests of PCI-designed rich/lean catalytic combustor modules at conditions representative of Solar's 7.5 MW Taurus 70 engine. The rig testing will serve as a proof-of-concept evaluation of the PCI technology in a realistic test configuration and at realistic industrial gas turbine operating conditions. In FY01, PCI completed the design and fabrication of a full scale prototype catalytic reactor module for the Tarus 70 engine.

Teledyne Continental Motors

Teledyne Continental Motors will apply advanced material systems to the turbine stage components (turbine rotor, turbine inlet nozzle, and turbine inlet scroll) for an advanced version of their 50 kW microturbine. FY01 accomplishments included a preliminary design of the stage components. Teledyne is fabricating and verifying the components in FY02.

General Electric

This program focuses on the application of Melt Infiltrated Ceramic Matrix Composites (MI-CMCs) to shrouds and combustors of advanced industrial gas turbines. MI-CMCs are a new class of material consisting of continuous SiC fibers in a matrix of SiC plus Si, and made by a molten silicon infiltration process into a pre-form containing SiC fibers. Partners in the project include Power Systems Composites, LLC, Goodrich Aerospace, and ORNL. For FY01, GE designed and fabricated 1st stage shroud components and will rig test and field engine test them in FY02. Also planned is the design, fabrication, rig testing, and field engine testing of a combustion liner system in a GE engine.

Solar Turbines, Inc.

Solar Turbines Incorporated is improving the durability of advanced combustion systems while reducing life cycle costs. The goal of the program is to demonstrate a fully integrated Mercury 50 gas turbine combustion system, modified with advanced materials technologies, at a host site for 4,000 hours. Honeywell Ceramic Composites, University of Connecticut, ANL, and ORNL are partners in this effort.

Siemens Westinghouse

Siemens Westinghouse Power Corporation is evaluating the performance of innovative thermal barrier coating systems for applications at high temperatures in advanced industrial gas turbines. Siemens has partnered with Turbine Airfoil and Coatings Repair, Howmet Research Corporation, and ORNL for this project. In FY01 Siemens successfully deposited four new thermal barrier compositions. They plan to install coated vanes and blades in a test engine for Calpine Corporation.

Argonne National Laboratory

The purpose of this project is the development, application and evaluation of nondestructive, non-contact technologies for the ceramic components of advanced, high-efficiency microturbines and industrial gas turbines. Perkin-Elmer Electrooptics, Envision Product Design, Honeywell Ceramic Components, St. Gobain Industrial Ceramics, United Technologies Research Center, GE Power Systems Composites, Goodrich Ceramic Composites, Rolls-Royce/Allison, and ORNL are part of this development team. ANL will continue with developments toward technology for high-speed 3D x-ray tomographic imaging for large cross-section monolithic ceramic components.

Oak Ridge National Laboratory

Advanced ceramic materials are being incorporated into hot sections of land-based industrial gas turbines for these engines to meet strict emission standards by operating at higher temperatures. To date, this project has focused on understanding the material's degradation mechanisms in combustion environments to further improve the EBC and continuous fiber-reinforced ceramic composites (CFCCs) environmental stability. This collaborative effort involves material suppliers (CFCC manufacturers B.F. Goodrich and GE Power Systems Composites, EBC manufacturer United Technologies Research Center), turbine manufacturers (Solar Turbines and GE), and national laboratories (Oak Ridge National Laboratory and Argonne National Laboratory.) The work will continue to focus on conducting simulated exposures of (in ORNL's Keiser Rig) and subsequent microstructural evaluation of experimental CFCCs and EBCs provided by the manufacturers. Laboratory-exposed materials will be compared to actual components exposed in engine tests to evaluate microstructural stability in combustion environments and to fully evaluate degradation modes and failure mechanisms of both the CFCCs and protective coatings.

4 2002 Microturbine Program Evaluation

Peer Reviewers were asked to rate the overall Microturbine Program by answering the questions highlighted in the following section and to provide their perception of the program as a whole. Reviewers were asked to comment on the program's strategy, structure and resource allocation, implementation. Reviewers were also asked to identify any new areas of RD&D that should be funded and provide areas of strengths and weaknesses. The following comments were compiled from these evaluations.

1. **Program Strategy:** Are the stated vision, mission, goals and priorities of the program appropriate? Are these appropriate to the Federal role? Are they in line with the National Energy Policy and Departmental mission and goals? Do the goals and priorities properly reflect the needs of industry and other stakeholders? How could they be improved?

   - The stated vision and goals of the microturbine program are appropriate, and in line with the National Energy Policy. As the new environment of deregulated energy takes effect, it is important that consumers and businesses have the widest possible choice so that competition is truly effective. In energy supply, this choice will be enhanced by the availability of DER. Furthermore, energy independence for the United States will be helped by DER availability. Thus, it is in the national interest that the several DER technologies expand, and become economically viable. This will not happen in our economy without DOE assistance. The large, established energy interests have little incentive to develop DER.
   - The program is structured as initial support for a needed industry, and is appropriate and timely. As the basic microturbine infrastructure and technology improve, the DOE program should move toward true advancements in the enabling technologies of microturbines.
   - In general, the program is well-defined and well-organized and is attempting to address the key issues in engine design, materials, and market assessment. The program does address the needs defined by the National Energy Policy and the DOE mission and goals. A concern is whether the goals are realistic and achievable within the scope of the time and funding. Specifically, the goal of 40% efficiency at $500/kW seems like too much of a stretch of the technology for the time and funding. Having the nearer term intermediate ~35% goal is good. However, based upon the marketing information, will 30-35% efficiency be adequately competitive in the market place? Also, most of the markets will need to be proven and established, and some will not be easy to enter until lower price and reliability are demonstrated. For example, there seem to be more opportunities for a CHP microturbine system than for a baseline 40% efficient unit. Should there be more effort directed towards development and demonstration of viable microturbine CHP systems?
   - The objectives of making microturbines more competitive to satisfy an emerging market are appropriate. However, the efficiency and cost goals are mutually exclusive. It does not seem realistic to believe that the efficiency can improve over 40% while cutting the cost nearly in half. Due to the sensitivity of cost/kW to unit size, a sliding scale should be proposed that would be more logical. Driving the temperatures up to achieve the efficiency goal severely penalizes the cost and emissions levels. Unquestionably, the manufacturers need help, more

so than the participants in the ATS program. Although goals should be a stretch, I would suggest a review and modification of the ones set here.

- The program goals for efficiency (40%) and capital-cost ($500/kW) are aggressive, but appropriately so for use of Federal funds. The NOx goal (< 7 ppm) may not be aggressive enough in light of the likelihood that regulations in some states will require perhaps 3 ppm NOx. During the peer review meeting, an intermediate efficiency goal (35%) was mentioned several times. However, in reviewing the handouts from the meeting, there is no mention of such an intermediate goal. Since reaching 35% involves no major technology breakthroughs, it is inappropriate for DOE to support efforts aimed solely at achieving such an intermediate goal. While technology is the focus of the microturbine program, the biggest barriers to reaching DOE's vision of 2020 market penetration by DER are probably the non-technical barriers listed on one of Debbie Haught's slides. In this regard, the close coordination of the microturbine program with programs at DOE (and other organizations) that are addressing non-technical issues is important. Debbie indicated in one of her slides that such coordination is ongoing, but the full structure, content, and extent of this coordination was not evident from presentations given at the peer review meeting.
- The program is structured as initial support for a needed industry, and is appropriate and timely. As the basic microturbine infrastructure and technology improve, the DOE program should move toward true advancements in the enabling technologies of microturbines.
- The program's strategy is sound. It is attempting to address technology advances important to the success of small scale distributed generation as a viable option to consumers and end users. DG is also likely to be an important element of national security and energy security
- Scope of work addresses aggressive pre-commercial advances as well as less risky, incremental improvements. Both are necessary to achieve a self sustaining, viable market and business climate. Goals and priorities are appropriate for Federal Government and address the needs of industry-this is a good mix.
- The strategy makes sense; government is pushing deregulation as benefit to consumer (reality so far is that it reverses the subsidy that industrial/consumer users provided to residential consumer in regulated scenario). That will only happen for residential customers if technology lowers overall cost of this generation/transmission/distribution system.
- High-use distributed generation competes with transmission upgrades, not central generation and can be done through incremental investments. These units must play in both capacity and energy markets in order to support the owner's variable demand while attaining multi-unit economies of scale.
- Gas engine (piston) competition remains tough competition so RAM is critical design requirement. Small number of moving parts argument does not hold for parts that are expensive. Keep focus on high efficiency and low NOx – 9 ppm may not be good enough since competitive alternative is better—catalytic combustion may be a baseline absolute.
- It may be unrealistic to keep vendors alive when they drop out of system market. Let system suppliers keep them involved as subcontractors—maybe even on consortia basis so that government gets out of interface role. It's valid to argue that program rationale is based on need by government to nurture supplier base when it upsets marketplace with radical regulation, deregulation. Those government induced market transients are often not amenable to normal "silent hand" economic forces.

2. **Program Structure and Resource Allocation:** How well do the program activities support the overall program mission, goals and priorities? How would you assess resource allocation? How well balanced is the program (Given the resources available, is the relative emphasis placed on the various program elements appropriate?)

- The program activities and resource allocation are well balanced between low, medium, and moderate risk technologies for the microturbine industry. This is appropriate for the beginning phase of the program, which we are presently in.
- The program should consider adding an academic research component, to encourage higher risk research and more generic contributions to the technology, rather than only focused support of individual development programs.
- At this point in time the overall program has a good balance based on the original work statement. However, the projects are just starting. As component designs are completed, selected individuals from outside the performing companies should participate in design reviews and also provide feedback on the companies' plans for building and testing the first prototype engines or test rigs. In most cases, the allocation of resources could only be guessed or assumed based on the tasks and milestones presented. It would have been helpful to see all of the key milestones and schedules rather than only a few. Regarding design reviews, individuals like Dave Richerson and Don Anson could provide useful feedback to DOE and the companies.
- The program is well balanced and the resources are pointed at most key issues.
- The majority of the program funding goes to support microturbine system developers. The program has done well in attracting six competing microturbine system developers. Some of these projects are unlikely to result in competitive commercial products, but it would have been unwise for DOE to try to "pick winners" in advance and fund only those. Having one "far out" system development project that is costing a relatively small amount of funding is worthwhile. An appropriate question at this point is whether the funding levels for the less promising projects are commensurate with the diminished promise of these projects.
- Only a small fraction of total program funding is going specifically to ceramic materials development. This is seen as a deficiency in the program, because it appears that the use of ceramic components will be essential in microturbine systems if they are to meet the DOE performance and cost goals. One place where low-cost ceramics development might prove successful is at universities. University participation in the microturbine program is almost non-existent. Turning several universities loose on ceramics development would be a worthwhile change to make in the program.
- A concern with the program is the perhaps-excessive dependence of microturbine system developers on recuperator development by one manufacturer. The possibility of a single recuperator supplier dominating the commercial field is a concern. There is a lot of emphasis on metal recuperators. It is unlikely that metal recuperators, even with advanced alloys, will enable microturbine systems to meet DOE performance and cost goals. This latter concern reflects a more general concern the reviewer has that a fair amount of the program funds are being used to support work that will result in relatively modest improvements in technology. Such improvements are more appropriately funded by the companies that will benefit in the near term from having a new product – one for which there is almost certainly a market. Such technologies won't come close to meeting DOE performance (or cost?) goals. There is a question of the appropriateness of DOE support for such developments. A more appropriate distribution of DOE funds might be to shift funds from such lower-tech product development to higher-risk work aimed more directly at reaching the DOE performance and cost goals, e.g. ceramic materials research, development, and demonstration.
- The program is well balanced and resource allocation seems appropriate at this stage. Continued review is appropriate and there should be expectation that some activities will be found to be non-competitive and should be dropped. Others will show more promise or

potential and should be accelerated. Ceramic materials and EBC's are long term; breakthroughs can occur, but they are critical to +40% efficiency goal. Exploring and evaluating new/additional options is relatively low-cost/high return investment.

- Use of Oak Ridge for centralized material data is good. Centralized system test and evaluation at SCE and NRECA is great.
- The program should let subsystem and component development efforts flow through system suppliers or system supplier consortia instead of DOE.
- DOE should facilitate DER program involvement in ATS–University consortia.

3. **Implementation:** Is the program effectively leveraging its resources? Do we have an appropriate mix of industry, university and national lab participation? Is the coordination with other related DOE, Federal and State activities adequate? Are the mechanisms for technology transfer appropriate? How would you assess the productivity of the program? Are the accomplishments commensurate with the investment being made?

- The program is only 1-2 years old, so results are difficult to assess. Planning seems good, and the next 2 years will tell a more complete story.
- The overall program has a good cross section of industry and national lab participation. It seems a little short on university involvement. There is excellent coordination and networking and appears to be excellent program management. The programs in generally are on schedule, and the milestones are being successfully met. An executive summary type report on the engine programs quarterly reporting progress and status on each milestone would be helpful to people trying to follow and assess the programs.
- It is quite early in the program to assess productivity; many of the "easy" initial efforts are all that has been done. Regarding other Federal activities, it is unfortunate that the EPA's regulatory arm appears to have no connection to their technology assessment people. The manufacturers and DOE have poured millions into research to get NOx to single digits, but the EPA is insistent on SCR's anyway. Much of this funding could have been saved by requiring 20 ppm plus the SCR. Of course, the more millions that the consumer ends up paying for could be saved by accepting 5-9 ppm and dropping the SCR's.
- There is insufficient university involvement. Coordination with related DOE, Federal, and State technology activities appears to be good. Technology transfer from laboratory to commercial marketplace within a contractor company is excellent, but how effective is technology transfer to the community as a whole? Some focused effort should be made to insure that technology transfer to the community as a whole will result from spending of federal dollars. Productivity of the program: the first year appears to have been spent mostly on "easy" developments (by design). The real challenges to meeting DOE program goals, e.g. ceramic components, will come in the future.
- ORNL-participation is a clearinghouse for data is appropriate, good use and leveraging of test facilities. Good and appropriate mix of private sector industry. University participation might be increased in EBC initial screening and new approaches.
- Continued and enhanced collaboration with states and application/demonstrations would be best mechanism for technology transfer to end user and early adoption.
- Need university program involvement; the DOE national labs are weak in turbomachinery.
- The Oak Ridge material testing is fine—but keep materials development at suppliers or with university subs to supplier.
- It will be beneficial to get subsystem and component players into system contract supplier mode.

4. **Are there new areas of RD&D in which the program should be investing?**

- The key areas seem to be well covered; however, timing is a concern. For example, if ceramic components are going to be developed and qualified according to scheduled needs, there are milestones that should be happening in 2002. In some of the cases, these milestones were not visible in the presented materials and did not seem to be well-defined in the minds of the presenters based on subsequent discussions.
- Ceramic materials research, development, and demonstration at universities.
- As more microturbines become available to the market, more advanced concepts should be supported. Hybrid microturbine systems with fuel cells and other energy conversion devices should be investigated.
- Market pull is necessary for private sector investment +40% efficiency is a great goal long term but it must also meet consumers' needs. Continued market assessment should be part of program on continued bases, not just initial task. Consider addressing proven market niches for generation, i.e., certification of turbines for IEEE emergency generation specs huge market. IC engines prohibited from running on economic dispatch.
- Ultra-low NOx is a new area the program should be investing.
- Ceramics that are steam tolerant is a new area of RD&D that should be funded. A high quality university and/or material developer can get the program going.
- Increased MTBO.

5. **What are the overall strengths of the Microturbine Program?**

- There is a good mix of companies, approaches and networking. Also, the effort to benchmark 1st generation designs and to monitor a range of initial installations is a strength.
- Including a market study and a design phase to identify the engine size most likely to meet the program goals, particularly going to larger engine size, is a strength.
- Aggressive technology goals; spreading risk by contracting six microturbine system developers; managing well, as reflected by the large majority of contractors working close to schedule for the most part.
- It is aligned with national needs, well managed and planned.
- This is a well managed program.
- Several approaches are being pursued by qualified contractors. 1) Addressing both longer term and nearer term improvements. 2) High probability of meeting +36% efficiency target, with cost and emission objectives. 3) Longer term +40% target will be a challenge, but possible. Critical areas are being addressed with the possible exception of recuperator options.
- The system test program and materials test program are strengths.

6. **What are the overall weaknesses of the Microturbine Program?**

- Uncertainty of the market. Perhaps too high risk in achieving the 40% efficiency, $500/kW and 11,000 hours of durability.
- There is an over-reliance on ORNL for ceramics development; possible over-reliance on Solar as recuperator supplier; insufficient investment in pursuing "break out" technologies

(like ceramic components) relative to investment in microturbine systems that will reach performance and cost goals that are modest relative to DOE program goals.

- Some of the near-term developments that are supported might have happened without government support. Small companies who were not selected to participate might be placed at a disadvantage, with government support going to their competitors. There should be a larger long range research program component.
- Some of the near-term developments that are supported might have happened without government support. Small companies who were not selected to participate might be placed at a disadvantage, with government support going to their competitors. There should be a larger long range research program component.
- The dependency on Honeywell ceramic-EBC program to develop ceramic rotor.
- University research missing; it was a critical component of ATS that was claimed to have been modeled after.
- NOx target too high. MTBO too low.
- Subsystem/component vendors contracted to government (can go political) instead of to system primes or prime consortia.
- The program is underfunded.
- Vendors appear to be focused on margin Phase I units.

7. Other Comments or Recommendations:

- It was surprising to note the apparent lack of attention being paid by DOE and its contractors to potentially huge overseas markets (China, India, etc.) and the special requirements for technologies introduced into these markets. Technology developed for US markets may be able to satisfy some markets overseas, but other markets will require more tailored technologies and service infrastructures. A survey of overseas markets would be a starting point for understanding whether technology development in different directions from existing efforts should be pursued. Overseas markets for US technology are likely to be larger than U.S. markets, both in the short and long term. For example, the demand for reliable small-scale grid-independent power is enormous in Brazil, India, China, and many other developing countries. With the right technologies, U.S. companies, in partnership with local companies in these countries, have much to gain.
- Good program progress—especially given funding shortfalls.
- Good use of ATS results.
- Excellent DER/ATS coordination within EE.
- It is not clear that you can beat reciprocating engines at the TBOS and costs.
- Should you drop players like IR who decide not to meet targets and restrict themselves to markets that are not consistent with policy of program?

5 2002 Industrial Gas Turbine Program Evaluation

1. **Program Strategy:** Are the stated vision, mission, goals and priorities of the program appropriate? Are these appropriate to the Federal role? Are they in line with the National Energy Policy and Departmental mission and goals? Do the goals and priorities properly reflect the needs of industry and other stakeholders? How could they be improved?

- The program is appropriately focused on the national energy goals as presented in the overview talks. The supported programs are appropriate for federal government support because of the key importance of increased efficiency to reduce dependence on foreign energy supplies, and the demands for minimum environmental impact (emissions, especially NOx).
- The program identified a number of areas where further technology developments could lead to improvements in engine performance and emissions reduction. Programs have been established to pursue some of these developments.
- DOE has selected a good balance of technologies and contractors. There seems to be excellent enthusiasm on the part of all parties and a sincere drive to be on schedule and successful.
- There are competing technologies and there will be a need to assess down-selecting. However, it is too early in the programs to make definitive judgments.
- At this point in time, the programs are right on target and should continue as they are planned at least through 2002.
- Good extension of ATS program in areas of emissions, efficiency, and cost.
- Coordinating materials R&D with database at ORNL and NDT effort at Argonne are great investments.
- Continued investment (with expanded contractor base) would be good in the areas of TBCs and EBC.
- In general, the program goals and technology performance targets are appropriate, but could be more clearly stated. Some of the performance targets are clear, e.g., < 5 ppm NO_x. Several are vague, for example: "improved efficiency and environmental performance," "higher E/T that expands the market," "consideration for transition and back-up fuels,". One seems overly specific and vague at the same time, "elimination of cooling air >2% gain in efficiency and lower emissions."
- The technologies being investigated are the most promising to attain the desired result in the short term. The program is focused on enabling manufacturers to produce machines with the desired attributes.

- It appears to be progressing well, and many of the programs are addressing quite near- term developments with specific manufacturers.
- As the expected results are obtained, it is desirable to support longer range research to ensure continuing U.S. leadership in this important field.

2. **Program Structure and Resource Allocation:** How well do the program activities support the overall program mission, goals and priorities? How would you assess resource allocation? How well balanced is the program (Given the resources available, is the relative emphasis placed on the various program elements appropriate?)

- The resource allocation seems reasonable, although much more detailed information would be necessary to make a thorough assessment. The program seems balanced in that it addresses the key issues of performance, emissions, and durability through multiple approaches. There is good likelihood that at least a few of the approaches will be successful.
- The emissions portion of the program is balanced to investigate alternative solutions to achieving single digit NOx.
- The materials portion of the program includes both microturbine and industrial size efforts.
- Initially a broad program; may need to be focused later on highest potential developments.
- Expect that less emphasis may be placed on ceramics; more on super alloy deployment.
- Resource allocation is appropriate; the program might consider additional emphasis on fuels other than natural gas for national security reasons.
- Three projects on low-NO_x combustion systems constitute a good portfolio for this particular technology area. One concern about these 3 projects is that they all involve working with Solar. Is this a concern for wider technology transfer into the gas turbine industry?
- It is not clear to me how the technology characterization work mentioned by Merrill Smith in her overview talk fits as part of the IGT program.
- The program emphasis is on high temperature materials, and means to control combustion-generated NOx. These are presently the most important needed technologies in the gas turbine field.
- For the most part, the projects are well-managed and making progress. Some projects, as noted on the project review forms, should be improved. The focus on specific technology development and demonstration is clear. More emphasis on research and generic, long range technology would be desirable. There should be a companion academic research program.

3. **Implementation:** Is the program effectively leveraging its resources? Do we have an appropriate mix of industry, university and national lab participation? Is the coordination with other related DOE, Federal and State activities adequate? Are the mechanisms for technology transfer appropriate? How would you assess the productivity of the program? Are the accomplishments commensurate with the investment being made?

- Cost shares were generally not listed in the handouts, but the scope of efforts suggests that the engine companies in particular are offering significant cost share. There seems to be reasonable coordination with parallel programs and use of technology, rigs, and engines established in prior programs.

- How well resources are being leveraged is not evident in all projects because cost-share levels were not always discussed.
- So far the accomplishments seem very promising and in line with the investments being made. Not enough information was presented to comment on technology transfer. However, each program seems to have the key partnerships that will facilitate technology implementation as appropriate.
- The emissions work should concentrate funding on higher risk concepts rather than "conventional" approach (lean premix). At this stage, it is really too soon to tell which these might be.
- ORNL is rightly the focus for testing and characterization of materials, as it provides a service to all suppliers and users. Based on past experience, the program should be cautioned to make sure a disproportionate share of the funds do not go to National Labs.
- Progress on the long term prospects for ceramic blades and rotors needs to be closely monitored.
- This is a well managed program with an appropriate mix of industry and national labs.
- The program should consider additional inclusion of university impact in coatings area.
- Is there much university involvement in the program? Merrill Smith mentioned coordination with other DOE, Federal, and State activities in her overview presentation of the program, but there is not a sense of how substantive or effective this coordination is.
- In nearly all of the reviewed programs, collaboration and leveraging is claimed. University collaboration is inadequate, and should be increased. A separate, but coordinated, university program should be maintained.
- The accomplishments appear to be appropriate for the investment made, and the overall program is rated as productive.
- Although collaboration is evident, the transfer of the technology to the general gas turbine community will be inhibited by the large number of individual, manufacturer-specific programs with proprietary technology. DOE should work to make the developed technology more generally available, and support more efforts like those at ORNL. Again, universities should be doing related research work

4. Are there new areas of RD&D in which the program should be investing?

- There may not be enough effort on evaluating the life of catalysts and other hardware in the various catalytic combustion approaches.
- Based on cost concerns for microturbines, the reviewer would push materials works for metallic alloy applications.
- Alternative fuels such as methane (and other storable fuels) for national security and emission reductions.
- Advanced concepts as in-situ combustion in the turbine, possible MHD effects application, the use of alternate and biomass fuels, methods for wider range and more efficient off-design GT operations, closed cycle inert gas turbines for nuclear applications. The current emphasis is on important, near-term problems.

5. What are the overall strengths of the Gas Turbine Program?

- Good partnerships that should lead to rapid implementation of successful technologies. Also, most of the advanced technologies appear that they can be implemented without major redesign of the engines and are amenable to retrofit into existing engines.
- Emissions: Promising technologies using catalysts.
- Materials: Recuperator alloy investigations.
- The portfolio of low-NO_x development projects is a strong one.
- The program is characterized by well-managed, important development programs with manufacturers that will likely result in better GT products, meeting national needs.

6. What are the overall weaknesses of the Gas Turbine Program?

- As the NOx emissions continue to decrease, it appears there is a challenge to making accurate measurements and to demonstrating compliance to future federal and state regulations. It also appears from some of the discussions that some of the regulations and certification procedures do not give the turbines fair treatment. Are there any efforts within the overall program that are trying to address these more political issues?
- Emissions: Is 5 ppm an exercise in futility?
- For the materials projects, there may be over emphasis on ceramics.
- The program is too focused on development solutions to specific, present-day problems. A long range research component is needed

7. Other Comments or Recommendations:

- The program seems to be well managed at the DOE level and at each of the contractors.
- There is an apparent lack of attention being paid by DOE and its contractors to potentially huge overseas markets (China, India, etc.) and the special requirements for technologies introduced into these markets. Technology developed for U.S. markets may be able to satisfy some markets overseas, but other markets will require more tailored technology and service infrastructure. A survey of overseas markets would be a starting point for understanding whether technology development in different directions from existing efforts should be pursued. Overseas markets for U.S. technology are likely to be larger than U.S. markets, both in the short and long term. For example, the demand for reliable grid-connected or grid-independent power is enormous in Brazil, India, China, and many other developing countries. With the right technologies, U.S. companies, in partnership with local companies in these countries, have much to gain.
- Overall, the program is focused on and supporting the progress of the U.S. GT industry and solving important problems related to national energy production.

APPENDIX A

2002 PEER REVIEW AGENDA

U.S. Department of Energy, Office of Power Technologies, Office of Distributed Energy Resources

Peer Review of the Microturbine and Industrial Gas Turbine Programs

March 12-14, 2002
Hyatt Fair Lakes, Fairfax, VA

Day 1 – Tuesday, March 12, 2002

7:00 am	***Continental Breakfast***
7:00 am	**Conference Check-In/Registration**
8:00 am	***Opening Plenary Session*** —
	Welcome and Overview of the Office of Power Technologies *Robert Dixon*, U.S. Department of Energy
	Overview of the Office of Distributed Energy Resources and the Importance of Peer Review *Pat Hoffman*, U.S. Department of Energy
8:30 am	***Status of Microturbine and Industrial Gas Turbine Industries*** Moderator: *Debbie Haught*, U.S. Department of Energy
	Gas Turbine Market and Industry Study *Bruce Hedman,* EnergyNexus
	Meeting the DER Goal with Turbines *Paul Lemar*, Resource Dynamics Corporation
	Environmental Policies Bruce Rising, *Siemens Westinghouse*
10:00 am	***Break***
10:30 am	***Related Microturbine and Gas Turbine Efforts*** Moderator: *Debbie Haught*, U.S. Department of Energy *Mike Batham*, California Energy Commission (CEC) *Abbie Layne*, National Energy Technology Laboratory (NETL)
	Microturbine Program Overview *Debbie Haught,* U.S. Department of Energy
12:00pm	***Lunch***
1:30 pm	**Industry Presentations** Moderator: *Debbie Haught*, U.S. Department of Energy *Michael Bowman*, General Electric *Matt Stewart*, Capstone

	Jim Kesseli, Ingersoll-Rand
3:00 pm	***Break***

3:30 pm	**Industry Presentations (*continued*)** Moderator: *Debbie Haught*, U.S. Department of Energy *Tom Rosfiord*, United Technologies Corporation *Mike Ward*, Solar Turbines Corporation *Don Coates*, Los Alamos National Laboratory
5:30 pm	***Reception in Exhibit Area*** ***Sponsored by Gas Turbine Association***

Day 2 – Wednesday, March 13, 2002

7:30 am	***Continental Breakfast***
8:30 am	***Advanced Materials for Microturbines*** — **Program Overview** *Dave Stinton,* Oak Ridge National Laboratory **Ceramics** *Bjoern Schenk*, Honeywell *Matt Ferber,* Oak Ridge National Laboratory **Recuperator Foils** *Phil Maziasz*, Oak Ridge National Laboratory
10:30 am	***Break***
11:00 am	**Microturbine Applications** Moderator: *Dave Stinton*, Oak Ridge National Laboratory *Ed Torrero*, National Rural Electric Cooperative Association (NRECA) *Stephanie Hamilton*, Southern California Edison
12:00 pm	***Luncheon***
1:00 pm	**Program Overview Industrial Gas Turbine Technologies** *Merrill Smith*, U.S. Department of Energy
1:15 pm	**Low Emission Gas Turbines** Moderator: *Steve Waslo*, U.S. Department of Energy, Chicago *Dave Hatfield*, Catalytica Combustion Systems, Incorporated *Dr. Shah Etemad*, Precision Combustion Incorporated *Neil McDougald*, Alzeta Corporation
2:45 pm	***Break***
3:15 pm	**Low Emission Gas Turbines (*continued*)** Moderator: *Steve Waslo*, U.S. Department of Energy, Chicago *Ian Critchley,* Honeywell Engines and Systems *Mike Donovan*, Solar Turbines, Incorporated and *Dr. Shah Etemad,* Precision Combustion Incorporated *Duane Smith,* Rolls Royce Corporation
5:15 pm	***Adjourn***

Day 3 – Thursday, March 14, 2002

7:30 am	**Continental Breakfast**
8:30 am	**Advanced Materials for Industrial Gas Turbines** Moderator: *Jill Jonkouski*, U.S. Department of Energy *Ted Exley and Rob Stolnicki*, Teledyne Continental Motors *Ramesh Subramanian*, Siemens Westinghouse *Jeff Price*, Solar Turbines, Incorporated *Krishan Luthra*, General Electric
	National Laboratory Support for Advanced Ceramics *Karren More*, Oak Ridge National Laboratory *Bill Ellingson*, Argonne National Laboratory
11:30 am	**Closing remarks/Questions** *Debbie Haught and Merrill Smith*, U.S. Department of Energy
12:00 pm	***Adjourn***

Appendix B. Summaries of Microturbine and Industrial Gas Turbine Projects

Microturbine Project Summaries

Organization:	General Electric Global Research
Project Title:	Advanced Integrated Microturbine System
Presenters:	Michael Bowman
FY 2001 Funding:	$1,000,000
Start/Completion Dates:	October 2000 – September 2004

Overall Project Purpose and Objectives: The objective of the Advanced Integrated Microturbine System program is to develop the next generation microturbine system that will advance the current generation to be more efficient, cost effective, and environmentally friendly. The key target characteristics for the machine are single digit emissions, both NOx and CO, a unit cost of less than $500/kW and a usable life of 45,000 hours. The resulting system will be designed to address both the current and emerging distributed generation markets.

The technical focus of the program is to advance component performance and to pay special attention to the systems design. The process that is being employed is to improve the specific components, optimize the system layout, and lastly, prove out this level of technology. The second step on the path to a 40% electrical efficient (LHV) unit will be to increase the operating temperature through use of exotic materials.

The program is being executed in a semi-parallel method under all 5 tasks of the DOE solicitation. The first year of effort is focused on market analysis and conceptual design. At the completion of these efforts, the program works parallel tasks to develop the components and to complete the optimized system design, roughly a 2.5 year effort. At the time which the component design is complete, the fourth task begins which is to demonstrate the technology in a laboratory. This same activity is repeated once the second generation of components are completed. At the conclusion of the laboratory evaluation and once the designed systems are deemed safe and viable, the system will be installed in a commercial demonstration.

The technical efforts of the program are being completed primarily at the GE Global Research Center, while product direction, engineering reviews, as well as specific technical support are being supplied by both GE Power Systems and GE Industrial Systems. In addition to the GE team, Concepts NREC is supporting the design of the turbo machinery and Turbo Genset Company is designing the high speed alternator. Finally, for advanced materials support, Kyocera International is supplying material and Oak Ridge National Laboratory is performing some characterization studies.

The program is designed to develop technology that supports a clean environment and allows for additional choices for the US consumers.

FY 2001 Results and Accomplishments: During FY 2001, the team completed the market study and the conceptual design of the advanced system as well as kick off all major component design tasks. The team was working at a reduced level through the early part of the year awaiting the completion of the GE and Honeywell merger. Following the closure of this effort, the team reaccelerated the effort and has made terrific progress.

FY 2002 Plans and Expectations: The key milestone for FY 2002 will be the demonstration of the first unit. This demonstration will represent the first iteration on the advanced components as well as the optimized system layout. The hurdles associated with achieving this milestone are hardware availability from Venders and budgetary limitations.

Public/Private Partnerships: In FY 2001, a student intern from Princeton University spent the summer with the team on the program. The students efforts were focused on assisting the team to accurately evaluate the technology in the laboratory environment.

Organization:	CAPSTONE TURBINE CORP.
Project Title:	ADVANCED MICROTURBINE SYSTEM
Presenters:	MATT STEWART
FY 2001 Funding:	$1,258,000
Start/Completion Dates:	SEPTEMBER 29, 2000 – APRIL 28, 2006

Overall Project Purpose and Objectives: The goal of the project is to design and develop an advanced microturbine system that is complaint with the objectives of the Department of Energy's Advanced Microturbine Systems Program (i.e.: emission ≤7ppm NOx; efficiency ≥40%; cost ≤500$/kW; life: 11,000 hours to major overhauls, total service life 45,000 hours; multiple fuel option).

The project is divided into the following tasks:

TASK1: It includes cycle studies, preliminary design, rigs development and ceramic material testing and feasibility.

TASK2: It focuses on recuperator and high temperature materials process development.

TASK3: It is dedicated to controller development and its integration to the three evolutionary stages of the engine (Simple Cycle, Metallic Development and High Efficiency) and the development of the remainder of plant.

TASK4: It includes the all-metallic detail design and the advanced material detailed design. The design is followed by the integration and testing of the simple cycle, metallic development and high efficiency systems.

TASK5: It represents the last task of the AMTS program and is focused on building and field testing systems.

Project Milestones are:

1. Recuperator preliminary design: Definition of recuperator configuration ....03/28/01 (Complete)
2. Subtask A: Marketing study ....04/03/01 (Complete)
3. Complete Preliminary Design Review, Cost Estimates and Ceramic Feasibility .....06/29/01 (Complete)
4. Detailed Recuperator Analysis: Detailed analysis of the geometry defined in #1 ....01/31/02
5. Subtask B: Commercial implementation plan 03/29/02
6. Complete first recuperator core (SS 347 material) 07/26/02
7. All Metallic Development critical design review 08/31/02
8. Simple Cycle All Metallic Development full power operation 01/27/03
9. All Metallic Development full power operation 04/09/03
10. HE system (AMTS) critical design review 11/11/03
11. Complete first HE recuperator core (material TBD) 11/30/03
12. High Efficiency system full power operation 11/04/04
13. Report on development 01/12/05
14. Start field test 04/18/05
15. Report on field test 04/28/06

Expected benefits of this project: Microturbine systems are small power plants with ultra low emissions that are used to provide electricity and heat to small commercial and industrial energy users. They are typically used in combined heat and power applications, peak shaving and to provide customers base load power needs and can operate independently and in conjunction with the utility grid. Microturbines often can operate on a wide range of fuel sources, which can include renewable or waste sources.

Microturbines are a subset of distributed generation (DG) and the advantages of DG are substantial. By producing the energy at the site, transmission and distribution (grid) losses are eliminated, which also reduces the need for grid expansion and/or maintenance. When used in parallel with the grid at peak hours, this can reduce costs and grid capacity requirements. It can also be used to increase reliability due to grid interruption. As efficiency of DG systems increase, operating costs decrease. Microturbines are likely to be used in hybrid systems with other DG heat sources (such as fuel cells) to increase the system efficiency. With a fuel cell, a microturbine may be used to increase the system efficiency by $\approx$5% with little change in the first cost on a $/kW basis, while maintaining ultra-low emissions. Microturbines are one type of DG that utilizes fuel flexibility thus increasing the possible applications. One use of this fuel flexibility attribute is in resource recovery, where the fuel has limited value such as oil field wellhead gas. Emissions are reduced by many DG applications and Capstone MicroTurbines produce ultra low emissions, approaching levels of a fuel cell. These environmental benefits are enhanced in applications that use renewable fuel sources such as biogas. Due to their fuel flexibility, microturbines can achieve renewable status at landfills and digester plants.

This project is to develop an Advanced Microturbine and the goals are ambitious. The requirement of 40% thermal efficiency is greater than a 33% increase over current microturbines and will substantially reduce operating costs of DG. The cost target of $500/kW and life requirements creates a good value proposition that will encourage adoption in commercial applications. The emissions goals are in line with central power plants. These targets will push the entire microturbine industry towards a product that could redefine the way energy is delivered. The benefits to the public are clear as the economics allow for clean distributed power.

FY 2001 Results and Accomplishments: Activities planned for FY2001 included Task1 trough Task4 efforts. Completed the Preliminary Design, Task1 and progressed with Rigs Development, Ceramic Material Testing and Feasibility and Detailed Recuperator Analysis. Task2 was mainly focused on the recuperator with initial work on Process Development and Detailed Analysis. Task3 started with the Controller Development defining system requirements and the overall system architecture. Task4 involved the initial effort on the detail design of the All Metallic Development Engine. Due to the issues with the monolithic ceramic the last quarter of FY2001 and part of the first quarter of FY2002 were dedicated to define and evaluate several alternatives to the ceramic option.

FY 2002 Plans and Expectations: The overall program was revised according to the reduction in funding from DOE for FY2002. For this year the project will focus mainly on the All Metallic Development as precursor to the High Efficiency System. Effort on the High Efficiency System will be limited to mitigate the highest risk components like turbine wheel and combustor liner. As a result the All Metallic Development plan shows a delay of one month on the major milestones while the High Efficiency System is postponed about six months compared to the original schedule.

Public/Private Partnerships: Project major partners and subcontractors are listed below:

Goodrich	(CA)	Ceramic composite components development
COIC	(CA)	Ceramic composite components development
Honeywell CC	(CA)	Monolithic ceramic components development

Saint Gobain	(MA)	Monolithic ceramic components development
Haynes	(IN)	High temperatures recuperator material development
Elgiloy	(IL)	High temperatures recuperator material development
J.H. Benedict	(IL)	Recuperator process development
PCC	(CA, OH)	High temperature metallic turbine wheel development
ORNL	(TN)	Material testing and development
UCIrvine	(CA)	System testing and combustion development

Organization:	INGERSOLL-RAND ENERGY SYSTEMS
Project Title:	ADVANCED MICROTURBINE DEVELOPMENT PROGRAM
Presenters:	JAMES KESSELI
Total Funding:	TOTAL DOE CONTRIBUTION = $1,386,829, TOTAL IR CONTRIBUTION = $1,3,00,780 TOTAL PROGRAM= $2,687,609
Start/Completion Dates:	SEPTEMBER 2000 – SEPTEMBER 2004

Overall Project Purpose and Objectives: Ingersoll-Rand's PowerWorks™ program combines a novel application of industrial turbocharger equipment, an advanced recuperator, and proven industrial gas turbine design practices. Task 1 of the program will perform a comprehensive analysis of ceramics suitable for the turbine section and recommend the most suitable PowerWorks™ platform. Tasks 2, 3, 4 will proceed to design the turbine section, test, and ultimately commercialize the product.

The benefits that this program will bring to the gas turbine area will be focused on realizing the goal of large-scale deployment of ceramic turbine rotors. The associated benefits to the gas turbine and ceramics industries are:

- Significant increase in long-term exposure and endurance data of ceramic rotors
- Creation of a product that will lead to advances in high volume ceramic manufacturing techniques
- Broadening of engineering methods for integrating ceramic in gas turbines
- Improved ceramic rotor geometry optimization methods, coupling aero, mechanical, and manufacturing design experience.

Benefits for US economy and society as a whole are:

- Significant reduction in CO_2, and pollutant emissions
- Increased US export potential
- Increased energy efficiency in industry and hence competitiveness in the world economy

FY 2001 Results and Accomplishments:

- Cycle analysis for high firing temperature PowerWorks products – complete
- Designed turbine rotor for 2000 F (1100 C), including aero and FEA analysis
- Selected compliant monolithic silicon nitride material
- Performed iterative design modifications with candidate suppliers
- Performed recession rate analysis, demonstrating suitable life
- Preliminary design of high temperature turbine housing

FY 2002 Plans and Expectations:

- Purchase and receive finished monolithic silicon nitride rotors for advanced PowerWorks engine configurations
- Complete housing design
- Perform destructive testing on sample rotors
- Purchase and receive high temperature turbine housing
- Complete test plan for subsequent lab test

Public/Private Partnerships: Steve Duffy, ORNL, and various ceramic suppliers and developers.

Organization:	UNITED TECHNOLOGIES RESEARCH CENTER
Project Title:	COOPERATIVE RESEARCH AND DEVELOPMENT FOR ADVANCED MICROTURBINE SYSTEMS
Presenters:	THOMAS ROSFJORD
FY 2001 Funding:	$2,892,940
Start/Completion Dates:	SEPTEMBER 28, 2000 – DECEMBER 30, 2005

Overall Project Purpose and Objectives: United Technologies Research Center (UTRC) is leading a team to develop and demonstrate a 500-kW class microturbine that meets the following efficiency, environmental, durability and economy goals of the DOE Advanced Microsystems Program Plan:

- Electrical efficiency = 40% or more
- NOx = 7 PPM or less on natural gas
- Multi-fuel capability
- 11,000 hr between major overhauls
- System cost = $500/kW or less

The strategy is to utilize affordable, advanced technology to increase the electrical efficiency of the DTE Energy Technologies ENT400 microturbine system, powered by the Pratt & Whitney Canada ST5 engine and using a TurboGenset electrical generator, from 30% to over 40%, and lower NOx emissions to less than 7 ppm. The targeted technologies include ceramics, advanced recuperator materials, Organic Rankine cycle (ORC) systems, low-emission combustion, and electrical power generation/conversion systems. By basing the advanced system on the ENT400, the enhanced microturbine system has great probability of achieving the cost and durability targets. The advanced engine for this system is known as the ST5Plus.

The UTRC-led team, and their areas of responsibility, include:

- **United Technologies Research Center**. Responsible for prime contractor activities, ceramic materials, low-NOx combustion, and Organic Rankine cycle (ORC) development.
- **Pratt & Whitney Canada**, a division of UTC. Responsible for engine readiness, system integration and system performance testing.
- **DTE Energy Technologies**, an affiliate of DTE Energy Company (parent of Detroit Edison). Responsible for business perspectives and the durability demonstration test.
- **SatCon, Inc**. Competing for responsibility for power generation and conversion.
- **Hamilton Sundstrand**, a division of United Technologies. Competing for responsibility for power generation and conversion.

Program Major Milestones

Identify microturbine system meeting performance, emissions, and cost goals	3/1/01
Complete Preliminary Design Reviews for ceramic turbine, combustor and ORC	12/31/01
Demonstrate 80 kW from ORC with simulated ST5 exhaust	2/1/02

Demonstrate 5-point increase in system electrical efficiency with ORC	8/1/02
Demonstrate combustor emissions technology for NOx<7 ppm and CO<10 ppm	11/1/02
Demonstrate ceramic turbine performance and life potential in core engine	6/1/03
Demonstrate 40% electrical efficiency, low NOx performance in engine system	4/1/04
Initiate >4000 hr field tests to demonstrate life	1/1/05

The UTRC advanced microturbine system, by achieving 40% electrical efficiency, 40% reduction in customer payback period, and less than 7 ppm NOx, has great public benefit. It will expand customer choice for meeting reliable, secure, power needs. It will compete effectively against the grid, directly reducing customer electricity costs, and indirectly reducing cost by avoiding outages and infrastructure enhancements. When used with alternative waste heat devices, the microturbine can meet customer heating and cooling needs, and conserve resources by converting >70% of fuel energy into useful energy. At <7 ppm NOx, the microturbine is cleaner than diesel and many large gas turbine alternatives.

FY 2001 Results and Accomplishments: System analyses identified a combined recuperated-gas-turbine-engine/ ORC-bottoming cycle configuration to affordably achieve 40% electrical efficiency. The enhanced system based on raising the firing temperature of the ST5 engine and converting its waste heat to electrical power with an Organic Rankine cycle (ORC), at no additional fuel burn, was specified in March 2001. The ORC is a key to affordably achieving 40% efficiency. Efficiency gains from raising the gas turbine engine cycle temperatures are sought but limited because of recuperator cost constraints. Any turbine temperature increase requires use of more capable ceramic materials because the uncooled metal designs are at their useful life limit. Ceramic materials also benefit the system because of reduced cost and cooling flow, and permit engine performance growth as recuperator barriers are diminished.

<u>Ceramic Turbine Preliminary Design Review completed</u>. Analyses of ceramic vane and turbine component performance and life were performed and reviewed in December 2000. A ceramic integrally bladed rotor (IBR) design based on the use of fewer but thicker blades that the parent metal turbine design, was analyzed for disk structural integrity, blade foreign object damage tolerance, stage efficiency, and shaft attachment options.

<u>Combustor Preliminary Design Review completed.</u> A low emissions combustor design, based on achieving highly uniform fuel-air mixtures prior to combustion, was reviewed in September 2001. The combustor premixer was both analytically evaluated with CFD tools and experimentally evaluated using PLIF diagnostics to show mixture non-uniformity <5%. An affordable ceramic combustor liner was predicted to achieve full life. The value of the ceramic liner is to reduce the temperature rise of its cooling air because it also provides this function to the downstream transition scroll to the turbine. Combustor experiments verified the potential of a fuel-staging strategy to sustain low NOx and CO over a 70% to 100% targeted power range.

<u>ORC Preliminary Design Review completed and prototype system produced 64kW of power.</u> A prototype ORC was specified based on the use of near off-the-shelf components and refrigerant working fluid. System analyses indicated this prototype would convert engine exhaust heat into 60kW of electrical power in its original configuration, with a growth potential to 80kW with component enhancements. The prototype was reviewed in April 2001, assembled, and operated to produce 64kW of power using a heated airstream at full flowrate and temperature to simulate the engine exhaust in September 2001.

FY 2002 Plans and Expectations:

Demonstrate 80 kW from prototype ORC system. Completed in February 2002. Data obtained in 2001 tests were analyzed to determine deficiencies in the prototype ORC system and guide its improvement. System enhancements to reduce condenser pressure loss and improve turbine efficiency were implemented. Tests using full engine condition heated airflow produced 80kw of power.

Demonstrate 5-point increase in system electrical efficiency with ORC. Planned for completion by August 2002. The prototype ORC system does not represent a final product configuration because, for example, its layout is not compact, pump size and operation is incorrect, controls are preliminary, etc. A near product ready ORC module, responsive to the above issues, will be tested to show that its power output supports a 5-point increase in electrical efficiency above the ENT400 microturbine system.

Demonstrate combustor emissions technology for $NO_x<7$ ppm and $CO<10$ ppm. Planned for completion by November 2002. Prototype combustor configurations, combining both premixer bulkhead and liner alternatives, will be evaluated at full scale and at full-recuperated-engine conditions. The experimental setup will include both the off-board combustor and the turbine transition duct, with acoustic boundary conditions representative of the engine, to properly assess emissions control, turbine inlet temperature pattern factor, and acoustic instability avoidance. Pretest predictions of these features will be performed using existing analytical tools.

Public/Private Partnerships: The UTRC-led team continuously looks toward academia and national laboratories for new technologies that will reduce the risks in achieving the program goals. Collaborations with ORNL were established to characterize metal and ceramic materials required by recuperator and turbine components.

Organization:	SOLAR TURBINES INCORPORATED
Project Title:	COOPERATIVE RESEARCH AND DEVELOPMENT OF PRIMARY SURFACE RECUPERATOR FOR ADVANCED MICROTURBINE SYSTEMS DE-FC02-00CH11049
Presenters:	MICHAEL WARD
FY 2001 Funding:	$ 1,000,000
Start/Completion Dates:	SEPTEMBER, 2000 – APRIL, 2004

Overall Project Purpose and Objectives: Today's recuperator requirements are pushing the technology envelope of cost effective materials technology. All recuperated turbine manufacturers would like to increase cycle efficiencies by increasing firing temperatures. However, the recuperator exhaust-side inlet temperature often restricts turbine-firing temperatures. With millions of hours of experience, 300 series stainless steel is the most cost-effective material for gas turbine recuperators. Other choices such as nickel based alloys increase material costs by factors of 4 to 7X and increases manufacturing costs by 2X. The problem with thin gauge 300 stainless steel is an economic life temperature limit of 635°C. Increasing temperature capability by 50 to 80°C could allow significant gains in cycle efficiency through direct increase in cycle temperature.

Proposed Solutions **-** Solar is proposing to improve the recuperation aspect of the turbine systems by development work aimed at improvement in affordable foil alloys that will allow higher system temperatures (higher cycle efficiencies). The proposed scope of work focuses on the development of a new, economical stainless derivative recuperator material that will allow operation at higher temperatures. Laboratory tests to verify the material's capability are part of the proposed work scope along with the build of a full-scale recuperator for final material capability verification. Testing of the full-scale recuperator will be performed as part of other Solar-funded programs.

Team Members **-** The Solar led team will include a specialty alloy manufacturer, Allegheny Ludlum. Allegheny has unique expertise in recuperator material development and commercialization. If an advanced austenitic alloy proves to be a viable recuperator material, Allegheny plans to commercialize the new material making it available to all that wish to purchase the material.

Milestones **-** The following are the project major milestones:

♦ Materials selection for recuperator endurance test	26 July 2002
♦ Start of recuperator endurance test	5 June 2003
♦ Recuperator materials performance evaluation report	28 January 2004
♦ Project complete	2 April 2004

Benefits **-** Solar's recuperated Mercury Turbine, developed with the cooperation of DOE during the ATS initiative, is currently undergoing field evaluation prior to its commercialization. Solar desires to increase the performance capability of the Mercury through increases in recuperator temperature. This project will directly contribute to that goal. In addition, the majority of microturbine manufacturers desire higher operational temperature and greater recuperator durability. The results of this project will increase the application material data base to allow manufacturers to better match application with material capability and make available in 2004, a new austenitic alloy with better performance than available today.

By application of higher temperature alloys, turbine manufacturers will be better positioned to offer more durable, higher efficient turbine generators that produce electric power at a competitive rate and allowing greater market penetration. The cleaner operating turbines will assist the US in meeting the country's environmental goals and the goals of the DER initiative.

FY 2001 Results and Accomplishments: The following is a brief description of the status of four major recuperator material initiatives during FY2001.

Coated Type 347 SS Foil: Meetings with potential suppliers were completed and potential-coating processes evaluated. Coated specimens, for oxidation testing, were prepared.

Creep Resistant Type 347 SS Foil: Three test heats of this material were made and rolled to a foil thickness of 0.004 inches. Both Chemical and microstructure analyses have indicated the composition and metallurgy is according to design. Test specimens were made and both creep and oxidation testing began.

Advanced Austenitic Foil: Three test heats of material were made and processed to foil thickness. Both Chemical and microstructure analyses indicate the composition and metallurgy is according to design. Test specimens were made and both creep and oxidation tests were started.

Coated Advanced Austenitic Foil: Meetings with potential suppliers were completed and potential-coating processes were identified. Coated coupons were prepared for oxidation testing.

Dual Alloy Foil: Four alloy combinations of clad foil material were selected and processing began. Specimens were prepared for oxidation testing.

Advanced Nickel Alloys for Recuperator Applications: Small quantities of Alloy 625, Alloy X, and Haynes® 230-alloy foil were procured for oxidation and creep testing. Creep specimens were made.

FY 2002 Plans and Expectations:

- All creep, oxidation, and manufacturing (folding, forming, crushing, & welding) tests will be completed.
- Recommendation of the materials for the recuperator endurance tests will be made, 26 July 2002.
- Procurement of materials for recuperator endurance tests.
- Commercial processing parameters will continue to be refined during material processing for recuperator endurance tests.

Public/Private Partnerships:

- Allegheny Ludlum and Solar Turbines are working in cooperative efforts in the identification, development, material property quantification, material performance, commercial processing, and commercialization.

Organization:	LOS ALAMOS NATIONAL LABORATORY
Project Title:	SINGLE ROTOR MICRO TURBINE ENGINE
Presenters:	DON M. COATES
FY 2001 Funding:	$200,000
Start/Completion Dates:	JANUARY 1, 2002 – MAY 1, 2002

Overall Project Purpose and Objectives: Project Description: The LANL Micro Turbine engine design is a unique and new configuration that has high potential for enhanced operational efficiency, lower manufacturing costs, superior turbine-section cooling and a more compact footprint. The overall objective is to study this new configuration for viability, explore the design operational space and verify the promise for enhanced efficiency, compactness and likelihood for lower manufacturing cost.

Project goals, objectives and major milestones: Key steps and milestones include: 1. Complete design of initial rotor and create CAD/CAM files, 2. Form metal rotor by casting, machining methods, based on computer files 3. Build turbine engine test rig to test rotor, 4. Test initial metal rotor in rig, and 5. Analyze generated data and recommend path forward.

Partners & Subcontractors: POC Structurals Inc. has been subcontracted for casting prototype rotors per our CAD files.

Expected benefits: LANL will accrue enhanced expertise and experience in sophisticated turbine technology which will improve our ability to contribute to this field of technology. The U.S. DOE will gain an improved micro turbine capability for distributed power applications. The Nation will have, in the future, routes to higher efficiency lower cost distributed power generation that should reduce dependence on foreign energy and reduce stress on the domestic Grid.

FY 2001 Results and Accomplishments:

Milestones reached:

- Completed design of initial rotor and created CAD/CAM files,
- Successfully made first metal rotor
- Built turbine engine test system to test rotor

Technical results to date: Development of the rotor went through several stages of SLA solid model iteration. This modeling showed that the aerodynamic features of the interleaved passages can be largely controlled independently, thus easing optimization of the various compressor, diffuser and turbine sections. Initial stress analysis showed good radial support of all the structures is inherent in the design. Successful investment casting of the initial rotor in Inconel demonstrated that commercial production of the rotor's design with its unique internal passageways will likely be practical. A test rig has been designed and built which will be used for "first spool up" of the rotor. The rig will be able to produce the first look at the engine's operational parameter space.

FY 2002 Plans and Expectations: For the balance of the year, we will need to complete the last two milestones, namely, 4. test initial metal rotor in the test rig and 5. analyze the data and recommend path forward. It is a hope to have an actual running turbine engine as well. Possible constrictions would include unforeseen mechanical or design problems although none have been encountered to date perhaps since we are very early in the process of building the first engine.

Public/Private Partnerships: Private industry was initially notified of our efforts by a Commerce Business Daily ad and more recently by direct conversations protected by non-disclosure agreements, both of which generated considerable industrial interest. Partnerships with industry will be actively pursued after formal “roll-out” of the technology to be accomplished at this turbine Peer Review Meeting.

Organization:	OAK RIDGE NATIONAL LABORATORY
Project Title:	CHARACTERIZATION OF CERAMICS FOR MICROTURBINE APPLICATIONS
Presenters:	MATTISON K. FERBER
FY 2001 Funding:	$240,000
Start/Completion Dates:	OCTOBER 1, 2000 – SEPTEMBER 30, 2004

Overall Project Purpose and Objectives: One objective of this program is to develop test facilities for evaluating the influence of high-pressure and high-temperature water vapor upon the long-term mechanical behavior of monolithic ceramics having environmental barrier coatings.

The second objective is to evaluate and document the long-term mechanical properties of very small specimens machined from ceramic components (e.g., blades, nozzles, vanes, and rotors) in as processed and after engine testing at ambient and elevated temperatures under various controlled environments. This work will allow microturbine companies to verify mechanical properties of components and apply the generated database in advanced design and lifetime prediction methodologies. The work also provides a critical insight into how the microturbine environments influence the microstructure and chemistry, thus mechanical performance, of materials.

FY 2001 Results and Accomplishments:

(1) Modified existing tensile frames to allow for tensile testing in a water vapor environment. This facility will be used to evaluate the effect of water vapor upon the mechanical reliability of both uncoated and coated environmental barrier coatings (EBCs).

(2) Provided extensive characterization support to Rolls Royce in their two series of engine tests involving silicon nitride vanes. In the first test, the results of this characterization effort established the baseline recession behavior of uncoated silicon nitride. The characterization of the vanes in test 2 provided the first ever field evaluation EBCs applied to a silicon nitride ceramic.

(3) Established extensive data sets for silicon nitride and silicon carbide ceramics of interest to the microturbine community. These data sets, which are in the form of spreadsheets, have now been supplied to UTRC, GE (Curt Johnson), Ingorsol Rand Energy Systems, and Capstone.

(4) Based upon conversations with the companies listed above, we have identified other candidate ceramics to include in the database. In some cases, additional testing has been implemented to supplement the data.

(5) Have worked with ceramic suppliers including Saint-Gobain Ceramics & Plastics, Inc. and Kennametal (new to the microtubine effort) to identify promising materials and to implement characterization studies of those materials.

(6) We are providing extensive mechanical property and component characterization support to UTRC in both their microturbine program and their EBC development program. Our component characterization effort has been extremely useful for identifying processing-induced strength degradation in the complex shaped airfoils.

FY 2002 Plans and Expectations:

(1) Complete characterization of microstructure and mechanical properties for UTRC silicon nitride microturbine components by September 2002.

(2) Complete the database generation of commercial Si-SiC materials for microturbine companies' lifetime modeling task by June 2002.

(3) Design, fabricate, and evaluate steam containment system for existing creep-stress rupture rigs and issue letter report.

(4) Conduct preliminary environmental stability tests on uncoated SN282 and issue letter report.

(5) Modify 4 test frames to accommodate direct steam injection system.

Public/Private Partnerships: NA

Organization:	OAK RIDGE NATIONAL LABORATORY
Project Title:	ADVANCED ALLOYS FOR HIGH TEMPERATURE MICROTURBINE RECUPERATORS
Presenters:	PHILIP J. MAZIASZ (WITH B.A. PINT, R.W. SWINDEMAN, AND K.L. MORE)
FY 2001 Funding:	$250,000 ($400 K IN FY 2002)
Start/Completion Dates:	2 PREVIOUS RELATED PROJECTS COMPLETED IN SEPT. 2001; NEW PROJECT BEGAN IN OCT. 2002.

Overall Project Purpose and Objectives: Recuperators are compact heat-exchangers that are necessary to increase the efficiency of microturbines. Recuperators are a large portion of microturbine system hardware and initial cost. They are currently made from 347 stainless steel that limits them to maximum metal temperatures of about 675°C. Increasing microturbine temperatures to improve efficiency and/or using alternate fuels will reduce durability or reliability unless more expensive alloys with greater performance and reliability at higher temperatures are developed or selected. The object of this program is to work closely with the different microturbine OEM's to identify and tailor advanced alloys appropriate to their particular improved recuperator technology needs. Analysis of as-fabricated and engine-tested recuperator components will establish current performance benchmarks and help estimate the gains in performance and lifetime achieved from making the same components from advanced alloys. The goal is to obtain commercially produced foils and sheets of several cost-effective advanced austenitic stainless alloys that microturbine OEM's can then use to make higher performance recuperator components for evaluation and engine testing.

FY 2001 Results and Accomplishments: In FY 2001, two lab-scale materials testing programs were concluded to identify a range of stainless steels, stainless alloys and superalloys and select materials to make recuperators capable of operation at 750-800°C and above. Commercial Ni-based alloys and superalloys were identified that had the strength and oxidation/corrosion resistance to operate as foils or thin-sections at 800°C and above, including alloy 625, thermie-alloy (Special Metals), and HR 230 and 214 (Haynes). However, these are much more expensive (5-10 times) than the 347 stainless steel currently used in all types of microturbine recuperators. More cost effective austenitic stainless alloys, including HR120 and a modified alloy 803 (Special Metals) were identified as able to perform at 750°C or somewhat higher, at only about 3-3.5 times the cost of 347 stainless steel. It was also demonstrated that it is feasible to modify the composition/processing of 347 stainless steel to enable operation at 700-750°C without much additional cost.

FY 2002 Plans and Expectations: In FY 2002, a combined and integrated advanced recuperator alloy program began that was focused on obtaining commercial foils and enabling fabrication of advanced recuperator components by the various microturbine OEM's. This program is also coordinated with the ORNL Microturbine Recuperator Testing and Evaluation Project that is modifying a Capstone 60 kW microturbine to be materials testing facility. The goal of this program is to test the commercial as-processed standard 347 stainless steel foils or thin sections used by microturbine OEM's to fabricate existing recuperators, and to analyze fresh and engine exposed recuperator components to establish a benchmark for current component performance. HR 120 is commercially available as foil (Elgiloy) and it may be possible to scale up the modified alloy 803 (Special Metals) to produce similar foils. ORNL is currently completing an alloy development effort to boost the performance of type 347 stainless steel by alloy/processing modification. ORNL will work closely with the various microturbine OEM's to define and achieve each of their specific needs for cost-effective recuperators with enhanced performance and reliability at higher temperatures and/or with alternate fuels.

Public/Private Partnerships: This project benefits from collaboration and positive interactions with microturbine OEM's (Capstone and Ingersoll Rand) and materials producers (Elgiloy, Haynes, Special Metals, and Allegheny-Ludlum) to provide fresh and engine-tested recuperator components, share details of recuperator manufacturing and strategies for improved performance, provide commercial samples of foils and thin sections of current 347 steel and advanced alloys, and address issues related to getting commercial samples of advanced alloys (with modified processing, if needed).

Organization:	SOUTHERN CALIFORNIA EDISON [SCE]
Project Title:	MICROTURBINE GENERATOR [MTG] TESTING PROGRAM
Presenters:	STEPHANIE L. HAMILTON
FY 2001 Funding:	$ 260,154
Start/Completion Dates:	1996 – 2002

Overall Project Purpose and Objectives: SCE's MTG Testing Program envisions supporting the commercialization of MTGs by providing performance testing results against each MTG's manufacturer's specifications and industry or other standards such as power quality and emissions. Also assessed is ease of installation, operability, and maintainability. Each manufacturer is provided with individual feedback on suggested product development and improvements.

Project Description - the following are tested for each microturbine based on the manufacturer's specification and industry or other standards:

- Gross and net energy output for electrical and if applicable, thermal
- Efficiency/heat rate
- Power quality
- Emissions
- Noise
- Endurance
- Performance at various load levels
- As applicable, at various energy content of the fuel
- Ease of installation, operation, and maintenance

Specific project goals, objectives, and major milestones:

- Test as many different machines as possible with funding
- Characterize each machine performance after 4500 hours of testing
- Provide feedback to manufacturers to improve the technology and support its maturation

MTG	Installation Date	Total Operating Hours through 12/31/01	Status
Capstone "B" 30 kW	Jan-97	958	Completed
Capstone "B" 30 kW	Jan-97	967	Completed
Capstone 10 Pack	Apr-97	26	Completed
Capstone "C" 30 kW	May-97	3,794	Completed
Capstone "C" 30 kW	Jul-97	2,079	Completed
Bowman 35 kW	Feb-99	100	Completed
Bowman 60 kW	Jun-99	60	Completed
Capstone HP 30 kW	Apr-99	17,499	Operating
Parallon 75 kW	Jun-00	5,806	Completed
Capstone LP 30 kW	Aug-00	10,957	Operating
Bowman 80 kW	Jun-01	2,540	Operating

Total		44,786		

Expected benefits of project, for ORNL, the U.S. DOE, and the nation: SCE benefits by gaining a thorough understanding of the technology and how it will perform and can provide expert information to its ratepayers, its policymakers, regulators, government and other agencies.

The U. S. DOE is provided with information that makes it familiar with the technology and its level of maturity.

The nation gets an assessment of how well the technology meets its performance claims and satisfies industry and other standards.

FY 2001 Results [since 1996] and Accomplishments:

- $3.0+ million program in progress since 1996
- 12 MTGs tested or in test
- Two to four more MTGs expected for testing
- Completed machine performance tests on eight MTGs
- Completed initial electrical behavior testing
- Over 44,000 hours of testing

Have made the following presentations and developed and/or developing publications as listed below:

- Distributed Generation in a Deregulated World, 12/98, *Power-Gen '98, Orlando, FL*
- MicroPower -- Promised Land or Wilderness, 6/99, *Latin America Power '99,* Miami Beach, FL
- The Buzz Is From The Micro Turbine Generators, 7/99, *Deregulation Watch*
- Microturbine Generators Poised for Commercialization, 9/99, *Modern Power Systems*
- The Microturbine Generator Report to the CEC, 9/99
- Microturbines Under the Microscope, 11/99, *Power-Gen '99, Orlando, FL*
- Microturbine Generator Test Program, 12/99, CERA, Energy Forum, Houston, TX
- The Microturbine Generator Program, 01/00, *HICSS33 – IEEE Conference,* Wialea, Maui, Hawaii
- The Micro Turbine Testing Program, 03/00, WEPI *Conference,* Reno, NV
- Performance Testing of Micro Turbine Generators, 05/00, *ASME Turbo 2000,* Munich, Germany
- Microturbines – The Next Generation, 07/00, *SSGRR 2000,* L'Aquila, Italy
- Microturbine Testing, 11/00, *CERA Energy Forum*, Barcelona, Spain
- Micro Turbines – The Next Generation, 04/01, *Distributed Power*, Washington, DC
- Customer Applications -- Micro Turbines, 06/01, *ASME Turbo 2001*, New Orleans, LA
- Electrical Characteristics in Small Generation Systems, 06/01, *ASME Turbo 2001*, New Orleans, LA
- Micro Turbine Testing, 06/01, *CERA Energy Forum*, Cambridge, MA

- Distributed Generation: A Non-technical Guide, 07/01, PennWell Publishing, with A. Chambers and B. Schnoor
- Conditions for Autonomous Power Capability in New Versus Old Economy Firms, 08/01, *SSGRR 2001*, L'Aquila, Italy with F. Kaefer, Ph. D. and G. Nezlek, Ph. D.
- SCE's Microturbine Testing Program: Update & New Equipment, 12/01, *CERA Energy Forum,* Santa Fe, NM
- SCE's Distributed Generation Program, 01/02, *DOE Microturbine Workshop*, College Park, MD
- Research Program for Maturing Emerging Distributed Energy Technologies to Provide Infrastructure for E-Related Applications, 01/02, *SSGRR 2002W*, L'Aquila, Italy
- SCE's MTG Program, DOE MTG/Gas Turbine Peer Review, 03/02, Fairfax, VA
- Handbook of Microturbines [under contract with PennWell Publishing]

FY 2002 Plans and Expectations: Working with all MTG manufacturers to get their newest machines and/or versions of their machines. SCE is seeking such machines at no cost or reduced prices to use as much funding as possible for testing.

New MTGs desired for testing include the latest Bowman, Capstone 60 kW, Ingersoll-Rand PowerWorks 70 kW and Turbec 100 kW.

Level of funding is limiting the number of MTGs that can be tested.

Public/Private Partnerships:

Major partners:

MTG Manufacturers: Bowman, Capstone, Elliott, Ingersoll-Rand, Turbec
Test Site: Combustion Laboratory at the University of California at Irvine
Major Subcontractors: Energy Systems Services, CAMS Welding & Design, Paragon, Ferco
Funding Sources: SCE, DOE, EPRI, CEC, CERA, CERTS, Connected Energy

Organization:	NATIONAL RURAL ELECTRIC COOPERATIVE ASSOCIATION
Project Title:	MICROTURBINE PERFORMANCE EVALUATION
Presenters:	ED TORRERO
FY 2000-2001 Funding:	$50,000
Start/Completion Dates:	OCTOBER, 1999 – JANUARY 31, 2003

Overall Project Purpose and Objectives: Demonstrate and field test a comprehensive set of microturbine generators at a broad spectrum of participating cooperative sites across the nation in order to:

- Measure the performance, reliability, and maintainability of microturbine generators in actual real-world operation
- Determine representative economics including the impact of operational and thermal recovery factors
- Identify any major permitting, interconnection, and code compliance issues needing attention
- Benchmark the current technology and identify any crucial remaining developmental needs
- Identify promising types of applications and related electrical production modes
- Assess the prospect for future microturbine use by co-ops and by their customers

This program represents a synergistic partnership between the U.S. DOE Industrial Power Generation Program-Oak Ridge National Laboratory, nine major rural electric cooperatives, the Cooperative Research Network of the NRECA, and the Electric Power Research Institute. The overall demonstration cost is $1.3 million, of which DOE is funding $0.2 million.

This Program represents a broad range of microturbine manufacturers and climate-application environments. By year-end 2001, seven microturbine units have been installed and operated. These represent not only a broad range of climates but also three fuel types and encompass units from each of the major US manufacturers.

Promising technologies are being identified to improve the energy, environmental, and financial performance of power systems for commercial and industrial manufacturing and processing. The results will help enhance the development and implementation of more efficient customer-sited generation and distributed power systems including accelerated customer awareness of innovative power systems.

FY 2001 Results and Accomplishments: Detailed reporting procedures were developed to assure collection of key demonstration participant results including installation experience and related costs as well as operating energy profiles. To streamline reporting of critical operating data, the program developed special software spreadsheets that collect, verify, and analyze monthly energy performance. By year-end, seven co-op sites have been installed covering a wide range of environments and applications. One, for example, is a gas fired unit at a Colorado greenhouse; another, an oil fired unit at an Anchorage warehouse. Although the program is ongoing, its results have already combined with a joint data sharing from a related EPRI program to enable fundamental assessments of: technical maturity, installation and operation costs, energy efficiencies, and the likely impact of thermal recovery endeavors.

FY 2002 Plans and Expectations: Additional units will be installed from an additional U.S. manufacturer just now making units available. Additional installation and operating data will be acquired that will be sufficient to wrap-up the program by the end of CY2002.

Public/Private Partnerships: Imbedded in CRN research efforts is a strong outreach effort that includes presentations to co-op and industry working groups, as well as DoE meetings. Moreover, the CRN and EPRI microturbine programs share data and most importantly have a common Microturbine Users Group to exchange demonstration assessments. In addition, information and results are made available to all CRN co-op members and are posted on the NRECA-CRN web sites. Moreover, NRECA Annual Meeting displays and presentations reach over 10,000 key senior co-op management and Directors.

Industrial Gas Turbine Project Summaries

Organization:	CATALYTICA ENERGY SYSTEMS, INC.
Project Title:	COMPONENT DEVELOPMENT TO ACCELERATE COMMERCIAL IMPLEMENTATION OF ULTRA-LOW EMISSIONS CATALYTIC COMBUSTION
Presenters:	DAVE HATFIELD
FY 2001 Funding:	$1,600,000
Start/Completion Dates:	OCTOBER 2000 – SEPTEMBER 2002

Overall Project Purpose and Objectives: Catalytica Combustion Systems, Inc. is commercializing catalytic combustion technology for gas turbines to achieve nitrogen oxides (NOx) concentrations in the turbine exhaust of 2.5 ppm or lower. This technology, incorporated in the Xonon Combustion System, is operating in a 1.5 MW industrial gas turbine engine connected to the electric power grid at Silicon Valley Power in Santa Clara, California. Achieving NOx emissions at these levels in the combustion system (rather than through cleanup of the exhaust gas), without compromising gas turbine performance, will reduce the cost and potential environmental impact of ultra-low emissions in gas turbine installations and make ultra-low emissions performance available in more gas turbine applications.

In view of the value of catalytic combustion in gas turbines, this program is directed at overcoming the remaining risks and barriers that inhibit widespread commercial adoption of catalytic combustion technology. These barriers lie in the technical challenge of adapting catalytic combustion technology to gas turbines having different cycles and/or operating requirements. Also, reducing the cost of the technology can accelerate its acceptance.

In light of these barriers, Catalytica is engaged in an effort to develop an expanded technology base for catalytic combustion to facilitate its application in the engines of a broad set of manufacturers and applications, and to reduce its cost. In this program, opportunities for facilitating market acceptance of catalytic combustion are placed in three categories: 1) Cost reduction, 2) Broadened operating range and 3) Extension to backup diesel fuel.

Most system designs incorporating catalytic combustion into a gas turbine employ a preburner to obtain the optimal catalyst inlet temperature. The development of the preburner with the required low NOx can be a time consuming effort that extends the time to a commercial product. Two innovative preburner designs will be developed and evaluated and demonstrated on full-scale engine hardware.

Some fraction of the industrial gas turbine market will require the ability to use a backup fuel stored on site. The traditional and most available backup fuel is diesel oil. An innovative system design is proposed to utilize diesel as a backup fuel in a gas turbine equipped with catalytic combustion. Work will be directed at preliminary system design, life cycle cost evaluation and subscale rig demonstration of the technical approach.

FY 2001 Results and Accomplishments: This program is divided into 5 major tasks, each to be reported separately.

Task 1.1: Catalyst Life Extension (Cost Reduction)
Development of a new formulation of Pd-based catalyst for use as an interim hot-stage catalyst was completed in September 2001. Two catalyst formulations were tested in CESI's subscale test facility and both were aged for 2000-h under severe simulated combustion conditions. A formulation with a new supporting oxide and modified method of preparing the active Pd phase was chosen because of superior activity, superior aging resistance, greater cohesiveness, and simplified processing compared with our current hot stage materials. CESI expects to adopt this catalyst for commercial applications following a process development (optimization and scale-up) project by our Process Development department.

The development of alternative (not including the platinum group metals) catalyst materials also made significant progress during 2001. A high throughput test reactor was used to investigate about three dozen (1-gram scale) catalyst samples. Two refractory supporting oxides were developed. Promoters (activators and stabilizers) are being sought and processing conditions optimized using the screening reactor to test performance. Specific candidate catalysts were examined after aging in a high-temperature, high-pressure, high-steam environment for several thousand hours.

Task 1.2: Catalyst Module Cost Reduction (Cost Reduction)

Axial Support Structure (TFA)
Material testing started to validate the design and manufacturing processes for this critical component. As a result of testing, modifications were made to provide a more consistent weld. Weld process specifications were generated and published for improved process controls.

Catalyst Module Container
Catalyst module container cost reduction design has resulted in a preliminary design for which analysis is continuing. Preliminary design reviews have been completed and the final design is in process.

Task 2.1: Preburner Catalyst Secondary (Broadened Operating Range)
CESI has identified performance requirements and completed analysis the secondary catalyst. Technical risks have been identified and evaluated. Analysis indicates lower NOx emissions and lower combustor pressure drop compared to the current designs.

Task 2.2: Catalytic Pilot Secondary (Broadened Operating Range)
Testing has commenced in UCI's generic atmospheric combustor rig with promising results. Additional concepts for a catalytic pilot design have been proposed to, and discussed with Solar. Preparations for an "intermediate pressure" test are ongoing at UCI. Preparations have started for a high pressure test at Solar.

Task 3: Conversion to Backup Diesel Fuel (Extension to backup diesel fue)
Chemical processes for processing No. 2 Diesel into a gaseous mixture were reviewed to define the range of gas compositions that would be the fuel for the catalytic combustion system. A range of compositions was defined representing catalyst fuel feed composition from processed diesel fuel. A catalyst test plan has been developed. Initial evaluation of the fuel processing system with an outside Vendor is nearly complete. Initial results show a capital cost above target.

FY 2002 Plans and Expectations:

Task 1.1: Catalyst Life Extension
New correlations for transport and for kinetic rates derived from this task will be incorporated into CESI's catalyst design model. A program to continue development of this catalyst with a full-scale (15-in vs. subscale 2-in. diameter) test is schedule for mid 2002. If the performance of the new

interim catalyst is acceptable, CESI will adapt it as the commercial standard for the hot-stage catalyst material.

Task 1.2: Catalyst Module Cost Reduction
Work will continue on the axial support materials testing and evaluation. These tests will determine the creep/rupture properties and confirm the structural analysis of the axial support. Fatigue testing will validate material capability as well as geometry specific elements of the TFA design.

Task 2.1: Catalyst Secondary in Preburner
Analysis of autoignition and flame holding in the main stage fuel/air mixer will continue. Design and analysis of the catalytic module will be continuing. Full scale atmospheric testing of the selected design is planned to bring the task to completion

Task 2.2: Catalytic Pilot
Testing will be completed at UCI in the atmospheric. High pressure rig testing at Solar Turbines will be the final activity for this task.

Task 3: Conversion to Backup Diesel Fuel
The design of the catalytic system will be completed. The system will be tested for technical feasibility. The economic analysis will be completed to determine the economic feasibility of this system in commercial practice.

Public/Private Partnerships: Task 2.2 (Catalytic Pilot) includes support from Solar Turbines and University of California, Irvine. UCI is conducting rig tests to define the parameters of performance of a catalytic pilot system. Solar Turbines participation is full scale, full pressure testing of the system to validate UCI testing for engine conditions.

Organization:	PRECISION COMBUSTION, INC.
Project Title:	CATALYTIC COMBUSTOR FOR ULTRA-LOW NOX ADVANCED INDUSTRIAL GAS TURBINES
Presenters:	DR. SHAHROKH ETEMAD
FY 2001 Funding:	$ 1,400,000
Start/Completion Dates:	SEPTEMBER 2000 – SEPTEMBER 2002

Overall Project Purpose and Objectives: Develop a superior catalytic combustor technology for industrial gas turbines applications that offers ultra-low NOx (<3ppm), low temperature catalytic reactor lightoff, high firing temperature operation, high resistance to pre-ignition or flashback, tolerance to fuel/air unmixedness, wide turndown, more durable catalyst and fuel-flexible operation.

Partner: Solar Turbines Inc. is providing technical requirements as well as high-pressure rig time.

Milestones:

- Fuel-flexible sub-scale reactor operation.
- Full-scale full-pressure operation demonstrating ultra-low emissions.
- 1000-hour durability demonstration.

Benefits:

- Successful demonstration and development of this approach will provide a major incentive for follow-on engine testing and field-testing by industrial gas turbine engine manufacturers.
- This ultra-low emissions technology can be incorporated in new machines and also be readily retrofitted to existing industrial engines.

FY 2001 Results and Accomplishments:

- Demonstrated sub-scale reactor operation at 6 atm. on natural gas, biomass, gasoline and pre-vaporized diesel fuel.
- Designed, developed and successfully demonstrated 16 atm. operation of full-scale hardware with natural gas at Solar T70 operating conditions with the following attributes:
- Low lightoff operation without need for a preburner.
- Simple and compact premixer technology.
- Ultra-low emissions. (NOx<3ppm, CO<10ppm)
- Operation at high pressure without flashback or auto-ignition.
- Low combustion dynamics. (<0.18% peak to peak, 0.15 psi)

Milestones Achieved:

- Fuel-flexible sub-scale reactor operation.
- Full-scale full-pressure operation demonstrating ultra-low emissions.

Patents: Method and apparatus claims allowed, 6 additional applications filed.

Technology Migration: A catalytic pilot application for the catalytic combustor has been developed and successfully demonstrated at high-pressure under a separate program with Solar Turbines Inc.

FY 2002 Plans and Expectations:

- Successfully completed 1000 hour durability demonstration. (Dec 2001)
- Completed full-scale, full-pressure demonstration with ultra- low emissions and wide turndown (200F). (Jan 2002)
- Issue final report (March 2002)
- Pursue follow-on full-scale engine test program. (In progress)

Public/Private Partnerships: Working with Solar Turbines to develop follow on program for full-scale engine and field testing. In discussions with a micro-turbine company to develop a catalytic combustor for their product.

Organization:	ALZETA CORPORATION
Project Title:	DEMONSTRATION OF THE SURFACE STABILIZED COMBUSTOR FOR ADVANCED INDUSTRIAL GAS TURBINES
Presenters:	NEIL K. MCDOUGALD
FY 2001 Funding:	$ 832,760
Start/Completion Dates:	SEPTEMBER 29, 2000 – SEPTEMBER 30, 2002

Overall Project Purpose and Objectives: The specific objective of the project is to demonstrate that surface stabilized combustion can achieve ultra-low emission in industrial gas turbines. The demonstration is to be on a test engine in the four to seven megawatt class at Solar Turbines (Solar). The emissions targets are 3-ppm for NO_x, and 10-ppm for both CO and unburned hydrocarbons, all corrected to 15% O_2. The design will be compatible with in-line industrial gas turbine combustion systems. Controls will not introduce undue complexity. Further, the hardware will be comparable in cost to existing lean premixed systems and have an operational life consistent with existing hot section components. The two-year project was initiated in the first quarter of FY 2001. A series of milestones is listed below:

- Kick-off meeting 11/28/00
- Cast injector development
  - Procure vender samples 4/01
  - Process and test samples 7/01
  - Procure injectors from vendor 9/01
  - Process and test injectors 12/01
  - Develop advanced casting process 1/02
  - Finalize advanced casting process 6/02*
- 2-zone injector fabrication for Parallon-75 .... 9/01
- Saturn Engine Demonstration at Solar 5/01
- Taurus 60 injector pressure tests at Solar
  - Improve fuel/air mixing 9/01
  - Single injector tests over operating range 12/01
  - Partial annular test of multiple injectors 4/02*
  - Duel zone injector test over full range 5/02*
- Full annular engine test at Solar
  - Preliminary controls specification 6/02*
  - Fabricate full scale set of injectors 7/02*
  - Finalize operation and control of engine 7/02*
  - Demonstrate over load range of engine 9/30/02*

* FY2002 planned activity

Major partners include:

- Solar Turbines is a leading gas turbine manufacturer and a key partner providing engineering support, pressurized test facilities and engine test facilities as indicated in the milestones above.
- US Filter was a subcontractor and supplier of the initial cast injector bodies. Continuing support is not anticipated.
- Manufacturing Resources Incorporated has initiated manufacturing cost estimates and will ultimately merge the analysis with ongoing evaluations of other Solar components.

- Honeywell participated in design of test hardware for the Parallon-75. Subsequent withdrawal of the Parallon-75 from the market by Honeywell terminated all further involvement.

Project benefits include:

- Cost effective ultra-low emissions combustion system for industrial turbines (4-7 MW) for which exhaust gas treatments are prohibitively expensive.
- For the nation, a simpler and less expensive means of achieving ultra low emission while expanding the energy saving benefits of distributed energy generation.
- For ALZETA, the introduction of a major new low emission technology to ALZETA's product offerings.
- For DOE, clear justification of the value of their support of emerging energy technologies.

Results and Accomplishments to Date: Significant project milestones are listed above with their completion dates. Below are details relative to each milestone that has been met.

- Cast Injector development

  Concepts introduced prior to initiation of the project have proven successful in creating a monolithic metal fiber structure that has the characteristics needed to adapt the low pressure products in commercial use to the high pressure and mass flows associated with gas turbine application of surface stabilized combustion. Previously, only metal fiber sheet material was available for burner fabrication. Manufacture of this material involved air-laying and compression of fiber layers that were subsequently sintered. Welds necessary to form cylindrical geometries from flat sheets introduce heat transfer paths in the extremely high flux gas turbine environment that could lead to flash back. To create monolithic three-dimensional shapes a wet laying process was developed involving suspension of metal fibers, pressure casting, and sintering. US Filter accepted our challenge and provided some promising early samples which were used in atmospheric and pressure testing. A need for further product development resulted in ALZETA initiating internal development yielding a product with strength and pressure drop characteristics more appropriate to high pressure engine application. The initial products of this development are currently being prepared for high pressure testing.

- Two-zone fabrication for Parallon-75:

  Based on earlier successful tests in Parallon-75 hardware, a two-zone surface stabilized metal fiber burner was designed and fabricated. The cast two-zone burner and combustor modifications were completed in September. Honeywell subsequently announced the closure of their Power Systems division which was responsible for Parallon-75 development. Planned tests were canceled and the hardware placed in storage when Honeywell withdrew the Parallon-75 from the microturbine market.

- Saturn engine demonstration:

  A Saturn one megawatt gas turbine adapted for single injector operation was made available by Solar for demonstration of the control characteristics of a surface stabilized combustion injector. The engine was brought through the ignition and start ramp to idle condition the first day of testing. By the third day the system achieved repeatable, stable operation with straight forward control logic. The system responded well when driven by fuel command and by speed control.

- Taurus injector pressure tests:

  While engine compatible mixing systems are being developed at Solar, an idealized mixing system was fabricated to eliminate that variable from injector data analysis. This provided a spatially uniform mixture within ± 3% of the mean fuel concentration. A surface stabilized combustion injector (now referred to as the nanoSTAR™ injector) sized for introduction into the Taurus-60 gas turbine was mounted to this mixer and installed in a high pressure test rig. The injector was tested according to a 'ramp' of pressures, inlet temperatures, and fuel flows which were selected to simulate the Taurus 60 operating conditions from zero to full load. The injector demonstrated stable operation at each of the ten pressure, temperature and fuel flow combinations specified in the test plan. Over a broad range of conditions, where no attempt was made to minimize emissions, NO_x, CO and hydrocarbon emissions were achieved that were simultaneously below 9-ppm, 3-ppm and 1-ppm (all corrected to 15% O_2), respectively. At full load pressure and scaled air flow, low emissions operation was explored resulting in several data points with NO_x emissions less than 3-ppm and CO emissions less than 25-ppm.

FY2002 Plans and Expectations:

- Cast injector development:

  Based on the success to date in the development of an injector fabrication technique, further refinements are planned to optimize flame stabilization at high pressure and preheat conditions.

- Taurus injector pressure tests:

  At least two more series of tests are planned for completion in the next three months. A multi-injector partial annular test will study possible interaction effects between adjacent injectors and further define the low emission operating range of the injectors. A second series will evaluate the control benefits and emission characteristics of a two-zone injector where separate fuel control is provided to two surface zones.

- Full annular engine test at Solar:

  Solar Turbines' final qualifying step prior to engine installation is performed in a full annular test using a modified Centaur engine. Operation and controls specifications for a series of tests will be updated based on data from the Taurus injector tests. An array of injectors will be cast, sintered and instrumented. Tests will be performed over the load range of the engine.

- No known issues will constrict the scope of work.

Public/Private Partnerships:

- The California Energy Commission is co-funding key aspects of the effort proposed to DOE plus additional tasks included in this overview of the composite project.
- Siemens Westinghouse and Chevron are interested observers but have no active role.

Organization:	HONEYWELL INTERNATIONAL
Project Title:	FUEL–FLEXIBLE ULTRALOW–EMISSIONS COMBUSTION SYSTEM FOR INDUSTRIAL GAS TURBINES
Presenters:	IAN CRITCHLEY
FY 2001 Funding:	$ 668,738 (DOE SHARE IS FULLY FUNDED)
Start/Completion Dates:	OCT 2000 – JULY 2002

Overall Project Purpose and Objectives: The objective of this program is to reduce risks in the provision of a catalytic combustion system design aimed at reducing NOx and CO emissions from industrial gas turbines. It is intended that natural gas NOx levels will be below 5 ppm and that the catalyst system be capable of running on Diesel fuel. The catalytic combustion system will be based on the Honeywell ASE50DLE 3.9 MW industrial engine.

The program is split into three sub-tasks:

Sub-Scale Catalyst Development will be carried out by Precision Combustion Inc. (PCI). In this sub-task, the catalyst will be designed and optimized for ASE50DLE engine operating conditions, pressure drop, and emissions on natural gas. This will be achieved by a sub-scale, catalyst test program including conversion rate and combustion tests. Diesel and an alternate fuel will be included. PCI will carry out both the catalyst module design and the sub-scale test program. This task was completed in November 2001.

Combustor Preliminary Design and Development will be carried out by Honeywell, with support from PCI. In this sub-task, the preliminary design of a dual fuel catalytic combustion system for the ASE50DLE engine will be carried out. This will define the form, fit, and function of a combustion system to integrate the catalyst modules into the ASE50DLE engine. This task is scheduled for completion by July 2002.

Emissions Sensor Development will be carried out by Texas A&M University. In this sub-task, an optical, emissions sensing system will be developed to prototype level. This is intended to provide direct measurements of engine exhaust NO and CO emissions levels, which can ultimately provide control signals for the engine air-staging system. In this way, closed loop control of the exhaust NO and CO emissions can be achieved. Specific tasks for this program are; the development of a prototype unit and a demonstration of this unit in an engine environment. This sub-task is scheduled for completion by July 2002.

Potential benefits from this program are as follows:

- The technology being developed combines ultra-low emissions catalyst technology with the accuracy of air-staging control. This allows precise control of flame temperature to minimize emissions over a wide range of power settings, ambient conditions and fuel properties. When combined with direct emissions sensing, the emissions optimization process may be automated, thereby eliminating costly, on-site fine tuning and improving operability.
- By offering ultra-low emissions, this technology can eliminate the need for expensive exhaust clean-up systems. This will reduce costs to the point where it becomes economically feasible for engines in the <10 MW class to meet the most stringent of regulations. Even for less stringent emissions regions, the ultra-low emissions offered will decrease the

environmental impact, easing the permitting process and increasing the market appeal of low emissions systems both in the US and overseas. Lowering pollution from power generation benefits the environment and public health and will encourage the use of energy efficient gas turbines for distributed power generation.

- Fuel flexibility and the ability to burn back-up fuel encourages wider market acceptance of low emissions technology. This can be of benefit here in the US while expanding overseas marketing opportunities where alternative fuels and Diesel are of greater interest.
- The system will be focussed on a current production engine yet will be designed to be retrofitable, encouraging adoption of low emissions technology.
- Continuous emissions monitoring (CEM) is easily incorporated at much lower cost than currently possible with conventional CEM systems. The technology will also be able to offer a substantial improvement in emissions measurement accuracy, an increasingly important factor as emissions levels are lowered. The emissions measurement technology is applicable to any engine.

FY 2001 Results and Accomplishments:

- Sub-scale catalyst module tests have demonstrated the ability to achieve less than 5 ppm NOx at 100 to 50% load conditions operating on methane or simulated land-fill gas (65/35% methane/carbon dioxide). Corresponding HC levels were less than 1 ppm. Data shows that the catalyst will light-off at conditions above ~60% power on natural gas. However preheating may be necessary for the land-fill gas. Hysteresis allows the catalyst to operate to power levels below 50% once lit on either fuel
- Initial sub-scale catalyst testing with Diesel fuel has demonstrated that the catalyst module can light off and operate on prevaporized Diesel fuel. NOx emissions were 9 ppm at 4 bar, somewhat higher than for the gaseous fuels, possibly due to fuel bound nitrogen. Nevertheless, extrapolation to full power conditions suggests that less than 25 ppm NO_x will be achievable.
- Detailed temperature surveys within the catalyst modules have shown temperatures to be well below the metal substrate material limit, at all tested conditions, for all three fuels. Testing showed no degradation of reactor performance resulting from exposure to partially vaporized Diesel fuel.
- A CFD model of the ASE50DLE combustor was created and run, using combustor inlet conditions corresponding to the catalyst exhaust conditions supplied by PCI. As expected, results suggest lower CO levels than the standard DLE design despite the lower flame temperature.
- Based on the results of the sub-scale conversion rate and combustion tests the catalyst module form and sizing for the ASE50DLE application were defined.
- A conceptual design for the integration of the catalyst modules into the ASE50DLE engine was completed. The engine casing design was modified accordingly and hardware is now available for future full scale testing.
- The optical emissions sensing systems for NO and CO were designed and all parts procured.

FY 2002 Plans and Expectations:

- The Diesel fuel sub-scale catalyst combustion testing was completed by PCI in November 2001.
- Honeywell will complete the preliminary design for the integration of the catalyst modules into the ASE50DLE engine. This includes CFD modeling of the catalyst inlet region, this has already been accomplished. Using this model, design refinements will be identified to

minimize parasitic pressure losses and to optimize the air distribution into the catalyst modules. Planned completion is June 2002.

- Texas A&M University completed the laboratory demonstrations of the prototype NO unit in December 2001. A detection limit well under 1 ppm NO per meter of path length in 300 K gas has been demonstrated with this prototype system. The CO prototype system is targeted for April 2002. A demonstration test will be run on an engine at the Honeywell site. This is planned for May 2002.
- Program is to be completed by July 2002.

Public/Private Partnerships: The program is being performed by a team led by Honeywell with Precision Combustion Inc., Texas A&M University and Vericor Power Systems.

Organization:	SOLAR TURBINES INCORPORATED, PRECISION COMBUSTION INC.
Project Title:	NEAR-ZERO NOx COMBUSTION TECHNOLOGY
Presenters:	MIKE DONOVAN (SOLAR) , SHAH ETEMAD (PCI)
FY 2001 Funding:	$254 K
Start/Completion Dates:	OCTOBER 2000 – SEPTEMBER 2002

Overall Project Purpose and Objectives: This project assesses a unique catalytic combustion concept that has the potential of reducing gas turbine NOx emissions to < 3ppm on natural gas. Solar and sub-contractor Precision Combustion (PCI) are conducting rig tests of PCI-designed rich/lean catalytic combustor modules at conditions representative of Solar's 7.5 Mw Taurus 70 engine. The rig testing will serve as a proof-of-concept evaluation of the PCI technology in a realistic test configuration and at realistic industrial gas turbine operating conditions.

The major program milestones are:

- the successful operation of a single module at Taurus 70 conditions with sub-3 ppm NOx emissions
- the testing of a set of four catalytic modules in a Saturn engine test facility at Solar. The Saturn testing will be the first ever test of the PCI technology in an engine environment and will establish the control requirements of the rich/lean catalytic combustion concept.

The direct benefit of the technology being advanced in this project will be the ability to achieve ultra-low NOx emissions from gas turbines without exhaust gas cleanup. Such a technology, when commercialized, will allow extremely strict air quality regulations to be met more economically. Benefits will include:

- expanded use of gas turbines for cogeneration and distributed power generation
- lower cost electricity
- reduced emissions
- energy conservation through the growth of gas turbine-based cogeneration.

FY 2001 Results and Accomplishments: PCI completed the design and fabrication of a prototype, full-scale catalytic reactor module for the Taurus 70. A single module was fabricated for high-pressure rig testing at Solar. The full annular combustion system of the Taurus 70 will require twelve such modules.

Initial tests results demonstrated the <3 ppm NOx capability of the PCI system with simultaneously low CO and UHC emissions. Injector modifications and retests were conducted to optimize reactor performance and reduce the flame length downstream of the module.

The program scope was expanded to include an evaluation of the rich/lean catalytic concept in a 1 Mw Saturn gas turbine test facility at Solar. Four Taurus 70 reactors will be required to operate the Saturn engine. Modifications to the test facility have been completed. Fabrication of the reactor modules was started.

FY 2002 Plans and Expectations: The catalytic reactor hardware for the Saturn test will be completed in Q1 of FY 2002. Testing in the Saturn facility is expected to begin in Q2. The tests will represent the first test of the PCI technology in an engine environment. Emissions performance across the engine load range will be documented. Control system requirements will be defined.

Public/Private Partnerships: Discussions are being held with the Caterpillar Technical Center to explore the feasibility of performing catalyst durability tests at the Center.

Organization:	TELEDYNE CONTINENTAL MOTORS – TURBINE ENGINES
Project Title:	ADVANCED MATERIALS IN ADVANCED INDUSTRIAL GAS TURBINES
Presenters:	TED EXLEY OR ROBERT STOLNICKI
FY 2001 Funding:	$103,000 DOE 70% COST SHARE
Start/Completion Dates:	NOVEMBER 1, 2000 – SEPTEMBER 30, 2002

Overall Project Purpose and Objectives: For an advanced version of the 50 kW output power Model 105 microturbine, Teledyne Continental Motors - Turbine Engines (TCM-TE, Toledo, OH) will apply advanced material systems to the turbine stage components (turbine rotor, turbine inlet nozzle, and turbine inlet scroll) to enable a cycle temperature increase from the first generation design to obtain improvement in the thermal efficiency performance by over a factor of 20%. The advanced material systems will also offer a unit manufacturing cost reduction by 50% for the turbine rotor and providing significant other cost reductions in the stationary turbine components.

Two unique and innovative advanced material systems will be investigated to provide the objective benefits. The first is a low cost process for pressure consolidation of powder nickel superalloys, which will be supported by Titanium Products, Inc. TCM-TE has proven the validity of the concept through preliminary efforts using lower temperature alloys. Extension of the manufacturing process to nickel superalloys is the development of the technology proposed for the turbine rotor. Achievement of the objective unit cost reduction is further enhanced by the use of a system, which introduces a new patented flexible pattern mold process to be used for powder consolidation for net shape processing, which will be supported by Consolidated Technologies, Inc.

The second advanced material system is the introduction of a relatively new class of layered materials represented by the application of Titanium Silicon Carbide (Ti_3SiC_2) for stationary turbine stage components, such as the turbine nozzle and scroll. Development of the material characteristics will be supported by 3-ONE-2 LLC. The material offers unique properties for fracture toughness, damage tolerance, high temperature strength, thermal shock resistance, low creep, and oxidation resistance. The material is near net shaped processed by either injection molding or slip casting followed by sintering. Final machining of critical surfaces is easily accomplished as well as mechanical joining to surrounding metallic structures.

The technical effort will conclude with completion of the evaluation of prototype preliminary design components that will establish the validity of these advanced material systems being able to contribute to performance improvement for high thermal efficiency as well as offer substantial cost reductions. Both of these objectives are necessary for microturbines to acquire market share in the industrial markets of the future.

FY 2001 Results and Accomplishments:

- Preliminary design of the turbine rotor, inlet nozzle and scroll accomplished; with the completion of the final thermodynamic cycle, structural analysis, mechanical design and release of drawings.
- Turbine scroll final slip cast tooling fabricated and with initial process development trials completed using the Ti_3SiC_2 material.

- Turbine inlet nozzle segment tooling fabricated for injection molding, debind and sintering trials with the Ti_3SiC_2 material.
- Sub-scale turbine rotor molds produced using flexible rubber patterns, for HIP trials using INCO 713 powder.

FY 2002 Plans and Expectations:

- Process Development. Initial efforts in 2002 will focus on completing the manufacturing process development efforts to successfully HIP (Hot Isostatically Press) the Inco 713LC turbine rotor, fully densify the Ti_3SiC_2 turbine inlet nozzle samples and sinter the Ti_3SiC_2 turbine scroll.
- Component Fabrication. Complete fabrication of tooling and produce a minimum of four each deliverable parts.
- Component Verification. Conduct dimensional inspections and material mechanical property testing. Conduct scroll and inlet nozzle thermal cyclic rig test. Conduct rotor spin test to 120% of design speed.

Public/Private Partnerships: NA

Organization:	SIEMENS WESTINGHOUSE POWER CORPORATION
Project Title:	CO-OPERATIVE RESEARCH AND DEVELOPMENT FOR ADVANCED MATERIALS FOR ADVANCED GAS TURBINES
Presenters:	RAMESH SUBRAMANIAN
FY 2001 Funding:	$650,000 (DOE COST SHARE)
Start/Completion Dates:	OCTOBER, 2001 AND EXPECTED COMPLETION SEPTEMBER, 2003

Overall Project Purpose and Objectives: Siemens Westinghouse Power Corporation is evaluating the performance of innovative thermal barrier coating systems for applications at high temperatures in advanced industrial gas turbines. Improved thermal barrier coating systems are essential to meet the increased performance and reliability requirements of advanced industrial gas turbines.

It has identified that, with an increase in TBC surface temperatures, failure of the coating system can be initiated by sintering of the ceramic top coat – 8 wt. % yttria stabilized zirconia, long before the failure of the bond coat. This program will build upon on new thermal barrier coating concepts, already laboratory proven to be superior to the current state-of-the-art coatings, in overcoming the above limitations and culminate in the completion of an 8000 hour engine test with components coated with advanced TBC systems by October 2003.

After optimizing the manufacturing processes, the new thermal barrier concepts and materials will be proof-tested at a world-class, high heat flux rig. Once proven here, the coatings will be deposited onto components utilizing standard manufacturing processes and demonstrated in a commercial environment. This engine site will provide a low risk, commercial testing environment prior to testing in an advanced industrial gas turbine such as the W501G or next generation (NG) gas turbines.

The early demonstration of coating durability reduces the technical risk of the technology to a level that will be acceptable to our customers. This is the minimum risk, demonstration path for a high pay-off technology and successful infusion of this technology back into our fleet of engines with significant benefits in improved reliability and performance. This initiative to advance the development of thermal barrier coatings for advanced industrial gas turbine components is vital to Siemens Westinghouse in reaching the goal of providing cost effective, efficient, and environmentally sound power generation solutions. Increased efficiency of gas turbines is expected from utilization of advanced TBCs and this leads to a lower cost of electricity and also reduced emissions – both key objectives for US DOE.

Project Events/Milestones Achieved Till 09/30/01:

	Events/Milestones	Date
1	Establish Optimized Parameters for Sinter Resistant TBCs (Concept#1)	5/31/01
2	Complete Determination of Optimized Parameters for Promising Oxide Systems	7/30/01
3	Complete Compilation of Critical Materials Properties	5/27/01
4	Complete Assessment of Cyclic Furnace Life	11/30/01
5	Submit Report on Market Analysis	2/15/01

	Events/Milestones	Date
6	Establish Optimized Parameters for Deposition of TBC (Concept#2)	4/30/01
7	Identify Critical Component Coating Issues	5/30/01
8	Complete TBC (Concept#2) Production Feasibility Study	8/23/01
9	Complete Optimization of Ingot Preparation	8/30/01
10	Determine Cost Effective Process for Deposition of Sintering Inhibitor	6/30/01

Subcontractors and their role:

Turbine Airfoil and Coatings Repair (TACR, llc, formerly Chromalloy Turbine Technologies) is a key partner in our effort to transfer the advanced coatings technology on to components by participating in the deposition trials onto components for the engine test. Initial deposition trials have been completed at Howmet Research Corporation and the process window has been optimized. Howmet also participates in the program by casting superalloy test specimens, blades and vanes. Key performance data of TBCs were conducted at Westinghouse Plasma Center and has participated in the program by providing testing of new TBC coatings. Several key material properties have been determined at Oak Ridge National Laboratory, which will be essential for TBC life prediction. Praxair surface technologies has provided the ceramic powders for APS deposition trials of TBCs. Transtech Corporation has provided ingots for EB-PVD. Applied Thin Films has actively participate in the program by providing coatings for improved TBCs. ECI/LoTEC has participated in the program by examining the feasibility of sol-gel based TBCs for blades and vanes.

FY 2001 Results and Accomplishments:

1. High temperature capable EB-PVD TBC: Four new compositions, initially proposed, have been successfully deposited by EB-PVD and a columnar microstructure was obtained. The sintering resistance of all coatings are superior to that of EB-PVD 8YSZ and this is key to maintaining strain tolerance at high temperatures. The process parameters are also optimized for the best thermal cyclic life.

2. High temperature capable APS TBC: One of the four new compositions was successfully deposited by APS and evaluated for sintering resistance and thermal conductivity. SEM observations of the aged microstructure showed clear indications of superior sintering resistance over APS 8YSZ. Inter-splat boundaries, key to strain tolerance in APS TBC systems, were retained significantly better in the new material than in 8YSZ. An additional benefit of the new chemistry is a 20% lower bulk thermal conductivity, a key parameter for improving engine efficiency.

The ability to deposit new sinter resistant, phase stable chemistries both by APS and EB-PVD increases the range of components that can be coated significantly, consequently increasing the benefits of these new coatings.

3. New TBC chemistries deposited on IGT components: Component coating trials were completed on two W501 FC Row 1 vanes and blades. Optimized deposition conditions were utilized and preliminary eddy current thickness measurements showed that they met production thickness requirements. Microstructure evaluation, composition, thickness profile and determination coating costs are currently underway.

FY 2002 Plans and Expectations:

Project Events/Milestones Planned for FY-2002 (10/01/01-9/30/02):

	Events/Milestones	**Date**
1	Resolve Component Coating Issues and Complete Process Optimization	4/30/02
2	TBC deposition process scale up (Concept#1)	4/30/02
3	Complete Feasibility Study of Disposition of Promising Chemistries by APS	3/31/02
4	Conduct Design Review for risk assessment	6/30/02
5	Deliver W501 FD* Row 1 vanes (for APS new TBC) and Row 1 Blades (for EB-PVD new TBC) for coating deposition	7/30/02
6	Complete Component Coating Qualification	8/30/02
7	Deliver Coated W501 FD Row 1 Vanes (with APS) and Row 1 blades (with PVD) to demonstration site – **tentatively** at a site owned by Calpine in Houston, Texas.	9/15/02
8	Submit Commercialization Plan	3/30/02
9	Final Recommendation & Report on TBC Performance	6/30/02
10	Installation of 501 FD Row 1 vanes and Row 1 blades in the W501FD engine in operation for Calpine Corporation.	9/30/02

Key issue to achieve milestone#7: Availability of engine for demonstration at the right time.

Public/Private Partnerships: Work performed in this program at Oak Ridge National Laboratory has provided key materials property data for life prediction of coatings. Critical TBC performance data is expected to be generated at Westinghouse Plasma Center (a small business), a world class high heat flux facility at Waltz Mill, PA. TACR llc (formerly Chromalloy Turbine Technologies) and Howmet provide production EB-PVD coaters for deposition of advanced TBCs. Several of the new ceramic compositions have been prepared as ingots for EB-PVD by Transtech and as plasma sprayable powders by Praxair.

Organization:	SOLAR TURBINES INCORPORATED
Project Title:	ADVANCED MATERIALS FOR MERCURY 50 GAS TURBINE COMBUSTION SYSTEM
Presenters:	JEFFREY R. PRICE
FY 2001 Funding:	$3,090,000
Start/Completion Dates:	SEPTEMBER 29, 2000 – AUGUST 31, 2003

Overall Project Purpose and Objectives: Solar Turbines Incorporated, under cooperative agreement number DE-FC02-00CH11049, is improving the durability of advanced combustion systems while reducing life cycle costs. This project is part of the Advanced Materials in Advanced Industrial Gas Turbines program in DOE's Office of Power Technologies. The targeted development engine is the Mercury 50 gas turbine under development by Solar Turbines, Inc under the DOE Advanced Turbine Systems (ATS) program (DOE contract number DE-FC21-95MC31173). The original program goal was to improve the durability of the Mercury 50 combustion system to 20,000 hours. Through changes to the combustor design to incorporate effusion cooling in the Generation 3 Mercury 50 engine which resulted in a drop in the combustor wall temperature, the current standard thermal barrier coated liner is predicted to have 18,000 hours life. With the addition of the advanced materials technology being evaluated under this program, the combustor life is predicted to be over 30,000 hours, which is Solar's standard time before overhaul. The ultimate goal of the program is to demonstrate a fully integrated Mercury 50 combustion system, modified with advanced materials technologies, at a host site for 4,000 hours.

The program focuses on a dual path development route to define an optimum mix of technologies for the Mercury 50 and future gas turbine products. For liner and injector development, multiple concepts including high thermal resistance thermal barrier coatings (TBC), oxide dispersion strengthened (ODS)alloys, continuous fiber ceramic composites (CFCC), and monolithic ceramics are being evaluated before down selection to the most promising candidate materials for field evaluation. Preliminary component and sub-scale testing is being conducted to determine material properties and demonstrate proof-of-concept. Full-scale rig and engine testing will validate engine performance prior to field evaluation at a host site.

To ensure that the CFCC liners proposed under this program will meet the target life, engine field testing previously conducted under the DOE sponsored Ceramic Stationary Gas Turbine program is continuing under this program at the two end user field sites. The goal is to demonstrate significant component life, with the milestone of 30,000 hours. Demonstration of long term durability for CFCC combustor liners is critical to the commercialization of CFCC liner materials for the Mercury 50 engine. The current field test engines offer the opportunity to achieve long term testing on the CFCC material systems with environmental barrier coatings through production operation in the gas turbine environment. Successful demonstration of 30,000 hours of production operation will enable CFCC liners to be considered to meet the target life for the Mercury 50 liners. Successful demonstration will also enable the CFCC materials to be considered for other gas turbine engines.

The technical program team assembled by Solar for this project includes:

TBC Suppliers: The Welding Institute, Praxair Surface Technologies, Inc.
University of Connecticut, United Technologies Research Center
CFCC Suppliers: Honeywell Advanced Composites Inc., Goodrich Corporation

Monolithic Ceramic Supplier: Honeywell Ceramic Components, Kyocera Industrial Ceramic Corporation
ODS Alloy Suppliers: Schwarzkopf Technologies Corporation, Special Metals Inc.
TBC Life Prediction: Research Applications Inc.,
Material Characterization: Oak Ridge National Laboratory
Nondestructive Evaluation: Argonne National Laboratory
End Users: Clemson University, Chevron/Texaco, Malden Mills Industries

By reducing life cycle costs, the Mercury 50 gas turbine will be more attractive to the distributed power generation and co-generation market. As the market penetration of the Mercury 50 expands in the near- and mid-terms, the U.S. will benefit from:

- single digit NOx and CO emissions, NOx being a major smog precursor
- reduced CO_2 emissions (on a pound per unit of useful energy basis) due to the growth in co-generation in the near-term and the use of high efficiency gas turbine systems in the mid-term
- lower cost electricity as the benefits of distributed power generation is realized
- more efficient use of natural gas in the U.S. and a reduced reliance on imported oil
- a more robust electric power infrastructure through distributed power generation

FY 2001 Results and Accomplishments: Promising high thermal resistance TBC systems have down selected for testing on sub-scale combustor liners. These systems include thick yttria stabilized zirconia coatings and coatings compositions with lower thermal conductivity. These coating systems will reduce the combustor metal wall temperature, resulting in increased life of the combustion system. Six sub-scale combustor liners have been coated and will be tested in a single injector test rig. Testing has been delayed due to leakage problems at the aft end of the test rig. Modifications to the rig will be completed in March 2002 and testing will begin. Four braze materials are being evaluated for joining of the ODS alloy materials. Sub-scale liners will be manufactured for testing in the single injector rig, following selection of the best joining method. To-date, CFCC liners have been tested for over 40,000 hours of commercial operation at Chevron/Texaco and Malden Mills Industries. A CFCC liner with an environmental barrier coating was tested for 14,000 hours at the Chevron/Texaco site. A method was developed to refurbish CFCC liners following testing. CFCC liners, which had seen over 7000 hours of engine operation, were refurbished with a new environmental barrier coating and are currently continuing engine operation at Texaco.

FY 2002 Plans and Expectations: Sub-scale liner testing of high thermal resistance TBCs and ODS alloys will be conducted this fiscal year. In addition, a full scale Mercury 50 combustor will be coated for early engine demonstration of the most promising TBC system. ODS and monolithic fuel injector tips will be evaluated in the single injector rig. Field testing of CFCC liners at Chevron/Texaco and Malden Mills Industries will continue. Lower cost CFCC liners fabricated with lower ceramic cost fibers will be further evaluated.

Public/Private Partnerships: A set of lower cost CFCC liners, fabricated by Honeywell Ceramic Composites under their DOE sponsored CFCC program, will be tested at the Chevron/Texaco field test site. These liners were provided to the program at no cost. Also, high thermal resistance TBC systems developed by the University of Connecticut under a DOE funded AGTSR program will be evaluated. The program will continue to work closely with Argonne and Oak Ridge National Laboratories in the areas of nondestructive evaluation and material characterization.

Organization:	GENERAL ELECTRIC GLOBAL RESEARCH CENTER
Project Title:	MELT INFILTRATED CERAMIC MATRIX COMPOSITES FOR SHROUDS AND COMBUSTOR LINERS OF ADVANCED INDUSTRIAL GAS TURBINE ENGINES
Presenters:	KRISHAN L. LUTHRA
FY 2001 Funding:	$ 806,000
Start/Completion Dates:	JUNE 15, 2000 – MAY 31, 2003

Overall Project Purpose and Objectives: The major goals of the current program are to design, fabricate, rig test and field engine test 1st stage shroud components made of MI-CMC in a GE 7FA class gas turbine (~150 MW in simple cycle). This effort will be followed with the design, fabrication, rig testing and field engine testing of a combustor liner system in a similar GE gas turbine. Preliminary design & qualification tasks for the shroud application have been completed. CMC shrouds for rig and engine testing have been fabricated, including CMC component processing, deposition of Environmental Barrier Coating (EBC), final machining, and NDE. Rig testing of the shrouds is currently in progress and has already proven to be useful in identification of shroud system design needs. All rig validation testing for the shroud component will be completed in Spring '02. Current plans are to begin engine field testing of the shrouds in the Fall of this year. Development of an MI-CMC combustor liner system is following the shroud effort by about 18-24 months, and is expected to start in Spring '02.

GE Global Research Center (GRC) is the prime contractor and is responsible for fabrication of MI-CMC components using the prepreg preform fabrication approach. GRC is also responsible for developing and validating NDE approaches, for scale-up of the EBC deposition process for components, for validation rig testing of the CMC shroud design, and for general program management. Major partners in this program are GE Power Systems, GE Power Systems Composites (formerly Honeywell Advanced Composites, Inc.), Goodrich Aerospace, and Oak Ridge National Laboratory (ORNL). GE Power Systems is responsible for the design of the shroud and combustor systems, fabrication of all metallic hardware needed for the shroud and combustor systems, rig testing of the combustor liner component, and eventual engine testing of both components. GE PSC and Goodrich are serving as suppliers of shrouds made by the slurry casting perform process for MI-CMCs. ORNL will be assisting GE in the post-test characterization of both shroud and combustor components.

GE's F-class and H-class turbines (70MW to 280MW in simple cycle) are among the most advanced industrial gas turbines currently being offered, and use the highest firing temperatures of the gas turbine fleet. The need for advanced materials, such as CMCs, is therefore much greater than for smaller turbines, which typically operate at lower firing temperatures and still have growth potential using metals with thermal barrier coatings and advanced cooling technologies. At the end of 1999, the installed power generating base for F-class gas turbines in the US and worldwide totaled ~36 GW and ~64 GW, respectively. The proposed program would target application of MI-CMCs to first stage shrouds and combustor liners of F-class machines, which represent an installed base of over 1000 units for retrofit applications. The technology developed would then migrate to other stationary hot stage components, such as transition pieces and nozzles and to all engine sizes.

The use of CMCs in stationary hot stage components such as shrouds, combustor liners, and nozzles could provide an improvement of up to 1.1 percentage points in simple cycle efficiency beyond the current efficiency of ~34%. Furthermore, the use of CMCs in all of these types of components could increase the output by up to 3%, thereby further reducing the cost of electricity. Assuming a growth rate of 6% per year and a market penetration of 20% by 2020, the use of CMCs in gas turbines offers the potential to save annually ~290 trillion BTU of energy, which is equivalent to ~0.29 trillion cubic feet of natural gas at a cost of ~$960 million. The use of CMCs also offers the potential to save ~4.3 million MTCE of CO_2 emissions and ~51,000 MT of NOx emissions per year.

FY 2001 Results and Accomplishments:

- The shroud design for the rig test was completed.
- Critical shroud system features, such as the attachment between the MI-CMC inner shroud and the metallic outer shroud block, were evaluated using several different types of sub-element testing.
- The EBC deposition process was scaled-up and tailorable coatings were demonstrated on shroud components.
- Over 30 MI-CMC inner shrouds were fabricated for rig and engine testing.
- Machining process trials were completed which identified critical quality requirements.
- Metallic shroud system hardware for the rig test was designed and procured.
- The design of the shroud test rig was completed, the test rig was assembled and its operation verified. Initial rig testing of the MI-CMC shroud system was started.
- Transient IR thermography was demonstrated as a useful technique for evaluating MI-CMC components.
- Ranking procedure was developed for identifying quality components using specific property results.
- A commercial engine site (FP&L near West Palm Beach) was identified for field testing of the shroud.
- Presentations of program-sponsored activities were made at the 2000 Power Gen Conference, the 2001 Cocoa Beach Meeting, and the 2001 ASME/IGTI Turbo Expo.

FY 2002 Plans and Expectations: Major 2002 goals for the shroud development effort include the completion of the shroud component rig testing and incorporation of any necessary shroud modifications needed for engine field tests. The high liability associated with a field test in a 7FA machine (~150 MW in simple cycle), especially during summer months, requires that all reliability issues with the shroud design be resolved during rig testing. This heightened scrutiny may require additional rig testing iterations to be performed before the utility customer will be satisfied with associated risks and we can proceed to the field engine test. Also, the timing of the engine test will be dependent on the engine maintenance schedule of the FP&L test site, but is currently expected to begin in Sept-Oct of 2002.

Efforts on the MI-CMC combustor liner component are to start in Spring'02, with preliminary design of the system to be used for rig testing, and fabrication trials of the CMC liner from this design, to be completed in FY02. A major technical risk for this effort is that a full-sized CMC liner would be larger than any previous MI-CMC component made by GE or any other vendor. Consequently new sources of processing equipment of sufficient size and capability may be needed for CMC liner fabrication. Splitting up the fabrication process into separate steps to be performed at various vendor locations adds technical risk to the program in terms of assuring the quality of the fabricated liners. Coordination of the efforts at these new vendors also adds risk to the program schedule. Another technical risk, as with the shroud program, is the interface loading of CMCs from the metallic support structure.

Public/Private Partnerships: The recent acquisition of Power Systems Composites, LLC, (formerly Honeywell Advanced Composites) serves as an indication of GE's commitment to making CMC turbine components a commercial reality. Also, as noted above, Goodrich Aerospace and ORNL are active participants in the program.

Organization:	OAK RIDGE NATIONAL LABORATORY
Project Title:	MICROSTRUCTURAL EVALUATION OF CFCCS IN SUPPORT OF THE GAS TURBINE INDUSTRY
Presenters:	KARREN L. MORE
FY 2001 Funding:	$250,000
Start/Completion Dates:	START FY 1997 – CURRENT AND ONGOING WORK

Overall Project Purpose and Objectives: Advanced ceramic materials are being incorporated into hot sections of land-based industrial gas turbines in order for these engines to meet strict emission standards by operating at higher temperatures. Recent advancements in the development of SiC-based continuous fiber-reinforced ceramic composites (CFCCs) and protective coatings (environmental barrier coatings or EBCs) having improved thermal and environmental stability have resulted in the use of these materials (CFCC with an EBC) as combustor liners in several Solar Turbines' engines at two different test sites (Chevron and Malden Mills). The most recent engine-test completed at the Chevron test site that included a set of EBC/CFCC combustor liners accumulated ~14,000h in a Solar Turbines Centaur 50S engine. However, in order to achieve the lifetimes required (>25,000h), considerable materials development work must still be conducted, especially in the area of EBCs.

To date, this project has focused on understanding the material's degradation mechanisms in combustion environments in order to further improve the EBC and CFCC environmental stability. This collaborative effort involves material suppliers (CFCC manufacturers B.F. Goodrich and GE Power Systems Composites, EBC manufacturer United Technologies Research Center), turbine manufacturers (Solar Turbines and GE), and national laboratories (Oak Ridge National Laboratory and Argonne National Laboratory.) The work will continue to focus on conducting simulated exposures of (in ORNL's Keiser Rig) and subsequent microstructural evaluation of experimental CFCCs and EBCs provided by the manufacturers. Laboratory-exposed materials will be compared to actual components exposed in engine tests to evaluate microstructural stability in combustion environments and to fully evaluate degradation modes and failure mechanisms of both the CFCCs and protective coatings.

For combustion environments, high-temperature oxidation of the Si-based materials limits the lifetime of current CFCCs. In particular, high water-vapor pressures and extremely high gas velocities in such environments cause accelerated oxidation as well as volatilization of protective silica layers that form during oxidation. Recent exposures of SiC/SiC composites either to actual engine tests in a Solar Turbines engine or simulated combustion environments in ORNL's Keiser Rig revealed unacceptable levels of materials corrosion and recession rates that significantly reduced the lifetimes of the material or component. Due to the susceptibility of Si-based materials and composites to moist environments, the development of stable EBCs has become necessary for the successful implementation of these materials in gas turbines.

The experience and materials knowledge gained from the current project (that has focused only on land-based industrial gas turbines) will also be applied to the possible implementation of EBC/CFCC combustor liners for use in microturbines. As microturbines seek higher operating temperatures to attain higher operating efficiencies, improved materials for hot section components will be required. Thus, accelerated oxidation at high water-vapor pressures will also be a problem in microturbines. However, as this issue has been addressed in the current industrial gas turbine work on CFCC combustor liners and as degradation mechanisms of Si-based composites become better understood as part of the current program, the advanced techniques used to understand materials performance in a stationary gas turbine can be applied to the development of these materials for similar application in microturbines.

The microstructural evaluation of Si-based composites conducted at Oak Ridge National Laboratory is in support of the Office of Power Technologie's current programs to develop improved, advanced materials for the next generation of clean, energy efficient, reliable, and affordable distributed generation technologies including gas turbines and microturbines. The primary goal of this particular ORNL project is directed at the incorporation of Si-based ceramic composites into hot-sections of land-based industrial gas turbines and microturbines in order for these engines to significantly improve operating efficiencies and to meet strict emission standards by operating at higher temperatures.

FY 2001 Results and Accomplishments:

- Completed detailed analyses of water-vapor effects on SiC/SiC composite stability and life. This involved the exposure of different manufacturer's SiC/SiC materials to high-temperature, high-water-vapor pressure environments in the ORNL "Keiser Rig" to evaluate the microstructural stability and to determine recession rates of the composites in simulated combustion environments. The composite materials were exposed for >4000h for comparison with similarly-processed materials exposed in engine tests. (FY 2001 Milestone)
- Completed investigation of the long-term durability of selected environmental barrier coatings (EBCs) on SiC/SiC CFCCs in high water-vapor pressure environments. The EBC/CFCCs were exposed for >6000h in ORNL's Keiser Rig. Extensive microstructural evaluation was conducted to evaluate the protective capability of different EBC formulations. (FY 2001 Milestone)
- Conducted full microstructural and mechanical evaluation of EBC/CFCC combustor liners which ran in an engine test for ~14,000h at the Chevron, Bakersfield, CA test site. EBC and CFCC areas which appeared undamaged as well as those exhibiting extensive structural damage on both the inner and outer liners were characterized in order to understand degradation mechanisms in the combustion environment. These results were presented to all project collaborators at a meeting held at Oak Ridge National Laboratory on March 14, 2001.
- Invited Talk at IGTI TurboExpo 2001, June 5, 2001, New Orleans – "Recent Evaluation of CFCC Combustor Liners With EBCs After ~14,000h Engine Test," K.L. More, P.F. Tortorelli, L.R. Walker, K.S. Trent, H.E. Eaton, E.Y. Sun, G.D. Linsey, N. Miriyala, J. Kimmel, J.R. Price, W.A. Ellingson, J.G. Sun, D. Landini, and P. Craig.
- "Effects of High Water Vapor Pressures on the Oxidation of SiC-Based Fiber-Reinforced Composites," K.L. More, P.F. Tortorelli, and L.R. Walker, *Materials Science Forum* Vol. **369-372** (2001) pp. 385-394.
- Visited GE Power Systems Composites (formerly Honeywell Advanced Composites, Inc.) on August 29, 2001 to review (1) combustor liner project status and (2) ongoing characterization work of GE Power Systems Composites advanced composite materials.
- Collaborative Industry-Laboratory Partnership on CFCC Combustor Liner Project received the *2001 Research Partnership Award* from The Office of Power Technologies "Ceramic Stationary Gas Turbine Development Team: Nondestructive Evaluation Development for Stationary Ceramic Components"

FY 2002 Plans and Expectations:

- Prepare a report and present results on the evaluation of the set of EBC/CFCC combustor liners which were engine tested for ~14,000h at Chevron test site (FY 2002 Milestone). This milestone is currently being met. A manuscript has been reviewed and submitted to ASME for publication (and for presentation at IGTI TurboExpo 2002, Amsterdam, June 3-6, 2002) "Evaluating EBCs on Ceramic Matrix Composite Combustor Liners After ~14,00h Engine Exposure," K.L. More, P.F. Tortorelli, L.R. Walker, J.B. Kimmel, N. Miriyala, J.R. Price, H.E. Eaton, E.Y. Sun, and G.D. Linsey.
- Will continue using ORNL exposure facilities to evaluate new and improved EBC formulations for CFCC combustor liners for future engine tests.
- Will conduct extensive microstructural and mechanical evaluations on a new set of engine-tested combustor liners having different EBC and CFCC materials.
- Will begin evaluation of GE melt-infiltated SiC/SiC composites after engine testing at GE facility.
- Will apply experience gained and techniques used as part of current CFCC combustor liner project for stationary gas turbines to similar application for CFCC combustor liners in microturbines.
- Co-organizer of a session at TMS 2002 – 131st Annual Meeting, February 18-20, 2002 "Water Vapor Effects on Oxidation of High-Temperature Materials"
- Co-organizer of a session at IGTI TurboExpo 2002, Amsterdam, June 3-6, 2002 "Environmental Barrier Coatings for Advanced Ceramics"

Public/Private Partnerships: N/A

Organization:	ARGONNE NATIONAL LABORATORY
Project Title:	NONDESTRUCTIVE EVALUATION TECHNOLOGY DEVELOPMENT FOR MATERIALS FOR DISTRIBUTED ENERGY RESOURCES
Presenters:	WILLIAM A. ELLINGSON
FY 2001 Funding:	$300,000
Start/Completion Dates:	MAY, 1999 – SEPTEMBER, 2007

Overall Project Purpose and Objectives: The purpose of this project is the development, application and evaluation of nondestructive, non-contact technologies for ceramic components for advanced, high-efficiency microturbines and industrial gas turbines. Ceramic components are being developed to increase the operating temperature and resulting efficiency of gas turbine engines. These advanced high-temperature ceramic components include; (a) low-cost monolithic ceramics for hot-section components of microturbines and industrial gas turbines and (b) environmental barrier coatings (EBCs) being developed to protect monolithic and composite ceramics from oxidation or material recession caused by turbine environments.

Specific goals for this project include: 1)development of high-speed 3-D volumetric x-ray computed tomographic imaging technology with defect detection capability of less than 400um throughout the volume of large monolithic ceramic rotors or similar components, 2)development of appropriate automated 'feature" recognition digital image processing packages that would allow the 3-D x-ray imaging system to be a "stand-alone" automated system, 3)-development of NDE methods for EBCs applied to monolithic ceramics that allow determination of EBC thickness reductions, detection of delamination between the EBC and the substrate, 2-D mapping of extent of foreign object damage(FOD) on the EBC and determination of changes in certain physical properties of the EBC such as thermal conductivity and 4)-Development of NDE methods for EBCs applied to composite ceramics that would allow determination of EBC thickness reductions, detection of delaminations between the EBC and the composite substrate, 2-D mapping of extent of foreign object damage(FOD) and determination of changes in certain physical properties of the EBC such as thermal conductivity.

Selected milestones include: in FY02 1)-Complete high speed 3D x-ray CT image test of rotor with correlation between NDE data and destructive analysis 2)-Complete NDE data acquisition, destructive correlation of NDE data with damaged EBC/monolithics; FY03 1)-Complete initial automated feature detection scheme for 3 images; 2)-Complete comparison of CMOS to TFT detector, 3)-Complete NDE data acquisition with various laser wave lengths and correlate with damaged EBC-monolithics; FY04 1)-Complete initial high speed 3D x-ray acquisition set up with selected x-ray detector, 2)-Correlate NDE data with destructive data for several EBC-monolithic specimens; FY05 and beyond: To be established based on earlier results.

In this project, we are cooperating with several industrial partners as well as involved National Laboratories. These partners include: a)-Perkin-Elmer Electrooptics in Santa Clara, CA, for development of large-area, high read-out speed, high spatial resolution flat panel detectors, b)-Envision Product Design in Anchorage, AL, for new CMOS-based high spatial resolution line and area x-ray detectors, c)-Honeywell Ceramic Components in Torrance, CA, as part of the development of low-cost large-size monolithic ceramic rotors, d)-St. Gobain Industrial ceramics as part of new efforts to develop low-cost monolithic components (In discussion process), e)-United Technologies Research Center (UTRC) as part of their effort to develop EBCs for ceramics composites as well as monolithic ceramics, f)-GE-Power Systems Composites in Newark, DE, as part of their development of lower cost ceramic composites g)- Goodrich Ceramic composites in Santa Fe Springs, CA, as part of their development efforts for lower cost ceramic composites, h)- Rolls-Royce/Allison in Indianapolis, IN, as part of their efforts to evaluate EBC/monolithic components in a field test engine, and i)-Oak Ridge National Laboratory as part of their interests in development of EBCs for monolithic ceramics as well as development of a knowledge base for monolithic ceramics.

The benefits that this project on NDE technology would provide on a national basis (including DOE) include: 1)- providing a necessary technology without which advanced materials would not be employed because it is absolutely necessary to reliably ascertain the "status"(health) of any component of these materials at scheduled or unscheduled engine outages and 2)- providing a technology that allows advanced ceramic materials to become a viable material option in the market place through improved reliability and lower cost.

FY 2001 Results and Accomplishments: There are several results and accomplishments. First, as part of the NDE development effort to reduce costs and reduce the probability of flaws in large monolithic ceramic components for microturbines, specifically rotors of diameter 7-inches, work on high-speed 3-dimensional x-ray tomographic imaging was advanced through acquisition, installation and computer interfacing of a large 17-inch by 17-inch amorphous silicon flat panel x-ray detector. Tests were conducted with this detector that demonstrated full volume x-ray image data acquisition in less than 6 minutes. Further, this year, we imported a new image reconstruction algorithm developed at Argonne and we wrote necessary software to allow output of the 2-D area detector to be interfaced to this high-speed reconstruction software. This resulted in reducing the full-volume image reconstruction time from over 1 hour to less than 10 minutes. Since the blades on the rotors have very complex contours, these contribute to noise in the x-ray tomographic images. Data was obtained that allowed comparisons between rotor sections without blades to those with blades. Use of various image-processing methods has demonstrated that very small defects, less than 300 um can be detected at the very center of the interior of the bladed rotors. Work was also initiated on the development of a detail-detection diagram for the flat-panel detector that will allow estimation of the smallest feature detectable at any region inside the rotor. The technology of the flat panel detectors is changing and new detectors are to be installed in FY02 with a pixel size reduce by 20%. We also began to study how to do "automated' feature analysis of features detected by the 3D images. In our efforts to develop NDE technology for EBCs, we conducted our first series of exploratory NDE tests on monolithic silicon nitride vanes that had a proprietary EBC. These vanes had been run in the Rolls-Royce/Allison field test engine. We received these coated vanes from Oak Ridge National Laboratory as part of our cooperative effort. The vanes received had various run times (542 and 1621 hours), but also included as-produced vanes. Initial laser scatter NDE tests suggested that the laser scatter data are related to EBC thickness. Limited destructive analysis verified this. Arrangements were made to have optical transmission characteristics established for these EBCs as the laser wavelength selected for the initial scans was selected based on prior data from other coatings but not this composition. In addition, since the vanes have a very complex shape, trying to use an x-y-z-theta motion stage would not be effective. Therefore a 6-axis robot was installed and initial coupling to a computer established. The CAD file of the turbine vanes can now be transported to the robot for positioning. We also conducted limited studies of specially prepared coupons made with UTRC's EBCs on SiC/SiC ceramic composites. Tests were run on delamination specimens, but not specimens with variations in porosity or specimens with cracks. This will receive more attention in the next FY.

FY 2002 Plans and Expectations: Efforts for FY02 will further the various NDE technologies in order to achieve the goals of the project. To further the low-cost, higher reliability efforts, we will continue with developments toward technology for high speed 3D x-ray tomographic imaging for large cross section monolithic ceramic components. To this end we plan to develop a detail-detection diagram that demonstrates the probability of detection of various sized features of various densities at selected interior positions within a large component such as a full sized ceramic rotor. Extensive correlation's between the NDE data and destructive analysis will be conducted. All initial work will be done on gelcast AS800 rotors or segments of these rotors, as these are available. In addition, as part of this work, since the current large-area detector has 400um square pixels, negotiations are underway for an experimental 200um square pixel detector also to be 17-inches by 17-inches. We plan to have this in during this FY and run initial tests. Additionally, in cooperation with another NDE project, we will evaluate a new 80 um square x-ray detector, but this is now limited to a line detector and not an area detector. We will also pursue developments for NDE technology for EBCs on monolithic ceramics. In this effort, we are utilizing EBCs on AS800 from the Rolls-Royce/Allison field tests. Specific efforts are addressed to use of elastic optical laser scatter for detection of thickness reductions and delaminations. Tests for damage detection will also include tests using impact damage using an impact facility at ANL. As a part of this effort, analytical modeling efforts are under way in order to allow parametric studies that would allow correlation between the resulting laser scatter data and material parameters such as a delamination or a reduction in thickness. Efforts in FY02 will be increased towards quantifying detectability of delaminations, porosity variations and cracks in EBCs deposited on SiC/SiC composites.

Public/Private Partnerships: There are several related NDE activities from which this project benefits. These include: 1)-Development of elastic scatter laser methods for study of machining damage to monolithic ceramics funded by DOE/EERE/OTT, 2)-Development of NDE technology for Thermal Barrier Coatings (TBCs) funded by DOE/Fossil/ Advanced research, 3)-Evaluation of NDE technology for study of positioning of laser-drilled holes in C/SiC composites funded by private industry, 4)-Development of NDE technology for oxide-based composites funded by DOE/Fossil/NGT and 5)-Direct Digital x-ray imaging funded by DOE/BES/Technology Research.