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The DOE Turbine Program: Overall Program Description

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6.0.1-1 Introduction

The focus of the DOE Office of Fossil Energy (FE) Advanced Turbine Program is on the key technologies needed to enable development of advanced turbines that will operate cleanly and efficiently when fueled with coal-derived synthesis gas and hydrogen fuels. Developing turbine technology to operate on these fuels is critical to the development of advanced zero-emission power generation technologies such as FutureGen type plants that will minimize emissions of carbon dioxide. These plants will most likely be based on integrated gasification combined-cycle systems, and consequently should be capable of utilizing coal-derived synthesis gas as well as hydrogen. The Turbine Program is an investment in secure U.S. electric power production that is clean, efficient, affordable, and fuel-flexible, and will make possible the continued use of coal our Nation's largest domestic fossil energy resource — coal.

The FE Turbine Program R&D is supporting the adaptation and development of existing and new advanced gas turbines for application to coal-derived hydrogen fuels and synthesis fuels. Studies, both ongoing and completed, have identified concepts for optimization and modification of large frame combustion turbines in integrated gasification combined-cycle (IGCC) applications. These studies have determined the concepts, technologies, and modifications needed to meet the goals for near-zero emissions, higher efficiency, and lower capital cost machines for application to coal-derived fuels such as syngas and hydrogen. Technology base activities will provide the basic underpinning for the Program areas to resolve advanced systems, material, heat transfer, aerodynamic, and combustion technical issues, as machines and systems are modified for high-hydrogen fuels derived from coal.

The FE Turbine Program, as administered by DOE's National Energy Technology Laboratory (NETL), is designed to provide low-cost solutions to Presidential initiatives, and provide technological solutions to high level DOE goals. These initiatives include:

1) Climate Change Initiative
(http://www.whitehouse.gov/news/releases/2002/02/climatechange.html)
2) Clear Skies Initiative
(http://www.whitehouse.gov/news/releases/2002/02/clearskies.html)
3) FutureGen Initiative
(http://www.fe.doe.gov/programs/powersystems/futuregen/)
4) Hydrogen Initiative
(http://www.eere.energy.gov/hydrogenandfuelcells/pdfs/review04/2_miller_philadelphia_04.pdf)

Specific goals presented below are written for Advanced Coal-Based Power Systems, and are designed to support these Presidential initiatives. The Advanced Power Systems goals are addressed for the most part by the efforts of the DOE-FE Gasification and Turbine Programs. This is particularly true for the 2010 goal, with improved efficiency and costs. The 2012 goal brings in the additional accomplishments and progress made by the CO_2 Sequestration Program.

The Advanced Power Systems goal for 2010 states:
By 2010, develop advanced power systems capable of achieving 45–50% thermal efficiency at a capital cost of $1,000/kW or less for coal-based plant utilization.

The Sequestration interim goal for 2012 states:
By 2012, R&D will be completed to integrate this technology with CO_2 capture and sequestration into a zero-emissions configuration(s) that can provide electricity with less than a 10 percent increase in cost.

A main objective of the Advanced Turbine Program is to support the FutureGen Initiative. The FutureGen Initiative and the associated project can be described as an effort to "…*validate the technical feasibility and the economic viability of "zero" emission energy from coal. By 2012, begin operation of a nominal 275-megawatt (MW) prototype plant that will produce electricity and hydrogen with "zero" emissions; and prove the effectiveness, safety, and performance of CO_2 sequestration."*

The Fossil Energy 2015 goal states:
"Create partnerships that provide technology by 2015 for near-zero emission plants (including carbon) that are fuel-flexible and capable of multi-product output, and efficiencies over 60 percent with coal and 75 percent with natural gas.

It is FE's intent that program spending will be completed during the stated goal date, thereby completing the R&D at a full-scale prototype or component scale. It is through this prototype scale testing that the ability to meet these goals will be demonstrated and substantiated. Subsequent testing and deployment of the technology at a demonstration scale will be completed through other programs and is expected to take four years.

- FE Turbine Program contributions to the 2010 Advanced Power Systems goals are planned to be:
- Efficiency: Demonstrate 2–3 percentage points of improvement in combined-cycle (CC) performance (above base line).
- Cost: Demonstrate a 20–30% reduction in CC capital cost plus enhanced value for lower COE.
- Emissions: Demonstrate combustor emissions with 2 ppm NO_x (@15% O_2) in simple cycle exhaust.

It is expected that these advances to achieve the 2010 goal will contribute to the 2012 goal for IGCC-based power systems that capture carbon. The challenge here is maintaining the 2010 performance advances but now the turbine fuel will be nearly pure hydrogen. Additionally, the Turbine Program plans to contribute to the 2012 Carbon Sequestration goal by providing advanced and highly integrated CO_2 compression technology to reduce the compression penalty (auxiliary load) by 25–40%.

In supporting the FutureGen Project is a primary goal of the FE Advanced Turbine program. The Turbine Program takes the approach to provide the latest advances made through pursuing the 2010, 2012, and 2015 goals. This will allow installation of the most advanced hydrogen fueled turbine at the FutureGen project. It is envisioned that the FutureGen turbine could be installed with a plan that would allow the machine to be optimized in the field for combustion and firing temperature performance. This approach would allow for a machine fueled with 100 percent hydrogen to operate with the highest efficiency and lowest NO_x emissions.

Plans for the FE Turbine Program contributions to the 2015 goal are:

Efficiency:
- Hydrogen turbine CC with 3–5% points improvement (total above base line).
- Oxy-fuel turbine based IGCC system > 50% eff. (HHV) with CO_2 capture and compression.

Cost:
- Competitive COE for zero emission systems.

Emissions:
- H_2 Turbine-based IGCC demonstrated with 2 ppm NO_x (@15% O_2)
- Oxy-fuel turbine based IGCC with zero emissions (100% turbine exhaust captured and sequestered, and zero criteria pollutants and CO_2)

Multiple Products:

- H_2 turbine-based IGCC with higher capacity gasification.
- Oxy-fuel turbine based IGCC with multi-product production.

A generalized technical approach to realize the 2010 goals is presented below in Table 1.

Table 1. Generalized Technical Approach to 2010 Goal, and Potential Benefits

Technical issue to pursue	**Benefit to gas turbine or power plant**
Combustor for 2 ppm NO_x	Eliminates SCR and other penalties (NH_4 slip, cost back pressure)
More durable catalysis for in combustor NO_x formation prevention	Reduced O&M, makes catalytic combustion possible
H_2 Premixing with out flash back	Enables low NO_x combustion and related robust combustion techniques
Higher turbine inlet temperatures (TIT) (~ 210 °F)	Approximately 1% pt. improvement to simple cycle per each ~ 70 °F increase
Better TBC materials	Higher TIT, less air extraction, reduced RAM overall improvement in efficiency
Enhanced cooling techniques	Higher TIT and less air extraction
Increase rotor torque limitation	Higher power output with reduced capital cost (~ 20%)
Compressor and air separation unit integration	0.5–1.0% points efficiency improvement
Ceramic parts	Higher TIT
Enhanced aerodynamics	Higher throughput & specific power

Table 2 below presents a list of current FE turbine projects that received funding in FY06. Following the table is a summary of individual projects. The University Turbine Systems Research (UTSR) Program is summarized in a separate section of the Handbook.

Table 2 Active Turbine Program Projects That Received Funding in FY 06

Turbine Program Key Activities	**Contractor**	**Contract ID**
Hydrogen Turbines For FutureGen		
Advanced IGCC / H_2 Gas Turbine	General Electric	42643
Advanced Hydrogen Turbine for FutureGen	Siemens Power Generation	42644
Catalytic Combustion for Ultra-Low NO_x Hydrogen Turbines	Precision Combustion Incorporated	42647
Micro-mixing for Ultra-low emissions H_2 / SYNGAS Combustion	Parker Hannifin	42648
Catalytic Combustor for Fuel-Flexible Turbine	Siemens Power Generation	41891
System Study for Improved Gas Turbine Performance for IGCC Application	General Electric	41889
Fuel Flexible Combustion System for Coproduction Plant Applications	General Electric	41776
Syngas & Hydrogen Combustion	NETL In House Turbine Support	NETL
Partial Oxidation GT for Coproduction from Coal in Industrial Applications	GTI	42649
Advanced Oxy-Fuel Turbines for FutureGen		
Zero Emissions Coal Syngas-Oxygen Turbo machinery	Siemens Power Generation	42646
Coal-Based Oxy-Fuel System Evaluation and Combustor Development.	Clean Energy Systems	42645
Advanced Research for FutureGen		
University Turbines Systems Research	SCIES	41431
Systems Analysis of Advanced Brayton Cycles	UC Irvine	42652
Turbine Materials & TBC for High Hydrogen Fuels	ORNL	FEAA070
HX in Hydrogen Fuel Turbines	Ames Lab	AL05205018
Novel Concepts for the Compression of Carbon Dioxide	SwRI	42650
Super Sonic Shock Compression for Compression of CO_2	Ramgen	42651
Low-swirl Injectors for Hydrogen Gas Turbines	LBNL	FWP678402

Summary of Active Turbine Program Projects

Individual Turbine Program project descriptions provide insight into the breadth and depth of research being supported by DOE. The descriptions provide a detailed overview of turbine activities, and tie individual project goals to the larger national goal of energy security, which is attainable by using the nation's most abundant fossil energy resource — coal.

Project Summary: NETL In-House Combustion R&D in support of Turbine Program

NETL's Energy Systems Dynamics Focus Area is actively involved in a number of projects to support DOE's Turbine Program. These projects include research in low-emissions combustion, model validation, sensor and controls development, and materials. Research in turbines combustion in focused primarily on development of hydrogen and oxy-fuel combustion approaches to meet Future Gen efficiency and emissions targets.

Hydrogen combustion: To meet DOE FutureGen targets for zero carbon and low-NO_x emissions, new combustion technologies will be required. To facilitate carbon capture, IGCC systems will remove carbon upstream of the turbine by shifting the syngas composition to produce a high-hydrogen-content fuel. High-hydrogen-content fuels will present some new challenges for combustor development. Lean-premix combustion strategies currently employed for natural gas (NG) fired engines will not be easily retrofit for high-hydrogen-content fuels due to the potential for flashback. Early IGCC systems will likely employ diffusion flame combustion systems for this reason, but diffusion flame combustors are not likely to meet FutureGen NO_x targets of 2ppm. Solutions may come from the NETL Combustion Program, which has several projects focusing on assessing the flashback potential for fuels with a hydrogen content ranging from 20–100 percent. In addition, alternative combustion approaches such as trapped vortex combustion are being investigated, which have the potential for good flame stability and higher velocity flows to avoid flashback with premixed hydrogen flames.

Research also is under way to assess the potential for dilute diffusion flame systems burning hydrogen. Oxygen-blown gasifiers will have nitrogen available from the air separation unit, and NETL is investigating approaches to using this nitrogen to dilute the hydrogen fuel, enabling both efficient, stable combustion *and* low-NO_x emissions. Hybrid approaches employing dilute diffusion flame and partial premixing are also being investigated. These hydrogen combustion studies combine chemical kinetic and computational fluid dynamic (CFD) simulations, with laboratory and bench scale combustion testing at pressures up to 30 atm using NETL's High Pressure Combustion research facilities. On a more fundamental level, NETL has an optically accessible, swirl stabilized combustor that is being used to develop validation data for Large Eddy Simulation and other advanced simulation methods. This activity is a multi-agency collaboration involving DOE, Department of Defense, National Aeronautics and Space Administration, and several major research Universities to develop and validate advanced simulation tools that are being used to design fuel-flexible combustion systems.

Oxy-Fuel Combustion: NETL also is investigating fundamental issues associated with oxy-fuel combustion. Oxy-Fuel combustion systems are being considered for zero- emission power cycles where all of the carbon from the fuel can be captured. These systems will either use steam or carbon dioxide as a diluent to manage combustion temperatures. Thermodynamic and chemical kinetic modeling of the combustor indicates that CO_2 dilution may result in unacceptable CO levels in the combustor effluent. NETL is examining combustion issues associated with high steam-loaded systems to develop the database necessary for oxy-fuel combustor design.

Sensors and Controls: NETL is working on development of flame sensors and controls to improve emissions and stability of advanced turbine systems. NETL's Combustion Control and Diagnostic Sensor (CCADS) is a flame ionization sensor with a demonstrated capability to measure flashback and lean blow-off for gas turbine combustors. Continued development of this sensor system now is focusing on measuring the fuel-air equivalence ratio, which will offer the potential for adjustment of fuel flows and lower NO_x emissions.

Project Summary: Advanced Hydrogen Turbine for FutureGen (CID: 42644)
Participant: Siemens Westinghouse Power Corporation

Siemens Westinghouse Power Corporation (SWPC), with support from Florida Turbine Technologies, major universities, and others, intends to advance the state-of-the-art gas turbine for integration into a coal-based IGCC power plant that will be fueled with coal-derived hydrogen fuel and syngas. The project objectives will lead to significant advancements in IGCC plant efficiency, near-zero emissions, and a reduction in plant cost. The project will further develop and optimize integration of this advanced G-class gas turbine into an IGCC plant to ensure that DOE's FutureGen Program objectives of plant efficiency, NO_x emissions, and capability for CO_2 sequestration are achieved.

The proposed three-phase, 10-year SWPC project will begin with Phase I, which will focus on identifying and down-selecting the advanced technologies needed to achieve the challenging program goals, producing the required new component conceptual designs, and generating an R&D implementation plan. Phase II will entail development of new component detailed designs, and technology validation test programs. Engine and system fabrication, with deployment and testing in an IGCC plant, will be carried out in Phase III.

SWPC will focus key development efforts on gas turbine combustion system, performance enhancements, and required materials/coatings advances. Combustion development will concentrate on advanced concepts evaluation, down-selection, and development to produce operational systems for burning coal derived hydrogen and syngas fuels, with natural gas burning capability as a back-up. To implement the new performance enhancing concepts, the program will include evaluating and down-selecting the most promising concepts for improving component efficiencies, enhanced cooling, and maintaining the turbine's rated inlet temperature while operating on the above range of fuels. Materials/coatings selection and development will support the goal of higher efficiency, while supporting the extended fuel flexibility capability by targeting improvements in component durability and life cycle costs. Advancements in sensors and controls will be carried out to provide a capability for monitoring flame temperature, emissions, individual component metal temperature, coating durability, and turbine blade tip clearance control.

Overall plant performance and economic optimization efforts of the SWPC program will lead to the effective integration of advanced G-class gas turbines into future low-emissions, coal-based IGCC plants, thereby ensuring that a cost-effective supply of electricity is available in the United States that uses our domestic coal resources. (DOE award: $45.5 million; plus contractor cost-share; project duration: 56 months, Phase III of this contract was not awarded)

Project Summary: Advanced IGCC/Hydrogen Gas Turbine Development (CID: 42643)
Participant: GE Energy

GE Energy proposes a gas turbine development project entitled Advanced IGCC/Hydrogen Gas Turbine Development. This project will develop gas turbine technology for advanced IGCC and FutureGen power generation plants, to support DOE's overall coal-based power generation goals of high efficiency (45–50% (HHV), near-zero emissions (<3 ppm NO_x @ 15% O_2), and competitive capital costs (<$1,000/kW). Gas turbine improvements in this program address DOE's Turbine Program goals of 3–5 points of improvement in combined-cycle efficiency, less than 2 ppm NO_x emissions, and compatibility with either traditional IGCC coal synthesis gas fuel or with high-hydrogen fuel produced from FutureGen type plants.

The proposed GE project will leverage existing state-of-the-art gas turbine technology, while developing, validating, and prototype testing the technologies and systems needed to meet DOE's goals. Emissions reductions for low-Btu and hydrogen fuels will be addressed through combustion technology advancements, with the goal of achieving the same type of emissions improvement DLN (dry-low-NO_x) technology accomplished for natural gas fueled gas turbines. Based on previous technology program developments, combustion testing of promising combustion technology platforms and enablers will be performed and evaluated, leading to full-scale design and development of an optimum system. IGCC plant level efficiency improvements will be achieved primarily through increased IGCC gas turbine firing temperature, to the same levels as today's natural gas fired gas turbines. This will be enabled through application of high-temperature 7FB gas turbine materials/design technology and development of technologies to allow increased turbine mass flow and output. Environmental testing of advanced high-temperature materials and coatings exposed to IGCC/hydrogen fuels will be performed, along with selective coating development/improvements.

The GE technology advancements will start with R&D in Phase I, proceed to design and validation at the component level in Phase II, and result in prototype testing in a GE 7FB IGCC gas turbine in Phase III. (DOE award: $45.6 million; plus contractor cost-share, project duration: 75 months, Phase III of this contract was not awarded)

Project Summary: Coal-Based Oxy-Fuel System Evaluation and Combustor Development (CID: 42645)
Participant: Clean Energy Systems, Inc.

Clean Energy Systems, Inc. (CES) will develop and demonstrate operation of its proprietary oxy-fuel combustor technology on syngas. Currently, CES is demonstrating a 20-MWt combustor on natural gas. CES' next objective is to demonstrate its combustor technology on coal syngas, enabling zero-emission coal plants with higher heating value efficiencies between 50% and 60%, coupled with 100% carbon dioxide capture.

CES will implement a research, design, development, and validation project with three phases, as prescribed by DOE. Phase I will include an R&D Implementation Plan and Conceptual Design. Part of the design process calls for a System Study consisting of definition of subsystem performance parameters, power system modeling, evaluation of alternative system configurations, and fuel variability evaluation. The deliverables from Phase I will be a report of optimized cycles and an oxy-coal syngas fuel combustor conceptual design. CES will team with SWPC, and the design progression will be conducted in collaboration to assure that the final combustor/turbine product is viable, useful, and optimum for both available and next-generation turbine hardware. Similarly, CES will team with other major subsystem suppliers and consultants, including ConocoPhillips for gasification, Air Products and/or Air Liquide for air separation, Kinder Morgan CO_2 Company for carbon dioxide systems, G.C. Broach Company for heat recovery steam generators, and Western Research Institute for computer modeling.

CES will employ existing assets to the maximum extent possible as it develops the oxy-syngas combustor. In particular, CES will use the previous cycle studies undertaken by DOE/NETL, Lawrence Livermore National Laboratory (LLNL), and numerous other parties; as well as using the existing Kimberlina Power Plant demonstration facility. The Kimberlina facility will be evaluated to confirm that, with reasonable modification, it can be configured to burn simulated coal syngas from tube trailer supplies of mixtures of hydrogen, carbon monoxide, and methane. This approach will allow the introduction of various syngas compositions, which will validate operation of the combustor over a wide fuel range.

System studies will include air separation units, turbine types, gasification methods, and syngas cleanup methods and requirements. CES will work with suppliers and subcontractors to obtain the various subsystem parameters. System modeling and subsystem integration opportunities will be evaluated by CES and outside contractor(s) using the Aspen Plus® software program.

Phase II of the CES program will entail developing a detailed design and conducting validation testing, to allow a pre-commercial combustor to be fabricated and tested in Phase III. CES will incorporate information and knowledge gained from SWPC, including operating states, combustor size, and combustor configuration (single or multiple combustors). Operating state flexibility is one of the merits of the CES combustor, and its design can be initiated prior to knowing precise desired operating parameters, though nominal guidelines from the turbine manufacturer will be incorporated.

Phase III will involve fabricating an appropriately sized pre-commercial prototype combustor and conducting longer-term testing using actual and/or simulated coal syngas. Testing at this stage of the product development will be conducted at the Kimberlina Power Plant using blended syngas, and then transition to a site with actual syngas if an appropriate site is available. (DOE award: $4.5 million; plus contractor cost-share, project duration: 39 months)

Project Summary: Zero Emissions Coal Syngas-Oxygen Turbo Machinery (CID: 42646)

Participant: Siemens Westinghouse Power Corporation

Siemens Westinghouse Power Corporation (SWPC), with support of Clean Energy Systems (CES), Florida Turbine Technologies, a major university, and others, intends to propose a multi-phase project for research and development of turbines and related systems to utilize high-hydrogen fuels derived from coal. Activities will include development of a turbine for an Oxy-Fuel Rankine Cycle System that would be integrated into a highly efficient, near-zero emission power plant. The focus on fuel flexibility through combustion with oxygen syngas is seen as key to continued use of coal, our largest domestic fossil energy resource, coupled with capture of CO_2 and all of the Clean Air Act criteria pollutants.

Phase I will initially review cycle optimization based on previous work on a limited number of system studies to assess likely operating conditions of the turbines. This will require that both the combustion part of the cycle along with the secondary part of the cycle be optimized together to select the most optimal pressure and temperatures in the bottoming cycle. In order to evaluate the range of cycle options, three cycles will be considered. The baseline cycle will be based on the ultra-supercritical steam cycle, in which turbo machinery designs can be developed using materials from current industrial gas turbine frames. A second cycle will be developed by moving beyond the current ultra supercritical designs, emphasizing realistic near-term achievements with an acceptable increase in risk. Finally, a high-efficiency, higher risk cycle will be developed incorporating concepts from the latest advanced gas turbine frames. Conceptual designs of equipment for selected cycles will follow to identify total plant costs and technology challenges. Critical component identification and cycle selection will lead to a more specific cycle with proposed cost and schedule at the end of Phase I. The required R&D that will be conducted in Phase II and Phase III will also be identified as part of Phase I of the program.

The Phase II of this SWPC project will involve the detailed design of the components and selected material development, both of which are required to support component development. A significant effort will address the challenges of how a working fluid, composed mainly of H_2O and CO_2, impacts rotating components, as well as the associated material issues such as stress corrosion, general corrosion/erosion, creep effects, and thermal mechanical fatigue. It is expected that material development will not only be required for major components, but also for surface engineering and innovative cooling schemes so that the turbo machinery can withstand the elevated temperatures required for the coal Syngas-Oxygen turbo machinery.

Phase III will involve prototype testing of certain sub-components, and a scale-model test of a steam turbine component. Fabrication and testing will include the specialized components such as rotating blades and other stationary components critical to the overall performance of the power plant. It is expected that by the end of successful completion of Phase III, feasibility of this type of high-efficiency, zero-emission cycle will be demonstrated.

DOE award: $14.5 million; plus contractor cost-share, project duration: 56 months, Phase III of this contract was not awarded

Project Summary: Catalytic Combustion for Ultra-Low NO_x Hydrogen Turbines (CID: 42647)
Participant: Precision Combustion, Inc. (PCI)

The proposed PCI project will develop and demonstrate an ultra-low-NO_x rich catalytic combustion system for fuel-flexible hydrogen combustors in megawatt-scale turbines. This will further develop PCI's rich catalytic combustion technology for fuel flexible hydrogen application, in collaboration with Solar Turbines, and provide a roadmap to commercialization of the technology across all size ranges of power generation turbines. In a current DOE program, this technology has demonstrated subscale ultra-low-NO_x with syngas and with hydrogen diluted with nitrogen (low single-digit NO_x corrected to 15% O_2 with operation at IGCC base load combustor temperatures and 10 atm. pressure). The technology offers low single-digit NO_x emissions, even with hydrogen as the only fuel; fuel flexibility for similar low emissions of syngas or natural gas; and the potential to support increased firing temperature (and efficiency) while maintaining low emissions. The benefits include combustors capable of delivering near-zero NO_x without costly post-combustion controls and without the need for added sulfur control. This advances DOE objectives for achievement of low single-digit NO_x emissions, improvement in efficiency versus post-combustion controls, fuel flexibility, a significant net reduction in IGCC system net capital and operating costs, and a route to commercialization across the power generation field.

In the proposed project, PCI will develop the technology for fuel flexible use of hydrogen in a megawatt-scale combustor through design and analysis (CFD, Chemkin), and sub-scale, mid-scale, and full-scale testing. The work plan is in three phases. Phase I involves development of conceptual designs for catalytic combustion technology for hydrogen fuel, and an R&D implementation plan including supporting analysis, fabrication, and testing of several small to intermediate scale components. Phase II, Detailed Design and Validation Test Program, concentrates on development of multiple full-scale modules for validation testing, to include full pressure testing and resolution of key issues related to startup, load shifting, turndown, shutdown, module interactions, and system design. In Phase III, the full-scale design will be frozen, and a full combustor system with multiple catalytic combustor modules will be fabricated for an initial engine rig testing. This will be followed by either engine loop test using the full-scale engine hardware at mid-pressure, or full-scale engine testing.

Solar Turbines, the world's largest manufacturer of mid-range industrial gas turbines (1–15 MW), will be an active participant, developing combustor design and hardware for its engines as well as design, testing, and system-level interactions with PCI. Solar and PCI have an established interactive relationship, with a current DOE-supported engine trial program now under way for natural gas-fired catalytic combustion. The new focus on the smaller machine will facilitate more rapid yet economic combustor development targeted to an engine 5- to 15-MW size that may be considered a building block for larger turbine applications. Because the catalytic system is scalable and modular in nature, integration to larger engines can be facilitated. (DOE award: $4.9 million; plus contractor cost-share, project duration: 60 months)

Project Summary: Micro-mixing Lean Premix System for Ultra-LOW Emission Hydrogen/Syngas Combustion (CID: 42648)
Participant: Parker Hannifin Corporation, Gas Turbine Fuel Systems Division

The general focus of this project is to develop the next generation of environmentally friendly, hydrogen/syngas, gas turbine fuel injection technologies. Parker intends to prototype and test innovative, multi-point fuel injector technologies that satisfy DOE's objectives of reducing NO_x emissions to 2 ppm. Detailed studies and experimentation with these injectors are proposed to elucidate the effects of various operating parameters on overall turbine performance. The impact of nozzle design and operating conditions on combustion efficiency, emissions, and lean stability will be characterized.

Burner technologies will be developed for lean and ultra-lean premixed hydrogen/syngas combustion in combustor geometries similar to those used in gas turbine engines, and with compositions similar to those obtained in coal gasification plants. Parker will investigate the impact that hydrogen content in syngas has on flashback and emission characteristics in lean premixed combustion systems, and will develop strategies to mitigate the impact of flashback and auto-ignition. Through a university partner program, data on flammability limits, stability characteristics, laminar and turbulent flame propagation, as well as the impact of the anchoring mechanism, burning conditions and syngas composition, will be collected and synthesized into models. Diagnostics, corroborated with computational analyses, will be used to determine the role of chemistry, and transport and fluid mechanics in the mechanisms of combustion.

Starting from already proven, Macrolamination technology, Parker's general approach is to adapt the proven designs and concepts to hydrogen/syngas combustion and hydrogen enriched combustion. With Macrolamination technology, elegant and sophisticated multi-point lean-premix nozzles and burners can be developed with exceptional affordability. Parker proposes to develop, build, and test a large number of burners spanning a wide range of sizes, from small-scale single-cup premixers to 1-Megawatt size premixers. The modularity of the macrolamination approach affords the flexibility to build multiple scales of these injectors from a basic building block (a single mixing cup) affordably and expeditiously.

The combination of lean conditions and multiple point injection (for fast and efficient mixing) will be the primary vehicle for achieving low-NO_x emissions in this project. In order to further reduce NO_x levels, consideration will be given to operability at ultra-lean conditions, and designs that mitigate lean-combustion instabilities will be developed. Stability augmentation will be achieved through optimization of swirl and other aerodynamic features. Zone staging will also be used to enhance lean operability.

Parker has assembled a seasoned team to perform the proposed scope of work, including industrial participants (Parker Hannifin and Solar Turbines), and a University partner (University of California Irvine). Parker Hannifin will lead the project and the other participants will be subcontractors to Parker. The team believes that the nozzles and combustor development tasks defined in this project will serve national interests by helping to maintain U.S. leadership in the gas turbine market for power generation applications. (DOE award: $1.2 million; plus contractor cost-share, project duration: 32 months).

Project Summary: Partial Oxidation Gas Turbine for Power and Hydrogen Co-Production from Coal Derived Fuel in Industrial Applications
Participant: Gas Technology Institute (GTI)

The objective of this project is to provide a detailed assessment and evaluation of the feasibility, opportunities, and challenges of using MW-scale Partial Oxidation Gas Turbines (POGT) for coal-based co-production of electricity and hydrogen or syngas for steel, forest and paper, oil refinery, food, and other industries. The feasibility and performance assessments will be conducted for turbine-based plants that are integrated and optimized to provide high efficiencies, ultra-low emissions of criteria pollutants (2 ppm NO_x), and reduced costs.

This assessment and evaluation project will build upon the existing POGT technology that has been under development by GTI since 1995, and can be effectively combined with a coal gasifier. The POGT operates under reducing conditions as a combustion gas turbine — generating power through the partial oxidation of the gasifier product gas, and achieving highly efficient extraction of both thermal and pressure energy from the partially oxidized stream. Because of the partial oxidation reactions, the POGT also acts as a fuel reformer to convert hydrocarbons that are present in gasifier product gas into hydrogen-rich syngas. The ultra-low NO_x emissions are achieved because the oxygen-deficient atmosphere suppresses NO_x formation and converts the NH_3 and HCN present in the gasifier product gas into N_2. The POGT uses a smaller air compressor than an equivalent conventional gas turbine. All of these factors, combined with system integration benefits, will provide significant cost reductions for industrial applications.

In this project, the Team will conduct detailed techno-economic and engineering assessments of a plant consisting of a coal gasifier, a POGT, and a hydrogen purification unit, with emphasis on the POGT. The POGT evaluation will be based on the analytical, experimental, and modeling results from ongoing GTI projects. The engineering evaluation of modifications needed to convert a conventional gas turbine to POGT will be based on, but not limited to, estimates by two leading turbine manufacturers (Solar and SWPC) for converting their own product lines and future planned products. A comprehensive market evaluation will be conducted to define the specifics and applicability of the proposed system in different industrial segments. System configurations will be chosen for specific applications and required co-products. These selected configurations will be optimized to provide the best achievable energy efficiency, and lowest emissions. The major result of the project will be an R&D Implementation Plan, cost, and schedule to bring the technology to commercialization, and an R&D Plan for modification of one or more existing gas turbines to a POGT will be developed and reported to DOE.

Large industrial users (in particular, the steel, glass, forest and paper, oil refinery, and food industries) will directly benefit from this project. GTI anticipates that this new technology, providing a single on-site source of co-products from coal (electricity, syngas, or hydrogen), will provide customers with reduced product costs and improved efficiencies.

GTI will lead a team that includes Solar Turbines Incorporated (Solar) and Siemens Westinghouse Power Corporation (SWPC). These gas turbine manufacturers command a large share of the current world turbine market, where Solar's share of the 1- to 30-MW gas turbine market is the largest of all manufacturers. SWPC is one of the largest worldwide vendors of gas turbine technology in the 30- to 100-MW range. The team will also include Oak Ridge National Lab to assist with material studies for POGT components, and Georgia Tech University as a major U.S. expert in basic combustion science and flame stability. This team has the experience, the resources, and the will to bring this new technology to the industrial marketplace quickly and effectively. The U.S. energy markets, overall U.S. economy, and U.S. taxpayers will benefit from the project due to a wider use of domestically available coal for industrial energy needs, which will replace imported premium fuels. (DOE award: $999,992; plus contractor cost-share, project duration: 22 months)

Project Summary: Super Sonic Shock Compression for the Efficient Compression of Large Volumes of Carbon Dioxide (CID: 42651)
Participant: Ramgen Power Systems, Inc.

Ramgen Power Systems is applying its super sonic shock wave compression technology toward the efficient and cost-effective compression of large quantities of CO_2 for sequestration. Ramgen will design, validate, fabricate, and test a 100:1 pressure ratio, two-stage super-sonic compressor through three phases and 5 years of development. The development plan has numerous design reviews, risk assessments and go/no-go decision points. At the conclusion of Phase III, the sub-scale pre-commercial test unit will be the basis for a full-scale optimization and test program.

The benefits of Ramgen's technology approach are: fewer stages, higher efficiency, lower part count and therefore lower capital and maintenance costs, and smaller size for comparable mass flow and pressure ratio. Shock compression technology has the potential to simultaneously develop a very high compression ratio per stage, and very high efficiency. Shock compression is affected by the mole weight of the gas. Since CO_2 is heavier than air, Ramgen's shock compression approach benefits from the low speed of sound characteristic. Conversely, conventional compressors are at a disadvantage with the heavy CO_2 gas, because shocks are bad for performance in a conventional compressor. This allows Ramgen to build a 2-stage CO_2 shock compressor for a pressure ratio of 100:1, while conventional technology will typically require six stages of compression. The efficiency of the shock compression system will be at least as good as conventional approaches.

In addition, development of Ramgen's compression technology is cross-cutting and capable of delivering benefits to many of the technical areas of concern in zero-emission clean coal facilities. These benefits include high-efficiency electric and fuel-fired air compressors to reduce the significant operating and capital cost of the supporting Air Separation Unit (ASU) subsystem, both for cryogenic and Ionic Transport Membrane (ITM) technologies. (DOE award: $11 million; plus contractor cost-share, project duration: 60 months)

Project Summary: Novel Concepts for the Compression of Large Volumes of Carbon Dioxide (CID: 42650)
Participant: Southwest Research Institute

In the effort to reduce the release of CO_2 greenhouse gases to the atmosphere, sequestration of CO_2 from IGCC and oxy-fuel power plants is being proposed. This approach, however, requires significant compression power to boost the pressure of CO_2 to typical pipeline levels. The penalty can be as high as 8–12% on a typical IGCC plant. The goal of this project is to reduce this penalty through novel compression concepts and integration with existing IGCC processes.

The primary objective of this project is to boost the pressure of CO_2 to pipeline pressures with the minimal amount of energy required. First, fundamental thermodynamics will be studied to explore whether pressure increases in liquid or gaseous states would be preferred. Since the first phase of the project involves conceptual brainstorming, flexibility has been built into the project to permit investigation of several concepts.

For gaseous compression, the project seeks to develop novel methods to compress CO_2 while removing the heat of compression that is internal to the compressor. The high pressure ratio compression of CO_2 results in significant heat of compression. Since less energy is required to boost the pressure of a cool gas, both upstream and inter-stage cooling is desirable. While isothermal compression has been utilized in some services, it has not been optimized for the IGCC environment. This project will determine the optimum compressor configuration and develop technology for internal heat removal. Furthermore, other process streams within the IGCC environment will be utilized to provide a total system solution by fully integrating the air separation units, combined cycle, and the gas cleanup system. Other concepts that liquefy the CO_2 and boost pressure through cryogenic pumping will be explored as well.

Phase I will identify the concept that best meets the efficiency goals and integrates into the IGCC environment. Based on the selected concept, Phase II will design the optimum solution and perform prototype development testing. Phase III will apply a full-scale compression solution to an existing IGCC plant. This project is being co-funded by Dresser-Rand Company. (DOE award: $175,033; plus contractor cost-share, project duration: 12 months, Phase II and III were not awarded).

Project Summary: Systems Analyses of Advanced Brayton Cycles for High Efficiency Zero-Emission Plants (CID: 42652)
Participant: Advanced Power and Energy Program (APEP), University of California at Irvine

The FutureGen plant concept is aimed at reducing the environmental impacts of fossil fuel usage while generating electric power and providing a clean fuel for transportation and for distributed power generation. Developing turbine technology to operate on coal-derived synthesis gas and hydrogen is critical to the development of advanced power generation technologies and the deployment of FutureGen plants. The FutureGen plant concept may also be deployed in natural gas based plants with respect to generating power with near-zero emissions, while utilizing these advanced Brayton cycle machines and securing fuel diversity. This APEP project therefore represents a key investment in implementing the FutureGen concept, and in helping to secure clean, efficient, affordable and fuel-flexible electric power generation for the U.S. As with the other turbine projects, APEP also will help make possible the continued use of our nation's largest domestic fossil energy resource, coal.

Numerous projections estimate that gas turbines will comprise a significant portion of the required generation capacity in the 21st century. Novel advanced gas turbine cycle modifications, intended to improve the basic Brayton cycle performance and reduce pollutant emissions, are currently under development or being investigated by gas turbine manufacturers and R&D organizations. Preliminary conceptual analyses of advanced cycles indicate that it may be possible to achieve an improved combination of efficiency, emissions, and specific power output, which in turn should reduce the power generation equipment cost on a $/kW basis. Thus, a need exists to evaluate advanced Brayton cycles and identify the best opportunities worthy of support by DOE for their development, and to assess their R&D needs and the most likely commercialization path.

APEP will focus this study on defining advanced Brayton cycles and addressing the key technologies needed to enable development of such advanced turbines and turbine-based systems that will operate cleanly and efficiently when fueled with coal-derived synthesis gas, hydrogen fuels, and natural gas. System integration issues will be addressed that will allow the combination of high-performance technology modules and subsystems into safe, reliable, environmentally friendly, and economic power plants.
Specifically, the project will develop concept(s) and present approach(es) that will increase the state-of-the-art Brayton cycle (in a combined-cycle application) from today's 58–60% efficiency (LHV on natural gas) to >65% equivalent efficiency. The proposed machine(s) will consider integration into advanced coal-based and natural gas-based zero-emission systems, with the ability to attain a 60% (HHV coal) efficiency and 75% (LHV natural gas) efficiency respectively (prior to carbon separation and capture). Options for zero CO_2 emissions will be considered for both coal- and natural gas-based plants, and will show how the turbine design, operation, and overall system performance are affected. The integration of subsystem technologies such as advanced gasifiers, membrane technology for air and H_2 separation, and fuel cells as they evolve, will be accounted for in the advanced Brayton cycle design(s), while performance of the resulting integrated advanced systems will be quantified. Start-up, shutdown, and off-design operating needs will be taken into account while configuring the advanced cycles. (DOE award: $603,012; Plus contractor cost-share, project duration: 24 months)

Project Summary: Catalytic Combustion for Fuel Flexible Turbine (CID: 41891)
Participant: Siemens Westinghouse Power Corp.

Under the sponsorship of NETL, a team of organizations led by Siemens Westinghouse Power Corporation (SWPC) proposes a 3-year R&D program entitled "Catalytic Combustor for Fuel Flexible Turbines." In this program, the team will develop and demonstrate a cost effective catalytic-based turbine combustor that will achieve the aggressive target of 2 parts per million NOx emissions at the turbine exhaust without the need for expensive back-end after treatment systems currently employed in gas turbine combined cycle generating plants.

The catalytic combustor will be suitable both for retrofit into the installed base of operating turbines and also for deployment in the latest generation of advanced, high firing-temperature turbines, while achieving the low emissions objective at even the high firing temperatures of advanced turbines. The combustor will support fuel-flexible power generating facilities, with equal performance capabilities when operating on either conventional natural gas fuels or on synthetic fuels derived from coal. The program supports objectives of highly efficient, environmentally friendly power generating plants operating on our nation's abundant resource of coal reserves. The program culminates in the demonstration of the combustor on syngas at the Power Systems Development Facility in Wilsonville, Alabama.

SWPC has teamed with Solar Turbines, Penn State University, and Southern Company Services in the pursuit of the program objectives. (DOE award: $6,998,071; Plus contractor cost-share, project duration: 45 months)

Summary: Heat Transfer in Advanced Hydrogen Fueled and Oxy-fuel Turbines
Participant: Ames Laboratory/Iowa State University

The purpose of this project is to analyze gas turbine thermal performance with a variety of new fuels, and optimize heat transfer within the turbine. Initially, the work will focus on cooling needs of turbines with new fuels, and then work toward a system-based understanding of turbine performance.

Developing turbine technologies to operate on coal-derived synthesis gas (syngas) and hydrogen fuels is critical to the development of advanced power generation technologies such as integrated gasification combined cycle (IGCC) and the deployment of FutureGen type power plants that can lead to the capture and separation of carbon dioxide (CO_2). The goal of this project is to develop an analysis tool that can be used to examine and explore heat transfer design and operation issues in turbine components to support the development of turbine technologies used in advanced coal-based power systems. The tool will consider heat transfer from the hot gases, thermal barrier coating systems that protect the superalloys, and cooling strategy as a function of:

1. Fuel used (natural gas, syngas with different ratio of CO/H_2, H_2)
2. Firing temperature and turbine inlet temperature that account for convective and radiation heat transfer to the combustor walls and combustion kinetics
3. Amount of diluents and the diluents used (*e.g.*, N_2, steam, or CO_2 to control NO_x formation)
4. Water steam content and different ratio of CO_2/H_2O in the working fluid
5. Mass flow rate
6. Cooling strategy with and without turbine blade cooling
7. Different thermo cycles (*e.g.*, coal-based oxy-fuel Rankine cycles or advanced Brayton cycles).

As a first step for this project, the primary goal is to conduct a thorough literature survey on what has been done and assess available modeling methods and codes.

This includes:

1. Available studies on applications of gas turbine (originally designed for natural gas) fueled with syngas, and reports on existing gas turbine fueled with syngas in IGCC power plants. The focus is on thermal management, heat transfer, and failure mode.
2. Studies on H_2 fuel combustion and its effect on turbine heat transfer.
3. Studies on syngas fuel combustion with CO_2 sequestration and its effect on turbine heat transfer
4. Studies on different working fluid (*e.g.*, CO_2, CO_2 plus water vapor, or water vapor only)
5. Assess available turbine design tools.

IGCC Turbine Issues

• **Turbine inlet temperature.** So far, power generation gas turbines have been designed for the utilization of natural gas fuel. When they are used in IGCC applications, i.e., using syngas as fuel, the machines are derated in firing temperature to accommodate long term operational issues associated with excessive temperature of materials in the hot gas path. This temperature reduction is believed to be on the order of 200–300_°F for the current F-frame machines when compare to the same machine fired on natural gas. This temperature reduction has a directed affect on system efficiency. With the increase of turbine inlet temperatures, material degradation issues will be evaluated and improvements to thermal barrier coatings explored.

• **Heat flux increase.** Besides the firing temperature, the heat flux conditions can also affect the material temperatures. For the combustion of the coal derived syngas, oxidants and diluents determine heat flux conditions at critical hot gas path locations. Heat flux can increase depending on the combustion by products and the diluent used to control NO_x emissions. Higher heat flux conditions gives rise to higher material temperatures.

• **Mass flow increase.** Furthermore, commercially available gas turbines have been developed for the use of natural gas, *i.e.*, a fuel with high calorific value (LHV). With these turbines adapted to the use of syngas, a low LHV fuel, the gas turbine encounters two major changes:

1. For the same fuel heat input, the fuel mass flow is several times greater than for natural gas, due to the lower LHV.
2. Diffusion burners are used with syngas, and control of NO_x is achieved by diluting the syngas with nitrogen, steam or carbon dioxide.

These two factors increase substantially the overall mass flow through the turbine. The higher mass flow coupled with rotor torque limitations results in higher average temperature profiles at individual turbine stages. Due to this situation, last stage blades may experience temperatures higher than the original design specification. It is also believed that this higher mass flow and associated volume increase leads to higher local velocities and higher local heat transfer coefficients.

The following factors will be considered in the heat transfer analysis tool development: (1) fuel used (*e.g.*, natural gas, syngas (including different ratio of CO/H_2), H2; (2) firing temperature; (3) amount of diluents and diluents used (e.g., N_2, water vapor, or CO_2 to control NO_x formation); (4) amount of water and different ratios of CO_2/water in the working fluid; (5) mass flow rate; (6) different cooling strategies with and without a thermal barrier coating; and (7) different thermo cycles (*e.g.*, coal based oxy-fuel Rankine cycles and advanced Brayton cycles).

Ames will conduct a thorough survey on what has been done so far, and available modeling methods and codes will be assessed. This study will include: (1) available studies on applications of gas turbine (originally designed for natural gas) fueled with syngas, and reports on existing gas turbine fueled with syngas in IGCC power plants, the focus is on thermal management, heat transfer and failure mode, (2) studies on H_2 fuel combustion and its effect on turbine heat transfer, (3) studies on syngas fuel combustion with CO_2 sequestration and its effect on turbine heat transfer, (4) studies on different working fluid, *i.e.*, CO_2, CO_2+water vapor, or water steam only, and (5) an assessment of available turbine design methods, codes and tools.

For this project, Ames will work closely with engineers and researchers at NETL and at the Oak Ridge National Laboratory to ensure that the work is relevant and compliments other related activities on-going at those laboratories.

Project Summary: Material Issues in Coal-Derived Synthesis Gas/Hydrogen-Fired Turbines
Participant: Oak Ridge National Laboratory

Large gas turbines (i.e., about 250 MWe) firing on natural gas have been operating in combined-cycle systems since the mid 1990s, providing around 400 MWe of power output with efficiencies in excess of 55% in many cases, and with very low NO_x and SO_x emissions. Also, advanced concepts were evaluated to give efficiencies of up to 60%. With the rising cost of natural gas in recent years (the price generally tracks that of oil), attention has turned to the opportunities associated with the production of gas from coal (and from other feedstocks, including waste products). One consequence has been an interest in improving the technology of gas turbines burning low-Btu gases, with the aim of building on the advances made with the current generation of engines to improve generating efficiency with IGCC plant. In the United States, the FutureGen Program is specifically focused on producing electricity, hydrogen, or chemical feedstocks via the gasification of coal; in the power generation mode, gas turbines will be required to deliver efficiencies comparable to the machines resulting from the U.S. Advanced Turbine Systems (ATS) Program (1), and NO_x levels < 5 ppm, while burning coal-derived syngas and / or hydrogen (2). Not unexpectedly, there are specific problems associated with the combustion of low-Btu gas, depending on its source, which will require additional development efforts, both in specific aspects of turbine design, and in materials performance, in order to provide cost-effective solutions.

The objectives of this project are to provide materials guidelines for the reliable operation of gas turbines when fired with syngas and H2-enriched fuel gases, in terms of firing temperature and fuel impurity levels (water vapor content; sulfur; condensable species). The research effort in place aims to provide underpinning understanding needed in the consideration of materials issues associated with these new operating conditions. The intended outputs of this project are:
• understanding of the factors limiting the firing temperatures of syngas turbines;
• assessment of the potential for deposition, erosion, or corrosion (D-E-C) when firing syngas; and
• evaluation of approaches for improved coatings to provide the basis for more robust hot gas path components.

Current activities involve the development of a plan for addressing the overall materials and manufacturing needs of syngas-fired turbines. Input for this plan is being obtained from a detailed review of published literature concerning issues confronted in the combined cycle operation of gas turbines, with emphasis on design and operating changes necessitated to allow operation on fuels other than natural gas; cycle analyses that address the trade-off issues associated with optimizing the combined gas turbine and steam generation system; as well as practical experience (where this is available and accessible). Reports from international conferences, from demonstration programs in the U.S., Europe, and Japan, and from operating IGCC plants in particular has been sought and critically reviewed. A report summarizing the outstanding materials and manufacturing issues is being compiled, and the views of the GT manufacturers and materials suppliers and other specialists on suggested priorities are being sought and incorporated. This preliminary listing of materials needs and priorities will be tested at a workshop of turbine materials specialists, and the findings of this workshop will be incorporated into the final draft of the Materials Needs Report.

This report is intended to summarize available information concerning the critical materials issues resulting from the desire to increase the efficiency of operation of gas turbines applied to power generation and, in particular, to achieve high efficiencies (and reduced emissions) with turbines fired by syngas and/or hydrogen derived from coal. The effort has involved a review of published information from the U.S., Europe, and Japan, including input from various current major programs (where available) which are mainly focused on the materials needs for advanced, natural gas-fired turbines, as well as an attempt to understand differences that arise from adaptation of these technologies to firing the coal derived fuels of interest. Since there is little published information concerning changes in design or materials needed because of specific influences of alternative fuels on the performance of gas turbines, contacts have been made with key organizations involved in pilot/demonstration IGCC projects to obtain reports and/or first-hand information, and visits have been made (or are planned) to the major U.S. gas turbine manufacturers. It was considered particularly important to initiate an interaction with the General Electric Company, because of its activities (including the recent acquisition of the Texaco/Chevron gasification technology) intended to position the company as a leader in supplying complete IGCC plants.

Project Summary: Low-swirl Injectors for Hydrogen Gas Turbines in FutureGen Power Plants
Project Participant: Lawrence Berkeley National Laboratory

This goal of this research is to develop a robust ultra-low emission combustor for the gas turbines in FutureGen power plants that burn hydrogen derived from gasification of coal. The objective is to adapt low-swirl combustion (LSC) to these utility size turbines. LSC is a dry-low-NOx method conceived at LBNL. Under DOE-EERE, this technology has been commercialized for industrial heaters by Maxon Corp. of Muncie, Indiana. DOE Office of Electricity is supporting its development for natural gas and fuel-flexible industrial turbines (5 – 7 MW) in partnership with Solar Turbines of San Diego, CA. The California Energy Commission is supporting a combined heat and power project that includes the development of LSC for Elliott Energy Systems' 100 kW microturbine. This research leverages the knowledge and experience gained from these R&D activities.

FutureGen power plants produce hydrogen which is separated from a concentrated CO2 stream that is then captured for subsequent sequestration. One of its key components is a cost-competitive all-hydrogen fueled turbine with ultra low NOx emission and high efficiency. To lower NOx, the current approach is to operate the H2 turbine at lower firing temperatures in combination with selective catalytic reductions (SCR). This approach sacrifices efficiency and impacts costs of electricity (via capital cost, efficiency and capacity output). Therefore, a cost-effective combustion technology that meets the FurtureGen emissions and efficiency targets is critical to achieving its ultimate goal of no more than a 10% increase in cost of electricity for mature FutureGen type plants that include CO2 capture and sequestration.

Preliminary laboratory studies have shown that LSC has good promise to be an effective enabling technology for the H2 turbine to meet the FutureGen goals of 2 ppm NOx (@ 15% O2) at a firing temperature of 2500to 2600F. LSC is a sophisticated yet simple and very cost effective combustion technology that can operate with a variety of gaseous fuels including H2 fuel blends under a broad range of inlet and outlet conditions. As one of the components of a complex and fully-integrated FurtureGen power plant, the H2 turbines have to be reliable and sufficiently flexible and adaptable to meet the inlet and outlet requirements without compromising electricity output efficiency and emissions. With LSC, the H2 turbine will have greater flexibility in their operations than is achievable by current technology. Greater flexibility provides more options for developing a power plant scheme that offers an optimum balance between efficiency, reliability, emissions and costs through intelligent integration of technologies including gasification, separation technologies, combustion turbines, and steam turbines without the need to invoke SCR for exhaust gas cleanup.

The feasibility of burning H2 in a LSI has been demonstrated in a recent laboratory study of the fuel effects on LSI flow fields and flame characteristics [3]. The fuels tested in this study consist of seven diluted and undiluted hydrocarbon mixtures, pure H2 and a fuel mixture consisting of 50% H2 and 50% CO2. The lean blowoff limits for the two H2 fuels are found to be less than 0.2 and are close to the theoretical flammability limit. These results demonstrate the LSI's capability to support ultra-lean premixed turbulent flames with H2 fuel mixtures. Within the velocity range afforded by our experimental setup (3 < U < 9 m/s) intermittent attachment of the H2 flame to the LSI rim occur at greater than 0.3 showing that the high diffusivity of H2 can lead to phenomena that are unique to H2 firing. However, the significant conclusion of this study is that the NOx emissions from the hydrocarbon fuels depends primarily on the adiabatic flame temperature set by the fuel air equivalence ratio. For the very lean H2 flames (< 0.3), the NOx emissions are below the detectable limit of our instrumentation (0-5 ppm).

This study demonstrates that the LSI concept is amenable to a very wide range of gaseous fuel mixtures. The reason is due to the self-similarity of the LSI flow field and its linear coupling with the turbulent flame speed. By invoking an analytical equation for the flame position that involves the self-similarity parameters, the turbulent flame speed and turbulence intensity, we obtain a theoretical proof on why the LSI enables the lifted flame to remain stationary throughout a very wide range of velocities from 5 to 80 m/s. The analytic model based on this equation [4] also shows that the higher H2 flame speeds are not expected to cause a significant change in the overall behaviors of the flame and the LSI flow field. It indicates that the first order effect of switching from hydrocarbon to H2 is associated with a change in the correlation of its turbulent flame speed with the turbulence intensity. The change can be accommodated by adjusting the swirl number of the LSI. The second order effects will be associated with heat release and higher H2 diffusivity. Therefore, the knowledge and insights gain from this study and the analytical model grounded on fluid mechanics and turbulent combustion theories will be useful for guiding the developmental effort to optimize the LSI for FutureGen turbines.

<u>FY06 Define H2 LSI specifications and develop a skeletal R&D plan</u>

As in our prior technology developments, a close partnership with gas turbine OEM is critical to the success of this research. In FY06, the initial step is to discuss with their combustion engineers to obtain a preliminary set of specifications for the configuration as well as the operational and performance criteria of their H2 turbines being developed for FutureGen. These include information on the geometric arrangement, the physical size, the form factor and the number of injectors and the size and shape and size of the combustion chamber, the anticipated fuel compositions (i.e. H2 and the anticipated concentrations of N2 as a diluent) the firing temperatures, firing pressures, firing rates for the injectors, and exit temperature etc. The outcome will be an assessment of the compatibility of LSI with their hardware and a skeletal research and development plan that highlights the critical issues as well as the pathways, and the roles and responsibilities toward resolving them.

In parallel to the discussion with OEMs, laboratory studies will be conducted to obtain the basic information needed to optimize the LSI for H2. These experiments will include the measurement and correlation of the turbulent flame speed for diluted H2 fuels as well as simulated syngases. Our air flow supply systems will be upgraded to enable experiments at velocities up to 20 m/s. Operating the LSI at higher velocities will allow us to better understand the second order effects such as intermittent flame attachments and heat release.

<u>FY07 Design and fabricate H2 LSI prototype</u>

For H2 turbines, the challenges in achieving ultra-low emissions while balancing the tradeoffs between efficiency, complexity, reliability and costs are similar to those for natural gas turbines. The design of the H2 fueled LSI, however, needs to address additional specific issues concerning with the high flame temperatures, faster flame speeds, auto-ignition risk, shorter premixing, preferential diffusion, and inherent H2 flame instability. Our approach in FY07 is to follow the development pathway for natural gas turbines by applying our understanding of the LSC principle to optimize the LSI for burning lean H2 flames in a configuration that is compatible with the proposed H2 combustor. In parallel, laboratory and analytical studies will continue and focus on assessing the potential impact of the H2 fuel specific issues and seeking effective solutions. We anticipate that the FutureGen H2 turbine will utilize diluents and staged premixing schemes (e.g. premixing of H2 with N2 before injecting in air) to control auto-ignition and flashback. Mixing of an inert gas such as N2 readily available from the coal gasification process into the H2 stream is an effective means to reduce flame speed, lower flame temperature and increase ignition delays. For example, our estimation shows that H2 with 50% N2 dilution at = 0.4 produces a flame temperature of about 2600F. A properly designed LSI should be able to burn this mixture or similar mixtures of various combinations of N2 concentrations and equivalence ratios. As to mitigating the hazards associated with auto ignition, the established approach is to reduce the residence time by injecting the fuel as close as possible to the burner tip. The LSI is conducive to this treatment because it can tolerate some variations in mixture homogeneity without sacrificing flame stability and emissions. Additionally, there are other means that can further reduce the risks of auto-ignition and flashback. One simple method worthy of consideration is by blending of N2 into the H2 stream prior to injection into the air stream. Obviously, the optimum solution will depend on which combination of fuel blend, fuel treatment and injection scheme would be the best to meet the specifications and requirements of the OEM. The outcome of these studies will be applied to develop and fabricate a full-scale or pilot-scale prototype H2 LSI. This prototype will include mixers and fuel injectors that can mitigate the H2 fuel related issues.

Project Summary: Fuel Flexible Combustion System for Co-Production Plant Operations
Project Participant: GE

High-efficiency, low-emissions co-production plants that produce electric power, transportation fuels, and/or chemicals from fossil fuel feed stocks require a new class of fuel flexible combustors. In this 36-month program, a validated combustor approach will be developed which will enable single-digit NO_x operation of cogeneration plants with low-Btu off gas and high-hydrogen fuels, with the flexibility of process-independent backup with both natural gas and liquid fuels. This combustion technology will overcome the limitations of current syngas gas turbine combustion systems, which are designed on a site-by-site basis, and enable improved plant designs. In this capacity, a fuel-flexible combustor will enhance the efficiency and productivity of IGCC based coproduction plants.

One of the major challenges for coproduction plants is handling a fuel stream with a time varying heating value and hydrogen content. In current Integrated Gasification Combined-Cycle (IGCC) practice, the combustor is tailored to the fuel properties at each site. In addition, there are emerging needs for high-hydrogen fuels, which currently require diluent injection to meet emissions and safety constraints.

The approach in this program is to unify and improve these existing designs and introduce the latest technology, where appropriate. A hybrid combustor, successfully incorporating the low-NO_x performance of our most advanced premixed combustion systems with enhanced versions of the Integrated Gasification Combined-Cycle (IGCC) nozzles currently in production, will lead to a fuel-flexible combustor design capable of meeting fuel flexible IGCC performance requirements. The success and the resultant quality of the fuel-flexible combustion system is enhanced by the Design for Six Sigma (DFSS) quality process, which is a statistically based methodology focused on flowing performance specifications and tolerances from the high level of customer or power plant objectives down to the low level of component parts. The current process capability of each component flows back up to understand the influence of its variability on system performance.

Using this methodology with a conceptual plant configuration will ensure that the combustion system is robust and flexible enough for highly efficient operation. The program focuses on plant optimization, low emission combustor design, and development of tools for syngas flame modeling. A study of market fuel variations and gas turbine combustor operating conditions will be studied to determine optimal plant efficiency. The fuel space definition will be used with a combined cycle plant model to determine combustor inlet and required firing conditions. The combustor design study will evaluate several design options in the quest to define a design space that will meet the operating requirements. The flame modeling tools are based upon fundamental data characterizing the syngas flames. Data for H_2 flames and H_2/CO mixtures has been obtained at atmospheric pressures.

Project Summary: System Study for Improved Gas Turbine Performance for Coal IGCC Application
Project Participant: GE

This 15-month study will identify vital gas turbine parameters and quantify their role in meeting the overall DOE Integrated Gasification Combined-Cycle (IGCC) plant goals of 50% net HHV efficiency, $1,000/kW capital cost, and low emissions. The proposed project will analyze and evaluate gas turbine conceptual cycle designs, and quantify their influence on IGCC plant level performance. The study will provide DOE with information as it develops strategies for identifying future technologies needed to advance IGCC gas turbine performance.

A baseline conceptual IGCC system design will be established utilizing current General Electric (GE) F-class gas turbine technology, based on a U.S. IGCC site such as the Tampa Electric Polk IGCC Project or the Wabash River Coal Gasification Repowering Project. Confirmation of plant level performance goals would help lead to the selection of gas turbine cycle concepts to be further investigated. An overall IGCC system performance model will be constructed utilizing GE in-house proprietary software for the gas turbine and steam turbine, and commercially available software for the balance of the systems. The model will be exercised through parametric analysis to quantify gas turbine performance impact at IGCC plant system level. Results from the system analysis will be used to identify gas turbine technology improvements for development consideration in future program phases.

The proposed program will be performed through the following five major tasks utilizing GE's Design for Six Sigma methodology:

- Overall System Requirements Identification
- Requirements Prioritization & Flow-Down to Gas Turbine Subsystem Level
- IGCC Conceptual System Analysis
- Gas Turbine Cycle Options vs. Requirements Evaluation
- Recommendations for Gas Turbine Technical Improvements

In conclusion, the goals and project summaries outlined above represent the approach for the Advanced Turbine program in the 2010, 2012, and 2015 time frames, and how these goals will be realized by way of each project.