Distributed Energy Program

FY04 Accomplishments

Materials

OAK RIDGE NATIONAL LABORATORY

MANAGED BY UT-BATTELLE FOR THE DEPARTMENT OF ENERGY

Oak Ridge National Laboratory

FY 2004

Accomplishment Report

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INTRODUCTION

October 2004

On behalf of Oak Ridge National Laboratory's Distributed Energy Program, I am pleased to introduce the FY 2004 Accomplishments Report. The objective of the Distributed Energy (DE) Program is to develop the next generation of clean, efficient, reliable, and affordable DE technologies and to successfully integrate them into end-use applications. These systems are powered by microturbines, reciprocating engines, or industrial gas turbines and can produce from 30 kW up to about 10 MW of electricity. Waste heat produced by the prime mover is captured and converted to useful energy for heating or cooling of buildings. The target for these integrated systems is to demonstrate at least 70% total fuel efficiency with a payback period of less than 4 years.

The Distributed Energy Program at ORNL is divided into three areas: 1) Advanced Reciprocating Engine Systems (ARES), 2) Materials and 3) Cooling, Heating and Power (CHP). The overall goal of the research is to increase the efficiency of the turbines, dramatically reduce the emissions from the reciprocating engines, and optimize the efficiency of integrated systems. FY 2004 featured notable accomplishments in each program area. The remainder of this report summarizes the most significant accomplishments—three from the ARES Program, five from the Materials Program, and six from the CHP Program. The last section of the report summarizes the new packaged Integrated Energy Systems (IES) projects that were selected from a competitive solicitation held during FY 2004. These cost-shared projects will demonstrate integrated systems in four very significant market sectors for DE – healthcare, education, hotels, and supermarkets – and will be a focus of our program for the next 3 years. Experience gained in the installation and initial operation of these projects will be documented and disseminated to encourage broader use of these technologies.

If you have any comments or questions about these accomplishments, please feel free to contact me or the contacts listed on each document.

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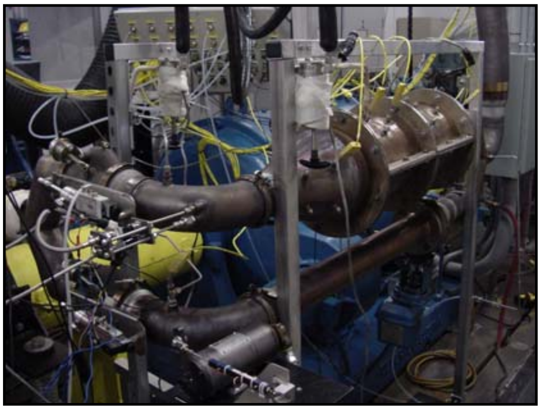
Lean NO_x Trap Technology Surpasses ARES Emissions Goal for 2010

NO_x Emissions from Natural Gas Engines Reduced by 90%

Background

Lean burn combustion (with a high air-to-fuel ratio) is utilized in natural gas reciprocating engines for its better fuel economy, engine durability, and lower emission levels; however, lean burn engines currently use selective catalytic reduction (SCR) requiring the addition of potentially toxic chemicals (such as ammonia or urea) in order to reduce nitrogen oxides (NO_x) to acceptable levels.



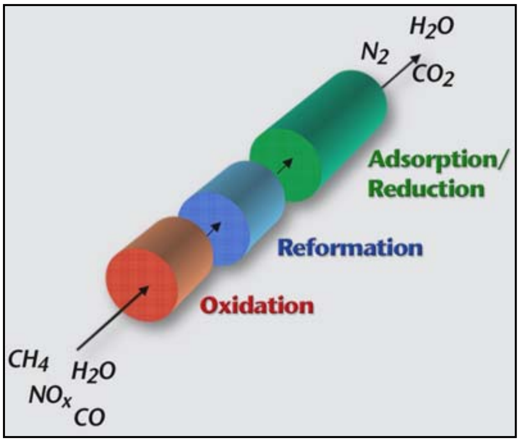
A state-of-the-art lean engine used at ORNL to evaluate a Lean NO_x Trap

The ORNL lean NO_x trap (LNT) technology has successfully met and surpassed the 2010 target for the Advanced Reciprocating Engine Systems (ARES) Program to reduce NO_x emissions to less than 0.1 g/hp-hr. ARES is a collaborative program between industry, universities, and national laboratories with the following goals:

- To reduce NO_x emissions to 0.1 g/hp-hr by 2010
- To increase fuel to electrical efficiency to 50% (lower heating value) by 2010
- To reduce cost of engines by 10%
- To have multiple fuel capability
- To maintain availability, reliability, maintainability reflecting state-of-the-art systems

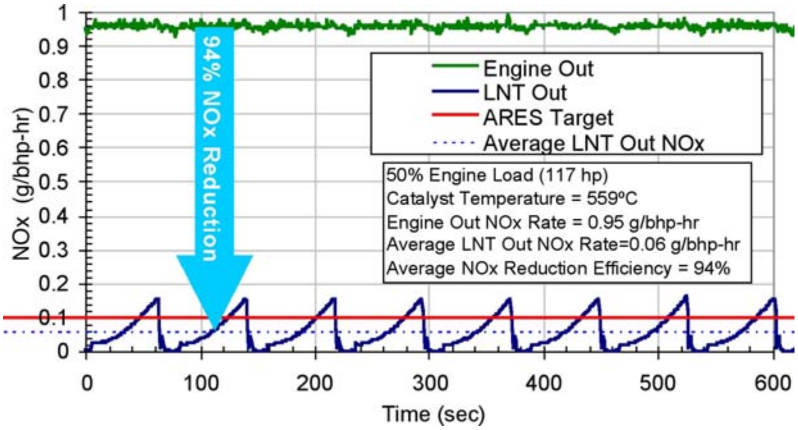
Technology

LNT technology traps NO_x on a catalyst surface; it is then periodically released for reduction to harmless N_2. NO_x is trapped in lean exhaust, but rich exhaust conditions are required for NO_x release and reduction (a process called "regeneration"). The required rich exhaust conditions are produced by controlling valves in the exhaust system and injecting fuel from the engine natural gas supply into the exhaust pipe upstream of the catalysts. Oxidation and reforming catalysts then break down the methane in natural gas into rich combustion species such as carbon monoxide (CO) and hydrogen (H2) to regenerate the lean NOx trap.



Lean NO_x Trap catalysis processes in natural gas engine exhaust.

ORNL has demonstrated operation of a lean NO_x trap on an 8.3-liter Cummins lean natural gas engine. High NO_x trapping and regeneration efficiencies were demonstrated, reducing the NO_x level emitted from the engine by over 90%. Average NO_x emissions levels were lower than the ARES program goal of 0.1 g/bhp-hr. In addition, carbon monoxide (CO) and methane (CH_4) emissions from the engine were reduced by over 90% and 50%, respectively.



>90% NO_x Reduction Efficiencies Demonstrated. NO_x emission rates measured from the engine ("Engine Out") and lean NO_x trap ("LNT Out") catalyst during catalyst operation show greater than 90% NO_x reduction efficiency. Average LNT out emissions are less than the ARES program target of 0.1 g/bhp-hr NO_x (~7 ppm NO_x).

Benefits

The ability to utilize natural gas as the sole fuel source throughout the LNT process is a key benefit of the technology. The emission of multiple pollutants is reduced without the use of additional chemicals for NO_x reduction. Operation of lean natural gas engines for stationary power would be greatly simplified by eliminating the need for the delivery and storage of a second fuel for NO_x reduction. Consumption of natural gas for NO_x reduction does represent a fuel penalty for the customer; however, it is anticipated that only 0.5 to 1.5% of the engine fuel flow is required for catalyst regeneration. Thus, the catalyst system is efficient enough to maintain the key advantage of fuel efficiency for lean natural gas engines. Furthermore, the lean burn engines can be optimized for fuel efficiency without having to de-tune the engine to minimize NO_x emissions. LNT can be added to any lean burn natural gas engines making it an extremely practical innovation to industry.

- NOx emissions below 0.1 g/bhp-hr
- Reduction of CO and CH_4 pollutants
- Only natural gas fuel required (additional toxic agents unneeded)
- Low fuel penalty for operation maintains energy efficiency benefits
- Can be added to existing lean burn natural gas engines

Future Work

LNT is a promising technology for the reduction of NO_x emissions in efficient lean natural gas engines, but cost and durability are key performance areas to be addressed before it becomes commercially viable. Future studies will also characterize the chemical processes and unregulated emissions of the technology.

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Champion Partners with ORNL to Develop High Performance Spark Plugs

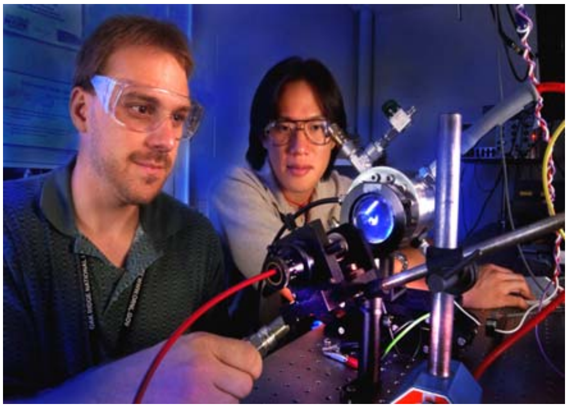
Failure Mechanisms Identified Through Advanced Microscopy and Microanalysis

Background

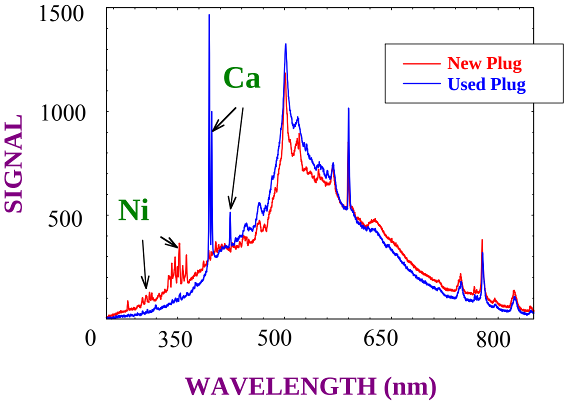
Ignition systems have been identified by natural gas reciprocating engine manufacturers as a key technology to achieve cost, performance, and emission goals for lean and stoichiometric engines. Spark plug erosion is a major problem in natural gas ignition. Current spark plug lifetimes last only 1000-4000 h, which results in loss of performance and necessitates frequent costly downtime maintenance for plug replacement. Lifetimes of 8000 h (1 year) are desired. As cylinder pressures, compression ratios, and ignition voltages are increased, and conditions further moved to lean burn to reduce emissions, spark plug reliability and lifetime performance will become even more of an issue and could limit further engine development. Key efforts of this research are to (1) characterize optical spectra of spark plug arcs to evaluate the ignitability and erosion characteristic, (2) measure spark plug erosion as a function of engine-tested time, (3) provide understanding of corrosion and erosion mechanisms, and (4) develop advanced alloys to improve the corrosion/erosion resistance and extend the lifetime of electrodes and spark plugs.

Technology

Analyses of erosion and spectral emission of new and used spark plugs are carried out using a specially constructed spectroscopic chamber that can be pressurized up to 200 psig with air. The electrode tip surfaces of new and worn plug were also examined by optical microscopy and scanning electron microscopy (SEM), with qualitative compositional analysis by energy dispersive x-ray techniques. Quantitative compositional analysis was performed on the polished cross-sections by electron probe microanalysis (EPMA) using pure element standards.



Optical spectroscopy test chamber used at ORNL to measure erosion and analyze elements emission



Emission spectra indicate presence of Ca in used plug and absence in new plug

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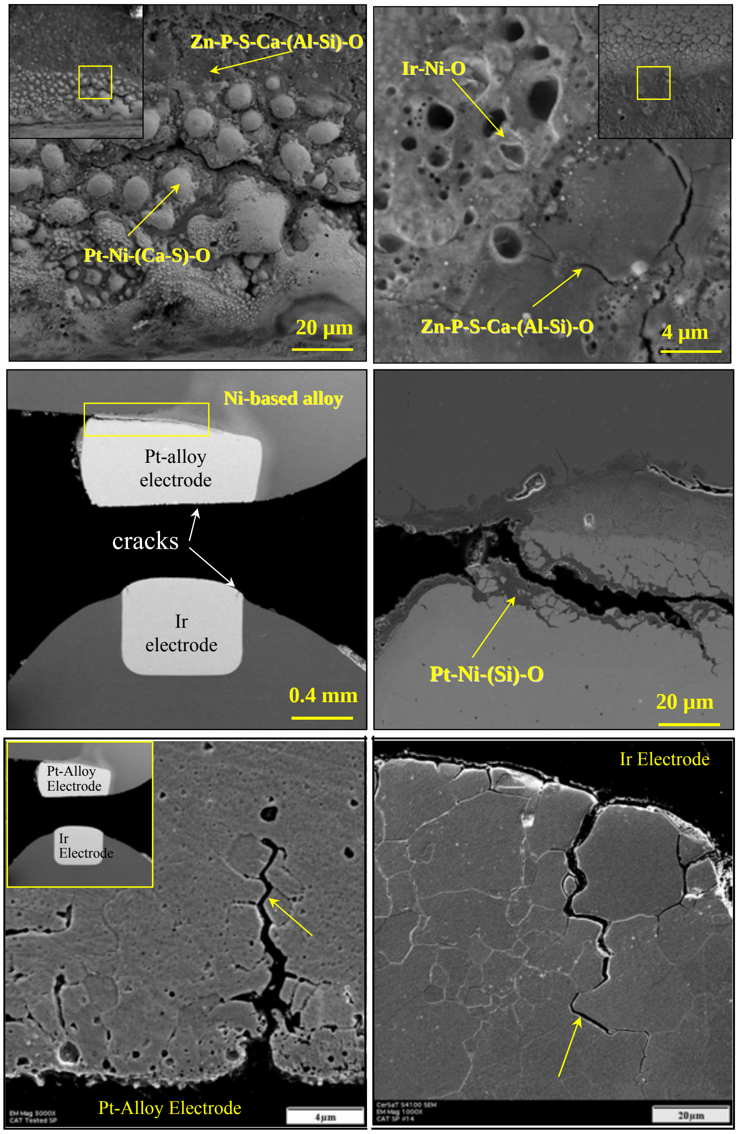

Key Findings

Substantial oxidation plus glassy phase formation, enriched with Ca and other engine lubricant impurities, was observed on both central and ground electrode side surface after field service. The presence of Ca, which significantly reduces the softening point, would enhance the erosion process.

Crack generation and growth through an oxide reaction zone were observed at Pt-alloy tip insert and Ni-based electrode interface. This phenomena would significantly degrade the ignitability and performance of spark plugs, and is likely a key life-limiting step.

Substantial intergranular cracking occurred in both Pt-alloy and Ir electrode tip inserts after field service. Coalescence and growth of crack and subsequent material flake-off would further accelerate the erosion process and limit the long-term durability and life of spark plugs.

Benefits

ORNL has established a partnership with a natural gas engine spark plug manufacturer, Federal Mogul (Champion). This effort will include the manufacture and testing of prototype spark plugs incorporating developmental alloys for improved erosion resistance and enhanced plug lifetimes based on insights gained from the characterization of the degradation mechanisms in field tested plugs. Several developmental alloys have already been fabricated and delivered to Champion for evaluation.

Future Work

A systematic study will be conducted for the characterization of field-tested spark plugs provided by Caterpillar and Cummins. These tests will determine when specific, life-limiting degradation phenomena are initiated as a function of engine test time. Spark plugs fabricated from developmental alloys for improved erosion resistance will be provided by Champion and will be bench top or engine tested.

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NO_x Sensor Technology Developed to Monitor and Enable Emissions Reduction

Advanced Sensors Meet Goals for Sensitivity and Response Time

Background

Attempts to minimize environmental impacts have prompted efforts to reduce emissions from reciprocating engines. NO_x emissions are among the pollutants of primary concern. NO_x is resistant to decomposition in the oxygen-rich conditions existing in exhausts from diesel and lean-burn gasoline engines. NO_x catalysts, NO_x traps, or selective catalytic reduction (SCR) are potential mechanisms to achieve NOx remediation. Both NOx traps and SCR will require on-board NOx sensors to control regeneration of the NOx trap or reagent injection in SCR. A suitable sensor would demonstrate the following characteristics:

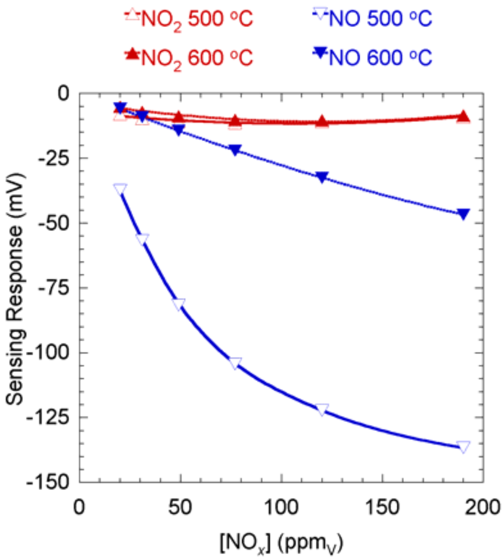
A state-of-the-art lean sensor test facility used to evaluate NO_x sensors.

- Operate at temperatures around 600–700° C
- Measure NO_x in the range 1 ppmV ≤ $[NO_x]$ ≤ 1000 ppm
- Exhibit minimal cross sensitivity
- Response time ≈1 second

Technology

Complete characterization of NO_x emissions will require accurate measurements of NO, NO_2, and total-NO_x (NO + NO_2). Both NO-selective and total-NO_x sensing elements are under development at ORNL.

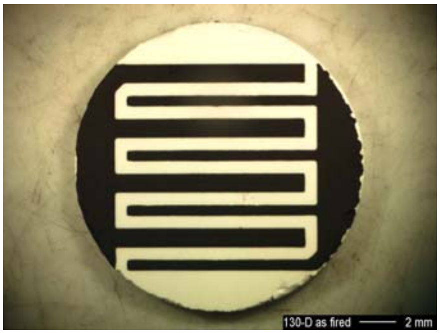
The development of a total-NO_x and a NO-selective sensors are the keys to monitoring and controlling NO_x emissions and the regeneration cycle for a lean NO_x trap. Current technology requires the LNT to regenerate every 1 to 5 minutes. The NO_x sensor will determine when breakthrough occurs and initiate the control strategy to regenerate the trap. Furthermore, the technology being developed by ORNL utilizes standard commercial microelectronics manufacturing processes and thus is anticipated to be as inexpensive as the current industry standard.

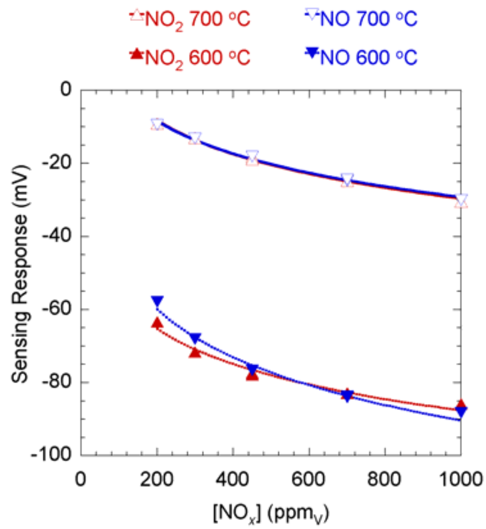


Sensor response to NO and NO_2 at 500 and 600°C for a NO-selective sensor.

Improved sensor designs, such as the one shown here with interdigitated electrodes, have led to improved sensor signals. The sensor output is further enhanced by coupling advanced design concepts with the application of a voltage across the electrodes. When tuned to the appropriate voltage, the sensors can be adjusted to be NO_x-selective.

Voltage across interdigitated electrodes can be adjusted to provide NOx-selective data





Benefits

NO_x sensor technology may serve as a key enabling technology for control systems to reduce NO_x emissions. The ORNL-developed sensing elements are demonstrating a number of promising characteristics. Sensors may be either current or voltage biased, allowing flexibility in final sensor design. Furthermore, their sensitivity to low O_2 levels will be desirable since lean-burn engine exhausts vary in their O_2 concentrations. These sensors will be particularly attractive to engine manufacturers because sensor designs will no longer require catalysts to convert NO_x to NO or NO_2 prior to contact with the sensing element. The 90% response/recovery time of the elements is ≈1 second.

- Flexibility in final sensor design
- Low O_2 sensitivity
- Eliminates use of catalysts to convert NO_x to either NO or NO_2 before impingement on the sensing element
- 90% response/recovery times at ≈1 sec
- Inexpensive manufacturing process

Future Work

NO_x sensors will be further tested for durability and cross sensitivity to H_2O, hydrocarbons, and ammonia before commercialization. Studies will also be conducted to optimize the catalyst and the fabrication process prior to sensor prototyping.

This project is a collaboration between ORNL and the Ford Motor Company and is jointly funded by the US DOE EERE Offices of Distributed Energy and Office of FreedomCar Technologies.

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Materials

ORNL Facility Evaluates High Temperature Recuperator Materials

New Alloy Demonstrates Outstanding Creep and Corrosion Resistance at High Temperatures

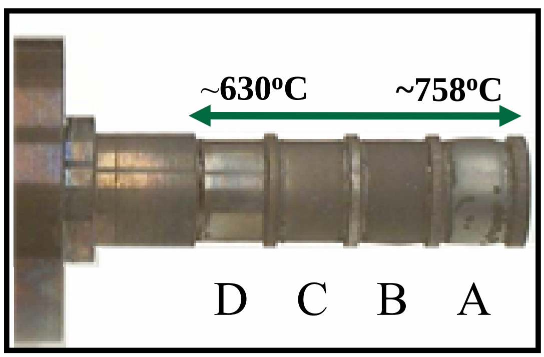
Background

ORNL Microturbine Recuperator Test Facility

One of the most challenging performance targets for the next generation of microturbines requires fuel-to-electricity efficiency of 40%. Significant increases in microturbine efficiency can be achieved by increasing the engine-operating temperature, but this can only be realized through the use of advanced metallic alloys for high temperature recuperator material. Most modern microturbine recuperators are manufactured with 300-series stainless steels and are used at exhaust-gas temperatures below 600°C. At higher temperatures, these materials are susceptible to creep formation and oxidation, which lead to a reduction in the effectiveness and life of the recuperator.

As part of the U.S. DOE Advanced Microturbines Program, a test facility was established at ORNL to screen and evaluate candidate, next generation recuperator materials. Several alloys have been evaluated at the facility in collaboration with Capstone Turbine Corporation, Ingersoll Rand, and Solar Turbines. Haynes Alloy 120®, demonstrated excellent creep and corrosion resistance after 500 h exposure tests at temperatures as high as 760°C.

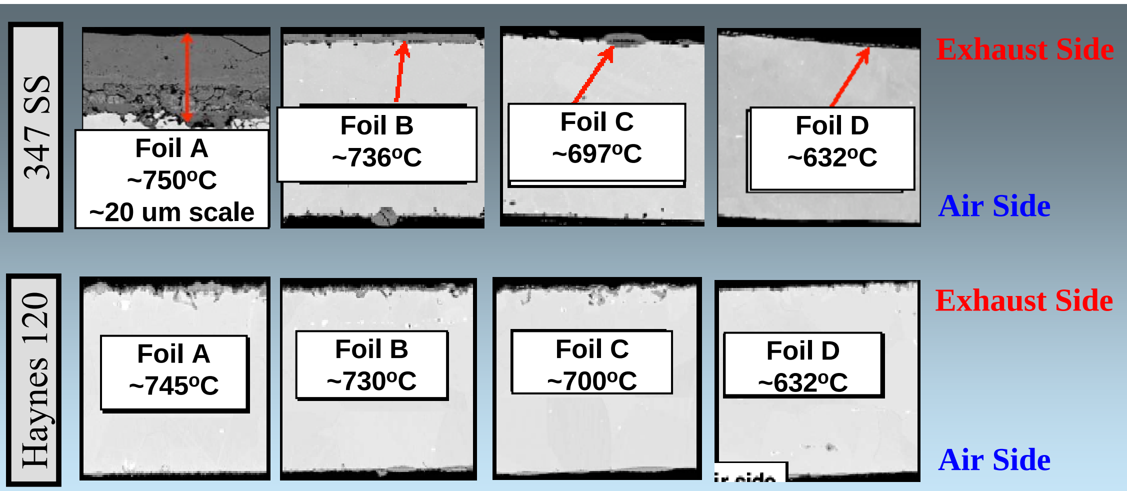
Technology



After exposure, foils are removed from the sample holder and evaluated for microstructural change and residual tensile strength.

The ORNL facility uses a 60kW Capstone microturbine which is modified to achieve higher turbine exit temperatures. To simulate the pressure differential experienced by the recuperator during service, thin metallic foil test specimens are welded onto a sample holder and mechanically stressed by pressurizing the sample holder with air. The specialized configuration of the microturbine allows the screening of test specimens over a wide range of temperatures in one test. After exposure, the residual mechanical properties of the test specimens are determined through tensile testing and their microstructure and composition is characterized using analytical electron microscopy.

The thickness of the oxide layer forming on the surface of 347 stainless steel (347 SS) foils was found to increase with temperature and become more than 20-µm thick after a 500-hr exposure at 760°C. The presence of water vapor in the microturbine exhaust gas stream leads to rapid growth of Cr_2O_3 followed by its evaporation as $CrO_2(OH)_2$. These two processes lead to an increased consumption rate of chromium in the metal compared to oxidation in dry air. Because the diffusion rate of chromium in the metal is not fast enough compared to the consumption rate, a chromium depleted region forms in the metal near the surface exposed to the exhaust gases. After an incubation period, nodules of iron oxide begin to form leading to accelerated attack. The 347 SS specimen also loses 50% of its tensile strength after the 500 h exposure at 760°C. In contrast, after a comparable exposure period the Haynes 120® alloy retains 85% of its ultimate strength and the corrosion products that form on the surface are much thinner. Haynes 120® alloy is one of the leading candidate alloys to manufacture the next generation of microturbine recuperators.



Corrosion of materials after a 500 h exposure test. 347 SS formed a 20 µm thick oxide scale on the exhaust side (top of image) while Haynes Alloy 120 demonstrates very thin oxide scales, even at the highest temperature of 750 ºC .

Benefits

The screening and evaluation of candidate recuperator materials in the actual operating environment of a next generation microturbine is a valuable capability provided by the ORNL Microturbine Recuperator Test Facility. Exposure tests can be carried out at temperatures as high as 850°C and at compression ratios of 15:1. Exposure tests, combined with subsequent mechanical and microstructural characterization of the materials examined provide information on the mechanisms responsible for their corrosion resistance (or lack thereof) and ways to modify them to improve their performance.

Future Work

In addition to Haynes 120® alloy, the behaviors of alloy 625, Haynes 214® and 230®, ORNL-modified stainless steels, and FeCrAlY are being investigated.

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Materials

ORNL Partners with Industry for Testing of Ceramics and EBCs

Keiser Rigs Evaluate Long-Term Stability of Materials in High Temperature and High Pressure Environments

Background

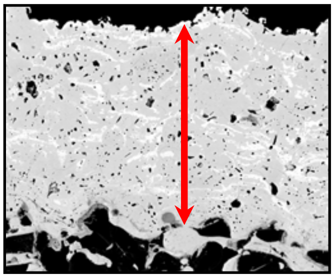
The use of Si-based ceramic materials in gas turbine and microturbine engines components is problematic due to their recession in high temperature, H_2O-containing environments. Surface recession of these ceramics in water vapor occurs by oxidation to form surface SiO_2 and subsequent volatilization of the SiO_2 as $Si(OH)_4$ in the high gas-velocities in turbine engines. Volatilization (surface recession) is the life-limiting factor for Si-based ceramics, and an environmental barrier coating (EBC) will be necessary to protect the gas-path surface. EBCs protect the ceramic substrate by creating a permeation barrier to oxidizing species (oxygen and water vapor) and exhibiting volatilization resistance.

ORNL's high-temperature, high-pressure exposure furnace -"The Keiser Rig"

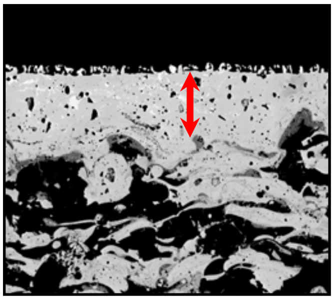
Technology

ORNL Keiser Rigs allow exposure of ceramic materials and candidate EBCs to simulated combustion environments (high water-vapor pressures) for very long times (>5000 h); post-exposure characterization provides an invaluable means by which to interpret and understand the exposure data.

The Keiser Rigs have been used during the past few years to quantify the recession rates of uncoated SiC-based continuous-fiber ceramic composites (CFCC) and Si_3N_4 materials using simulated gas turbine and microturbine environments. Conditions with high temperatures, high water-vapor pressure, but slow-flow gas velocities are employed to evaluate the permeation-resistance of many potential EBC compositions. Initial screenings of EBCs were conducted in a Keiser Rig at water-vapor pressures typically found in turbine engines (0.3–2.0 atm). More recently, very high H_2O pressures (~20 atm)



Original BSAS-based EBC top coat thickness ~200 µm.



Final EBC top coat thickness after ~14,000 h engine-test < 60 µm. Thickness loss due to recession of BSAS surface.

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have been utilized to evaluate EBC volatility. High water vapor pressure compensates for the slow-flow velocities in the Keiser Rig, and such exposures will be used to provide low-cost volatility screening of EBCs in water vapor.

Numerous collaborations have developed as a result of the ORNL research on water-vapor effects, and ceramic material exposures in the Keiser Rig have been extensive. As of September 2004, a total of more than 650,000 ceramic specimen hours have been accumulated in the ORNL Keiser Rigs.

SiC-SiC CFCCs	**GE Power Systems Composites** **Goodrich Corporation**
Oxide-Oxide CFCCs	**ATK-COI Ceramics, Incorporated**
Si_3N_4 and Sialon	**Honeywell Ceramic Components** **Saint Gobain Ceramics & Plastics** **Kyocera** **Kennametal**
Environmental Barrier Changes	**United Technologies Research Center** **ATK-COI Ceramics, Incorporated** **SMAHT Ceramics**
Gas Turbine and Microturbine Engines	**Solar Turbines, Incorporated** **General Electric Siemens Westinghouse**

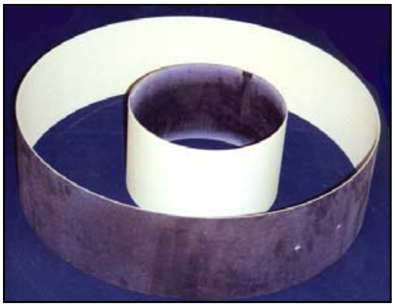
Benefits

There are numerous benefits for using ceramic materials for hot section components in gas turbine and microturbine engines; however, it has been demonstrated that Si-based ceramics will not survive long-term exposures in gas turbine and microturbine combustion environments. Rapid surface recession of these materials is life-limiting, which necessitates the use of protective EBCs. ORNL Keiser Rigs can be used to initially screen candidate EBCs for permeation- and volatilization-resistance prior to exposing the EBCs to significantly more expensive engine tests.

Long-term exposures of several SiC-based CFCCs and candidate EBC compositions in the Keiser Rig have resulted in the down-selection of materials to those with the best long-term stability potential in H_2O-containing environments. Combustor liners were produced from a SiC-SiC CFCC and a BSAS-based EBC based on Keiser Rig exposure data and were run in Solar Turbines Centaur 50S engines at the Chevron engine test site in Bakersfield, CA and the Malden Mills engine test site in Lawrenceville, MA for ~14,000 h at each site.

Future Work

Low-cost volatilization assessment of candidate EBCs will continue. Exposure data will also be used to develop a complete understanding of the role of water vapor on the permeation- and volatility-resistance of different EBCs. Many of the results will be compared with similar material exposures conducted in actual engine tests.



CFCC combustor liners with EBC on gas-path surfaces

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Materials

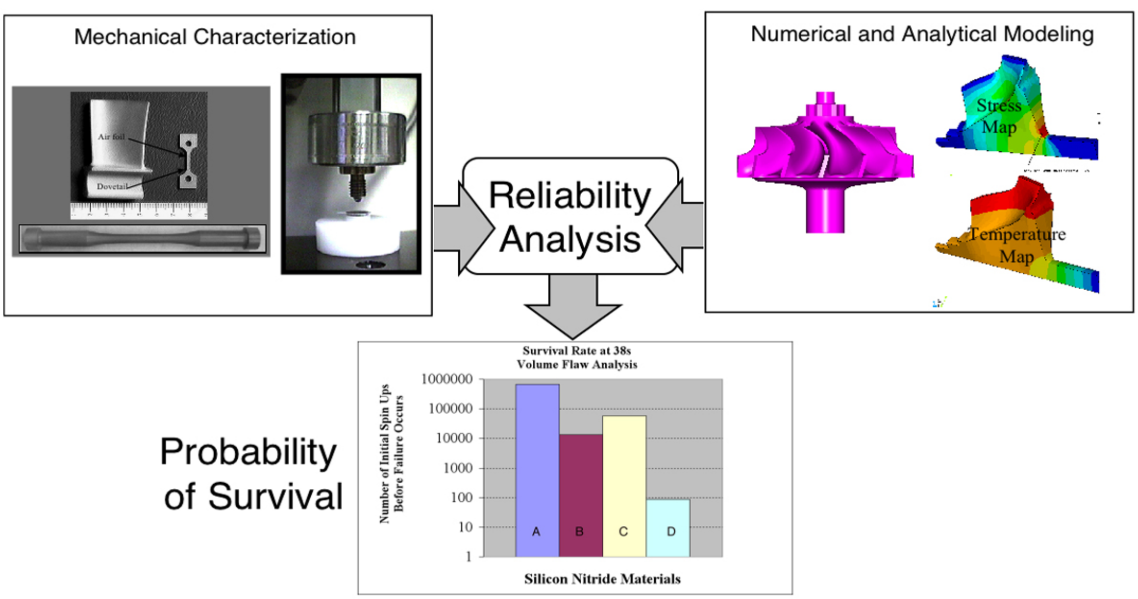
Software Evaluates Ceramic Materials for Turbine Efficiency

Integrated Reliability Assessment Software Selects Contemporary Ceramics for Structural Components and Predicts Properties Needed for Next-Generation Ceramic Materials

Background

The successful application of structural ceramic components in gas turbines requires the use of well-established life prediction methodology to estimate the probability of survival at the desired operating life of the component. This assessment of component reliability results after three critical inputs are combined. First, mechanical properties including strength, slow crack growth, fatigue, and creep for the candidate ceramic must be collected. Next, numerical analyses are used to predict the temperature and stress distributions for the component in question. Finally, life prediction software is used to combine the experimental mechanical property data with the stress and temperature maps to estimate the probability of survival. If this value is too low, then either the component geometry must be modified to lower the maximum stress or a better (stronger, more fatigue resistance, etc.) material must be selected.

The implementation of the the reliability assessment process faces a number of challenges. The first involves the difficulty of collecting all of the required input data, which is generally scattered among a variety of sources (e.g., the materials suppliers, research laboratories, and universities). A second challenge is that most reliability software algorithms do not have a user-friendly process for varying properties so reliability can be maximized.



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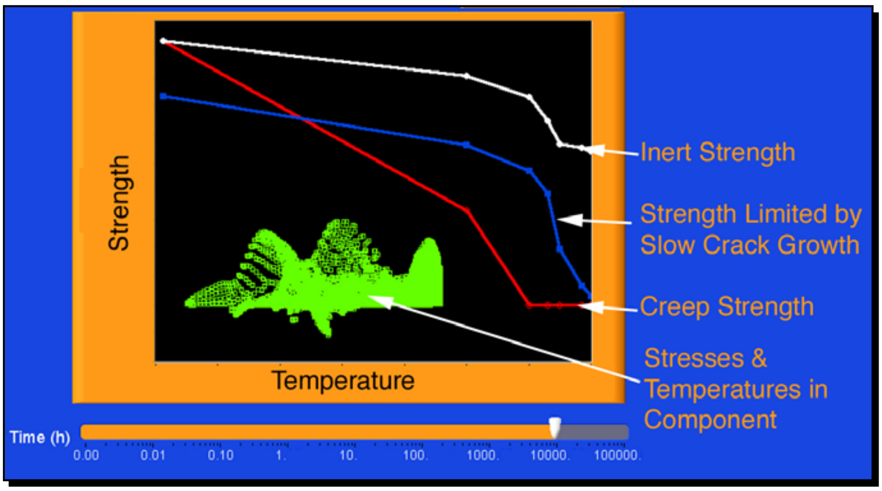
Software

The Integrated Reliability Assessment Software addresses the aforementioned challenges by first providing an integrated database for a number of commercial silicon carbides and silicon nitrides. As a result, the user is able to rapidly implement reliability estimates comparing a number of candidate materials. The results of each analysis are displayed graphically by generating strength/stress versus temperature plots to compare finite element results for a specific component with the strength-temperature data for a number of commercial ceramics from the database. The strength is adjusted to account for both slow crack growth and creep. At the same time, the effect of recession that would occur during turbine operation is simulated by increasing the finite element stresses as the material is lost. The program also allows the user to vary the key properties for a specific material so that component reliability can be maximized. The modified or target properties then become critical input to process optimization studies implemented by the materials suppliers in order meet the component lifetime requirements.



Fracture Map for Typical Silicon Nitride Ceramic

Benefits

Structural ceramic component end-users can readily screen the best ceramic material for their component. In those cases where the existing materials do not have properties sufficient to meet reliability requirements, the software can provide target properties of new or improved materials. The software also facilitates sensitivity analyses which illustrate how variation in key properties of the ceramic affect the component reliability.

Future Work

The program database currently includes strength distribution data for machining (surface) and bulk (volume) defects. It will be expanded to include available strength distribution data for as-processed surfaces.

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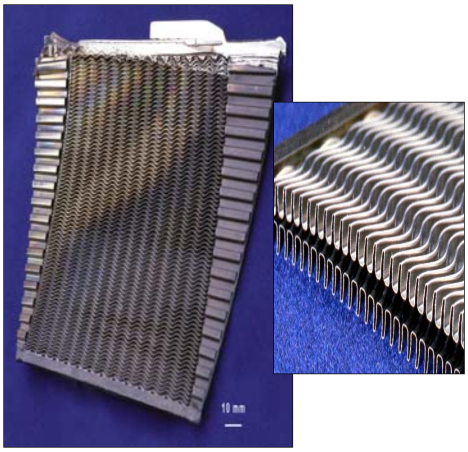
Materials

Long-Term Testing of Recuperator Alloys Provides Insight Into Oxidation Mechanisms

Recuperator Life Estimated Based on Cr-Depletion Rates

Background

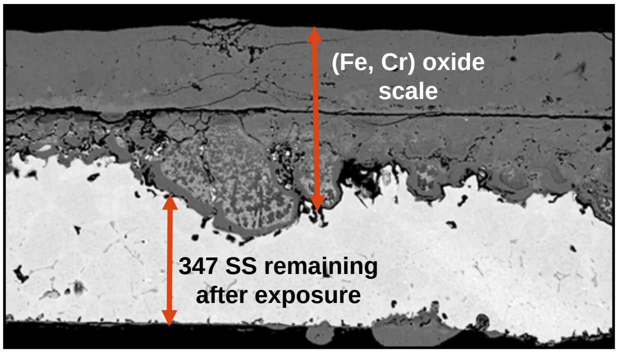
Higher temperature recuperator components are critical for improving the efficiency of microturbines to >40% and a primary focus area of the Department of Energy's Advanced Microturbine Program. Type 347 stainless steel (347SS) foil has traditionally been used for thin-walled recuperator components due to its creep and corrosion resistance at temperatures up to ~600°C. Improved microturbine efficiency, however, will require increasing the turbine inlet temperature (thereby increasing the exhaust gas/recupertor inlet temperature) to >600°C. Oak Ridge National Laboratory (ORNL) is leading an effort to develop and characterize alloys with improved high-temperature performance for higher efficiency recuperators.



Primary surface recuperator air cell made from corrugated type 347 stainless steel foil

Technology

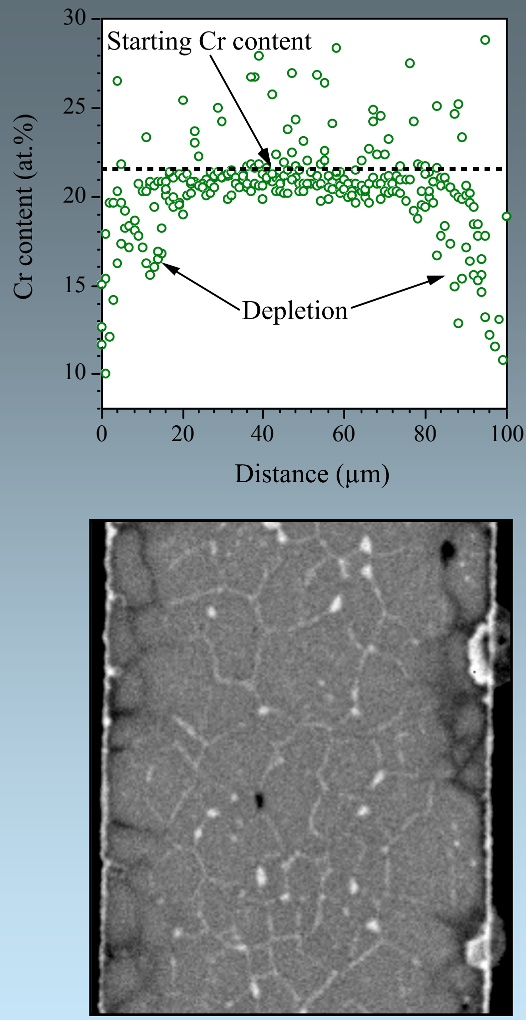
Recently, 10,000 h cyclic testing was completed on a series of commercial foil specimens; results from these tests are being used to better understand the detrimental effect of water vapor and the role of temperature on increasing the rate of corrosive attack. Air containing 10% water vapor and temperatures ranging from 650-800°C were used to simulate the microturbine exhaust-gas environment. Results at 650°C show that while 347SS showed accelerated attack and failure after exposure for <2000 h (rapid weight gain), the more durable alloys (120, 625, and 20/25/Nb) had much lower weight changes after exposure for 10,000 h. Mass change is a combination of oxygen uptake to form a surface oxide and mass loss due to the volatilization of chromium oxy-hydroxides. Specimen mass change is continuously monitored during corrosion testing and microstructural and compositional analyses are conducted on exposed foils at different time intervals.



Type 347 SS exposed in a microturbine at >650°C shows excessive surface corrosion. Alloys with improved corrosion resistance will be required for higher-temperature recuperators.

UT-BATTELLE

A series of laboratory exposures has shown chromium depletion to be one of the most important factors in predicting long-term alloy durability. Only a limited reservoir of chromium is contained in thin cross-section of the foil, and accelerated corrosive attack occurs when the chromium content drops below a critical level. Chromium depletion profiles across the cross-sectional thickness of the foils are being monitored as a function of time and will be used to predict alloy lifetimes at a given temperature. Elemental chromium maps are used along with the chromium profiles to evaluate additional changes in chromium distribution across the thickness of the foil. Chromium mapping shows regions of depletion, particularly along the grain precipitates in the center of the foil and at the surface oxide.



Typical chromium profile with corresponding chromium elemental map across foil cross-section showing chromium depletion at foil surfaces (Fe-20Cr-25Ni+Nb after 10,000h at 700°C in air + 10% H_2O).

Benefits

Conventional 347 SS recuperators cannot operate at temperatures >600°C without a significant loss in durability due to accelerated corrosive attack. The initial goal of the ORNL research was to identify higher-temperature alloys with improved corrosion resistance that could be used for this application at temperatures of 650-700°C. Long term laboratory testing has shown that several alloys, such as 120, 625, and 20/25/Nb (now being commercialized by Allegheny Ludlum), have demonstrated significantly higher temperature durability compared to 347 SS. Using these alloys will allow higher microturbine operating temperatures, with a commensurate increase in engine efficiency, while meeting the durability goals necessary for continuous operation to 40,000 h. Subsequent work will attempt to identify new, lower-cost compositions, which will assist in meeting cost reduction targets for microturbines.

Future Work

Laboratory testing of commercial and model alloys will continue in order to better understand the role of water vapor on the corrosion behavior of austenitic alloys. This information will assist in the development of better lifetime prediction capabilities and lower cost alloys for this application.

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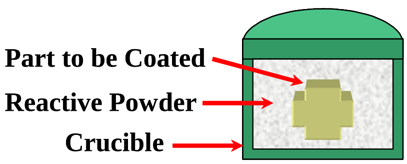
Environmental Barrier Coatings Formed by Low-Cost Pack Cementation Process

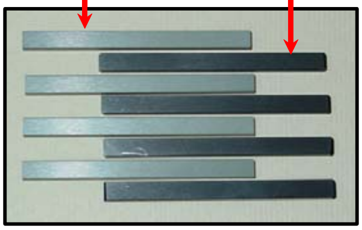
Allows Uniform Coating on Complex Shapes

Background

Monolithic silicon nitride (Si_3N_4) ceramics are currently the primary ceramic material being used in combustion engine environments and are under consideration as hot-section structural materials for microturbines and other advanced combustion systems. In oxidizing conditions, Si_3N_4 will typically form a surface oxidation layer (silicate). In a turbine engine environment, this silicate layer can undergo rapid degradation because of the corrosive and erosive effects of high temperature, high pressure, high gas velocity, and the presence of water vapor, thus severely limiting the useful life of the ceramic. The development of an environmental barrier coating (EBC) for the ceramic has become an essential goal for enabling the long-term utilization of these materials in advanced combustion engine applications.



Basic pack cementation configuration

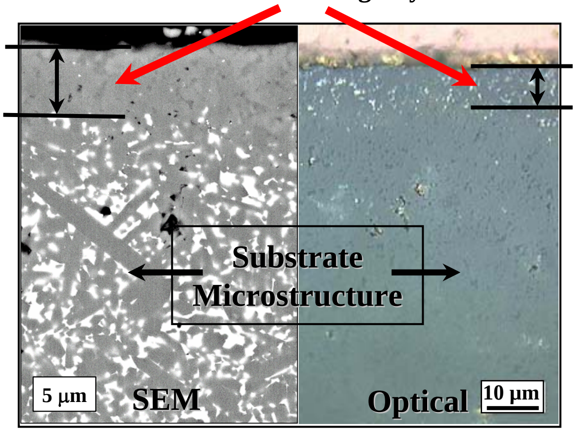


Coating of AS800 Si_3N_4 Bars
Pack: Al - NH_4Cl - Al_2O_3
Conditions: 1000°C, 5 hr., Ar

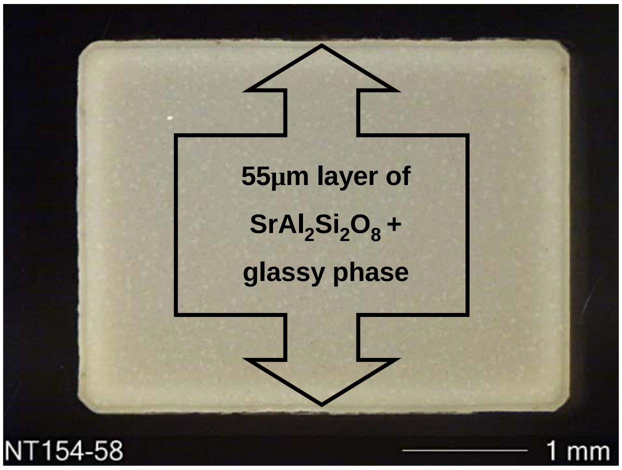
Example of coated parts

Technology

One approach that is being pursued to produce an EBC for Si_3N_4 is the formation of a surface conversion layer using the pack cementation process. Pack cementation has been used for many years to develop an oxidation protection coating on nickel-based superalloys that are used for hot-section components in gas turbine engines. The part is essentially heat treated in a reactive environment to chemically alter the composition of the surface region to form ceramic compounds that may provide enhanced corrosion and erosion resistance. Variables that affect the coating process include: substrate composition, powder bed composition, and heat treating conditions of temperature, time, and furnace atmosphere. In contrast to most other coating techniques, pack cementation is a non-line-of-sight process, which coats all surfaces of the part



Micrographs of polished cross-sections of coated bars shown above simultaneously and in a uniform manner. This provides a tremendous benefit for coating complex-shaped parts such as turbine blades and rotors. The pack composition can be varied to produce different coating phases. During FY04, coatings of $Y_2Si_2O_7$, $SrSiO_3$, Yb_2SiO_5, $SrAl_2Si_2O_8$, and $ZrSiO_4$ were produced on Si_3N_4 substrates having varying additive compositions. These include: Honeywell AS800, Saint-Gobain NT154, and Kyocera SN281. Analysis has shown that the coatings are typically multiphase, and efforts are now being focused on identifying the most protective composition and forming a single-phase coating. Industrial collaborators are providing substrate materials, as well as sharing ideas and suggestions for coating compositions. Collaborators include: Saint-Gobain Industrial Ceramics, Honeywell Ceramic Components, Kyocera Ceramics, Kennametal, United Technologies Research Center, and GE Aircraft Engines. Efforts are continuing to define the best pack cementation processing conditions and to identify promising coating compounds.



Optical micrograph of the cross-section of a coated bar shows the uniformity of the surface coating.

Coating compositions currently being investigated for environmental protection

$SrAl_2O_4$	$SrAl_2Si_2O_8$	Yb_2SiO_5	$Yb_2Si_2O_7$

Benefits

Pack cementation coating is a promising new method for producing coatings on high temperature ceramic materials for advanced gas turbine engines. It has an established and successful history for coating metal parts in the aircraft engine industry. Some advantages include:

- •Non-line-of-sight process for uniform coatings on complex shapes
- •Batch process which can coat hundreds of parts simultaneously
- •No unique equipment required to establish coating capability
- •Technology can be easily transitioned to industrial production

Future Work

The durability and uniformity of coatings on complex-shaped substrates exposed to a simulated gas turbine engine environment will continue to be assessed as the pack cementation process is further refined. There are also plans to evaluate new coating compositions and investigate substrate composition modifications for enhanced coating adhesion and protection.

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CHP Integration Laboratory Partners with Industry to Improve Performance and Design of DE-CHP Systems

Microturbine Generator in a CHP System is Characterized and Results Used to Develop an Optimization Model

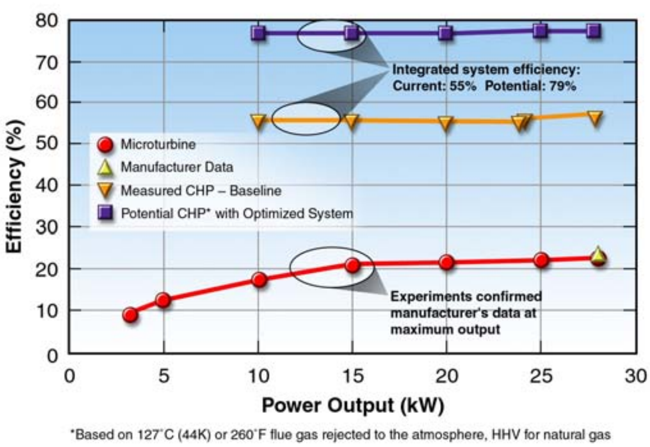
Background

The increased transmission line flow problems caused by deregulation of the electric energy market in the US and other developed countries have created a major opportunity for the implementation and use of distributed energy (DE) technologies with and without waste heat recovery. DE units are small, modular power generation systems located on or near the site where the energy that is generated is used. Unlike centralized energy resources, such as large power plants, they provide an opportunity for local control of power generation and more efficient use of waste heat to boost overall efficiency and reduce emissions.

Technology

ORNL CHP Integration Laboratory has been developed for testing IES-CHP Systems under a variety of conditions. This facility allows the interaction of the IES-CHP components to be optimized, so that their efficiency and commercial viability can be maximized. Tests were conducted on the following individual units, as well as the integrated system:

- •30-kW natural gas microturbine – measurement of electric power generation efficiency, emissions, and power quality
- •Heat recovery unit (HRU) – measurement of efficiency of heat transfer and advanced heat exchange materials/design. Testing of the first-generation HRU resulted in redesign/release of the second-generation unit with improved heat recovery (10% improvement)
- •Direct/Indirect desiccant dehumidifiers – measurement of latent cooling efficiency
- •Indirect-fired single-effect 10 ton (35 kW) Absorption Chiller – measuring efficiency of cooling



Integration Research Optimizes System to Realize Potential Efficiency

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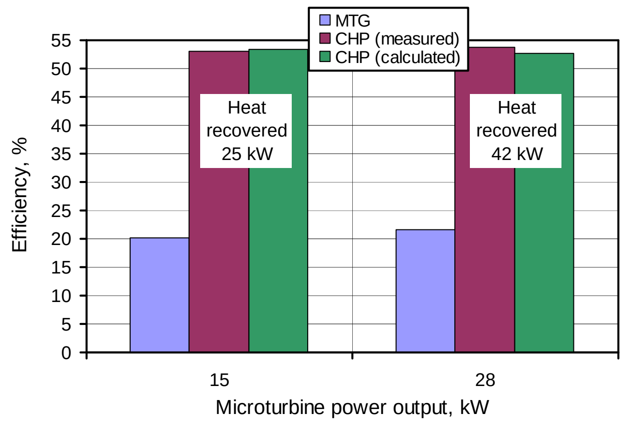
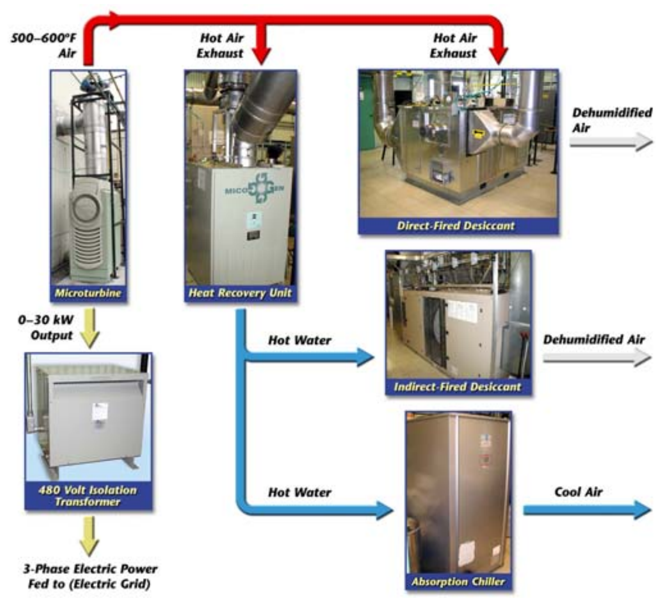
Testing at the ORNL CHP Integration Laboratory led to the development of the IES-CHP Design Optimization Model. This method of analysis will be used to characterize the operating characteristics of the various components involved in an integrated CHP system and to determine expected steady-state conditions based upon thermodynamic behavior of the system. From this effort, various CHP system configurations can be evaluated for their potential use in a given application. The test results have been used to optimize the design and performance of components and systems, reducing the potential risk to businesses and industries that are manufacturing and operating CHP systems.



Comparison between experimental and calculated CHP efficiencies

Benefits

- Full characterization of microturbine and integrated system components at various power and thermal loads with accurate measurement of emissions.
- Identify component and system improvements for "Next Generation" IES-CHP products and applications
- Computer-based modeling allows optimization of design and performance



ORNL CHP Integration Laboratory

Future Work

The ORNL CHP Integration Lab will test packaged systems as well as larger DE equipment such as reciprocating engines and larger microturbines. Researchers will also seek to supply reactive power from DE for voltage regulation. This will demonstrate that self-contained DE can provide reactive power locally for voltage regulation and power factor correction without extensive control infrastructure or impact to the distribution system.

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Screening Tools Determine Economic Feasibility of CHP Systems

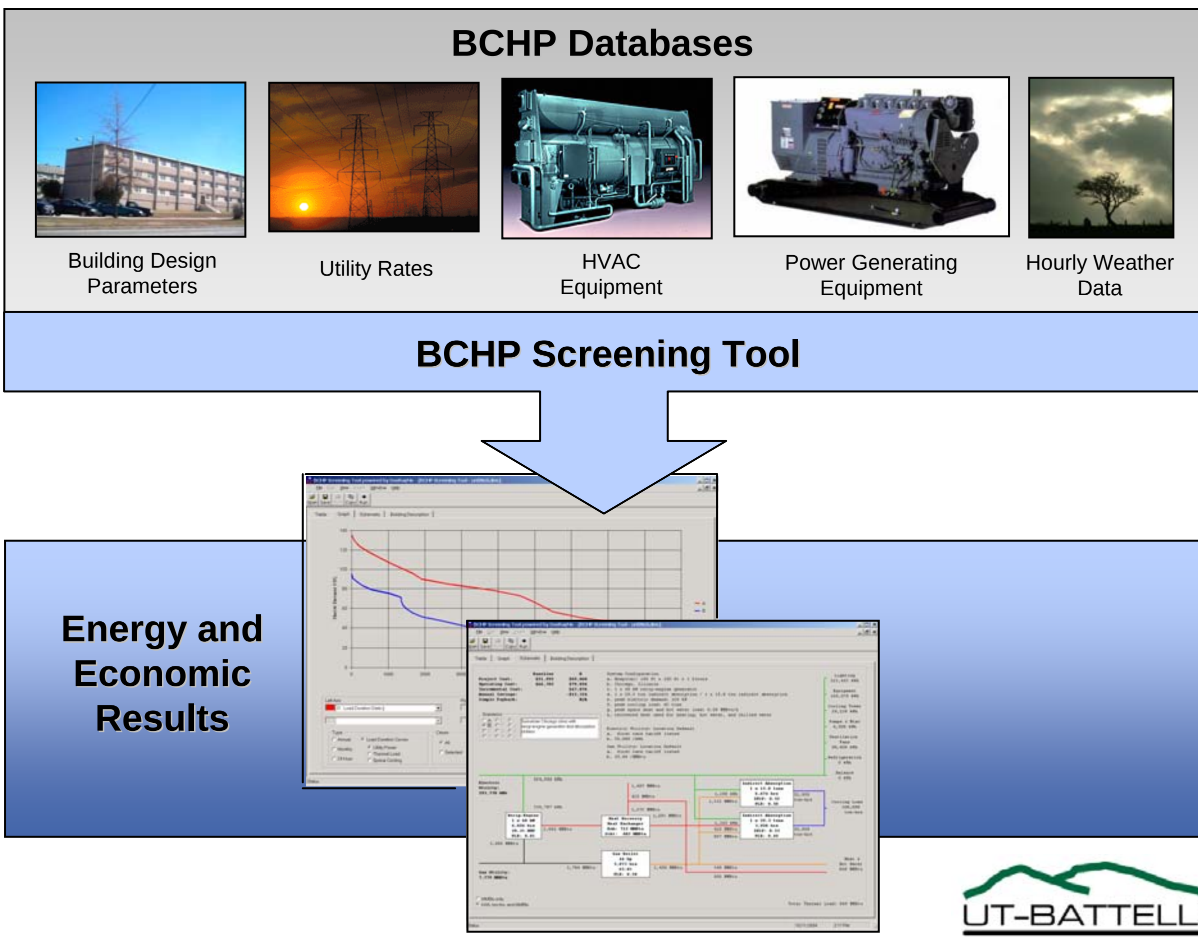
ORNL Partners with GARD Analytics to Enhance Screening Software

Background

The Building Cooling Heating and Power (BCHP) Screening Tool was developed through a partnership between ORNL and GARD Analytics in response to the need to predict economic feasibility of CHP system use at various commercial sites. Computer-generated simulations can determine potential gas and electricity use as well as equipment and energy costs for heating, cooling, hot water, and electricity when on-site generators are used to produce electricity and engine heat is recovered and used for space heating and cooling and potable hot water.

Technology

The BCHP Screening Tool is a computer-based modeling program that can predict user input and output (I/O) and perform building load, energy, and economic calculations for user specified buildings. The program utilizes built-in databases for building design parameters, utility rates, HVAC equipment, power generating equipment, and hourly weather information. Information for 14 pre-defined building



UT-BATTELLE

types are available for the computation of heating, cooling, hot water, and electrical loads. Utility rates for 160 different gas and electric utilities in the U.S. can be accessed. The HVAC equipment database includes cost and performance curves for gas, electric, steam, and hot water-driven heating and cooling equipment from 25 manufacturers as well as generic curves for heating and cooling equipment and thermal storage. The power generating equipment database includes equipment, installation, and operation and maintenance costs and performance curves for 104 generators powered by IC-engines, combustion gas turbines, microturbines, fuel cells, and gas turbine/fuel cell hybrids; generic curves are also available by prime mover type and heat recovery equipment. Hourly weather data are provided with the program for 239 U.S. cities.

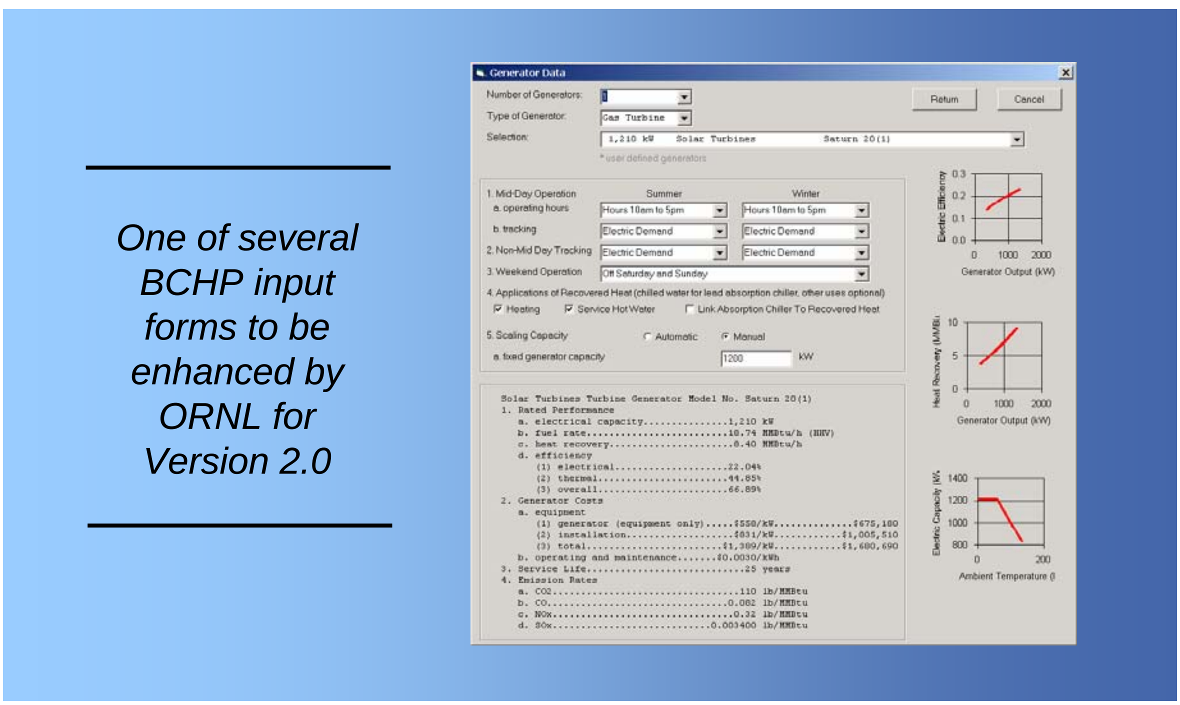
Users are able to edit information in each database and save the revisions as user defined values. ORNL improvements to the original tool offer increased capabilities in customizing results and display more user-friendly graphics.

Benefits

- •Prediction of economic feasibility of CHP systems in specific settings
- •Access multiple databases
- •New user-friendly graphics and expanded customization capabilities

Future Work

Future plans include development of stand-alone programs to access the equipment and utility rate databases and efforts to distribute the program for use throughout industry, academia, and other national laboratories.



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CHP

Innovative On-Site Integrated Energy System Commissioned by the City of Austin

CHP Plant Generates 5.5 to 6 Cents/kWh Peaking Power Plus 2,500 Tons of Chilled Water at 76% Efficiency and Exceeds State Emission Standards

Background

A first-of-a-kind Integrated Energy System (IES) was developed, constructed, and began operation in June 2004. ORNL's Distributed Energy Program formed a public-private partnership with Burns & McDonnell and Austin Energy (a municipal utility) to develop, install, and test one of the largest IES in the world. Tests will validate energy and cost savings of this onsite combined cooling, heating, and power (CHP) technology. The IES project provides energy resources to the Austin area while demonstrating:

- System energy efficiency of 70-80%
- System is simplified because waste heat from a gas turbine is recycled to an exhaust-driven absorption chiller
- Replicable, modular design facilitates future installations
- Interconnection with the grid and provision of electricity to the local area
- Permit based on output-based standard which recognizes environmental benefits

Austin Energy CHP plant's enclosed Solar gas turbine with exhaust ducted to in-line absorption chiller

The absorption chiller produces 2,500 tons of chilled water to the District's chilled water system and turbine air-inlet cooling

Technology

Waste heat exhausted from a natural gas-powered 4.5 MW Solar turbine is recycled to provide the only heat source for a Broad absorption chiller, which produces 2,500 tons of chilled water. By design, the turbine's exhaust heat closely matches the chiller's capacity. Since June 2004, this IES has provided supplemental power and cooling for a 1,200,000 ft^2 office, retail, industrial and residential park, "The Domain," in Austin, Texas. Operational tests are expected to verify fuel efficiency of 70% to 80% – the best central power plant is about 55% efficient.

Benefits

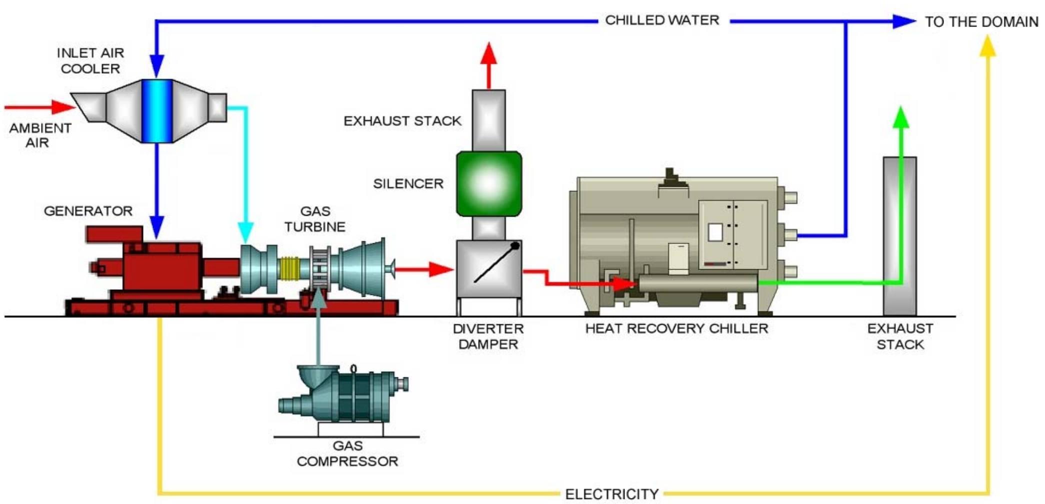
Optimized Energy Supply – System operation is demonstrating and confirming energy efficiency which is expected to be 70-80%. “Fuel free” chilled water produced from recycled turbine exhaust reduces electricity use during peak periods.

Simplified System – Use of an exhaust-fired absorption chiller reduces system complexity by eliminating steam and/or hot water generation equipment traditionally needed to drive absorption chillers. Exhaust-fired chiller can produce hot water to meet facility needs.

Modularity Promotes Replication – System is designed in seven modular, prefabricated skids easing application of the system to other district energy systems around the country. The modular design is adaptable to various capacity, space, and grid interconnection requirements. Replicable, modular design cuts capital costs while shortening construction and reducing installation costs.

Interconnection with Utility Grid – Austin Energy can dispatch the electrical output of the IES to provide grid support at the request of the Electric Reliability Council of Texas making the unit available for grid support during peak demand periods and aiding in transmission system congestion relief.

Output-Based Emissions Standards Demonstrated – Texas air permitting recognizes the environmental benefit of IES by issuing a standard permit when an onsite energy system recycles thermal energy. Turbine emissions are 0.67 while the emissions limit is 0.47lb NOx/MW-hr for units operating more than 300 hr/yr. The calculated, output-based limit is 0.24 allowing a 0.43lb NOx/MW-hr “credit” because of the reduction in electricity used for cooling and heating.



Integrated Energy System Components

Future Work

This project demonstrates advances in IES that can be applied to systems with other prime movers, such as reciprocating engines and microturbines, and in other district energy systems applications. Field data are being used to further develop an ORNL IES Design Model that provides a framework for analyzing system performance in other applications. Several aspects of this IES are being replicated at Seton Children’s Hospital also in Austin.

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Advanced IES to Recycle Energy at Fort Bragg Army Base

Annual Energy Savings Estimated at $1,800,000

Background

The latest improvements in Integrated Energy Systems (IES) were developed and installed at Ft. Bragg Army base in March 2004. ORNL's Distributed Energy Program formed a public-private partnership with Honeywell, FEMP, and the Public Works Business Center (PWBC) at Ft. Bragg to develop, install, and test an advanced IES. Tests will validate cost and energy savings of this on-site combined cooling, heating and power (CHP) technology. The IES project provides energy resources to the base while demonstrating:

- Turbine is dual-fuel capable: it can be fired with natural gas or fuel oil
- Turbine exhaust is recycled to provide the heat source for either an absorption chiller or a heat recovery steam generator
- System controls optimize energy supply under various operating conditions
- Electricity available for critical needs during power outage
- Reference system designs facilitate system replication in other applications

Ft. Bragg CHP plant's enclosed Solar gas turbine with exhaust ducted to in-line absorption chiller

Turbine exhaust is used as a heat source for steam generation and a 1000-ton absorption chiller which produces chilled water that is used to condition barracks.

Technology

A 5 MW Solar gas turbine, a 80,000 lb/hr heat recovery steam generator, and an exhaust-heat-fired Broad 1000 ton absorption chiller were integrated in a new, $11 million advanced IES. ORNL's Distributed Energy Program manages a contract with Honeywell Laboratories that supported design and installation of this system in collaboration with Ft. Bragg's PWBC through an U.S. Army/Honeywell Energy Services Performance Contract. System performance will be tested to verify energy efficiency, equipment performance, and system optimization and control.

Benefits

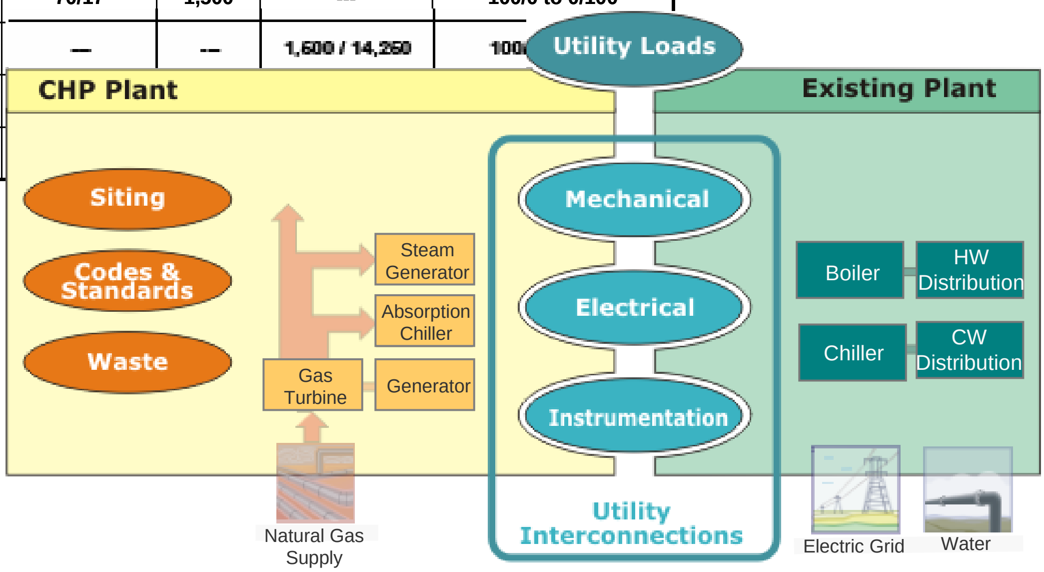
•**Two Fuels, Three Outputs –** The 5 MW Solar gas turbine can operate on natural gas or fuel oil increasing system reliability with this dual-fuel capability. Turbine exhaust provides the heat source for chilled water or steam while generating electricity.

•**Advanced controls –** Software developed by Honeywell optimizes equipment operation and interaction resulting in reduced energy consumption and emissions. Hot water and cooling is supplied to barracks and other buildings, resulting in better living and working conditions at significant cost savings. The upgrade also increases energy security with on-site generation that supports a hospital facility and critical base loads, reducing vulnerability to disruptions on the electric grid.

•**Reference Designs Promote Replication –** Reference system designs facilitate system replication in other applications by arranging various turbine sizes into advanced IES configurations. Interfaces between existing facilities and the IES were defined to facilitate replication of these systems in other district applications.

Reference Design	Turbine Generator	HRSG fired/unfired (kpph)	Chiller (tons)	Chiller/Heater (cooling tons/ heating MBH)	Heat Recovery (% cooling/ % heating)
R1	5.7MW	80/28	1,000	---	40/60 to 0/100
R2	5.2MW	---	---	2,500 / 23,750	100/0 to 0/100
R3	4.4MW	80/23	2,000	---	100/0 to 0/100
R4	4.4MW	---	---	2,000 / 19,000	100/0 to 0/100
R5	3.3MW	70/17	1,500	---	100/0 to 0/100
R6	3.3MW	---	---	1,500 / 14,250	100/[illegible]
R7	1.5MW				
R8	1.5MW				

Reference designs span 1.5-5.7MW system configurations.



System interfaces defined

Future Work

This project demonstrates advances in IES that can be applied to systems with other prime movers, such as reciprocating engines and microturbines, and in other district energy systems applications. Field data will be collected for a year and used to further develop an ORNL IES Design Model that provides a framework for analyzing system performance in other applications.

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CHP Technology Designed to Compete in Diverse Commercial Markets

PureComfort™ Offers Energy Efficiency, Savings, and Lower Emissions

Background

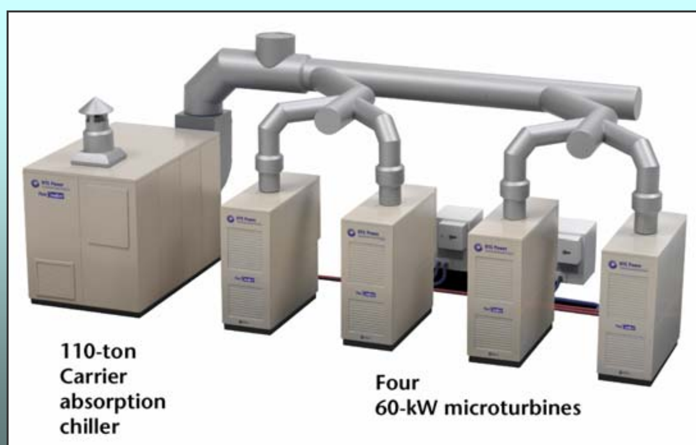
The DE Program partnered with UTC Power, a United Technologies Company, to develop technology for PureComfort™ cooling, heating, and power solutions. Each PureComfort™ system provides reliable power year-round and features a Carrier absorption chiller/heater that provides space cooling in the summer and space heating in the winter. These products provide a total building power and comfort generation system from a single reliable source. As a result, overall building electrical consumption from the grid can be significantly reduced throughout the year.

PureComfort™ solutions are well suited to applications in hotels, offices, schools, and hospitals, as well as supermarkets and other retail businesses that depend heavily on refrigeration. The first supermarket installation of the PureComfort™ 240 took place during July 2004 at a new A&P supermarket in Mount Kisco, New York. Tests show the system achieves greater than 70% overall efficiency, provides 240 kW of electricity, and converts waste heat from its four 60 kW microturbines into chilled water for air conditioning.

Technology

The integrated PureComfort™ system differs from traditional CHP installations in that the heat recovery unit is eliminated and the chiller/heater is directly connected to the microturbines. In this approach energy is directly transferred from the exhaust into the chiller working fluid, thus eliminating inefficiency and the cost of the heat recovery unit. The double-effect absorption chiller/heater achieves cooling and heating seasonally using the same unit; this conserves space and simplifies design. In addition, the design can achieve overall energy utilization of over 70% - far greater than the 33% typical of a central power plant.

UTC Power PureComfort™ System



Benefits

•**High Energy Efficiency –** PureComfort™ solutions provide high-efficiency cooling, heating, and power which can significantly reduce energy spending. All needed units run at full power; other units are shut down to avoid inefficient partial load operation. Also, the Carrier double effect chiller is a small unit by commercial standards and was designed specifically to handle the exhaust from 4 to 6 60 kW microturbines.

•**Reliable Power –** Power is generated continuously at your location, exclusively at your building. This reduces your dependency on the grid and helps minimize power interruption – for higher year-round productivity.

•**Environmentally Friendly –** The systems use no ozone-depleting fluorocarbons, and they produce ultra-low emissions which can qualify your building for significant financial incentives that can reduce your initial product and installation costs by as much as 30%.

•**Pre-engineered Solutions –** The systems were first introduced with 4 microturbines, but the product line has recently been expanded to include 5 or 6 microturbines enabling a total of 300 kW or 360 kW units respectively. Several modular, skid-mounted designs allow flexibility in choosing the model best suited to the needs of each building, without the higher costs and longer lead times of developing a fully customized system.

Future Work

DOE had a solicitation in FY04 to evaluate IES systems in different market sectors including hospitals, hotels, supermarkets, colleges, and universities. PureComfort™ systems are not only being installed in supermarkets, but will also soon be operating at Butler Hospital in Rhode Island and a Ritz Carlton Hotel in California. The successful implementation of this promising technology will establish confidence in its potential to serve as a cost-effective, commercially viable alternative to traditional power and HVAC products.

Points of Contact:

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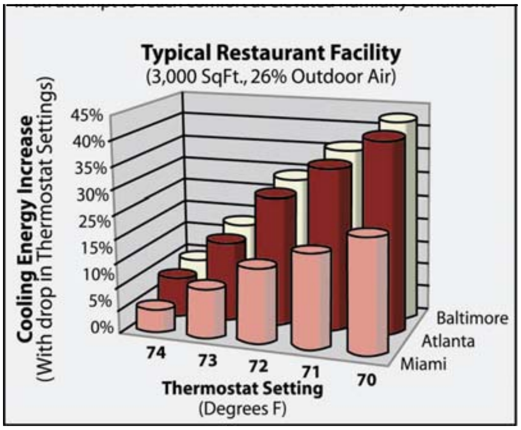
Desiccant Systems Commercialized to Independently Control Humidity and Temperature in Buildings

Advanced Air Conditioning Units Improve Comfort, Air Quality, and Energy Efficiency

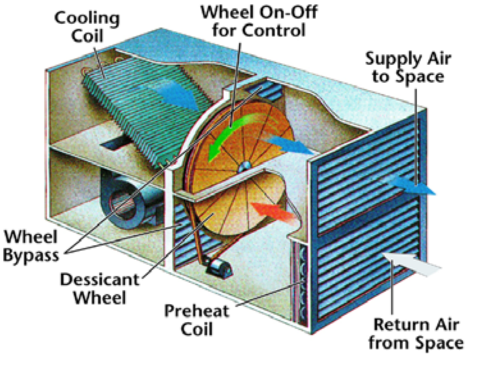
Background



The Distributed Energy's (DE) Thermally Activated Technologies program has worked with industry to develop and commercialize integrated desiccant air conditioning units that provide consistent environmental comfort in restaurants, hospitals, schools, movie theatres, and other specialized commercial and institutional settings. Currently, most rooftop air conditioning units cannot independently control temperature and humidity levels in modern, healthy buildings. This limitation in technology has created a tension between comfort, air quality, and cost issues. Increased delivery of fresh, outdoor air can increase indoor humidity, prompting occupants to set thermostats to lower settings. Buildings subsequently become too cold for comfort and energy costs are increased.

The installation of oversized compressors compound the problem. To meet humidity requirements, vapor-compression systems are often operated for long cycles at low temperatures, which reduces their efficiency and may require reheating the very cold dehumidified air to achieve comfort. This cycle occurs in thousands of buildings across the country everyday, putting an unnecessarily high burden on the electric grid during peak usage periods.

Technology

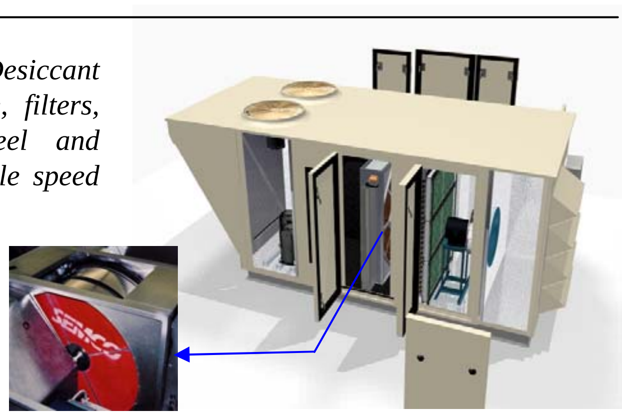


Trane CDQ™ Desiccant System

Newer, more integrated, desiccant system designs simultaneously deliver the benefits of vastly improved interior humidity control as well as fresh air ventilation rates. Desiccant materials naturally attract and hold moisture, and equipment employing desiccant dehumidification components provide a more efficient means of dehumidifying air without over-cooling. There are different approaches to designing a desiccant system, but the basics are the same. The systems remove moisture from air, then cool the air using either evaporative cooling or the cooling coils of a conventional air conditioner. Moisture is then removed from the desiccant with heat provided by waste heat, natural gas, or electricity.

Two examples of new, active desiccant product developments are the Trane, CDQ™, Active Cromer Cycle, and the SEMCO, *Revolution*™, Integrated Active Desiccant Rooftop (IADR); they are results of ORNL and industry R&D collaborations with Trane Company and SEMCO, Incorporated, respectively. Both technologies utilize an embedded desiccant wheel within a packaged system. Trane is an all-electric product that regenerates its desiccant wheel using a return air stream. It provides better humidity control at the cost of lower temperature settings. The SEMCO product thermally regenerates its desiccant wheel using both electricity and waste heat. Outside air or return air can be conditioned with the SEMCO product.

Supply side of SEMCO Integrated Active Desiccant Rooftop unit showing outdoor air intake, filters, evaporator coil, active desiccant wheel and integrated condensing section with variable speed scroll compressors



Integrated Active Desiccant Wheel

Benefits

- **Comfort –** Building occupants experience a higher degree of comfort when temperature and humidity are able to be independently controlled. For example, comfort can be achieved at 74°F with 60% humidity rather than in cooler 70°F conditions with 80% humidity.
- **Reduced Energy Costs –** Higher thermostat set points and use of smaller systems to achieve comfort result in cost savings. Furthermore, the systems run for shorter time periods reducing utility loads during peak demand hours.
- **Indoor Air Quality –** By providing effective control of space humidity, more fresh air circulation can occur without introducing the outdoor humidity that stimulates mold and mildew growth.

Future Work

This technology is particularly promising in schools located in the southern U.S. where humidity cycles vary greatly over the day and weekends allowing molds to grow and student health to be put at risk. Installation of a 200 kW reciprocating engine generator and SEMCO IADR units will take place at the new Pepperell High School near Atlanta, Georgia.

The SEMCO product has been introduced commercially through selected sales agencies at the SEMCO Corporate Headquarters in Columbia, Missouri. Cromer Cycle Air conditioner was licensed to Trane which will be introduced this year in a more expensive top-end unit.

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