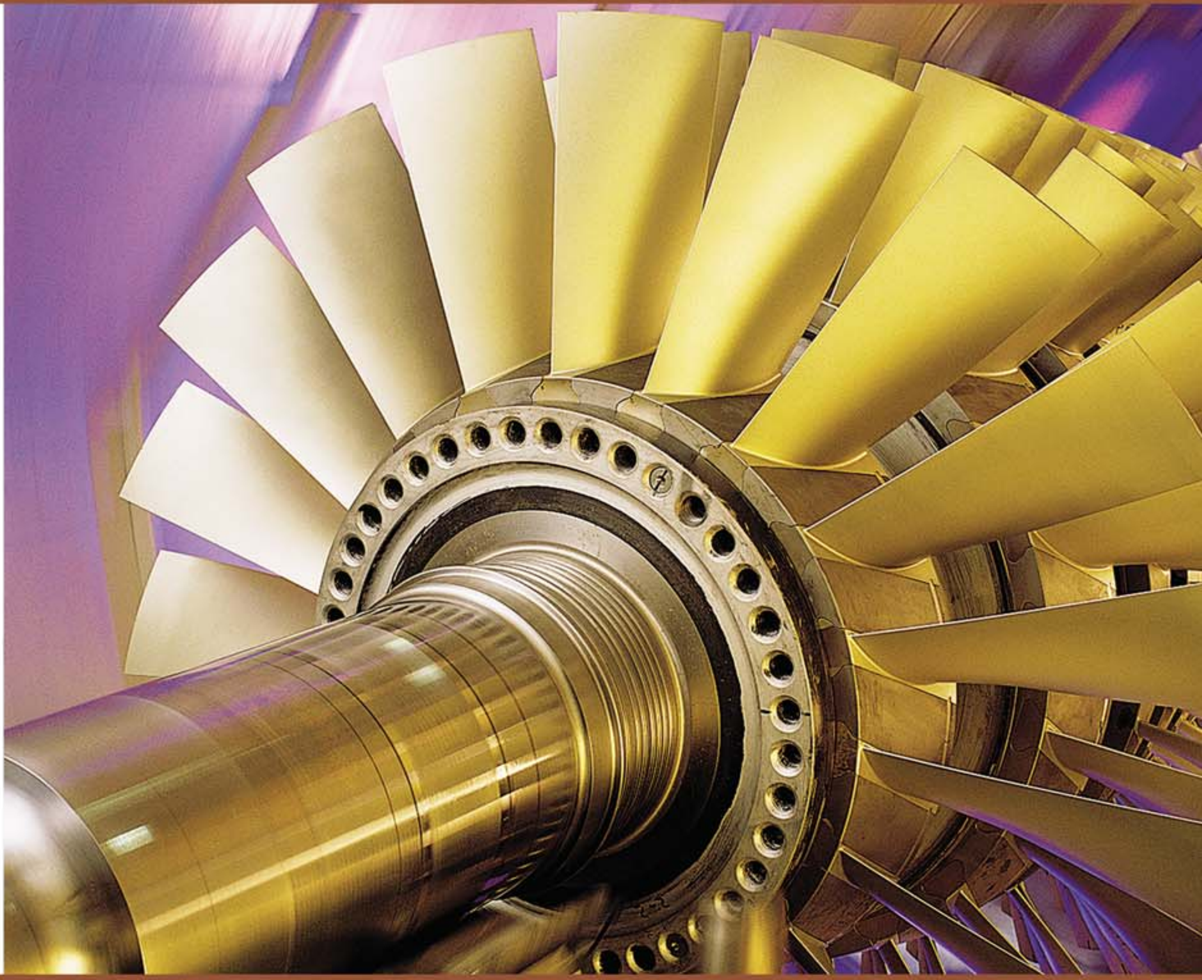
U.S. Department of Energy • Office of Fossil Energy
National Energy Technology Laboratory

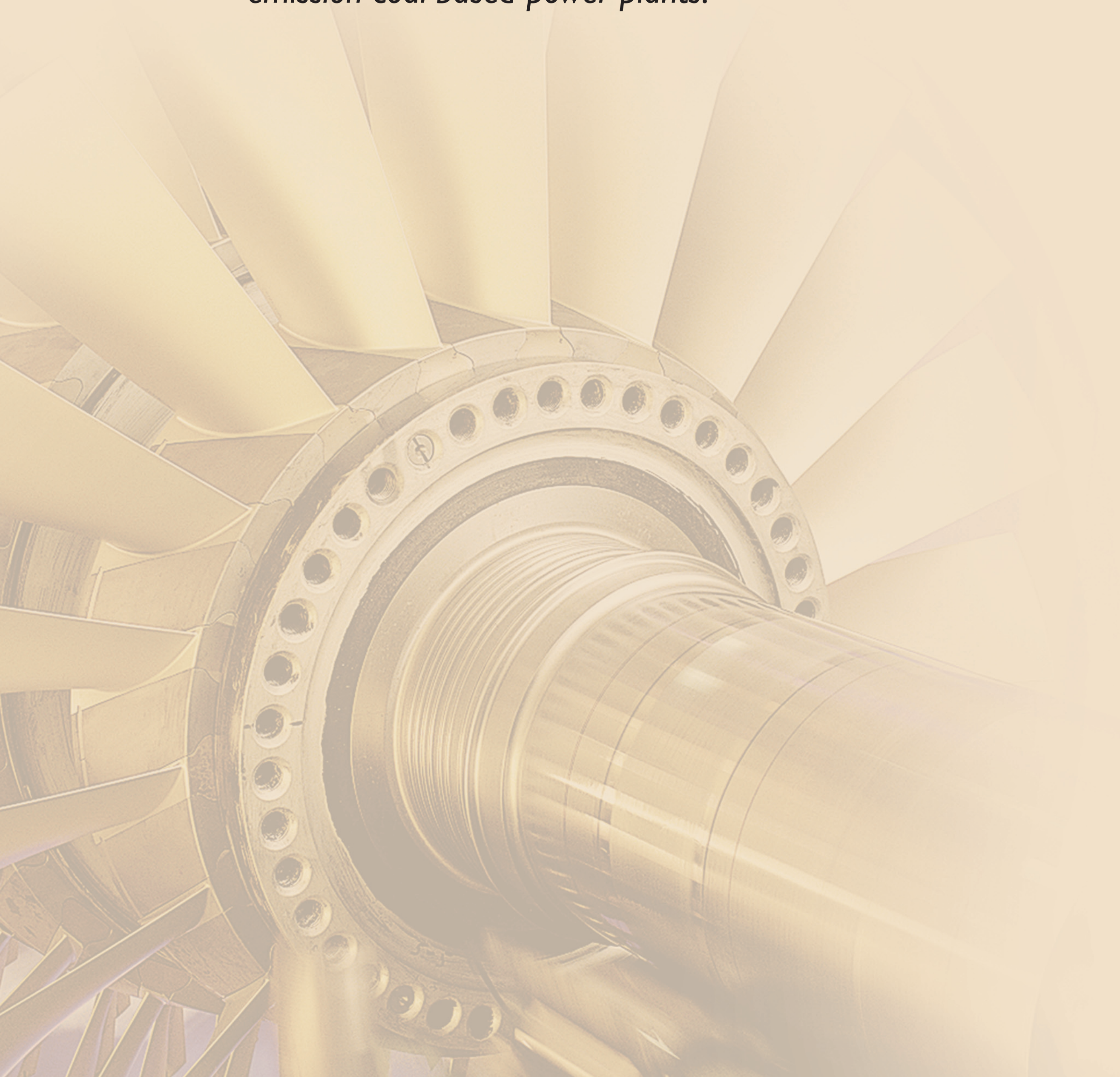
TURBINE PROGRAM

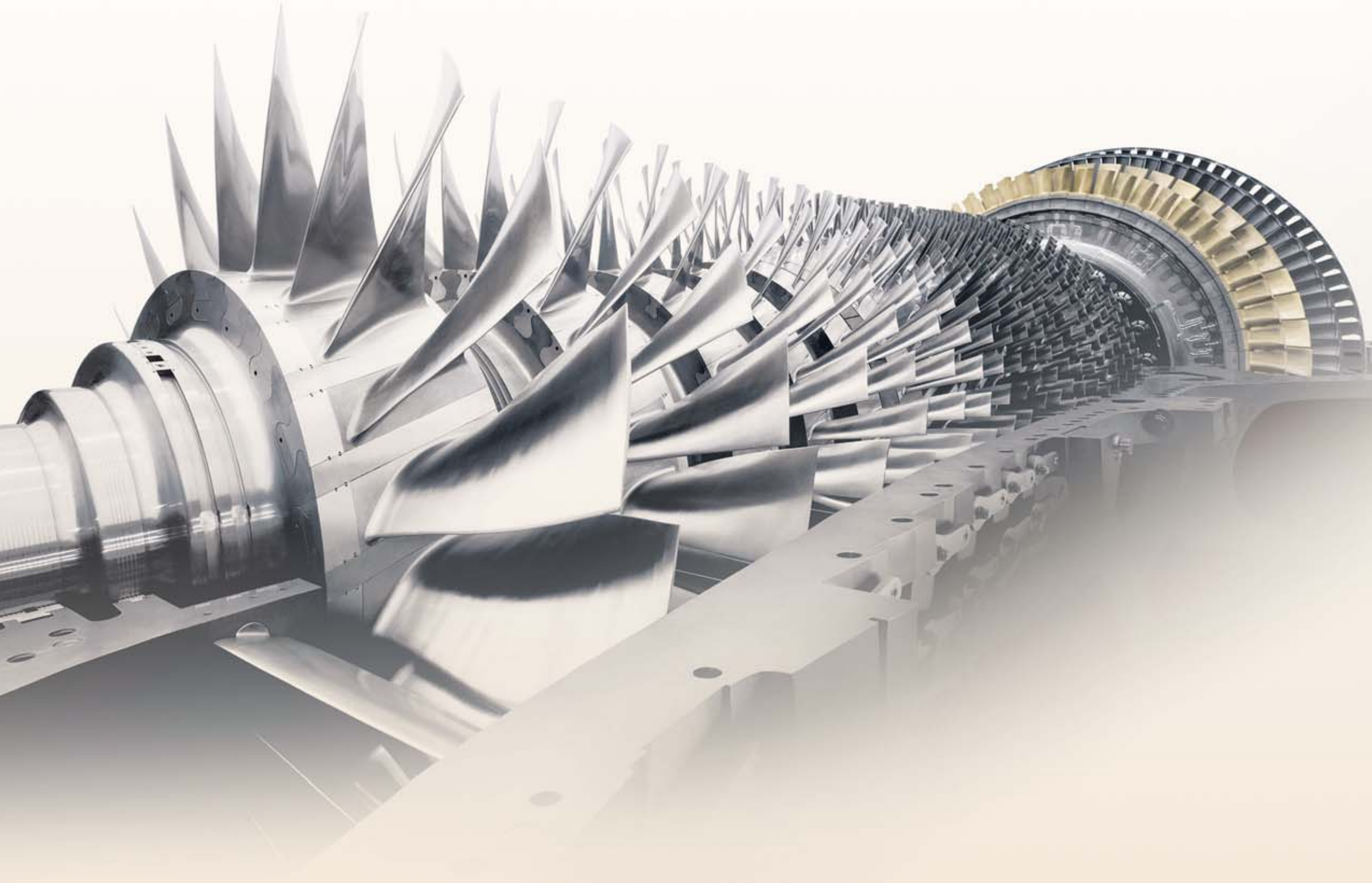


Enabling Near-Zero Emission Coal-Based Power Generation

In the 1990s, U.S. Department of Energy partnerships with industry and academia through the Advanced Turbine System (ATS) Program spurred advances in utility-scale, natural gas-fueled turbines to levels of performance seemingly unachievable at the time.

Today, the Department is embarking on a mission to leverage the knowledge base gained in the ATS Program to develop hydrogen-fueled and oxygen-fired turbines enabling near-zero emission coal-based power plants.





Turbines are the workhorse of the power industry. General Electric's *H System*™ gas turbine shown here, a product of the ATS Program, along with the Siemens Westinghouse ATS counterpart, are bringing unprecedented efficiency and low-emissions performance into the marketplace.

The current Turbine Program, described here, moves turbine technology to a new age of energy security and near-zero emissions.

Introduction

This document delineates today's U.S. Department of Energy (DOE) Turbine Program being implemented by the DOE National Energy Technology Laboratory (NETL). The Turbine Program leverages the knowledge gained in making unprecedented advances in natural gas-fueled turbine technology under the highly successful, predecessor Advanced Turbine Systems (ATS) Program. This knowledge will be applied to support DOE efforts to develop and deploy near-zero emission (including carbon dioxide) coal-based energy plants capable of producing both electricity and hydrogen.

The thrust of the Turbine Program is to develop:

- The capability to operate today's advanced natural gas-fueled turbines on hydrogen fuels, minimizing carbon dioxide (CO_2) emissions, and to reduce NO_x emissions to negligible levels without compromising operational performance;
- Oxygen-fired (oxy-fuel) steam generators and turbines that offer high efficiency through never-before achieved temperature regimes and that enable 100 percent carbon sequestration while producing electricity and hydrogen, with readily separated water and CO_2; and
- MW-scale turbines that can utilize hydrogen from coal efficiently and minimize or eliminate the emissions of NO_x and CO_2 and create the end-use technology for a hydrogen infrastructure network.

The Turbine Program: (1) applies a fuel flexibility strategy that enables fulfillment of key coal-based power system milestones on the road to near-zero emission plants, (2) provides for early spin-off of advances directly benefiting consumers and the environment, and (3) supports early entry of integrated gasification combined-cycle (IGCC) into the marketplace.

Technology roadmap timelines for the Turbine Program support FutureGen design efforts (expected to initiate operation in 2012) and are consistent with FutureGen timelines for product testing. FutureGen, a DOE initiative, is a 275-MW near-zero emission (including CO_2) coal-based power and hydrogen production research facility designed to test and demonstrate advanced subsystems and components (for production and sequestration). The Program strategy also provides a market pull for FutureGen type plants and a hydrogen economy by developing the technology to allow the full range of gas turbines to operate on hydrogen fuel.

Investment in turbine technology has a high potential payoff for the economy and the environment. Turbines are an integral part of the power generation industry and industrial sector. Almost all utility-scale electricity generation relies upon turbines to convert a range of fuels to electricity. Turbines are proven technologies in an industry that demands reliable, efficient performance. The U.S. turbine industry is highly competitive and is a major presence in the world market. Technological advances are adopted rapidly and applied in the marketplace.

This document provides background on turbine technology and challenges associated with achieving near-zero emission systems, summarizes national benefits derived from realizing program outcomes, and presents the DOE Turbine Program strategy and technology roadmap.

National Benefits

Outcomes expected from the DOE Turbine Program include the following:

- By 2010, to have significantly enhanced the performance and reduced the cost of large utility-scale gas turbines used throughout the industry for coal-based IGCC systems, applying a fuel-flexible approach so that advancements can be adopted throughout the industry.
- By 2015, to have further advanced performance and reduced the cost of large utility-scale gas turbines using the fuel-flexible approach; and to have culminated in a capability of achieving gas turbine efficiencies on hydrogen and synthesis gas (syngas) equivalent to current efficiencies when operated on natural gas while reducing NO_x emissions to 2 ppm or less.
- By 2010, to have developed the capability to efficiently operate industrial-scale turbines (100 MW or less) on hydrogen and achieve NO_x emissions of 2 ppm or less.
- By 2015, to have developed and demonstrated coal-based, near-zero emission IGCC systems using a hydrogen-fueled gas turbine and an alternate near-zero emission system using an oxy-fuel Rankine cycle.

Benefits derived from achieving these outcomes include the following:

- Enhances the nation's energy security by eliminating the major power industry barrier to expanded use of coal, our nation's most abundant energy resource.
- Increases reliability of electric service by making coal-based plants environmentally acceptable (essentially as clean as natural gas-fueled plants), which paves the way to new coal plant construction and relieves the generation burden on the aging fleet of existing coal-fired plants.
- Stabilizes domestic cost of electricity by enabling reliance on traditionally stable priced coal to fuel baseload generation as capacity grows to meet an estimated 45 percent increase in electricity demand over the next two decades.
- Begins to lay the foundation for a sustainable hydrogen economy, which brings with it true energy security and elimination of environmental concerns over fossil fuel use.
- Firmly establishes the United States as the world leader in turbine technology; provides the underlying science to maintain that leadership; and positions the United States to capture a large portion of a burgeoning world energy market, worth billions of dollars in sales and hundreds of thousands of jobs.
- Establishes the United States as world leader in near-zero CO_2 emission turbine technology, and in providing the world market the means to address global climate change and regional environmental concerns.

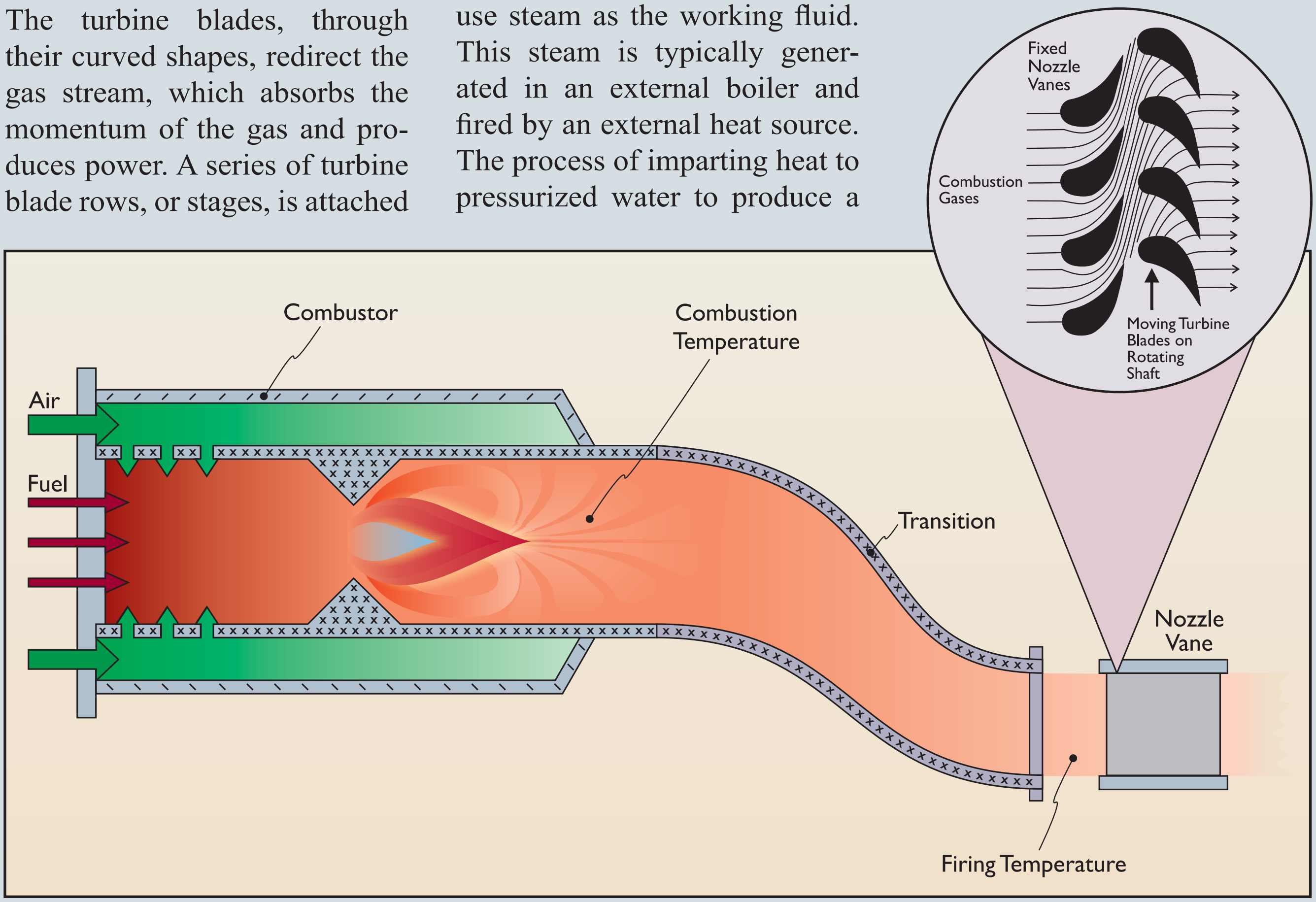
Turbine Basics and Intrinsic Challenges

Turbines and Cycles

Gas Turbines. A gas turbine is a heat engine that uses high-temperature, high-pressure gas as the working fluid to spin the turbine and generate power. Combustion of fuel in air is usually used to produce the needed temperatures and pressures in the turbine, which is why gas turbines are often referred to as "combustion" turbines. To capture the energy, the working fluid is directed by vanes at the base of combustor nozzles to impinge upon specially designed airfoils (turbine blades). The turbine blades, through their curved shapes, redirect the gas stream, which absorbs the momentum of the gas and produces power. A series of turbine blade rows, or stages, is attached to a rotor/shaft assembly. The shaft rotation drives an electric generator and a compressor for the air used in the gas turbine combustor. This process of imparting potential energy to a gas working fluid by adding heat and pressure, and translation of the potential energy to work through interaction of gas and blades, is called a Brayton cycle. In the simple Brayton cycle, the turbine exhaust is typically vented to the atmosphere.

Steam Turbines. Steam turbines work on the same basic principles as gas turbines, but use steam as the working fluid. This steam is typically generated in an external boiler and fired by an external heat source. The process of imparting heat to pressurized water to produce a high potential energy steam, and translation of the potential energy to work through interaction of steam and blades, is called a Rankine cycle. In the Rankine cycle, the turbine exhaust (steam), now at low temperature and pressure, is condensed and recycled back to a boiler or heat source in a closed loop.

Combined-Cycle. A combined-cycle integrates Brayton and Rankine cycles. High-quality exhaust heat from a gas turbine generates steam in a heat recovery steam generator to pow-

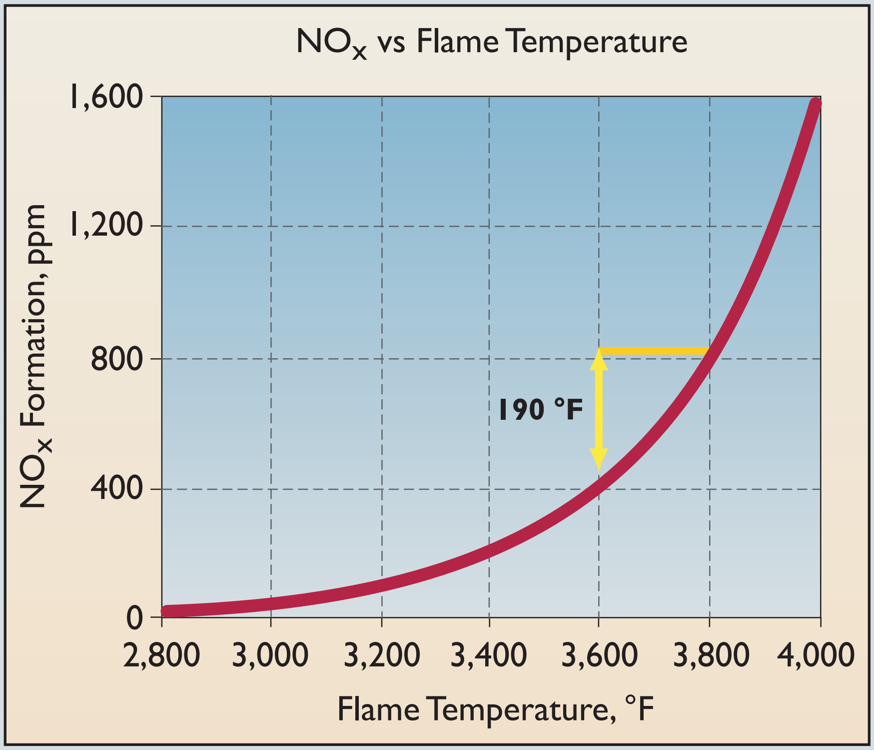


Gas Turbine Energy Generation and Conversion er a steam turbine, significantly enhancing efficiency. In utility applications, both turbines produce electricity. The trend in combined-cycle design is to use a single-shaft configuration, whereby the gas and steam turbines are on either side of a common generator to reduce capital cost, operating complexity, and space requirements.

Intrinsic Challenges

Efficiency Versus NO_x. For gas turbines, increasing efficiency while reducing nitrogen oxide (NO_x) emissions represent conflicting goals, which makes achievement particularly difficult. The difficulty stems from the fact that air is the predominant component of the working fluid, *e.g.*, natural gas, the most common gas turbine fuel, contributes only 2 percent to the volumetric flow through the turbine. Air is basically 78 percent nitrogen and 21 percent oxygen, and these elements combine at elevated temperatures to form NO_x. At a threshold temperature of approximately 2,800 °F, thermal NO_x formation increases exponentially. At the same time, a major approach to realizing higher gas turbine efficiency is to apply higher working fluid temperatures. Fortunately, 2,800 °F is well within the range of combustion temperatures envisioned for near-term efficiency gains.

Achieving Low-NO_x Emissions at High Firing Temperatures. In today's advanced gas turbines, the average temperature in the reaction zone, where combustion takes place, is approximately 2,750 °F. Within the reaction zone are hot spots resulting from imperfect fuel/air mixing that elevate local temperatures beyond 2,800 °F and are responsible for almost all of the NO_x formation. To achieve the targeted 2 ppm NO_x emission levels, these hot spots must be all but eliminated through premixing to produce lean, homogenized fuel/air mixtures. Lean (high air-to-fuel ratios) mixtures are needed to moderate combustion temperatures and ensure adequate oxygen supply for complete combustion and avoidance of CO emissions. Rapid mixing is required as lean combustion occurs almost instantaneously. Lean conditions introduce flame stability problems, which are evidenced by noise and often damaging vibration. To address flame stability, current combustors often inject a small portion of raw fuel at the base of the flame, which contributes to NO_x formation. New techniques look to sustain flame stability through the application of catalysts and physically induced flow regimes that recirculate hot combustion products to the incoming fuel/air mix, thereby maintaining ignition and a flame anchor. Cooling schemes for reaction zone components are also important. They can take air away from turbine flow (open loop systems), significantly reduce temperature at the turbine inlet (firing temperature), and create local cool spots that serve to prevent oxidation of CO to CO_2.



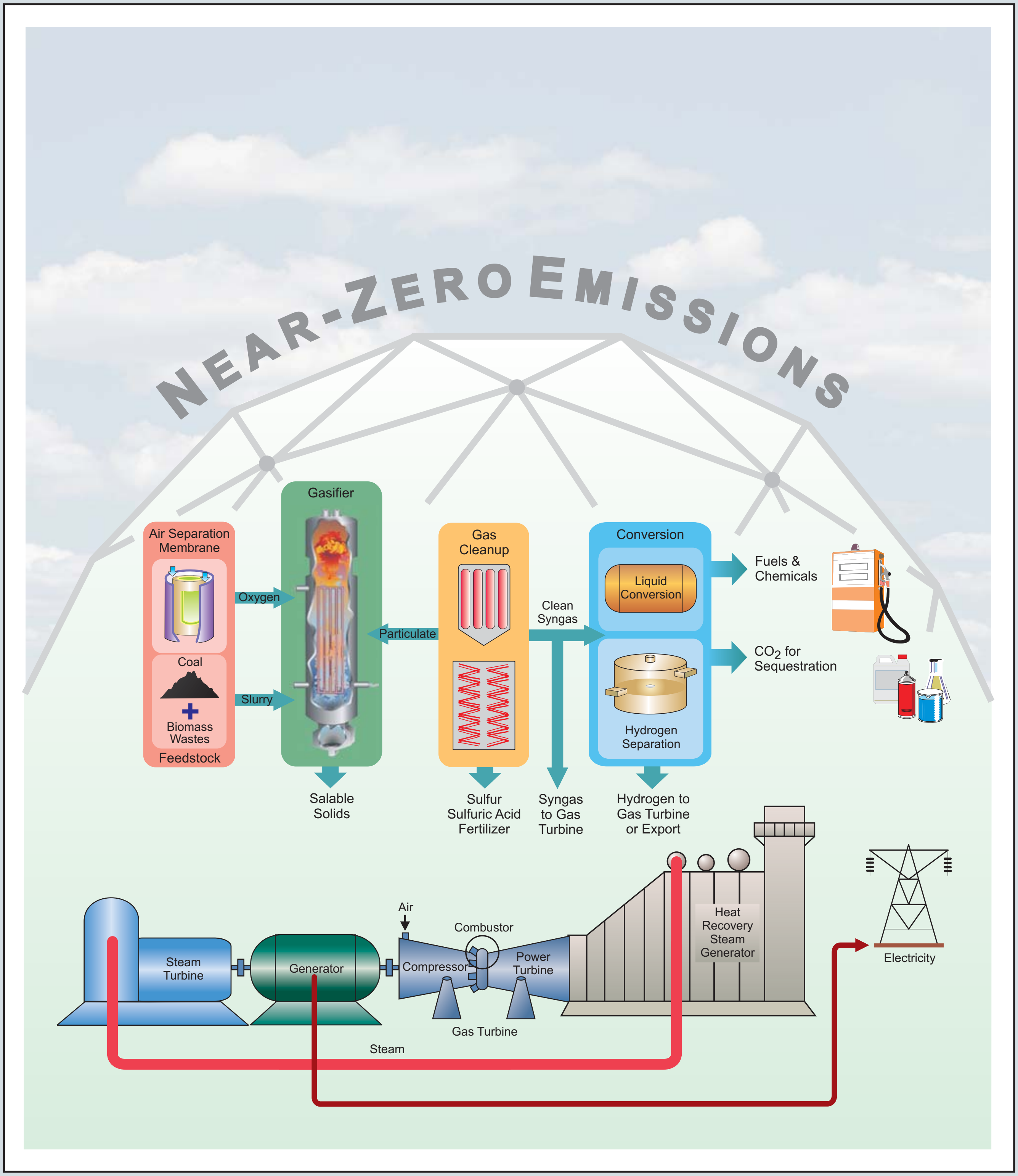
Thermal NO_x Formation Rate

Adapting to Coal

Adapting Advanced Gas Turbines to Syngas. Leveraging advancements made in natural gas-fueled turbines through the ATS Program is critical to achieving performance goals established for coal-based systems, particularly IGCC plants. Gas turbines applied in IGCC plants operate on syngas derived from gasification. Syngas, a low energy density fuel, typically contributes 15–20 percent to the volumetric flow through an advanced gas turbine to achieve the same heat input as natural gas. The additional mass flow theoretically increases gas turbine power output by 30−40 percent. However, aerodynamic issues due to high Mach numbers and negative operational outcomes associated with trying to capture the additional mass-flow energy (*e.g.*, shaft torque and/or axial compressor surge) currently limit power gains to values below those theoretically possible. Moreover, operating advanced gas turbines on syngas currently requires lowering turbine inlet temperatures below that possible with natural gas firing because of aerodynamic, heat transfer, and erosion issues.

Adapting Advanced Gas Turbines to Hydrogen. Pathways to near-zero emission power plants, *i.e.*, plants that minimize or eliminate carbon dioxide and pollutant emissions, include power systems that directly use hydrogen as fuel. Gas turbines, with their long history of efficient and durable performance in the utility and industrial sectors, are prime candidates as hydrogen-based power generators. However, development of hydrogen-fueled turbines with comparable performance to natural gas-fueled turbines represents a significant challenge in combustion technology. Stable, efficient low-NO_x combustion requires rapid, homogeneous mixing of fuel and air, which is challenging enough when using natural gas and made far more difficult with highly reactive hydrogen. On the positive side, the significant progress and accomplishments already made, and ongoing work in adapting turbines to syngas are applicable to hydrogen conversion because the technical challenges are similar in many respects.

Ultra-High Temperature Steam Turbine. Feasibility has been established for a highly efficient, near-zero emission oxy-fuel combustion turbine power system. This concept uses ultra-high temperature (3,100 °F) and high pressure steam derived from oxygen-fired combustion of clean fuels to drive a steam turbine. These clean fuels can be derived from coal gasification or other clean fossil fuels. Current state-of-the-art steam turbines are represented by units operating up to 5,000 psi and 1,100 °F. The most challenging aspect of moving this concept to reality will be in developing blade materials and cooling techniques to sustain 3,100 °F operating temperatures, coupled with the potentially corrosive nature of this working fluid.



IGCC-Based Near-Zero Emissions Concept

Program Strategy/Roadmap

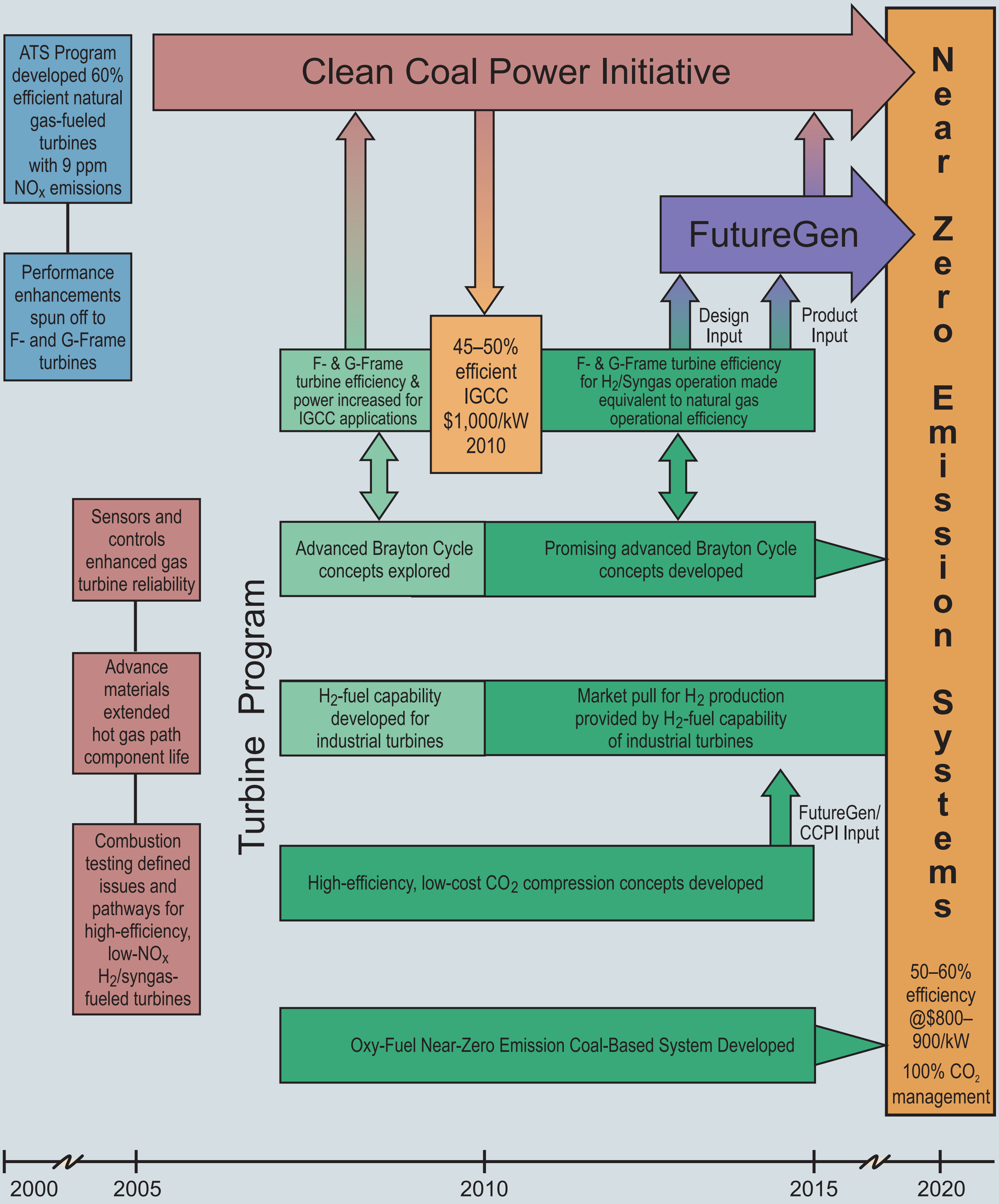
Turbines are key components in today's generating industry and the near-zero emission generating industry envisioned for the future. The Turbine Program technology roadmap embodies two basic destinations, or goals, for advanced coal-based power systems:

- By 2010, to have demonstrated a 45−50 percent efficient (HHV) coal-based power system at a capital cost of \$1,000/kW or less that reduces sulfur dioxide (SO_2) by 99 percent, mercury by 90 percent, and NO_x emissions to 2 ppm; and
- By 2020, to have demonstrated a 50−60 percent efficient (HHV) coal-based power system at a capital cost of \$800−900/kW that achieves near-zero emissions characterized by greater than 99 percent SO_2 removal, 95 percent mercury removal, 2 ppm NO_x emissions, and 100 percent CO_2 management.

There are two key initiatives that support demonstrating the systems showing greatest promise for reaching the roadmap destinations — FutureGen and the Clean Coal Power Initiative (CCPI). As previously mentioned, FutureGen is a 275-MW, near-zero emission (including CO_2) coal-based power and hydrogen production research facility. It is an IGCC system scheduled to come on-line in 2012 that is designed to test and demonstrate advanced subsystems and components for hydrogen production and CO_2 sequestration. CCPI is a roughly 2-billion dollar program begun in 2002 that is designed to support the stated goals by providing up to 50 percent of the cost of demonstrating a range of promising technologies. CCPI is to be implemented through a series of solicitations through 2014, two of which have been issued and implemented.

The Turbine Program is a research and development (R&D) program that engages industry, academia, and U.S. National Laboratories to address crosscutting technical issues, and to develop specific turbine technology and products in support of the overarching coal-based power systems goals. Developments by the turbine industry incorporate both inputs from their vast knowledge base and advances made by academia and National Laboratories in their pursuit of their relevant technical issues. Outcomes and attainment of the Turbine R&D Program goals are demonstrated and evaluated through FutureGen, CCPI, and potential commercial offerings.

Technology Roadmap



ATS Program developed 60% efficient natural gas-fueled turbines with 9 ppm NO_x emissions

Performance enhancements spun off to F- and G-Frame turbines

Sensors and controls enhanced gas turbine reliability

Advance materials extended hot gas path component life

Combustion testing defined issues and pathways for high-efficiency, low-NO_x H_2/syngas-fueled turbines

Clean Coal Power Initiative

FutureGen

Design Input

Product Input

F- & G-Frame turbine efficiency & power increased for IGCC applications

45–50% efficient IGCC $1,000/kW 2010

F- & G-Frame turbine efficiency for H_2/Syngas operation made equivalent to natural gas operational efficiency

Turbine Program

Advanced Brayton Cycle concepts explored

Promising advanced Brayton Cycle concepts developed

H_2-fuel capability developed for industrial turbines

Market pull for H_2 production provided by H_2-fuel capability of industrial turbines

FutureGen/ CCPI Input

High-efficiency, low-cost CO_2 compression concepts developed

Oxy-Fuel Near-Zero Emission Coal-Based System Developed

Near Zero Emission Systems

50–60% efficiency @$800–900/kW

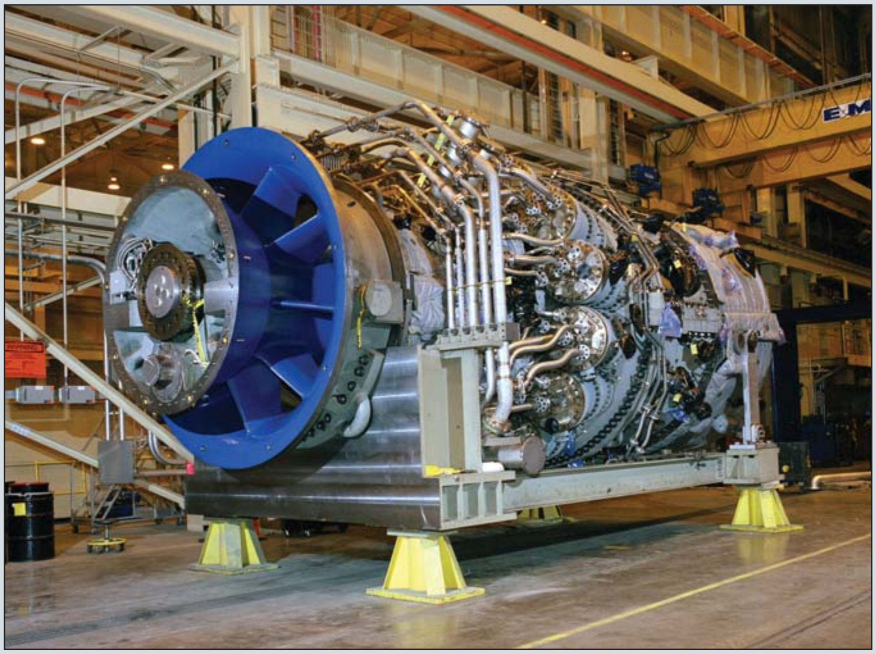
100% CO_2 management

Pathways

The Turbine Program strategy is to follow pathways that:

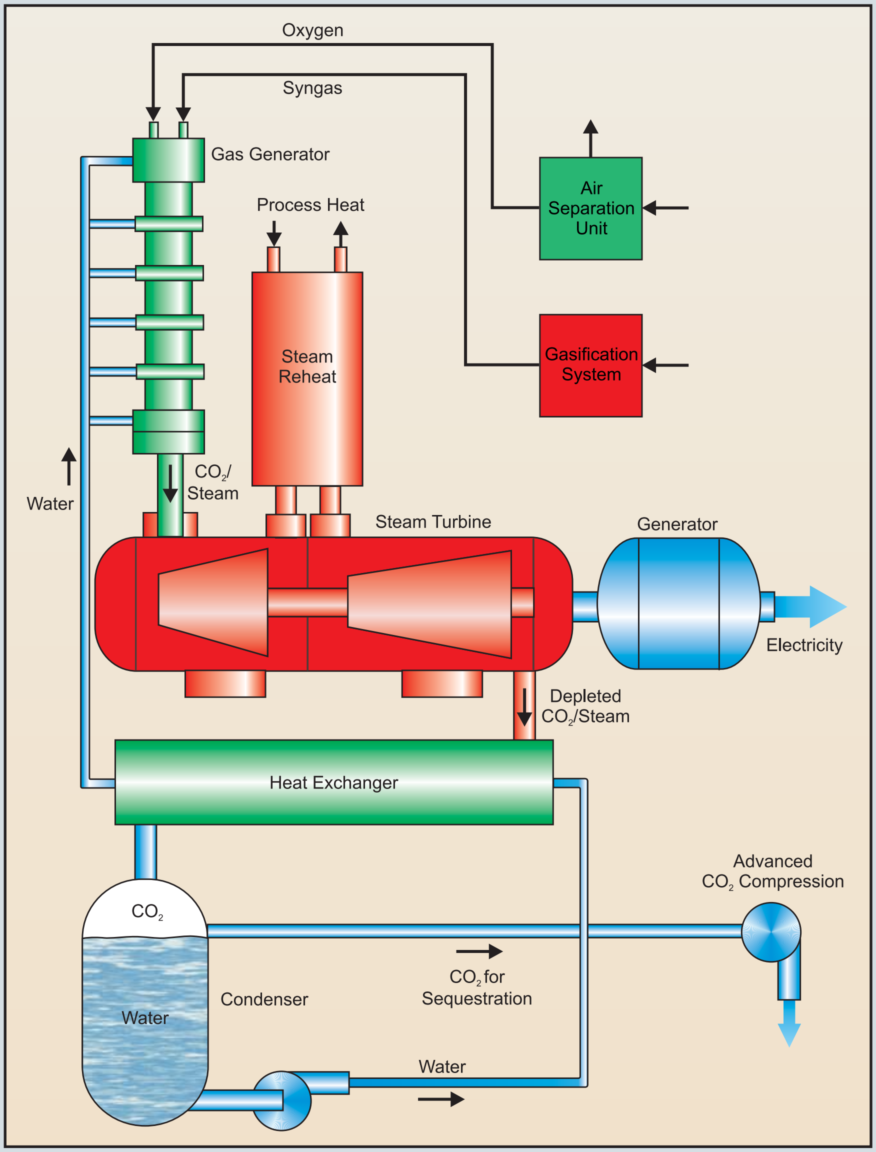
- Allow early spin-off of technological advances that benefit electricity users and the environment, and support early market adoption of advanced power system platforms, such as IGCC;
- Provide the technological advances to achieve 2010 near-zero emission systems goals for validation at the FutureGen IGCC test facility, and demonstration under CCPI;
- Support less mature, alternative advanced power system platforms for achieving ultimate 2020 near-zero emissions goals;
- Provide a market pull for FutureGen type plants that produce hydrogen for export, high-efficiency power, and near-zero emissions of CO_2 by developing MW-scale hydrogen turbines; and
- Support development of critical enabling technologies for carbon sequestration options that close the loop on CO_2 emissions for near-zero emission systems.

Meeting the 2010 Milestone. Gas turbine advancements are essential to meeting the 2010 coal-based power system milestone on the pathway to the ultimate 2020 destination. This milestone is critical to early adoption of IGCC, which is the coal-based system platform to be used in meeting the 2010 milestone. These systems currently use F-frame gas turbines operating on coal-derived syngas in combined-cycle mode. State-of-the-art IGCC systems have efficiencies of approximately 40 percent and capital costs of about $1,400/kW. A major thrust under the DOE Turbine Program is to engage industry, academia, and National Laboratories through partnerships to pursue development of F- and G-frame gas turbines that, by 2010, can operate on hydrogen and syngas (as well as natural gas), increase combined-cycle efficiency 2–3 percentage points when operated on syngas, and lower capital cost by increasing power output. Objectives include meeting 2 ppm NO_x emissions, which also lowers capital cost. The increased power output and efficiency result in lower cost of electricity as well. This technology is to be spun off and validated in IGCC applications through both CCPI and FutureGen. The fuel flexibility approach allows immediate adoption of technological advances by the power generation industry in general, and promotes entry of IGCC into the marketplace.



GE 7FB Turbine

Developing F- and G-Frame Hydrogen Turbines for FutureGen. Pursuit of F- and G-frame turbine fuel flexibility, efficiency enhancement, and power enhancement is to continue along with efforts to reduce NO_x emissions in preparation for testing at FutureGen. This is to culminate in 2015 with F- and G-frame turbines that: (1) operate on hydrogen and coal-derived syngas at efficiencies equivalent to current efficiencies when operated on natural gas (a 3–5 percentage point increase compared to current combined-cycle applications on coal-derived syngas); and (2) reduce NO_x emissions to 2 ppm when operating on hydrogen or syngas. This supports the 2020 near-zero emission coal-based power plant goal.

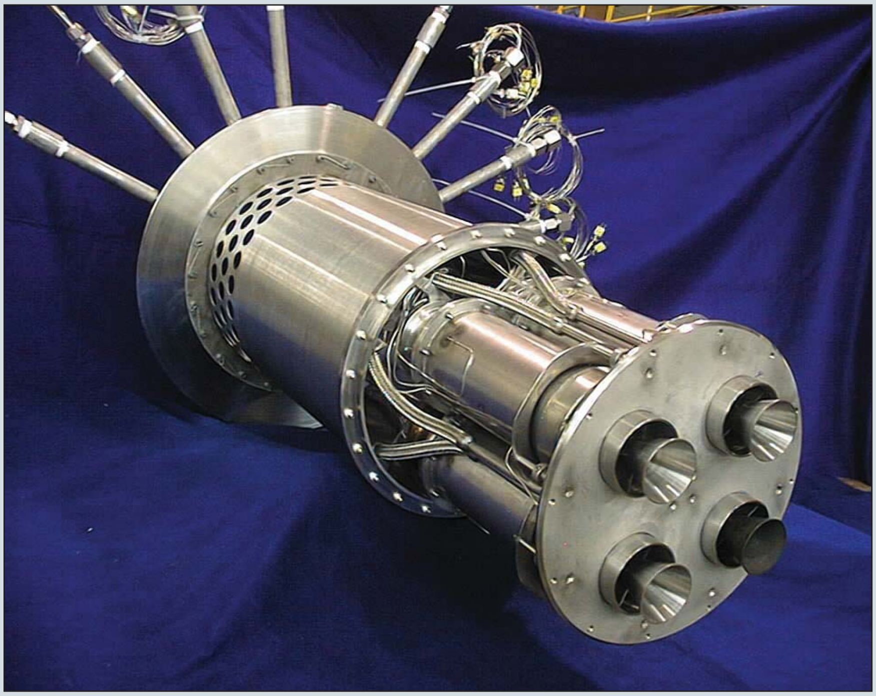


Oxy-Fuel System Concept

Developing Alternative Near-Zero Emission Coal-Based Systems (Oxy-Fuel Systems). Injecting water into a reactor where oxygen is used instead of air to combust clean gaseous fuels, such as coal-derived syngas or even natural gas, produces supercritical steam (over 3,000 psi) and a smaller amount of CO_2 at temperatures of 3,000–3,200 °F. The absence of nitrogen precludes NO_x formation, and other potential pollutant emissions are essentially eliminated by cleaning the fuel before combustion. Capture of this high energy steam in a steam turbine would result in a highly efficient power system with an exhaust that is easily separated into water and CO_2 for sequestration. The DOE Turbine Program is supporting development of an oxy-fuel system by 2015 that is capable of 50–60 percent efficiency (HHV) when operated on coal-derived syngas. Oxy-fuel systems envisioned are in the 300- to 600-MW range. Development is to take place along two parallel paths. One path is designed to evaluate oxy-fuel system options, identify state points for combustor design, and fabricate and test promising combustors. The other path is designed to develop and test steam turbines capable of using the high-temperature supercritical steam produced by the oxy-fuel combustors. Steam turbine developers may leverage ongoing materials research in ultra-supercritical steam turbines. In evaluating system options, consideration will be given to CO_2 and water separation, with emphasis on minimizing the penalty for CO_2 pressurization.

Enabling Hydrogen Utilization and Co-Production in the Industrial Sector. Gas turbines in the size range of 100 MW or less are widely used in the industrial sector in both simple and combined-cycle applications. Enabling use of hydrogen in these turbines, as a primary or supplemental fuel, reduces carbon and NO_x emissions and creates a market pull for hydrogen produced in FutureGen-type plants. Moreover, exploring systems options for industrial-scale coal-based co-production of hydrogen and power serves to identify technology opportunities in this market sector and associated research and development needs. The DOE Turbine Program supports development of combustion systems for retrofit of existing industrial gas turbines (100 MW or less) in the 2010 timeframe that enable operation on hydrogen either as a primary fuel or supplemental NO_x control fuel. The DOE Turbine Program also provides for design studies of coal gasification-based hydrogen and power generation systems in the 50- to 100-MWe size range that offer high efficiency and less than 2 ppm NO_x emissions. These turbines would operate under reducing conditions, which provides significant advantages in addressing NO_x emissions, and increases efficiency by reducing load on the compressor. The studies are to examine potential markets, issues, technology options, and research needs.

Closing the Loop for Near-Zero Emission Power Plants. Carbon sequestration is needed to close the loop on CO_2 emissions for near-zero emission power plants. Compressing the CO_2 separated from near-zero emission plant production streams is a prerequisite to carbon sequestration. The current efficiency penalty associated with CO_2 compression is quite high, ranging from 8–12 percentage points depending on the state of the CO_2 exhaust. The DOE Turbine Program is seeking novel concepts for trial at FutureGen in the 2012–2015 timeframe that can significantly increase the efficiency and reduce the cost of compressing CO_2 to 1,500 psi at flow rates of 600,000–700,000 pounds per hour. Integration of CO_2 compression with turbine systems is a logical extension because turbines provide the current power and compression in IGCC systems.



PCI Rich-Catalytic Lean-Burn (RCL®) Advanced Combustor

Advancing Brayton Cycle Efficiency in Near-Zero Emission Systems. To help identify and close technology gaps and to formulate turbine-based power system configurations that can meet the 2020 goal, system studies are to be carried out that look to increase Brayton cycle efficiency 7 percentage points in combined-cycle applications. The target is to achieve coal- and natural gas-based, near-zero emission plant efficiencies of 60 percent (HHV) and 75 percent (LHV), respectively. The system studies will examine the Brayton cycle in the context of near-zero emission plants, and address how near-zero CO_2 emissions affect turbine design and performance. Potential pathways include increasing turbine rotor inlet temperature to 3,100 °F or higher, increasing turbine compressor pressure ratios to 35 or higher, augmenting the working fluid, applying pressure gain combustion, using inter-stage reheat and inter-cooling, recuperating heat of combustion, and integrating air separation and CO_2 compression. Outcomes from the studies will identify research and development requirements for achieving the increased efficiency.

Conclusion

The DOE Turbine Program is an essential element in enhancing the Nation's energy security and environmental well-being by enabling near-zero emission power and hydrogen co-production plants, and shifting from current reliance on natural gas for power to abundant domestic coals. In moving toward near-zero emission plants, the Program provides for spin-off of advances in gas turbine technology that can be readily applied throughout the power industry to reduce natural gas consumption, CO_2 *emissions, and electricity costs to consumers. Ultimately, the Program positions the United States as a leader in the world market with technology capable of addressing global and regional environmental concerns.*

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