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Renewable and Distributed Systems Integration Program

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4.1.1 - Lean NOx Trap Aftertreatment for Lean Natural Gas Engines

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Objective

- Study the feasibility of using lean NOx trap catalyst technology to reduce the NOx emissions of lean burn natural gas engines.
- Determine if natural gas can be used as the reductant for regeneration of lean NOx trap catalysts.
- Address key technical barriers to implementing a lean NOx trap system, such as catalyst durability, sulfur poisoning, cost, etc.

Approach

- Study a lean NOx trap catalyst system installed on a lean natural gas engine (Cummins C8.3-G+) on a dynamometer engine platform.
- Evaluate catalyst performance and study process chemistry with analytical tools unique to ORNL.
  - An array of techniques are used to perform a complete exhaust gas species analysis.
- The lean NOx trap catalyst system consists of a chamber for housing the catalysts, exhaust valves to divert exhaust flow from the catalysts during regeneration, and natural gas fuel injectors for introducing reductant during catalyst regeneration.
- In addition to the lean NOx trap catalysts, oxidation and reformer catalysts were used upstream of the lean NOx trap catalysts to utilize the methane in natural gas for regeneration of the lean NOx trap.

Accomplishments

- Successfully demonstrated a low-cost catalyst service process for the mitigation of sulfur poisoning effects on the lean NOx trap catalyst. Sulfur is a known catalyst poison; the service technique extends catalyst durability to meet ARES program goals for durability and reliability.
  - Accelerated sulfur aging studies of the lean NOx trap catalyst in exhaust from a Cummins C8.3G natural gas engine were conducted; bottled SO_2 was used to control sulfur loading.
  - After significant sulfur exposure, the catalysts were serviced with an aqueous-based solution to remove sulfur poisoned NOx storage sites and reapply new sorbate material.
  - Evaluations of system performance were conducted before sulfur poisoning, during sulfur poisoning, and after new sorbate was applied. Results showed that the sorbate reapplication process successfully recovered lost performance due to sulfur poisoning.
- A comprehensive final report detailing all of the technical results from the multi-year research project has been completed. The report is being published as an ORNL Technical Report and will be distributed to the ARES industry partners and other stakeholders.

Future Direction

- Interest has been expressed in advancing the technology from a laboratory setting to a field study or demonstration site.

Introduction

Distributed energy is an approach for meeting energy needs that has several advantages. Distributed energy improves energy security during natural disasters or terrorist actions, improves transmission grid reliability by reducing grid load, and enhances power quality through voltage support and reactive power. In addition, distributed energy can be efficient since transmission losses are minimized. One prime mover for distributed energy is the natural gas reciprocating engine generator set. Natural gas reciprocating engines are flexible and scalable solutions for many distributed energy needs. The engines can be run continuously or occasionally as peak demand requires, and their operation and maintenance is straightforward. Furthermore, system efficiencies can be maximized when natural gas reciprocating engines are combined with thermal energy recovery for cooling, heating, and power applications.

Expansion of natural gas reciprocating engines for distributed energy is dependent on several factors, but two prominent factors are efficiency and emissions. Efficiencies must be high enough to enable low operating costs, and emissions must be low enough to permit significant operation hours, especially in non-attainment areas where emissions are carefully regulated. To address these issues the U.S. Department of Energy launched a research and development program called Advanced Reciprocating Engine Systems (ARES). Fuel efficiency and low emissions are two primary goals of the program. The work presented here was funded by the ARES program and, thus, addresses the ARES 2010 goals of 50% thermal efficiency (fuel efficiency) and <0.1 g/bhp-hr emissions of oxides of nitrogen (NOx).

The technical approach taken to meet the ARES goals in this work is to combine efficient lean spark-ignited natural gas combustion with low emissions from a lean NOx trap catalyst aftertreatment system. This approach can be applied to current lean engine technology or advanced lean engines that may result from related efforts in lean limit extension. Furthermore, the lean NOx trap technology has synergy with hydrogen-assisted lean limit extension since hydrogen is produced from natural gas during the lean NOx trap catalyst system process. The approach is also applicable to other lean engines such as diesel engines, natural gas turbines, and lean gasoline engines.

In the lean NOx trap catalyst system, three precious metal based catalysts are used. An oxidation catalyst and reformer catalyst partially oxidize and reform methane into CO and H_2 reductants for the lean NOx trap catalyst reduction. The lean NOx trap catalyst adsorbs (or "traps") NOx in lean exhaust, then reduces the NOx to nitrogen with the reductants produced by the oxidation and reformer catalysts. All catalysts are exposed to lean (oxygen-rich) and rich (oxygen-depleted) exhaust during system operation. Sulfur is the most critical poison for the lean NOx trap system since adsorption of sulfur dioxide (SO_2) on the lean NOx trap catalyst effectively blocks access of the NOx storage sites required for NOx reduction. Sulfur may potentially affect the oxidation and reformer catalysts as well. System operation is dependent on efficient function of all three catalysts, and sulfur is a critical issue for the durability of the catalytic system.

Previous studies of the lean NOx trap catalyst system applied to lean natural gas reciprocating engines have focused on NOx reduction efficiency, characterization of the partial oxidation and reforming processes, and analysis of the effect of sulfur exposure on the partial oxidation and reforming processes. ***Results from the NOx reduction efficiency study have shown that NOx emissions <0.1 g/bhp-hr (the ARES goal) can be achieved.*** The study of the partial oxidation and reforming processes showed the efficiency of producing carbon monoxide (CO) and hydrogen (H_2) reductants from methane as a function of temperature and other operating parameters. The combined database of research to date indicates that (1) NOx emissions in lean natural gas reciprocating engines can be reduced by >90% by the lean NOx trap catalyst and (2) a small amount of natural gas (~1-3% of engine consumption amount) can be catalytically converted into reductants necessary for lean NOx trap catalyst regeneration. Thermal management and system optimization are critical engineering issues that need to be addressed as the technology is developed since performance is a strong function of temperature and operational parameters.

With the work to date showing merit for the lean NOx trap catalyst technology in natural gas reciprocating engine applications, efforts from this study in FY2007 focused on durability issues associated with the technology and application. Due to long hours of operation and engine life, degradation or deactivation of catalytic performance in the lean NOx trap catalyst system must be minimized. Poisoning, the deactivation of active catalyst components through the chemisorption of an element or molecule, is a primary degradation mechanism that needs to be addressed to achieve the durability required.

In the work presented here, the effects of sulfur poisoning on the lean NOx trap catalyst will be studied. Sulfur is a common catalyst poison and is the most detrimental poison for the lean NOx trap technology. The experiments were conducted on an engine platform, and sulfur exposure to the catalysts was accomplished via addition of SO_2 to the exhaust from bottled gases. In lean engine exhaust SO_2 is the most likely form of sulfur since sulfur originates from lean combustion of fuel or oil. The performance of the lean NOx trap catalyst system was monitored to characterize performance as a function of sulfur exposure. Furthermore, a process for recovering lost performance by reapplying the sorbate component of the catalyst was performed and characterized for effectiveness. This study addresses the effect of sulfur on the critical processes involved in lean NOx trap operation.

Lean NOx Trap System and engine Platform

The experiments in this study have been performed on an in-line 6-cylinder 8.3-liter natural gas engine (Cummins CG-280) with a peak torque of 1153 Nm (850 ft-lb) at 1400 rpm and a peak power of 209 kW (280 hp) at 2400 rpm. The engine load and speed were controlled by a 600-hp dynamometer system (General Electric Model 42G61). All experiments were performed at 1800 rpm and steady-state conditions to simulate gen-set speeds. Intake air conditions were controlled to approximately 23.9°C (75°F) with a relative humidity of 55%.

The catalyst system mounted to the engine exhaust consisted of a two-chamber system with two exhaust brake valves (US Gear) controlling the flow to both chambers (see **Figures 1 and 2**). One chamber simply consisted of an empty pipe and will be referred to as the "bypass leg". The second chamber contained the oxidation, reformer, and lean NOx trap catalysts and will be referred to as the "catalyst chamber" or "leg". Downstream of the bypass and catalyst legs, the exhaust from the two legs combined again to exit the system. The order from upstream to downstream of the catalysts in the catalyst chamber was oxidation, reformer, and then lean NOx trap catalysts. All catalysts were supplied by EmeraChem LLC.

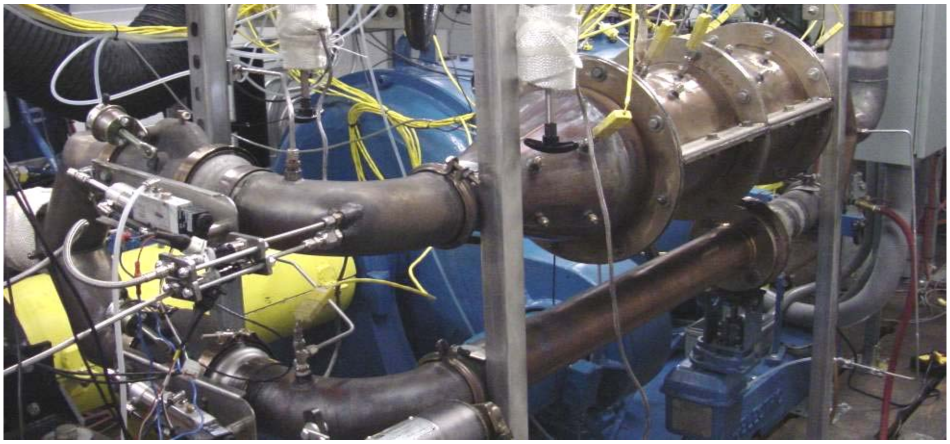

Figure 1. Picture of the lean NOx trap catalyst system installed on the ORNL engine-dynamometer platform.

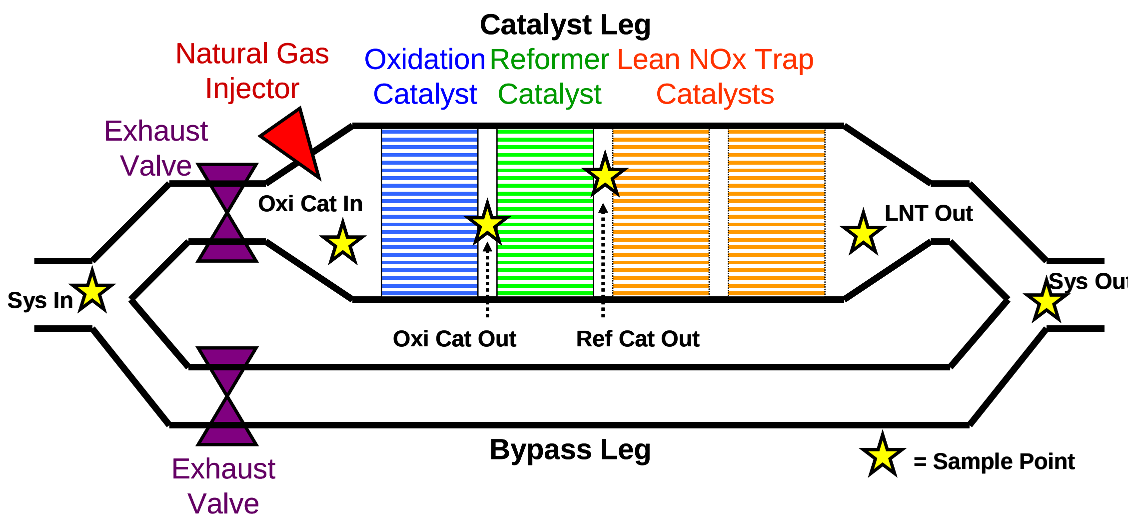

Figure 2. Lean NOx trap catalyst system.

Experiment Design

The basic outline of the experiment was to characterize the lean NOx trap catalysts prior to sulfur exposure, after sulfur exposure, and after sorbate reapplication; for reference, these phases of the study will be referred to as "Pre S", "Post S", and "New K", respectively. Various operational conditions were employed to characterize the lean NOx trap performance in engine exhaust in these phases.

The catalysts were exposed to sulfur in a controlled manner by adding SO_2 from a bottle gas source to the exhaust upstream of the catalysts. The source of SO_2 was 1% SO_2 in a N_2 balance. The flow of SO_2 gas was controlled to obtain a level of 3.0-3.5 ppm SO_2 in the exhaust which is a level at least one order of magnitude higher than levels commonly found in natural gas engine exhaust. During the sulfur exposure, the engine speed and load were held constant at 1800 rpm and 200 hp, respectively, and the catalyst system was operated in four different modes providing a duty-cycle simulation for the sulfur exposure and allowing the performance of the catalysts to be monitored during the exposure process at different operating conditions.

After sulfur poisoning occurred, the performance of the lean NOx trap catalysts were characterized again with the same techniques and parameters used before. Then, the lean NOx trap catalysts were removed from the system, and the sorbate component was reapplied with the procedure described below. After sorbate reapplication, the catalysts were reinstalled in the exhaust system, and again, the performance of the lean NOx trap catalysts were characterized with the same techniques and parameters.

Sorbate Reapplication Service Process

The lean NOx trap catalysts were treated with aqueous-based solutions to remove and reapply the K sorbate component. Often in the industry, aqueous-based processes for servicing catalysts are referred to as “washing” or “wash” procedures. The first step in the sorbate reapplication procedure was sorbate removal. The catalysts were submerged in deionized H_2O for 15 minutes; then, the catalysts were drained and the excess H_2O was removed. The H_2O wash was repeated three times to ensure that all of the K compounds were removed. After sorbate removal, the new K sorbate was applied by submerging the catalysts in a K_2CO_3 solution. The concentration of the K_2CO_3 solution was 10% by mass, and the catalysts were submerged in the solution for 17 minutes. After the soak in the K_2CO_3 solution, the catalysts were drained and excess solution was removed. The catalysts were allowed to dry in room conditions for more than 24 hours prior to use. During the drying process, the K_2CO_3 is left on the catalyst to form the active component for NOx adsorption.

Results

Figure 3 shows the cycle-based NOx reduction efficiency for the four modes of operation of the lean NOx trap catalyst during the experiment. In all cases, the engine was operated at a steady state speed and load of 1800 rpm and 200 hp, respectively. The operation modes differed in the sorption phase period of catalyst operation and the catalyst temperature as controlled by the upstream heat exchanger. The combinations of these variables were: 30 second sorption period at 520ºC catalyst temperature, 60 second sorption period at 520ºC catalyst temperature, 60 second sorption period at 460ºC catalyst temperature, and 30 second sorption period at 460ºC catalyst temperature. Here the catalyst temperature reported was measured with a Type K thermocouple inserted into the first lean NOx trap catalyst monolith. Note that temperatures fluctuated with time as the catalyst cycled; the temperatures listed are cycle-average temperatures. The catalyst capacity for NOx storage is lower at 520ºC vs. 460ºC; so, the 520ºC temperature points are more challenging. Since longer sorption periods require more NOx storage by the catalyst, the longer 60 second sorption periods are more challenging.

The period in the study where sulfur exposure occurred and the point where new sorbate was reapplied to the catalysts is noted in **Figs. 3**. NOx performance for all modes is relatively stable prior to sulfur exposure and after sorbate reapplication as expected. During sulfur exposure, the NOx performance degrades over time. The degree of degradation is different for each mode of operation. The 520ºC modes showed a larger loss in performance relative to the 460ºC modes as the sulfur poisoning of storage sites was more severe for the lower NOx capacity at the higher temperature. The sorption period had a much smaller affect on the degradation magnitude as both the 30 and 60 second cycles degraded at similar rates and with similar magnitudes of lost performance.

It is important to note that the laboratory sulfur exposure of the catalysts was performed with higher SO_2 concentration than would be experienced in real-world applications. The actual degradation rate experienced in the rapid laboratory aging process may differ from the slower real-world case on a mass of sulfur exposure basis. The main emphasis of this study was to determine if the sorbate reapplication procedure recovers lost performance due to sulfur poisoning. Even though the rate of sulfur poisoning and the distribution of sulfur on the catalyst may differ for both laboratory and real-world cases, the sulfur thermodynamically prefers to interact with the same K sorbate site; thus, the results from the sorbate reapplication procedure should hold for both cases since the chemistry is the same.

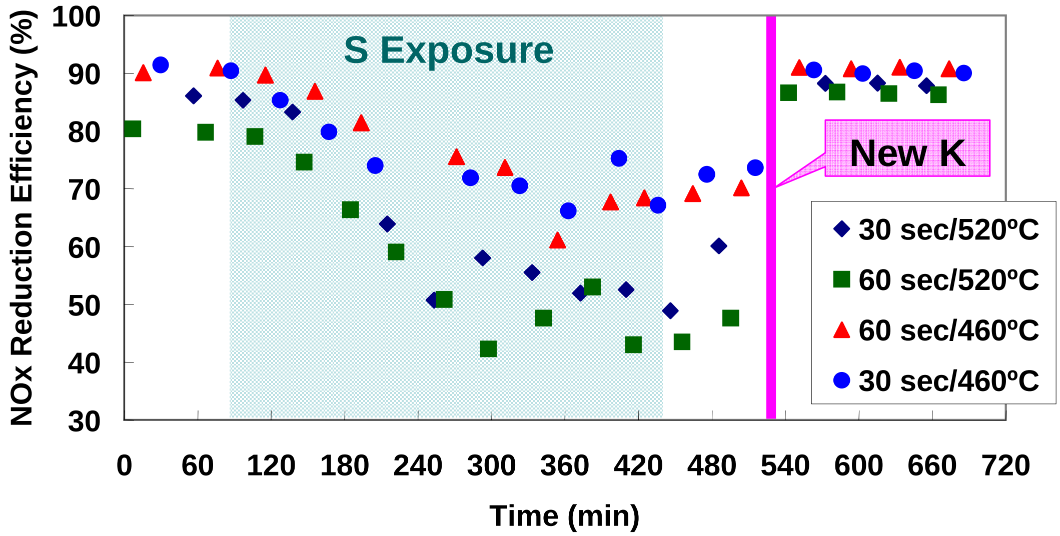

Figure 3. Cycle average NOx reduction efficiency for four operational modes over the course of the study.

After sulfur exposure stopped, performance increased slightly which may have been due to desulfation of the upstream oxidation and reforming catalysts. Previous studies showed that the oxidation and reforming catalytic processes are impacted by sulfur exposure but recover through desulfation processes. The recovery of oxidation and reforming efficiency leads to more reductant supply to the lean NOx trap catalyst which can improve regeneration of the catalyst for more NOx storage.

The sorbate reapplication was effective at restoring the lost performance. The level of NOx reduction after sorbate reapplication is essentially the same as the performance prior to sulfur exposure for the four modes examined. To analyze the performance over the course of study more closely, experiments were conducted at various points in the study to more broadly measure NOx performance of the catalysts. In these examinations, important differences were discovered that are not apparent from the four mode data shown in **Fig. 3**.

An experiment was conducted to measure the NOx reduction efficiency performance as a function of catalyst temperature by maintaining constant engine operating conditions while varying the catalyst temperature with the heat exchanger upstream of the catalyst system. Again, the engine was operated at a speed and load of 1800 rpm and 200 hp, respectively. A sorption period of 30 seconds was used. The data **Figure 4** shows the cycle average NOx reduction efficiency as a function of the lean NOx trap catalyst temperature from these experiments; the evaluations were conducted prior to sulfur exposure (Pre S), after sulfur exposure (Post S), and after application of new K sorbate (New K) as noted before.

As **Fig. 4** shows, although the NOx reduction efficiency above 450ºC is the same for the Pre S and New K cases, there are significant differences in the temperature range form 350ºC to 450ºC. In this temperature range, the NOx performance is dictated by the efficiency at which the methane injected for regeneration of the catalysts is oxidized and reformed into reductants CO and H_2 for reduction of the lean NOx trap catalysts. Apparently, a non-recoverable loss of oxidation and reforming performance occurred over the course of the sulfur exposure and sorbate reapplication processes. Note that the Post S data shows a loss for all temperatures relative to the Pre S case; thus, performance loss over sulfur exposure was due to lost NOx capacity (apparent from >450ºC temperatures) and lost oxidation and reforming efficiency (apparent form losses below 450ºC).

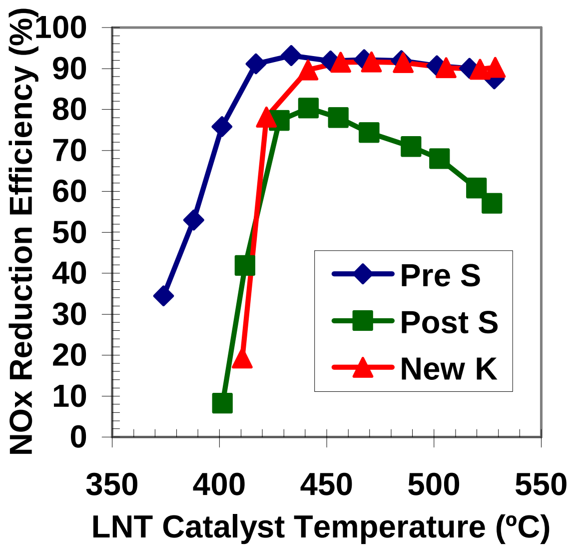

Figure 4. NOx reduction efficiency as a function of temperature before (Pre S) and after sulfur (Post S) exposure and after new sorbate application (New K).

Emission Test Cycle Performance

NOx emission reduction performance of the lean NOx trap catalyst system was characterized before sulfur poisoning (Pre S) and after sorbate reapplication (New K) by performing an ISO 8178 Type D2 emission test cycle. The performance at five engine modes is weighted, and the combined emissions from the weighted five modes results in a single emission level for the engine expressed in units of g/bhp-hr or g/kW-hr. It is important to note that the Type D2 ISO 8178 emission test cycle is similar to other stationary and off-road engine test cycles such as the U. S. Environmental Protection Agency's Code of Federal Regulations (CFR) 40 Part 89 Subpart E (89.407).

Table 1 gives specific detail of the ISO 8178 Part D2 emission test cycle performed in this study including typical power levels for each engine mode; the engine speed was 1800 rpm for all modes. The emission rates presented in this section represent a dual catalyst chamber system estimated by simply using the sorption phase emission rate from the single catalyst chamber system data; the dual chamber estimate is conservative since untreated exhaust leakage through the bypass leg significantly contributes to the emissions measured at the system out position during the sorption phase.

Table 1. ISO 8178 Emission Test Cycle

Mode	Torque (%)	Weighting Factor	Power (hp)
1	100	0.05	248
2	75	0.25	186
3	50	0.30	124
4	25	0.30	62
5	10	0.10	24.8

Table 2 summarizes the NOx emissions obtained in the ISO 8178 test cycle for the lean NOx trap catalyst system; in addition, fuel penalty data are shown. The weighted result for the system out NOx emissions were 0.094 g/bhp-hr before sulfur poisoning (Pre S) and 0.096 g/bhp-hr after sorbate reapplication (New K); ***both results are less than the ARES target of 0.1 g/bhp-hr and represent more than a 90% reduction from the engine out NOx emissions of 1.147 g/bhp-hr.*** The accuracy of the emission measurements is +/-0.01 g/bhp-hr; so, noise sources affect the catalyst out measurements greater than the engine out measurements on a percentage basis. The fuel penalties (averaged for both Pre S and New K data) ranged from 0.57% to 4.59% and represent the amount of fuel required to regenerate both catalyst chambers of a dual-chamber lean NOx trap system; the percentage is relative to the amount of fuel being consumed by the engine to produce power. The weighted average fuel penalty of 1.97% is not negligible from an operating cost view, but the level is significantly less than the ~12% fuel benefit associated with operating the engine lean (as compared with Stoichiometric operation). Thus, the benefits of the lean natural gas engine are maintained while the NOx emissions are reduced by the lean NOx trap system.

Table 2. ISO 8178 Emission Test Cycle

Mode	Engine Out NOx (g/bhp-hr)	**Pre S** System Out NOx (g/bhp-hr)	**New K** System Out NOx (g/bhp-hr)	Fuel Penalty (%)
1	2.150	0.288	0.310	3.56
2	0.760	0.057	0.694	1.83
3	0.456	0.033	0.027	0.57
4	2.772	0.168	0.101	2.33
5	1.662	0.191	0.119	4.59
Avg.	**1.147**	**0.094**	**0.096**	**1.97**

The fuel penalty and NOx reduction performance vary with each mode as catalyst temperatures change due to exhaust temperature variations (no control of catalyst temperature was forced during the test). However, the catalyst is effective at all engine modes. Performance peaks at the 50% torque mode (Mode 3) where NOx emission rates out of the engine are low and the catalyst temperature is optimal. The Pre S and New K results are similar and demonstrate that low NOx emission levels can be obtained after sulfur exposure using the sorbate reapplication technique to rejuvenate the catalyst.

Conclusions

Experiments were conducted on a lean natural gas engine platform to study the effects of sulfur exposure on a lean NOx trap catalyst system. Sulfur exposure caused degradation in NOx reduction efficiency as expected; however, a treatment of the lean NOx trap catalyst to reapply new sorbate material was effective in restoring lost NOx performance. The recovery of lost NOx performance was not complete for all temperature ranges. At temperatures where performance is capacity limited (above 450ºC), full recovery occurred. In contrast, at temperatures where performance is limited by the efficiency of methane oxidation and reforming (below 450ºC), performance does not recover fully.

The sorbate reapplication process is an effective means of recovering NOx reduction performance for most of the operating window of the catalyst. The technique is inexpensive since precious metal components are not removed or reapplied in the process. The process is appropriate for safe water soluble sorbate components such as potassium based materials. Frequencies required for the process to enable suitable performance by the catalysts is dependent on a number of factors including the emission requirements for the application of interest.

Acknowledgments

ORNL would like to thank EmeraChem LLC for supplying the catalysts for this study. This work is a part of the U. S. Department of Energy (DOE) Advanced Reciprocating Engine System (ARES) Program within the Office of Electricity Delivery & Energy Reliability. The ARES program is in cooperation with industrial representatives from Caterpillar, Cummins, and Waukesha. ORNL is managed by UT-Battelle LLC for the US Department of Energy under subcontract DE-AC05-00OR22725.

FY2007 Presentations/Publications

- James E. Parks II and Senthil Ponnusamy, “The Effect of Sulfur on Methane Partial Oxidation and Reforming Processes for Lean NOx Trap Catalysis”, *Proceedings of ASME Internal Combustion Engine Division 2006 Fall Technical Conference,* Paper No. ICEF2006-1535, ISBN 0-7918-3792-0 (2006).
- James E. Parks II, “Mitigation of Sulfur Effects on a Lean NOx Trap Catalyst by Sorbate Reapplication”, *Proceedings of ASME Internal Combustion Engine Division 2007 Fall Technical Conference,* Paper No. ICEF2007-1628 (2007) (*accepted for publication in October 2007*).

4.1.2 - Characterization and Development of Spark Plug Materials and Components

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Objective

- Provide insight into the wear mechanisms of natural gas spark plug electrodes as a function of field exposure time and engine conditions.
- Increase the wear resistance of spark plug electrode materials to at least 1 year (or a 2X improvement) in advanced natural gas reciprocating engines designed to meet aggressive emission and efficiency goals.

Approach

- Characterize engine tested spark plugs to identify key erosion mechanisms and limitations of existing materials.
- Develop, engine test, and optimize new electrode materials for improved erosion resistance based on findings from the characterization effort.

Accomplishments

- Completed evaluation and characterization of several model chromia-forming alloys, with 25 wt.% Cr to favor exclusive (or at least near exclusive) chromia scale formation, with additions of 0.4 wt.% Si and 0.15 wt.% La (nominal) after 500h accelerated testing in a laboratory gasoline engine in collaboration with Federal Mogul. Similar alloys were also tested in natural gas engine. These results suggest that the laboratory-modified gasoline engine can provide useful insight into NG spark plug electrode erosion materials issues, and also suggest an inherent degree of susceptibility of currently used electrode materials to oxidation/cracking attack, independent of specific engine/ignition conditions.
- Completed evaluation and characterization of Cr-6MgO base developmental alloy and Haynes 214 after 400h accelerated laboratory engine testing in collaboration with Federal Mogul. Results showed that the surface of the Cr-6MgO insert was smooth, with little evidence of significant oxidation or loss of material, which suggested that the Cr-6MgO base alloy exhibited great potential as an alternative to Pt and Ir insert pad alloys.
- A milestone of "submit an open literature paper reporting on the engine test results of developmental spark plug electrode alloys" (due September 30, 2007) was successfully accomplished.

Future Directions

- Complete accelerated laboratory or natural gas engine testing for Ni-NbC-Y base electrode alloy alone and with precious metal or Cr-6MgO insert pads, is planned.
- Complete transfer of technology via open literature publication relaying understanding gained over the course of this project.

Introduction

Natural gas (NG) reciprocating engine manufacturers have identified ignition systems as one of the key technologies to achieve cost/performance/emission characteristic goals for lean and stoichiometric engines. Spark plug erosion and subsequent failure have been identified as a major issue in long-term durability of natural gas ignition system. Current spark plug lifetimes are on the order of only ~2-6 months, which results in loss of performance and necessitates frequent, costly downtime maintenance for the plug replacement. Desired spark plug lifetimes for NG engine end users are on the order of at least 1 year (or a 2-fold increase in the spark plug life). It has been recognized that as cylinder pressures, compression ratios, and ignition voltages are increased, and conditions further move towards leaner burning combustion, spark plug reliability and lifetime performance will become even more critical and could limit further advances in engine development. The goal of this effort is to identify the mechanisms of electrode wear and to design new electrode materials to improve the lifetime and reliability of NG spark plugs to meet the lifetime goal.

Approach

Studies were conducted on several model chromia-forming alloys, with 25 wt.% Cr to favor exclusive (or at least near exclusive) chromia scale formation, with additions of 0.4 wt.% Si and 0.15 wt.% La (nominal). The Si was added to enhance the chromia scale formation and slow the oxide scale growth rate. The La was also added to further reduce scale growth rate and to improve scale adherence. These levels of Cr, Si, and La additions for oxidation resistance were explored in model ferritic, Fe-base austenitic, and Ni-base austenitic alloys to gain insight into the importance of alloy thermal and mechanical characteristics on erosion resistance, at relatively constant levels of alloy oxidation resistance. Ferritic alloys exhibit the lowest thermal expansion and highest thermal conductivity of this group, but are also quite weak at temperatures beyond ~500-600°C. The austenitic steels are stronger at elevated temperatures (~600°C to 800-900°C), but also exhibit higher thermal expansion and lower thermal conductivity.

Two alternative electrode alloy insert pad materials to platinum group metals also were evaluated, in an attempt to mitigate the loss of electrode material via oxidation and intergranular cracking observed in conventional insert alloys such as Pt-4W. The first alternate alloy was based on Cr-6MgO wt.%. Chromium is a potential replacement for Pt group metals because it is highly oxidation/corrosion resistant in many environments, has good thermal conductivity, and has a melting point in excess of Pt, 1860° vs. 1770°C. It is also significantly less expensive than Pt. Unfortunately, Cr has a high brittle-to-ductile transition temperature and most Cr-base alloys are brittle at room temperature. The Cr-MgO class of materials was originally developed in the early 1960's as an oxidation- and erosion-resistant material candidate for spacecraft re-entry; and exhibits useful levels of room-temperature ductility, which permits manufacture into wire form. A possible drawback of Cr for spark plug electrode applications is the potential for volatilization of the chromia scale formed on oxidation, although in the Cr-MgO class of materials an outer $MgCr_2O_4$ layer is typically formed and may be expected to reduce volatility-driven scale loss. The second alternative insert alloy pad examined was Haynes 214, due to its excellent oxidation resistance. Because this alloy relies on an alumina scale for oxidation protection, volatility-driven scale loss is not expected to be a significant issue.

Results

Figure 1 shows a cross-section of a Ni-15Cr base alloy electrode with a Pt-10Ni wt.% insert pad run under aggressive test cycle conditions in the laboratory-modified gasoline engine. The modes of attack were phenomenologically very similar to that observed in the NG engine field-tested J-type spark plugs, with extensive internal oxidation and cracking at the Ni-15Cr electrode/Pt-10Ni interface. Internal oxidation and intergranular attack of the Pt-10Ni insert, similar to that observed in the NG-tested Pt-4W insert alloy, were also observed. Both W and Ni are stable oxide forming elements, and would be expected to be internally oxidized in a Pt-base alloy. These results suggest that the laboratory-modified gasoline engine can provide useful insight into NG spark plug electrode erosion materials issues. Given the considerable general differences between NG and gasoline engines, these results also suggest an inherent degree of susceptibility of currently used electrode materials to oxidation/cracking attack, independent of specific engine/ignition conditions.

Gap growth vs. time responses in the laboratory-modified gasoline engine for a range of heat-resistant alloy types are shown in Fig. 2. The center electrodes were made from solid rods of the test alloys, with the exception of a control Cu-cored standard 95% Ni-base alloy center electrode run for comparative purposes. The ground electrodes were all made from standard Cu-cored 95% Ni-base alloy. The spark plugs were run under the same engine test conditions, and although the details are proprietary, the results provided can be used to provide a relative assessment of erosion resistance of the materials evaluated.

Despite its inferior oxidation resistance compared to the other alloys, a developmental optimized 95% Ni-base alloy electrode showed significantly lower gap growth rates than the highly alloyed, heat-resistant alloys tested, including 602 CA and Haynes 214. It is postulated that any gains in erosion resistance due to reduced oxide growth rate with chromia or alumina scales were overwhelmed by the accompanying reduction in alloy thermal conductivity due to the high levels of Cr and/or Al needed to improve oxidation resistance (Table 1). For example, the room-temperature thermal conductivity of Haynes 214 and 602 CA is in the range of 11-12 W/m-K, compared to an estimated range of ~20-45 W/m-K range for standard $95\%^{+}$ Ni-base alloys, and 90 W/m-K for pure Ni. These alloys would therefore have been expected to run hotter, negating their higher level of oxidation resistance. This supposition is consistent with the gap growth data for the control Cu-cored 95% standard Ni alloy electrode as compared to the solid 95% Ni standard alloy electrode, which showed a significant reduction in gap growth rate with the improved thermal conductivity and heat extraction gained with copper coring (Fig. 2 and Table 1). The exploration of the heat-resistant alloys using solid center electrodes allowed facile manufacture of spark plugs for engine testing, but may also have experimentally overemphasized the effects of differences in thermal conductivities between the alloys on erosion resistance. Such effects may be expected to be at least somewhat ameliorated by copper coring, although the high strengths and relatively low ductilities of many heat-resistant alloys may preclude mass production with copper coring.

Scanning electron microscopy (SEM) secondary electron mode cross-section images of the center electrodes after 500 h of laboratory-modified gasoline engine testing (Fig. 2) are shown in Fig. 3. It is interesting to note that, despite its relatively low gap growth rate, the developmental optimized 95% Ni-base alloy electrode showed significant oxidation-driven attack, with a loosely-adherent Ni-rich external oxide scale overlying an extensive internal oxidation zone containing Al and Si oxide precipitates. However, little cracking was observed in this alloy. By comparison, both the solid- and Cu-cored 95% standard Ni alloy electrodes showed extensive cracking, which may lead to significant material loss if the cracks coalesce.

Both alloy 602 CA and Haynes 214 showed complex Ni-Cr-Fe-Al base external oxide scales with preferential internal oxidation along alloy grain boundaries. Typically, these alloys form transient Ni-, Fe-containing oxides during the initial stages of oxidation before the establishment of a protective chromia or alumina layer at the alloy/scale. Constant removal of surface oxide by sparking may lead to oxidation behavior more representative of the transient stages of oxidation, rather than steady-state chomia- or alumina- dominated oxidation. Possible coalescing of the internally attacked grain boundaries (e.g. area marked by arrow shown for 602 CA) may explain the significant gap growth/materials loss experienced by these alloys. However, the model Fe-base chromia-forming alloys exhibited Fe-Cr oxide rich surface scales, consistent with Fe-Cr spinel, with little evidence of similar extensive internal oxidation or grain boundary attack. Despite the absence of cracking/internal oxidation attack in the Fe-base alloys, gap growth/materials loss rates were still quite high (Fig. 2).

Select alloys were also run as solid center electrodes in a short term (67 h) NG engine test. The ground electrode in this tests consisted of a standard Cu-cored 95% Ni alloy. SEM cross-section images of the center electrodes are shown in Fig. 4. It is interesting to note that the Ni-base electrode alloys again showed extensive intergranular cracking, while the Fe-base alloys were relatively resistant to this form of attack. It is speculated that this may be due in part to the local penetration of sulfur and formation of low-melting point Ni-sulfides.

Polynomial curve fitting of optical images of the electrodes pre and post engine test, averaged over 6 positional locations, were used to assess material loss for the solid center electrodes. Materials loss for the standard 95% Ni alloy, Ni-15Cr base alloy, and model chromia-forming Ni-base and Fe-base austenitic alloys were comparable, on the order of ~50-100 microns. Materials loss measurements for the model chromia-forming ferritic alloy suggested a much higher rate of erosion for this alloy, with material loss on the order of 300 microns. However, the cross-section images appeared comparable to the other materials and it is possible that the center electrode shifted or otherwise sagged during the testing due to the poor high temperature creep resistance of ferritic alloys.

The laboratory and NG engine testing results suggest that for spark plug electrodes that do not use a Pt-group alloy insert, thermal conductivity may be a more important factor to optimize than is oxidation resistance and scaling rate. This may not be the case for electrodes using Pt group alloy inserts, as significant oxidation and cracking attack was observed at the electrode alloy/insert interface in field tested NG spark plugs, which can lead to separation of the insert from the electrode, culminating in spark plug failure.

An additional set of laboratory gasoline engine tests were conducted using a Cu-cored standard Ni-15%Cr base alloy for both the center and ground electrodes, with insert pads of Cr-6MgO and Haynes 214 on the center electrode. SEM secondary electron cross-section images of the center electrodes after 200 h of engine testing are shown in Fig. 5. A control Cu-cored standard 95% Ni-base alloy suffered from internal oxidation and cracking, similar to that observed in the earlier engine tests. Similar cracking was observed in the Haynes 214 insert pad alloy. In both the standard 95% Ni-base alloy and Haynes 214, the internal attack and cracking were associated with internal penetration of oxygen and sulfur. The outer surface of the Haynes 214 pad also appeared rough and highly irregular, suggestive of significant loss of material. Oxidation and cracking at the Haynes 214 insert pad alloy/electrode interface, similar to that observed with Ir and Pt inserts, was also observed.

In contrast, no cracking was observed in the Cr-6MgO base alloy insert or at the insert/electrode alloy interface. Inter-diffusion at the Cr-6MgO insert/Ni-15Cr-base electrode alloy weld interface would be expected to result in a high local level of Cr, resulting in good oxidation and corrosion resistance. Cr-MgO electrode material's loss measurements pre- and post-engine test are not available; therefore a definitive assessment of the rate of erosion is not possible at this stage. It should be noted that the surface of the Cr-6MgO insert was smooth, with little evidence of significant oxidation or loss of material. This supposition is consistent with the similar appearance and distribution of the MgO dispersions at the surface and within the insert pad alloy, as significant material loss would be expected to alter and redistribute the MgO dispersions as Cr matrix material was removed.

CONCLUSIONS AND IMPLICATIONS FOR FUTURE DIRECTIONS

The laboratory gasoline and NG engine test results suggest that optimization of electrode alloy oxidation resistance must be pursued in conjunction with strong consideration of alloy thermal conductivity to achieve the goal of improved erosion resistance. The use of commercially-available, oxidation-resistant chromia- and alumina- forming, heat-resistant alloys did not improve erosion resistance. Rather, the improvement in oxidation resistance was seemingly overwhelmed by effects related to decreased alloy thermal conductivity with the levels of Cr or Al needed to impart improved oxidation resistance (Fig. 2 and Table 1). This speculation is supported by the marked reduction in gap growth rate observed for a copper-cored, standard 95% Ni alloy center electrode compared with a comparable solid 95% Ni alloy electrode. Even when used as an insert alloy pad on a Cu-cored standard Ni-15Cr base electrode alloy, the highly oxidation-resistant but low thermal conductivity Haynes 214 exhibited excessive attack.

The Cr-6MgO base alloy showed potential as an alternative to Pt and Ir insert pad alloys, and is therefore of interest for further investigation. Because the matrix is essentially pure Cr, thermal conductivity for this material is expected to be comparable to that of pure Cr (Table 1), which is relatively high. The chromium-base appeared to resist intergranular oxidation and cracking attack, both at the sparking surface and at the weld interface with the base electrode alloy. A concern with a Cr-base electrode material is materials loss via volatilization; however, this did not appear to be a significant factor in the short-term laboratory engine test run. Longer-term engine tests are needed to confirm this observation, as well as more fully quantify the possible low erosion rate and cracking immunity of the Cr.

In terms of electrode alloy design strategies, co-optimization of thermal conductivity and oxidation resistance in 95% Ni-base electrode alloys appears to be a viable path of interest. On this basis, alloys of the type Ni-NbC-Y would be expected to exhibit a high thermal conductivity due to an essentially pure Ni matrix, with small additions of Y to improve oxidation resistance. The absence of Al, Cr, Si, etc additions used in conventional 95% Ni-base electrode alloys is expected to minimize internal oxidation. NbC dispersions are very effective in imparting creep resistance in austenitic stainless steels, and may be expected to similarly improve creep resistance in Ni to maintain electrode integrity. Further, NbC has a low work function and a high melting point (3500°C range), and dispersion of Nb in the alloy may act as a preferential sparking site, resulting in improved erosion resistance. Literature reports have also long noted improved erosion resistance with oxide dispersions, which may have contributed to the good erosion resistance of the Cr-6MgO base alloy, and may be expected to occur for refractory carbide dispersions such as NbC. Engine testing of this electrode alloy, alone and with precious metal or Cr-6MgO insert pads, is planned.

Table 1- Alloy thermal conductivities and melting points

Element/Alloy	[b]W/m-K (room temperature)	[b]W/m-K at 800°C	T_{melt} (°C)
Elements			
Cu	398	350	1083
Ir	147		2450
Cr	90		1860
Ni	90	64	1452
Fe	76		1530
Pt	73	76	1770
Alloys			
Standard 95%[+] Ni type	20 - 45		up to 1440
Ni-15Cr type	15	28	1350-1410
[a]Model ferritic (type 446)	22	24	1500
[a]Model austenitic (type 310)	14	19	1450
[a]Model Ni base (type Nichrome)	13		1400
Haynes 214	12	30	1355-1400
602CA	11	25	1370-1400

[a] data estimated based on commercial alloys of similar composition.
[b] values estimated from multiple sources (Web Elements, CRC Materials Science and Engineering Handbook 3rd Edition, various alloy manufacturer datasheets)

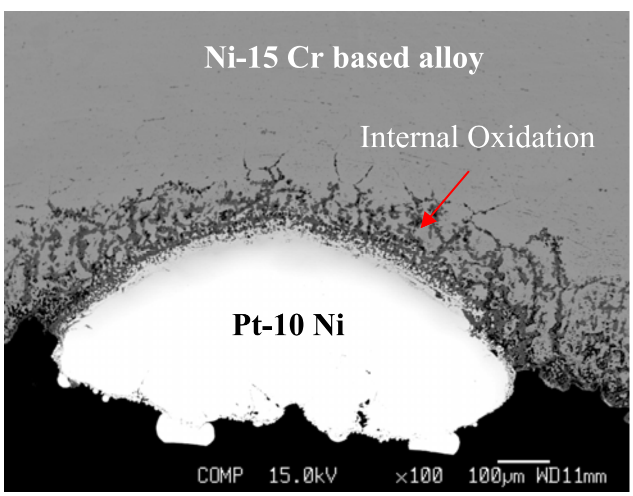

Fig. 1. SEM photomicrograph of polished cross-section of the center electrode from a 749 h test under severe cycle conditions in the laboratory modified gasoline engine.

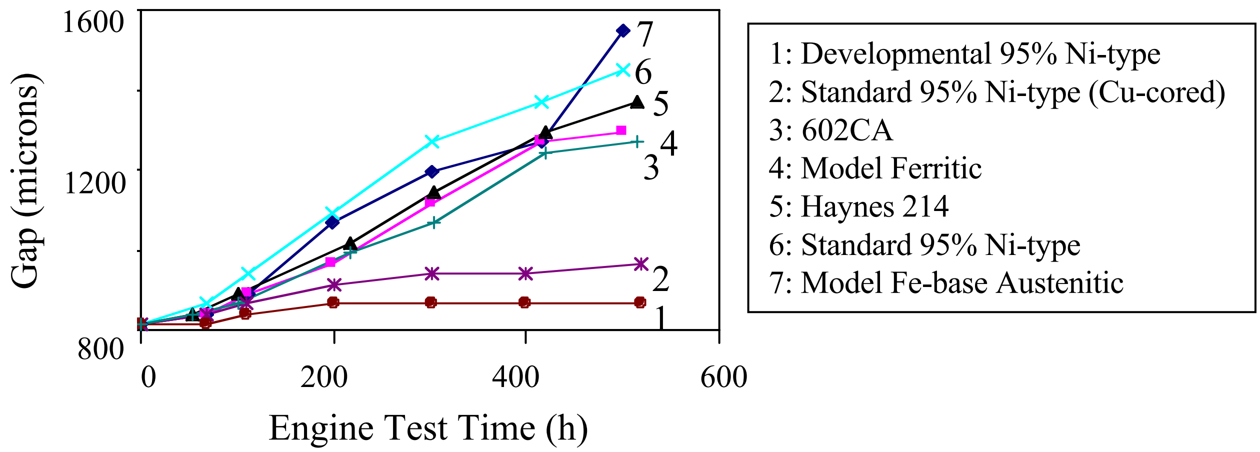

Fig. 2. Gap growth versus engine test time for severe durability laboratory test stand gasoline engine test with high thermomechanical stress introduced under high speed and high load operating conditions. The center electrode (negative polarity in this data) only was composed of alloys 1-7, and was solid (no Cu coring) unless otherwise noted. The ground electrode consisted of a standard, Cu-cored 95% Ni-base alloy for all tests.

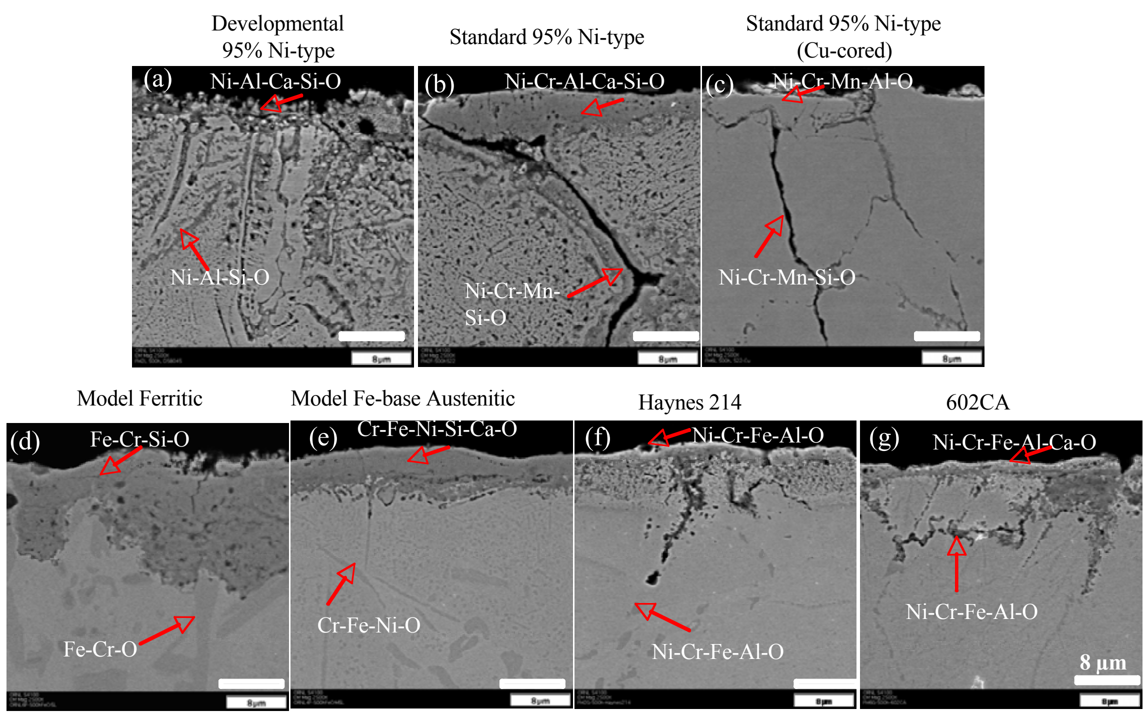

Fig 3. SEM photomicrographs of polished cross sections of electrode materials after 500h gasoline engine test.

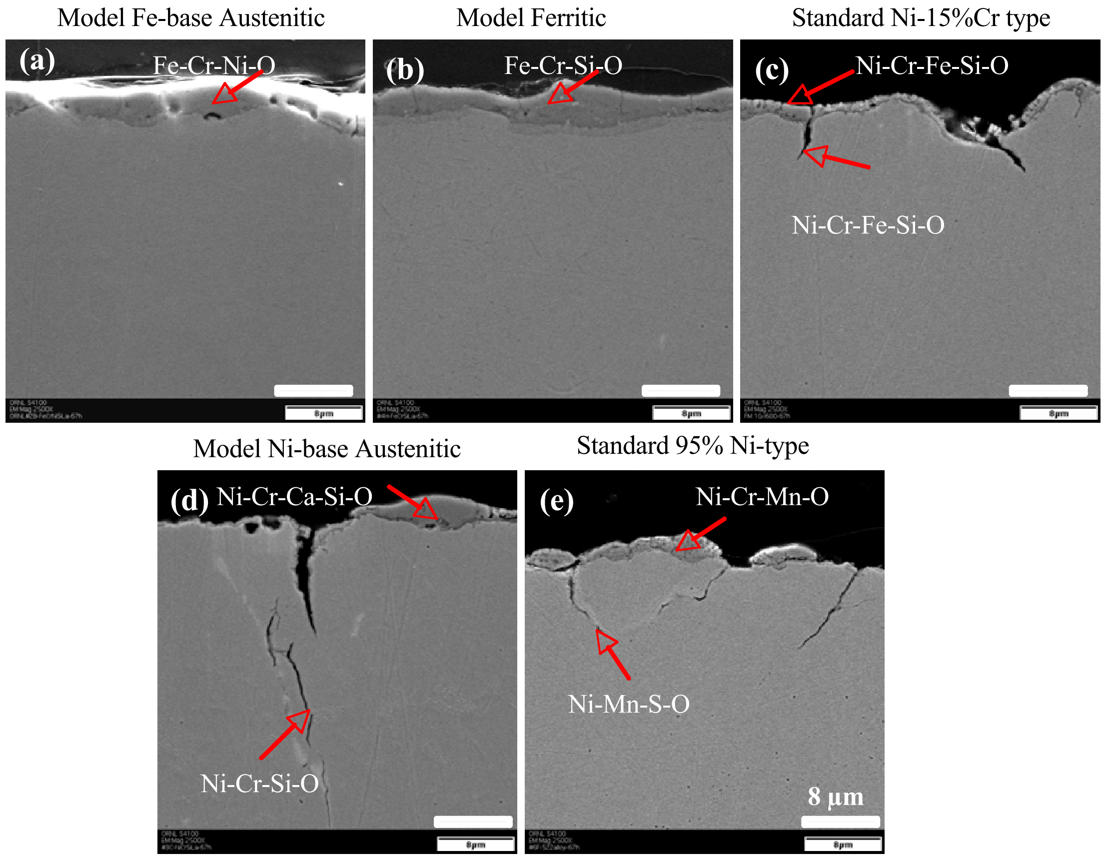

Fig 4. SEM photomicrographs of polished cross sections of electrode materials after 67h test in natural gas engine.

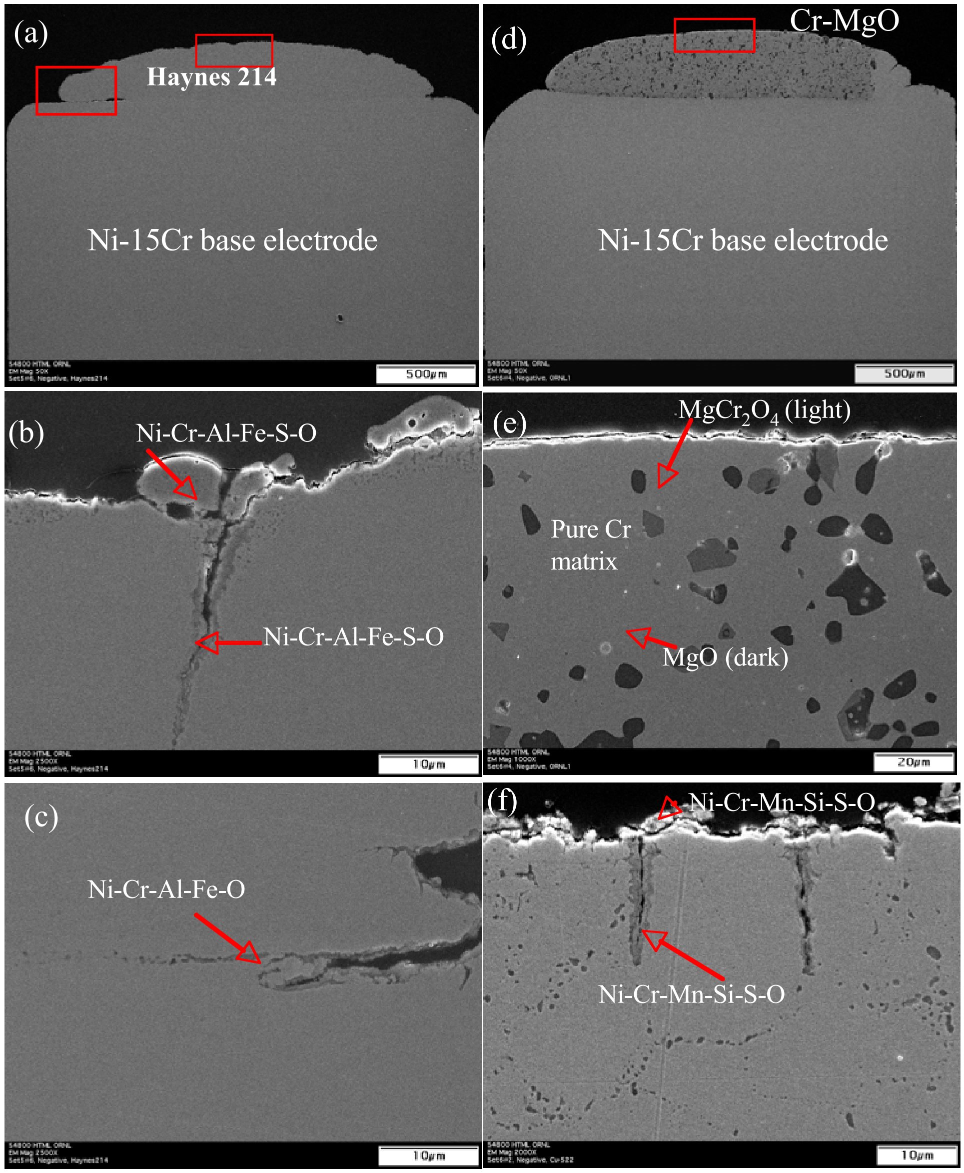

Figure 5. SEM photomicrographs of polished cross sections of electrode materials after 200h gasoline engine test.

4.1.3 – Siloxane Mitigation for Advanced Natural Gas Engines

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Objectives

- Provide fundamental insight into the detection of silica-based compounds from siloxane to assist the reciprocating engine manufacturers to mitigate engine damage.
- Develop a fundamental understanding of the detection methods for siloxanes.
- Develop a low cost siloxane sensor to effectively control fuel pre-treatment technologies.

Approach

- Experiment with different coatings for microcantilevers to meet the specifications for siloxanes in the presence of the normal landfill gas and anaerobic digester gas matrix.

Accomplishments

- Preliminary testing of microcantilever arrays with hexamethyl-disiloxane look promising for sub-ppm detection.

Future Directions

- Establish a collaborative agreement with a company that specializes in the design of waste-water treatment plants.

Introduction

Reciprocating engines remain the most logical distributed generation choice for reducing the peak demand on an electrical feeder due to their ease of siting and good economics. Increasingly, however, the high cost of natural gas is focusing attention on lower-quality fuel sources, such as landfill gas (LFG) or anaerobic digester gas (ADG) from waste-water treatment plants. These fuels often offer a low cost alternative to natural gas, and, in many cases, have environmental concerns with their disposal by flaring. A key impediment to the more pervasive use of low quality fuels is contaminants in the fuel, specifically siloxanes. Siloxanes are a group of silicon-based organic compounds that are prevalent in LFG and ADG and can form silica compounds (sand) in an engine. The increased maintenance costs and/or increased fuel pre-treatment costs can hamper the economics of using these lower quality fuels. The state of the art for siloxane mitigation is quite low; the industry recognizes the issue and the approach is to treat the gas at all times for siloxane removal. The actual concentration of siloxanes are dictated by the environmental conditions of the landfill or anaerobic digester; real-time monitoring of siloxanes would allow more cost-effective controls to be implemented.

Approach

This project seeks to provide fundamental insight into the detection of silica-based compounds from siloxane to assist the reciprocating engine manufacturers to mitigate the engine damage. Effort will be focused on developing an understanding of detection methods for siloxanes; development of a low-cost siloxane sensor to effectively control fuel pre-treatment technologies; and consideration of in-situ strategies to avoid the silica formation in the engine.

Through feedback control, a real-time sensor could dramatically lower treatment costs (and energy consumption) for the feed gas. For instance, the treatment loop would only be used when siloxanes reached some threshold level. Desired specifications for the sensor include:

- Sensitivity < 1 ppm
- Response time (t_{90}) : < 60 s
- Recovery time (t_0) : <300 s

The sensor will be based on microcantilever array technology first pioneered at ORNL in the 1990's. By tailoring coated cantilevers, selectivity and sensitivity to specific compounds is enhanced. The approach will be to experiment with different coatings to meet the specifications for siloxanes in the presence of the normal LFG or ADG matrix. This matrix includes CH_4, CO_2, H_2O, H_2S, and trace levels of many organic compounds.

Results

Researchers from Waukesha Engine Dresser (WED) have expressed an interest in the siloxane issue that faces reciprocating engines. Representatives from ORNL and WED have discussed various strategies that mitigate siloxane effects. ORNL researchers have begun testing microcantilever arrays with hexamethyl-disiloxane. Early results look promising for sub-ppm detection.

References
None

FY2007 Awards/Patents
None

FY 2007 Publications/Presentations
None

Acronyms

ADG – Anaerobic Digester Gas
LFG – Landfill Gas
ORNL – Oak Ridge National Laboratory
WED – Waukesha Engine Dresser

4.2.1 Microstructural Characterization of CFCCs and Protective Coatings

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Objectives

- Microstructural and mechanical characterization of baseline oxide/oxide CMC materials after exposure to simulated (ORNL's Keiser Rig) combustion environments.
- Characterize numerous sections of a hybrid oxide-oxide CMC+FGI outer combustor liner after engine testing for >25,000h.

Approach

- Collaborate with ATK-COI Ceramics, Siemens Power Generation, and Solar Turbines, Inc. to microstructually and mechanically evaluate a >25,000h engine-tested outer combustor liner at ORNL.

Accomplishments

- Completed study of the microstructural and mechanical stability of a Nextel 720 continuous-fiber reinforced alumina matrix composite (A/N720 CMC) after exposure to different H_2O pressure and 3 temperatures, 1135°C, 1200°C, and 1250°C, for 3000h (reported in FY06).
- Fully characterized several key damaged and undamaged areas of the A/N720 CMC + FGI outer liner using SEM and EPMA in order to elucidate degradation mechanisms of both the CMC liner and FGI coating.

Future Directions

- Summarize results of liner characterization on October 4, 2007 at review meeting with Solar Turbines, Inc., ATK-COI Ceramics, and Siemens Power Generation.
- Prepare presentation and paper for ASME/IGTI Tubo Expo 2008.

Introduction

Continuous fiber-reinforced ceramic matrix composites (CFCCs), or ceramic matrix composites (CMCs), have been developed to replace several metal components in stationary gas turbine engines. One such application is the un-cooled CFCC combustor liner, the use of which can significantly decrease CO and NO_x emissions at increased combustor wall temperatures (~1200°C and higher).[1] Two engine tests were initially conducted on a Solar Turbines Centaur 50S engine fitted with SiC/SiC CFCC combustor liners, however, as a result of the accelerated attack of SiC-based materials (especially CFCCs) in environments containing H_2O, such as found in combustion gases, excessive surface recession of the CFCC was observed.[2] In order to increase the life-times of the CFCC components, EBCs will be used on the CFCC liner gas-path surfaces. In recent years, SiC/SiC liners with a BSAS-based EBC ran for ~15,000 h in a single engine test.[3]

In order to attain significantly longer lifetimes (>30,000h) in combustion environments, alternative materials for the currently-used, commercially-available SiC/SiC+BSAS system are being evaluated for the combustor liner application for use in both gas turbine and microturbine engines. A promising option is the oxide/oxide CMC, based on continuous Nextel 720 (alumina+mullite) fibers in a porous alumina matrix (designated commercially as A/N720 CMC). This CMC material has demonstrated little loss in mechanical performance when exposed to water-vapor at temperatures up to 1200°C for 1000h.[4] However, microstructural instabilities of the Nextel 720 fibers used in alumina- or aluminosilicate-matrix CMCs have been reported following thermal aging at temperatures >1200°C.[5]

During the past 3 years (2003-2006), a 76cm X 18cm ‘hybrid’ A/N720 CMC outer combustor liner with a friable gradient insulator (FGI) coating on the gas-path surface, ran for >25,000h in a Solar Turbines engine test (at the ChevronTexaco test site in Bakersfield, CA). This engine-exposed outer liner was sent to ORNL for microstructural and mechanical characterization.

Approach

After removal from the engine in late 2006, the hybrid outer liner (A/N720 CMC+FGI) was inspected by NDE techniques at ANL and shipped to ORNL for microstructural and mechanical characterization. Prior to these analyses, changes to the liner thickness across the entire liner were evaluated using coordinate measuring machine (CMM) inspection. The liner was then sectioned such that varying degrees of visually-observed surface damage and areas displaying damage observed via NDE, could be evaluated by SEM (structural) and EPMA (compositional). Many areas of the gas-path surface (and the non-gas-path surface) were extremely friable to the touch, thus, the liner surfaces were covered in crystal-bond epoxy before machining or cutting into much smaller pieces. Small cross-sections were prepared and polished metallographically for analysis.

Results

The removal of the set of combustor liners engine-tested during FY2006 was delayed by Solar Turbines in order to accumulate a minimum of 25,000h engine test hours, the longest for a set of ceramic composite combustor liners, exceeding the field-exposure time for a set of BSAS+SiC/SiC liners by >10,000h. This is a significant achievement, but delayed start of the ORNL characterization effort until mid-2007. The outer liner was actually received at ORNL in late April, of 2007.

Prior to sectioning, the thickness variations across the entire 30” diameter out liner were measured using ORNL’s CMM. ~400 thickness profiles, fore to aft, were taken around the liner circumference in 6.35 mm steps. An unexposed A/N720+FGI outer liner, which was made at the same time as the exposed liner, was used as the baseline material. After CMM data were acquired, both the unexposed and engine-exposed hybrid liners were sectioned such that microstructural data from the different gas-path surface structures could be evaluated and compared. Three primary surface structures were the main focus of this study; much of the FGI gas-path surface (>90%) exhibited varying amounts of roughness and surface recession (Fig. 1(a)), a "patched" area, which represented a repaired FGI region (using a different FGI formulation) conducted after ~12,000h in the engine (Fig. 1(b), and a through-thickness hole (Fig. 1(c)).

A cross-section backscattered electron (BSE) microscopy image representative of the unexposed A/N720+FGI liner is shown in Figure 2. The thickness of the CMC was ~2.5 mm and the thickness of the FGI, which was on the gas-path surface, was ~5.0 mm, resulting in an "average" liner thickness of ~7.5 mm.

After 25,000h engine testing, most of the surface of the FGI (gas-path surface) appeared rough and uneven, as shown in Figure 1(a). The CMM fore-to-aft thickness data for these typical regions show liner thicknesses ranging from 4-6 mm, indicating 25-40% thickness loss along the center circumference region of the liner. Several fore-to-aft thickness profiles across roughened FGI surface regions are compared with the baseline liner thickness profile in Figure 3 and a representative cross-section BSE image of a roughened FGI region is shown in Figure 4. Figure 4 clearly shows that the loss of liner thickness was due to the loss of FGI during the 25,000h engine test.

The loss of liner wall thickness was due to recession (loss) of the FGI on the gas-path surface; the CMC thickness did not change (although significant delamination between fiber tows was observed). Elemental maps shown in Figure 5 demonstrate the contributing mechanisms of FGI recession due to exposure of this material to the exhaust (combustion) gas. The FGI is phosphate-based (P-Si-O phase) and is comprised of Al_2O_3-rich mullite hollow-spheres (see FGI in Figure 2) embedded in a mullite+phosphate matrix (with small amounts of excess/residual SiO_2 and Al_2O_3). During engine testing, volatilization of the phosphate phase occurs rapidly and, in fact, is nearly 100% depleted in the FGI layer (see P-map in Figure 5). In addition, nearly 50% of the remaining FGI is 100% depleted of silica due to volatilization from the mullite phase (see silicon map in Figure 5), which leaves only Al_2O_3 in this surface region/layer. Thus, the entire surface of the FGI is pure Al_2O_3 that remains from volatilization of silica from mullite present in both the hollow-spheres and FGI matrix. The Al_2O_3 particles in the layer adjacent to exhaust gas experience significant thermally-induced grain growth, and since there is no matrix "glue" to hold these particles in place on the surface, the Al_2O_3 particles erode from the surface. These three mechanisms, rapid phosphate volatilization and silica volatilization from mullite phase, and erosion of Al_2O_3 particles from the gas-path surface, contribute to the degradation of the FGI and significant loss of liner wall thickness.

Conclusions

An oxide/oxide hybrid outer combustor liner comprised of an A/N720 CMC with FGI on gas-path surface, was engine-exposed in a Solar Turbines Centaur 50S gas turbine for 25,404h. The microstructural changes were characterized at ORNL in order to elucidate FGI and CMC degradation mechanisms that contributed to observed surface loss (decrease in liner wall thickness). It was found that the A/N720 CMC experienced significant delamination between fiber tows during engine-testing, but the CMC thickness remained relatively constant. The phosphate-based FGI experienced surface recession due to rapid volatilization of the silica-containing phases (phosphate and silica from mullite) that resulted in an open, pure alumina surface. Thermally-induced grain growth and loss of matrix phases at the surface caused the alumina to lose connectivity and alumina particles were removed from the surface by erosion. CMM data showed that wall thickness losses were as high as 50%. New formulations of FGI have been tested (used as patch material on this liner) are nearly pure alumina and show significantly greater resistance to surface loss by either alumina or erosion (results not shown here).

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5. M.G. Holmquist and F.F. Lange, "Processing and Properties of a Porous Oxide Matrix Composite Reinforced with Continuous Oxide Fibers," *Journal of The American Ceramic Society* **86**[10] pp. 1733-40 (2003)

Awards/Patents

Karren More was elected Fellow of the American Ceramic Society.

Publications/Presentations

1. *Abstract Submitted; paper in progress:* K.L. More, L.R. Walker, and T.M. Brummett (ORNL), J. Price and M. van Roode (Solar Turbines, Inc.), A. Szweda (ATK-COI Ceramics), and G. Merrill (Siemens Power Generation), "Microstructural and Mechanical Characterization of a Hybrid Oxide-Oxide CMC Combustor Liner After 25,000h Engine Test," ASME/IGTI Turbo Expo 2008, Berlin, Germany.

Acronyms

A/N720 CMC (ATK-COI Ceramics alumina-matrix/Nextel 720 fiber ceramic matrix composite)

ANL – Argonne National Laboratory

CFCC – continuous fiber-reinforced ceramic composite

CMC – ceramic matrix composite

EBC – environmental barrier coating

ORNL – Oak Ridge National Laboratory

BSAS – barium strontium alumino-silicate

FY – fiscal year

FGI – friable graded insulator

(a)

(b)

(c)

Figure 1. Representative photographs of regions of the FGI gas-path surface of the engine-tested hybrid liner; (a) roughened surface typical of most of the gas-path surface (>90%), (b) patched FGI area, and (c) hole through FGI and into the CMC.

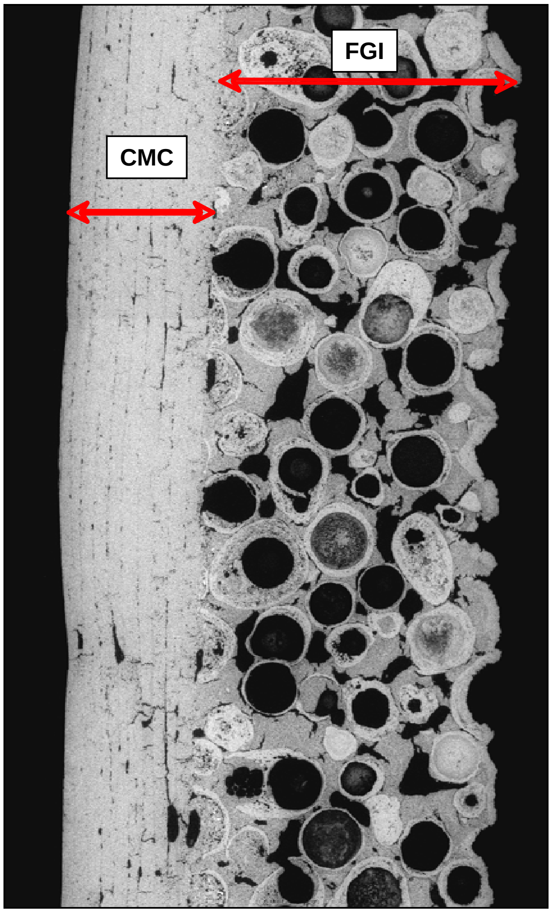

Figure 2. Cross-section BSE image of hybrid liner before exposure in engine.

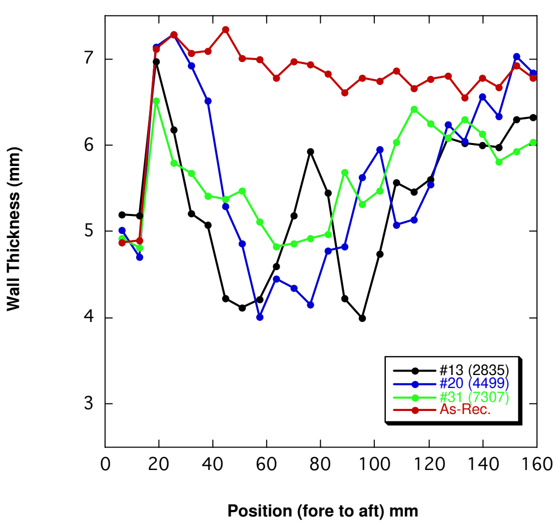

Figure 3. Fore-to-aft CMM thickness profiles from three different roughened gas-path surface areas of the hybrid liner compared with baseline (unexposed) liner data.

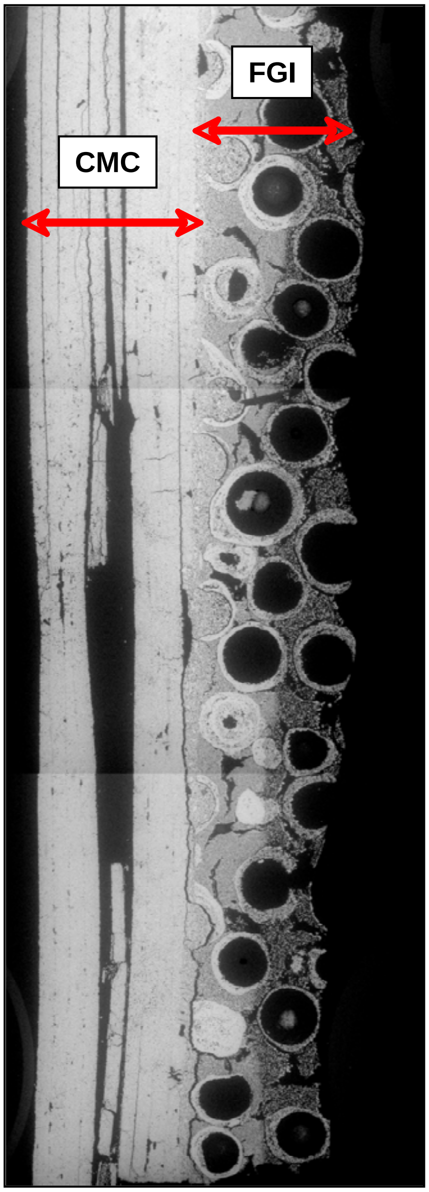

Figure 4. Cross-section BSE image of roughened gas-path (FGI) surface area after 25,000h engine-test.

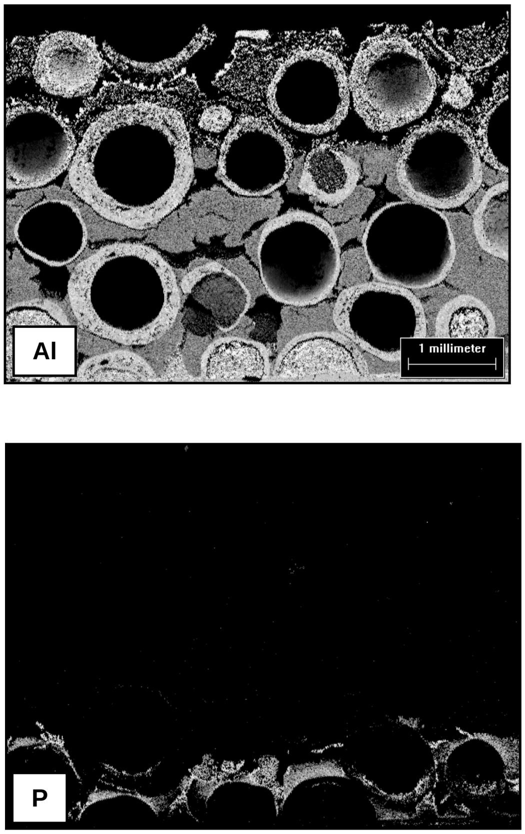

Figure 5. Elemental maps (Al, Si, P) from FGI gas-path surface showing depletion/volatilization of phosphate and silica phase in FGI and remaining Al_2O_3 at surface.

4.2.2 - Reliability Evaluation of Microturbine Components

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Contractor: Oak Ridge National Laboratory, Oak Ridge, Tennessee
Prime Contract Number: DE-AC05-00OR22725

Objective

- Facilitate the successful implementation of ceramic components in advanced microturbines to increase efficiency and reduce NOx emission.
- Provide a critical insight into how the microturbine environment influences the microstructure and chemistry, and thus the mechanical reliability of materials.

Approach

- Evaluate and document the mechanical properties of very small specimens machined from complex-shaped ceramic components for verification of probabilistic component design and life prediction.
- Characterize the evolution and changes in microstructure and chemistry of silicon nitride grains and secondary phase after exposure to engine environments.

Accomplishments

- Characterization of directionally solidified eutectic (DSE) oxide systems for potential ultra high temperature environmental barrier coating applications at temperatures up to 1400°C was successfully accomplished. Test results showed that the alumina phase component in the DSE oxide systems is not stable and thus exhibits significant material recession at temperatures ≥ 1300°C under a simulated combustion (steam jet) environment.
- Characterization of cyclic fatigue behavior of SiC-SiC CMCs with environment barrier coating under high-temperature steam environment at temperature of 1200°C for 2000h has been successfully accomplished. Mechanical and SEM results showed that composite with EBC exhibited no mechanical degradation after exposure to a combined steam-cyclic loading condition, which verified the life prediction modeling of the combustor liner carried out by the end users.
- Milestone of “Complete characterization of EBC-composite systems under a combined stress and steam jet test condition” (September 30, 2007) is successfully accomplished.

Future Directions

- Continue to collaborate with material suppliers to develop next generation silicon nitride ceramics with both high strength and high toughness and thus excellent mechanical reliability and performance for hot section components application.
- Continue to explore the application opportunities of high performance silicon nitride ceramic for high temperature structural components application with end users.

Introduction

The mechanical properties and reliability of complex-shaped ceramic and ceramic composite components play a key role in determining the long-term performance of advanced turbines and microturbines. Processing steps in fabrication and/or chemical compositions employed sometimes need to be modified in order to achieve consistent mechanical properties of components. In addition, thin airfoils are often used with as-processed surfaces, which can exhibit microstructures and chemistries that are different from those in the bulk material and test coupons. These differences influence the long-term mechanical reliability and chemical stability of the materials. At present, there is a critical need to generate a database for complex-shaped ceramic components designed and manufactured for advanced microturbines. The mechanical properties of very small specimens machined from ceramic components (e.g. blades, nozzles, vanes, and rotors) in the as-processed condition and after engine testing will be evaluated under various controlled environments. This work will allow microturbine companies to verify mechanical properties of components and apply the generated database in advanced probabilistic component design and lifetime prediction methodologies. The work also provides a critical insight into how the microturbine environments influence the microstructure and chemistry, thus mechanical performance of materials.

Approach

The long-term mechanical reliability study of SiC-SiC CMC with and without environmental barrier coating (EBC) was evaluated at 1200°C using a custom designed high temperature test rig under an externally applied low cyclic fatigue loading condition. The applied stress levels were 110 and 165 MPa, which was below and above the proportional limit of the SiC-SiC CMC substrate, respectively. The unloading/loading ratio was 0.1 and the frequency was 8h with unloaded duration of 0.1h. The test conditions employed were used to simulate the SiC-SiC CMC combustor liner subjected engine operating condition. Test results obtained will allow end user to confirm the probabilistic component design and life prediction of the combustor liner and to ensure a successful application of SiC-SiC CMC for advanced turbine engine system.

On the other hand, a high-temperature steam jet facility was employed to evaluate the long-term material (both microstructure and chemistry) stability of DSE oxides. The distilled water was pre-heated to ~ 250°C using a heating tap and injected onto the specimen surface via a water pump system. The localized steam speed was estimated to be approximately 30 m/sec. The system is housed in a tensile creep system. Thus, studies on the creep behavior of ceramics and composites under a combined stress and steam condition could also be carried out to simulate the combustion environments.

Results

SiC-SiC CMC with Environmental Barrier Coating

After the first 500h test under a combined steam and low cyclic fatigue condition the retained strength of SiC-SiC CMC specimens with and without EBC were evaluated in four-point bending at room temperature. Mechanical results showed that the SiC-SiC CMC without EBC exhibited significant strength degradation (~90%) arising from the substantial material degradation (both in fiber and matrix) due to sever water vapor attack. The ingression of water vapor along the cracks and interfaces resulted in substantial formation of SiO_2 from oxidation of fiber and matrix and also porous feature in the test specimen due to the subsequent volatilization of $Si(OH)_4$(g). The formation of SiO_2 would lead to a very strong interfacial bonding, resulting a very brittle fracture of the non-coated specimen, as shown in Fig. 1a. On the other hand, the specimen with EBC exhibited little or no strength degradation under the same test condition, which suggested that the EBC employed provided a good protection layer from both oxygen and water vapor at temperature even under an applied stress level above the proportional limit. Scanning electron microscopy (SEM) analysis showed that the specimen with EBC revealed no internal attack from the water vapor even under an applied stress above the proportional limit. Also, there were many fiber pullouts in the specimen with EBC (Fig. 1b), consistent with the good retained mechanical properties measured.

The success of the first 500h test allowed us to continue to carry out the long-term 2000h test with confidence. Due to the substantial environmental attack and thus material degradation observed in specimens without EBC after initial 500h test, the 2000h test was then solely carried out for those specimens with EBC. The 2000h steam test under a low cyclic fatigue condition was successfully accomplished. The subsequent mechanical evaluation revealed little mechanical degradation of those SiC-SiC CMC specimens with EBC. These long-term test results confirmed that the life prediction model of SiC-SiC CMC with EBC evaluated in the present study and the CMC system could be successfully implemented for the combustor liner application.

Ultra high-temperature directionally solidified eutectic oxides

Steam jet studies for several ultra high-temperature directionally solidified eutectic (DSE) oxides, such as Al_2O_3-$Y_3Al_5O_{12}$ (YAG) and Al_2O_3-$GdAlO_3$ (GAP), were successfully accomplished during this fiscal year. The objective of this study is to provide insight into the long-term material stability (both in microstructure and chemical composition) under a simulated combustion (steam jet) environment. It would also provide important information whether the eutectic oxide systems mentioned could serve as a potential alternative for EBC applications, and allow one to develop alternative EBC systems for applications at much higher temperatures up to 1600°C than the limit set by current EBC materials. These DSE oxides, provide by Ube Industries, Japan, were evaluated at 1300° and 1400°C for 500h using a custom-made steam jet system at ORNL.

Figure 2 compares the SEM micrographs of DSE Al_2O_3-GAP surface features before and after steam jet exposure at 1400°C for 500h. SEM observations clearly showed that the Al_2O_3 phase region in DSE Al_2O_3-GAP significantly recessed due to the presence of water vapor. Previous study by Opila [1] has shown that the Al_2O_3 would react with water vapor and form the $Al(OH)_3(g)$ at elevated temperatures, which then be swept away by the localized high-speed water vapor. SEM micrographs of fracture surfaces showed the recession depth of Al_2O_3 component is about 20 μm after 500h exposure at 1400°C (Fig. 3). However, little or no recession of GAP phase was observed after steam exposure, indicative of much better environmental stability than the Al_2O_3 phase. The calculated weight loss was ~1.1 mg, which was quite consistent with the value of 1.4 mg measured. Similar Al_2O_3 phase recession was also consistently observed in the steam exposed Al_2O_3-YAG oxide system as well, and again little or no recession in YAG phase region occurred after high temperature steam exposure (Figs. 4 and 5). It was not surprising to see that the recession depth of Al_2O_3 phase region in Al_2O_3-YAG system was also ~20 μm after 500h exposure, very consistent with the observation in Al_2O_3-GAP system.

Studies of long-term stability of DSE Al_2O_3-YAG and Al_2O_3-GAP oxides suggested that alternative DSE oxides needed to be engineered without the presence of Al_2O_3 phase to achieve the long-term material stability and performance under the combustion application environments. Also, the DSE oxides of YAG-YSZ and/or GAP-YSZ could be potentially alternative EBC systems for ultra high-temperature structure applications.

Summary

Characterization of SiC-SiC CMC with EBC after 2000h exposure under a combined water vapor and low cyclic loading condition has been successfully accomplished. Both mechanical and SEM characterization showed that the composite system evaluated in the present study could be successfully implemented for the combustor liner application in gas turbine engines. Also, test results provided important verification of life prediction task carried out by end users. On the other hand, studies of high temperature water vapor exposure of DSE oxide systems indicated that the Al_2O_3 phase component is not stable and readily recessed at temperatures ≥ 1300°C under the water vapor environment. Alternative DSE oxide systems need to be engineered without the Al_2O_3 phase presence to ensure the long-term material stability and lifetime performance of the components as well as EBC systems.

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Honors / Awards / Patents

1. Outstanding Alumnus Award, Materials Engineering, Auburn University, 2007.
2. Academician of the Class "Industry and Innovation" of World Academy of Ceramics, 2007. Only two were elected in this class among nominees from around the world.

US Paten Application

Paul Becher and H. T. Lin, a patent application entitled "Use of Additives to Improve Microstructures and Fracture Resistance of Silicon Nitride Ceramics" was submitted to US Patent Office on Sept. 7, 2007. The application number is 11/851,540.

Publications / Presentations

Publication

J. A. Haynes, S. M. Zemskova, H. T. Lin, M. K. Ferber, and W. Westphal, "Characterization of CVD Mullite + CVD Alumina Coating on Silicon Nitride Vanes," *J. Am. Ceram. Soc*., 89[11] 3560-3563 (2006).

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S. Ueno, T. Ohji, and H. T. Lin, "Development of Multi-layered EBC for Silicon Nitride Ceramics," to be published in the Proceedings of "Advanced Ceramic Coatings and Interfaces II," Ceramic Engineering and Science Proceedings, Vol. 28, Issue 3, 2007 (in press).

Presentations:

1. H. T. Lin, M. P. Brady, M. D. Kass, T. J. Theiss, N. Domingo, I. Levina, and J. Lykowski, Characterization and Mitigation of Spark Plug Electrode Erosion in Natural Gas and Automotive Engine Application," ICEF2007-1697, to be presented at the Internal Combustion Engine Division Fall Technical Conference, October 14-17, 2007, Charleston, SC.

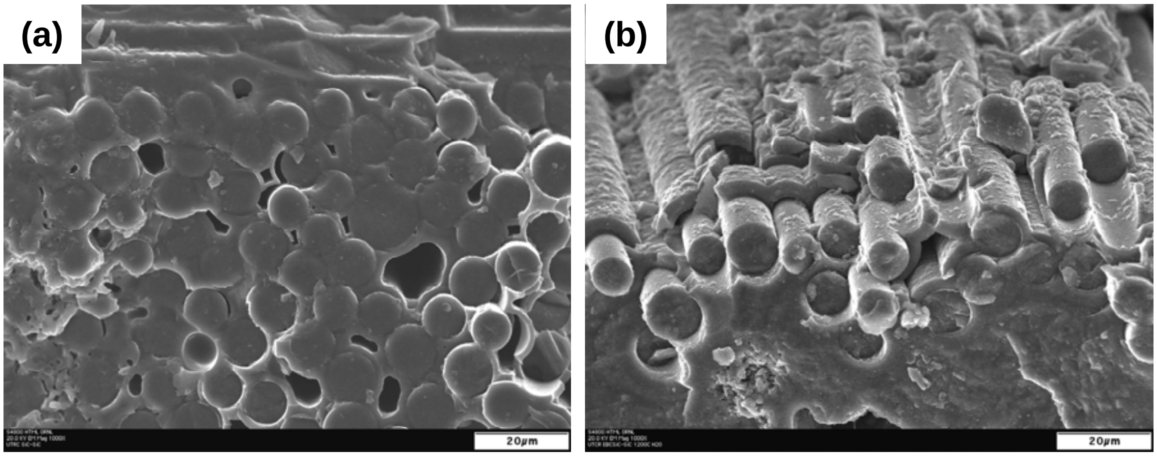

Figure 1. Fracture surface of SiC-SiC CMC specimen (a) without and (b) with environmental barrier coating after 500h exposure to a combined water vapor and low cyclic loading condition.

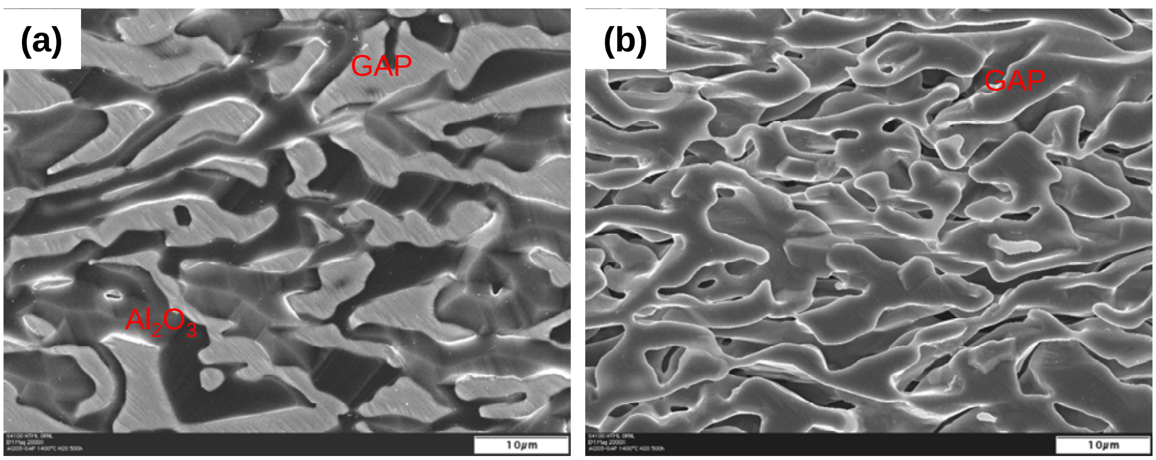

Figure 2. SEM surface feature of DSE Al_2O_3-GAP oxide in (a) as-received and (b) after 500h exposure to steam jet at 1400°C.

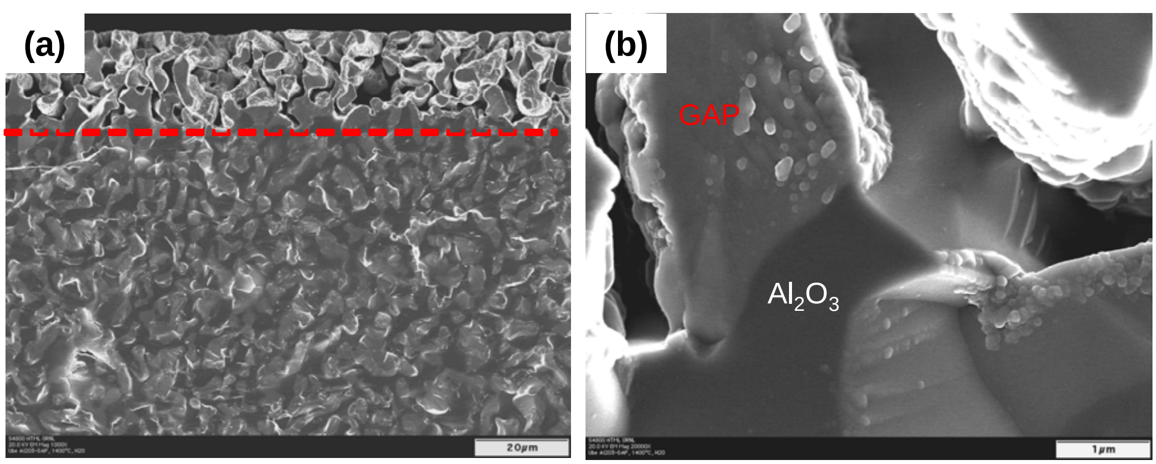

Figure 3. SEM fracture surface of DSE Al_2O_3-GAP oxide after 500h exposure to steam jet at 1400°C.

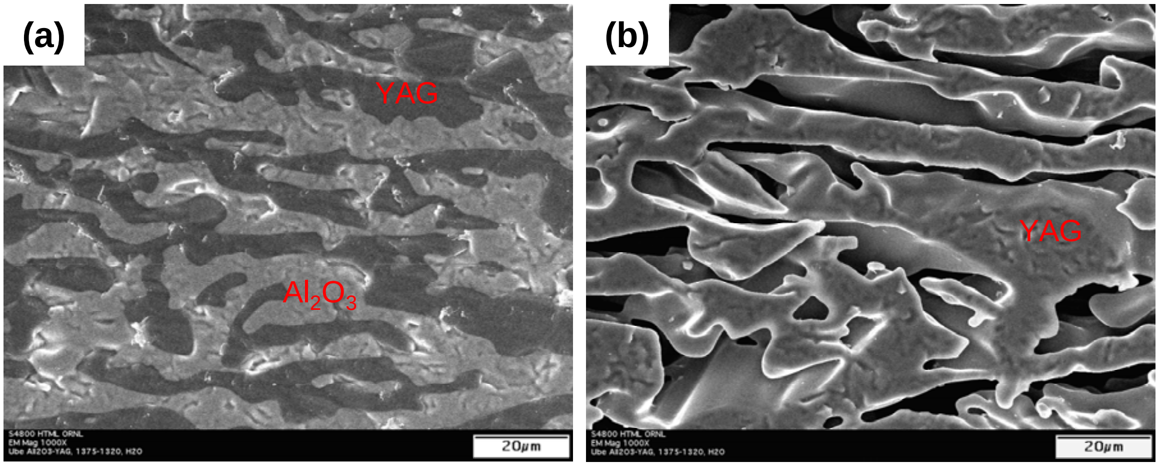

Figure 4. SEM surface feature of DSE Al_2O_3-YAG oxide in (a) as-received and (b) after 500h exposure to steam jet at 1400°C.

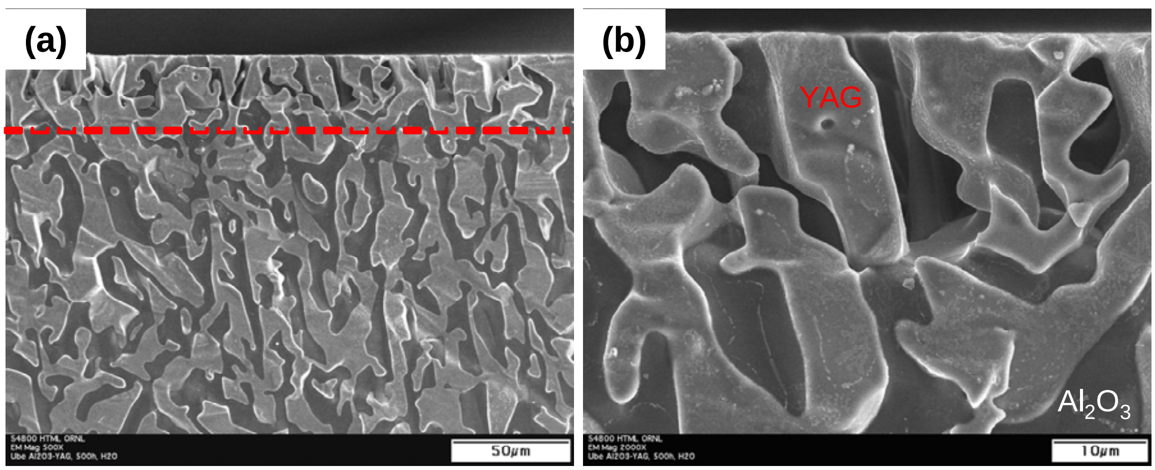

Figure 5. SEM fracture surface feature of DSE Al_2O_3-YAG oxide after 500h exposure to steam jet at 1400°C.

4.2.3 - Environmental Protection Systems for Ceramics in Microturbines and Industrial Gas Turbine Applications

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Objectives

- Evaluate a low-cost, slurry-based process to apply protective coatings for silicon-based ceramic materials for use in microturbine and/or industrial gas turbine applications.
- Evaluate the effect of contamination upon slurry and resulting coating properties for a doped rare earth silicate system.

Approach

- Study and implement mechanisms of colloidal chemistry for controlled contamination addition to coating systems in aqueous environments.
- Evaluate the microstructure of coatings cast with and without a substrate.

Accomplishments

- Demonstrated the sensitivity of the rare earth doped silicate coating systems as a function of rheological modifiers.
- Continued collaborations with several industrial parties to ensure that the needs for environmental barrier coating systems (EBCs) are being addressed.

Future Direction

- Continue with industrial parties to optimize and implement coating theory and technology.

Introduction

Monolithic silicon nitride ceramics and silicon carbide-silicon carbide ceramic matrix composites are currently the ceramic materials being used in combustion engine environments and are under consideration as hot-section structural materials for microturbines as well as other advanced combustion systems. Under oxidizing conditions, these materials typically form a surface oxidation (silicate) layer. In a combustion environment, this silicate layer can undergo rapid degradation due to effects of high temperature, high pressure, and the presence of water vapor. This degradation can severely limit the useful life of the ceramic in this environment. Thus, the development of an environmental protection system for the ceramic has become an essential goal for enabling the long-term utilization of these materials in advanced combustion engine applications. Similar to thermal barrier coatings for nickel-based super alloys that utilize a specialized oxide surface layer and a metallic bond coat, successful environmental protection systems for ceramics and ceramic composites will likely utilize multiple layers and complex combinations of materials. Most recent efforts have focused on the selection and deposition of the oxide surface layer, and due to numerous factors, the majority of the candidates have been from the alumino-silicate family of oxide ceramics. Stable rare-earth silicate deposits have been found on component surfaces after recent engine and rig tests, indicating there may be other stable oxide compositions that have not been fully investigated.

Approach

Previous efforts were focused on the development and refinement of a slurry-based processing method to deposit thin dense coatings of selected compositions on various silicon nitride substrates. FY06's work had shown that small amounts of contamination from the water source and/or the surfactant and rheology additives affected the resulting coating microstructure. Small levels of contamination resulted in porous coating microstructures in the yttrium silicate coating compositions.

The intention of the FY07 effort was to determine how contamination in slurry additives affects coating microstructure. Work, however, focused on developing a fundamental understanding of how slurry additives affect dispersion. Yttrium mono-silicate (Y_2SiO_5) and di-silicate ($Y_2Si_2O_7$) powders were characterized using zeta potential and classic sedimentation techniques. Slurries were made from the Y_2SiO_5 and $Y_2Si_2O_7$ powders and selected slurry additives to evaluate their effect of compositional surface change at the powder surface.

Results

Slurry Coatings Development

A wide variety of alternative additives were tested during the course of FY06 to evaluate the effect of contamination on coating microstructures. Even though the additive chemistry was changed, rheological behavior could still be modified to produce flowable and dripless coatings; however, the microstructures were dependent upon contaminants present in the additive. The ability to substitute additives to meet purity demands still indicated the robustness of the processing approach; however the robustness of a coating system due to the coating material's sensitivities to common salts and alkali materials during operation at high temperature remains a concern. The focus of FY07 centered on the yttrium doped silicates due to the perceived irreproducibility of behavior (zeta potential and rheology) of the materials from powder lot to powder lot. Both the monosilicate (Y_2SiO_5) and the disilicate ($Y_2Si_2O_7$) forms were selected in order to determine if sensitivity of the material could be attributed to the phase stability.

Zeta Potential

Zeta potential measurements were carried out on the $Y_2Si_2O_7$ (Praxair Specialty Ceramics, Woodinville, WA), Y_2SiO_5

(Praxair Specialty Ceramics, Woodinville, WA), Y_2O_3 (Unocal, Fairfield, NJ), and SiO_2 (Johnson Matthey) particles in dilute aqueous suspension using capillary electrophoresis (Zetasizer 3000HS, Malvern Instruments Ltd., Worcestershire, UK). Dilute suspensions (10^{-3} vol% solids) were prepared by adding the appropriate amount of powder to aqueous, KNO_3 solutions (0.01 *M*). The solutions were adjusted to varying pHs ranging from 2 – 11 using stock solutions of nitric acid or ammonium hydroxide. Measurements are made after 24 hours to ensure the surfaces have come to equilibrium.

Baseline zeta potential measurements were made on Y_2O_3 and SiO_2 powders to compare the behavior of the Y_2SiO_5 and $Y_2Si_2O_7$ relative to pH. The zeta potential behavior as a function of pH for all four materials is shown in Figure 1. The Y_2SiO_5 and $Y_2Si_2O_7$ powders have isoelectric points (IEPs) at pH's about 5.5 and 3, respectively, whereas Y_2O_3 is about pH 6.5, and SiO_2 is about pH 3. Even though IEP's for Y_2O_3 of 8-9 have been reported in the literature (1,2), an IEP of 6.5 is not out of line and can be attributed to sample purity, contamination effects, and other factors. Considering the overall trends of the zeta potential data, it can be stated that the Y_2SiO_5 powder behavior resembles that of Y_2O_3, while the $Y_2Si_2O_7$ more closely resembles SiO_2 powder. This would indicate that both the Y_2SiO_5 powder after reaching charge equilibrium in an aqueous environment has an yttria-like surface, and the $Y_2Si_2O_7$ powder has silica rich surface. Even though the IEPs vary from pH 3-6, these values still indicate the a cationic dispersant such as poly(ethylene imine) (PEI) could be used for both the Y_2SiO_5 and $Y_2Si_2O_7$ materials. Both a cationic and anionic dispersant such as poly(acrylic acid) (PAA) can be used in the mid pH range between 6-8. An anionic dispersant may be preferable for the Y_2SiO_5 if it truly does mimic an yttria surface.

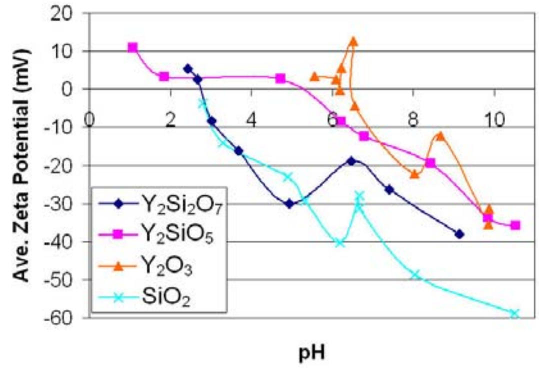

Figure 1. Zeta Potential as a function of pH for dilute Y_2SiO_5, $Y_2Si_2O_7$, Y_2O_3, and SiO_2 suspensions. The symbols reflect the average of ten individual measurements.

Sedimentation Study

In response to the mid range IEPs observed for the mono-silicate powder, a simple sedimentation study was completed for both the Y_2SiO_5 and $Y_2Si_2O_7$ materials to quickly evaluate the effectiveness of the dispersants with each material system. Dilute solutions with solids weight fraction of 0.01 were prepared by combining the appropriate amount of ceramic powder to deionized water and varying dispersants at a weight fraction concentration of 0.005 relative to the solids content. The dispersants used were PEI (Polysciences, Warrington, PA), PAA (Adrich, St. Louis, MO), WB4101 (Polymer Innovations, Vista, CA), AdvaFlow (W.R.Grace, Cambridge, MA), DS005 (Polymer Innovations, Vista, CA), and DS009 (Polymer Innovations, Vista, CA). The PEI species had an average molecular weight of 10,000 gm/mol. The PAA species had an average molecular weight of 450,000 gm/mol. The AdvaFlow dispersant is from the chemical family of carboxylated polyethers. WB4101 is a non-emulsion, water based binder solution, and the DS005 and DS009 systems are also water based polymer solutions. As the systems are proprietary to Polymer Innovations, the exact details and differences between the three systems are not known.

As indicated earlier by the IEP differences between the two ceramic powders, the results also differed. The experiments showed that WB4101 and the AdvaFlow dispersants kept the Y_2SiO_5 solids in solution for the longest time period whereas AdvaFlow and DS005 maintained the $Y_2Si_2O_7$ material suspension the longest. It was anticipated that the cationic dispersant PEI would be most effective for the $Y_2Si_2O_7$ material based on the earlier zeta potential measurements, however, that was not realized in this simple study. Since the behavior of Y_2SiO_5 powder most closely resembled the yttria powder, it was not unexpected that PEI was not the most effective dispersant for this powder. These results imply that WB4101 is an anionic dispersant, and DS005 is cationic.

Since electrostatic stabilization is an effective route for dispersion as well, and high purity acids or bases can be utilized, a second sedimentation experiment was completed using deionized water adjusted to pH 10 with ammonium hydroxide. To further define the behavior of the Y_2SiO_5 powder, pH stabilization at a high basic pH would confirm that an yttria rich surface does indeed exist. Dilute solutions with solids weight fraction of 0.01 were again prepared by combining the appropriate amount of ceramic powder to the pH 10 adjusted deionized water and varying dispersants at a weight fraction concentration of 0.005 relative to the solids content. The dispersants were limited in this study to the three dispersants identified as most effective in previous study: AdvaFlow, DS005 and WB4101. In addition, a condition using pH 10 adjusted water without additional dispersant was included. In this study the Y_2SiO_5 was best stabilized by the pH 10 water (no dispersant condition) and by pH10 with WB4101. All of the pH 10 adjusted water conditions with or without dispersant addition improved the slurry stability in the $Y_2Si_2O_7$. This simple result does indeed suggest that an yttria rich surface is present on the Y_2SiO_5 powder. The effectiveness of stabilization in basic conditions also confirms that the $Y_2Si_2O_7$ powder has a silica rich surface.

The sensitivity of these surfaces to changes in pH and additives is elucidated in these simple studies. The effect of ceramic powder and slurry additive concentration and additive molecular weight were ignored in this task due to the enormity of the effort and the limit of time afforded to this project. These results in no way imply that Y_2SiO_5 and $Y_2Si_2O_7$ are not candidate materials for use in EBC systems or that these materials can not be stabilized and developed into slurries suitable for dip coating. The changes in powder surfaces discussed in this report indicate how quickly a stable slurry can turn into a weakly flocculated structure which in turn will result in a porous final coating as previously reported.

Conclusions

Slurries were made from the Y_2SiO_5 and $Y_2Si_2O_7$ powders under varying slurry conditions such as pH and addition of selected slurry additives. The degree of stabilization of the Y_2SiO_5 and $Y_2Si_2O_7$ powders was controlled by their yttria or silica rich surfaces, respectively. Results indicate that slurry stability can be affected by additives due to charge changes or contamination. This is turn will affect coating microstructures. Not only is purity control critical to the implementation of a slurry-based EBC coating system, understanding the surfaces of the powders utilized in the slurry coating process is empirical to the control of the microstructure in any coating application.

Acknowledgements

The principal investigator would like to thank Kevin Cooley and Tamlin Matthews for all their hard work on this project.

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4.2.4 – Spark Plug Electrode Alloy Development+

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Objective

- Provide insight into the wear mechanisms of natural gas spark plug electrodes as a function of field exposure time and engine conditions.
- Increase the wear resistance of spark plug electrode materials to at least 1 year (or a 2X improvement) in advanced natural gas reciprocating engines designed to meet aggressive emission and efficiency goals.

Approach

- Characterize engine tested spark plugs to identify key erosion mechanisms and limitations of existing materials.
- Develop, engine test, and optimize new electrode materials for improved erosion resistance based on findings from the characterization effort.

Accomplishments

- Completed evaluation and characterization of several model chromia-forming alloys, with 25 wt.% Cr to favor exclusive (or at least near exclusive) chromia scale formation, with additions of 0.4 wt.% Si and 0.15 wt.% La (nominal) after 500h accelerated testing in a laboratory gasoline engine in collaboration with Federal Mogul. Similar alloys were also tested in natural gas engine. These results suggest that the laboratory-modified gasoline engine can provide useful insight into NG spark plug electrode erosion materials issues, and also suggest an inherent degree of susceptibility of currently used electrode materials to oxidation/cracking attack, independent of specific engine/ignition conditions.
- Completed evaluation and characterization of Cr-6MgO base developmental alloy and Haynes 214 after 400h accelerated laboratory engine testing in collaboration with Federal Mogul. Results showed that the surface of the Cr-6MgO insert was smooth, with little evidence of significant oxidation or loss of material, which suggested that the Cr-6MgO base alloy exhibited great potential as an alternative to Pt and Ir insert pad alloys.
- A milestone of "submit an open literature paper reporting on the engine test results of developmental spark plug electrode alloys" (due September 30, 2007) was successfully accomplished.

Future Directions

- Complete accelerated laboratory or natural gas engine testing for Ni-NbC-Y base electrode alloy alone and with precious metal or Cr-6MgO insert pads, is planned.
- Complete transfer of technology via open literature publication relaying understanding gained over the course of this project.

+For a detailed report, see Section 4.1.2, page 10.

Subtask 4.2.5 – Alloy Development and Optimization for Increased Corrosion Resistance in High Temperature Exhaust Gas Environments

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Objective

- Quantify the oxidation performance of alumina-forming austenitic alloys in order to assist in the development of materials for advanced microturbine recuperators capable of operating above 700°C for 40,000h.
- Develop an improved understanding of the role of water vapor on the accelerated corrosion of stainless steel foil including mechanistic and mathematical lifetime models.

Approach

- Study the corrosion behavior of model and commercial alloys in foil and sheet form in laboratory tests and compare to foil performance in the microturbine test facility
- Characterize the growth of reaction products and change in composition of the substrate alloy to quantify the rate of recuperator alloy degradation.

Accomplishments

- Demonstrated that first-generation alumina-forming austenitic steels have sufficient oxidation resistance to operate for 10-15kh at 700°and 800°C in simulated exhaust environments.
- Further confirmed the current gas transport evaporation model of $CrO_2(OH)_2$ by demonstrating a decreased Cr loss rate from alloy 709 foil in 17bar steam at 800°C compared to humid air.
- Demonstrated that boron alloy additions can inhibit the detrimental role of water vapor in ferritic and austenitic steels.

Future Direction

- Further develop and commercialize the current generation of alumina-forming austenitic alloys for recuperator and other high-temperature applications.
- Continue to study the mechanism of degradation in the presence of water vapor and further develop a predictive model for long-term performance of materials in recuperators.

Introduction

Higher engine temperatures are one strategy to increase the efficiency of current generation microturbines. However, increasing the temperature from <600°C to >650°C has been shown to result in a drastic loss in durability for conventional recuperators made from type 347 stainless steel foil (~75-100μm thick).[1] The problem has been attributed to the presence of water vapor in the exhaust gas and is now widely recognized. Engine manufacturers have switched to higher-alloyed steels such as alloy 120 (65kW microturbine by Capstone Turbine Corp.) or Ni-base alloy 625 (4.6kW Mercury 50 by Solar Turbines). A potentially less expensive alternative, Nb-stabilized Fe-20Cr-25Ni, is now commercially available in foil form from Allegheny Ludlum (AL20/25+Nb) for this application. The compositions of these alloys are given in Table I.

Further study of the degradation mechanism of chromia-forming alloys in the presence of water vapor suggested that the long-term Cr loss kinetics were linear due to the formation of $CrO_2(OH)_2$(g). A model was developed based on this evaporation reaction.[2] Linear kinetics, rather than parabolic kinetics typical of oxidation in air, limit the long-term durability of all chromia-forming alloys in this application. For example, Figure 1 shows Cr loss data for alloy 120 as a function of temperature in a laboratory test with air + 10vol.%H_2O. At 800°C, the Cr loss was less without the addition of water vapor. Extrapolating the laboratory-observed rates at 650° and 700°C to longer times suggests problems achieving >40kh lifetimes. A potential break-through solution for even higher temperature (750-800°C) recuperators was the development of an alumina-forming austenitic (AFA) alloy at ORNL.[3] By forming the more thermodynamically stable and slower growing Al_2O_3, this alloy class is less affected by the presence of water vapor. The goals of this project were to study this class of AFA alloys and continue to understand and predict the role of water vapor on the degradation of chromia-forming steels, particularly from engine exposures.

Table I. Alloy chemical compositions (weight %) and average grain sizes (μm) of the foil and sheet materials. (Balance Fe)

	Cr	Ni	Mn	Si	Other	Grain Size (μm)
Type 347	17.8	9.9	1.6	0.5	0.5Nb	5
709	20.3	24.7	1.0	0.4	1.5Mo,0.2Nb	16
AL20/25+Nb	20.3	25.4	1.1	0.3	1.5Mo,0.4Nb	n.d.
120	24.7	37.6	0.7	0.2		13,23*
625	23.1	63.8	0.04	0.2	8.9Mo, 4Nb, 3Fe	12
Fe-15/15+Al	15.1	15.8	4.8	0.2	3.8Al,4Cu,0.4Nb	30
Fe-14/16+Al	13.6	16.4	4.0	0.4	3.7Al,3Cu,0.3Nb	n.d.
Fe-14/20+Al	14.2	20.0	2.0	0.2	2.5Al,3Mo,0.9Nb	n.d.

* ORNL- and commercial-rolled foils, respectively

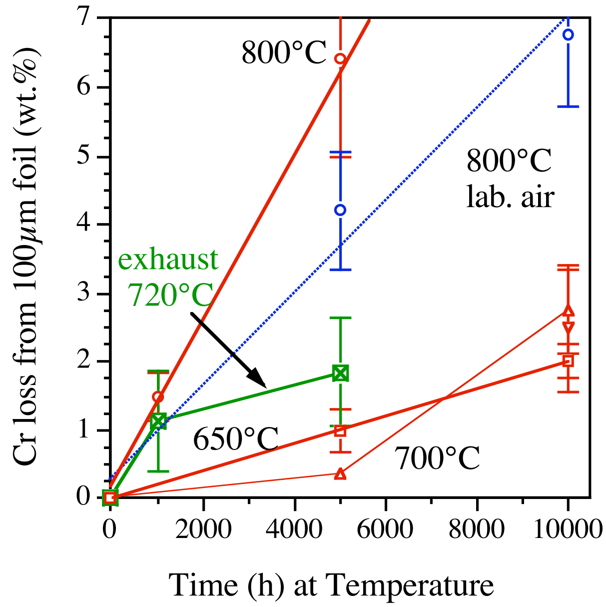

Figure 1. Chromium mass losses from alloy 120 foil specimens as a function of time after exposures to air + 10%H_2O (solid lines) at 650°-800°C and exhaust gas at 720°C. Values for 800°C exposures in laboratory air (dashed line) are shown for comparison.

Approach

Commercial foil specimens were obtained from alloy and engine manufacturers or rolled to foil from thicker starting materials and exposed in the as-rolled condition. Chemical compositions were measured by combustion and plasma analysis after casting, Table I. The oxidation tests were done in air + 10±1vol.% water vapor flowing at 850cc/min with 100h cycles at 650°, 700° and 800°C. Engine exposures were conducted in the ORNL microturbine test facility.[4] After oxidation, specimens were Cu-plated and sectioned for metallographic analysis and electron probe microanalysis (EPMA) to determine Cr depletion profiles.

Results

Alumina-Forming Austenitic Steels

Figure 2 summarizes the 750°C/100MPa creep rupture life of the various alumina-forming alloys, showing the tremendous improvement achieved when the Ni and Nb contents were optimized in the third generation, Fe-14Cr-20Ni-2.5Al-0.9Nb composition.[3] The alloy development on this generation is not yet complete so foil has not been made.

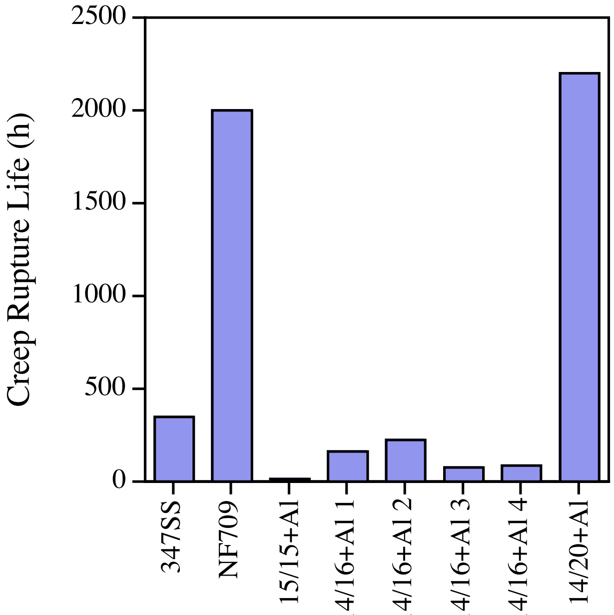

Figure 2. Creep rupture life (h) for various alloys in sheet form at 750°C and 100MPa. The AFA steels are listed with their Cr/Ni contents.

In order to assess the long-term behavior of this class of material in the presence of water vapor, first generation material, Fe-15Cr-15Ni-4Al, was characterized after 10 and 15kh laboratory exposures at 700° and 800°C in air + 10%H_2O.[5] Figure 3 shows cross-sections of the oxide formed after 10kh at 700° and 800°C. The oxide is thinner at the higher temperature because faster Al transport in the alloy allows a continuous alumina scale to form more quickly. In both cases, there is some Fe-, and Mn-rich nodule formation. Figure 4 shows an EPMA composition profile for the oxide formed at 800°C. Mainly Al is found in the surface oxide and there is no evidence of Al or Cr depletion in the underlying substrate. Thus, when an alumina scale forms on AFA alloys, very protective oxidation behavior is expected in this environment.

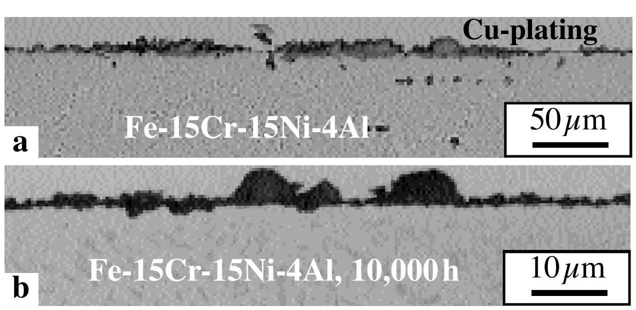

Figure 3. Light microscopy of a polished cross-section of Fe-15Cr-15Ni-4Al after 10,000h exposure in humid air at (a) 700°C and (b) 800°C.

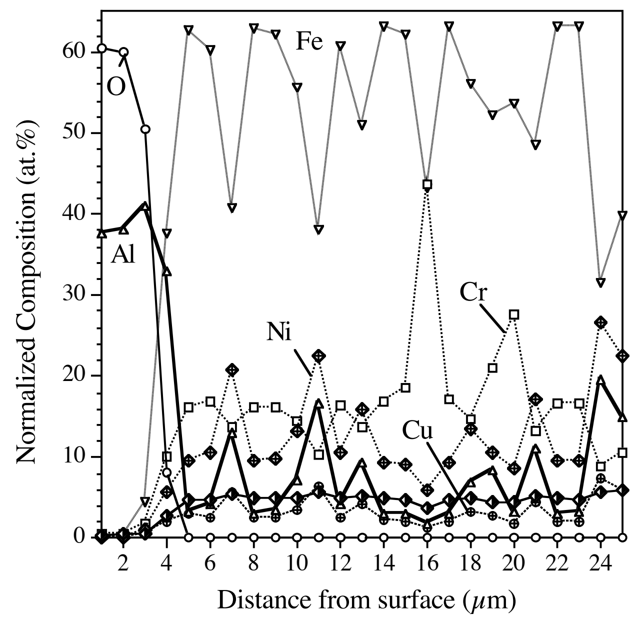

Figure 4. EPMA composition profile in Fe-15Cr-15Ni-4Al after 10,000h at 800°C in humid air. The outer scale was nearly pure alumina in this area and there was very little indication of Al or Cr depletion in the alloy.

Results from Engine Testing

Exposures in the ORNL microturbine facility have been performed under a separate task conducted by R. Trejo. Longer-term exposures were completed for alloy 120 (5,000h) and AL20/25+Nb (3,000h). The foil specimens were exposed to the microturbine exhaust and a hoop stress of ~50MPa also is applied using pressurized air.[4] The Cr depletion results for alloy 120 after exposure at 720°C are shown in Figure 1 with the laboratory humid air data. The rate of Cr loss is higher than at 700°C but the error bars are sufficiently high that it is difficult to assess the kinetics with only two data points. Additional exposures or more refined characterization is needed.

Laboratory Results

In order to test the predictions of the evaporation model, specimens of alloy 709 foil were exposed in 17bar steam for up to 4kh and the Cr loss measured. The model predicted that O_2 was needed to form the volatile $CrO_2(OH)_2$ phase. The experimental results in steam indicate a relatively low Cr loss in steam consistent with the model, Figure 5.

Finally, the effect of B additions was evaluated in Fe-Cr and Fe-Ni-Cr model alloys. Figure 6 shows results at 700°C for two sheet specimens of Fe-20Cr-20Ni-0.1B indicating some improvement in performance with B but no Mn or Si. While B alone may yield an imperfect benefit, it may be effective in

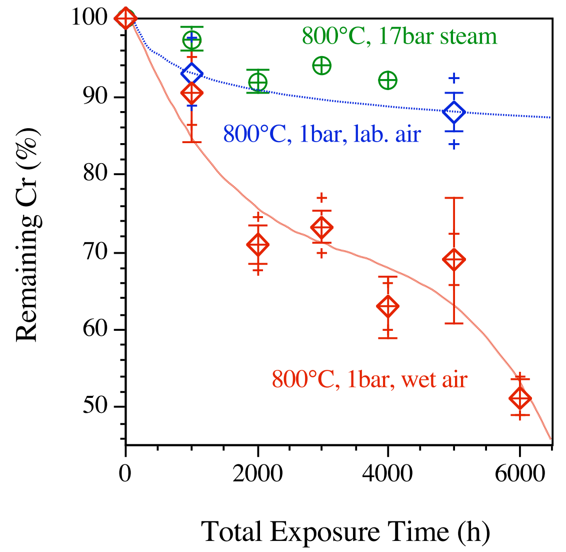

Figure 5. Specimen mass gains for various foil (80-100μm thick) materials during 100h cycles in humid air at 700°C.

conjunction with other additions.

Conclusions

Progress has been made in understanding and quantifying the effect of water vapor on the corrosion of commercial and laboratory-scale stainless steels at 650°-800°C. Alumina-forming steels show a significant opportunity for the development of recuperators with higher operating temperatures and longer lifetimes.

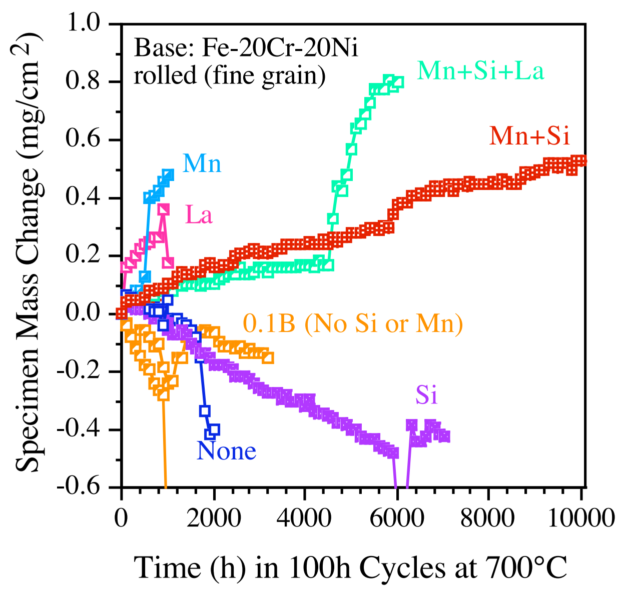

Figure 6. Specimen mass gains for Fe-20Cr-20Ni sheet specimens with various additions during 100h cycles in humid air at 700°C. The addition of B alone had a positive effect.

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FY 2007 Publications/Presentations

Y. Yamamoto, M. P. Brady, Z. P. Lu, P. J. Maziasz, C. T. Liu, B. A. Pint, K. L. More, H. M. Meyer and E. A. Payzant, "Creep-Resistant, Al_2O_3-Forming Austenitic Stainless Steels," Science, 316 (2007) 433-436.

B. A. Pint, J. P. Shingledecker, M. P. Brady and P. J. Maziasz, "Alumina-Forming Austenitic Alloys for Advanced Recuperators," ASME Paper #GT2007-27916, presented at the International Gas Turbine & Aeroengine Congress & Exhibition, Montreal, Canada, May 14-17, 2007.

B. A. Pint, "Design Strategies for New Oxidation-Resistant High Temperature Alloys," in W. Gao (ed.), New Developments in High Temperature Corrosion and Protection of Materials, Woodhead, Cambridge, UK, in press.

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M. P. Brady, Y. Yamamoto, M.L. Santella, and B.A. Pint, (2007) "Effects of Minor Alloy Additions and Oxidation Temperature on Protective Alumina Scale Formation in Creep-Resistant Austenitic Stainless Steels," Scripta Materialia, in press.

4.2.6 Materials Selection for Hostile Microturbine/Engine Environments

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Objectives

The project is to develop a unique facility at ORNL to evaluate the exhaust emission and assess the degradation of structural materials of turbines, reciprocating engines, and microturbines when conventional and nontraditional fuels are used.

- Measure the temperature and gas species at selected locations inside the turbine
- Evaluate materials degradation by placing coupons inside the turbine
- Measure the SOx, NOx, CO/CO_2, water vapor, etc in the exhaust
- Evaluate the degradation of candidate turbine/microturbine structural materials by exposing samples in an exhaust gas stream that is maintained at the desired test temperature and doped with toxic species or components that make the gas stream characteristic of the exhaust when nontraditional fuels are burned.

Approach

- ORNL Fuel-Flexible Turbine Environment Test Facility (FFTEF) is an upgrade of the Microturbine Recuperator Test Facility (MRTF), which is aging after four years of operation under vigorous conditions. In collaboration with Capstone Turbines, Inc., a new 65 kW microturbine was custom-built to have five sample ports with a removable aft dome.
- The Test Facility has two test chambers, i.e., 1) the main chamber: through four sample ports, samples can be tested inside a running microturbine; and 2) the environment chamber, which is a unique extension of the microturbine. A slip stream of the exhaust gas was diverted from an opening on the removable dome to a tubular chamber for testing more sample coupons in a controlled environment. Additional gaseous species can be added to the chamber to create an environment that simulates exhaust of nontraditional (“opportunity”) fuels.
- Gas sampling tubes and thermal couples were installed to monitor the gas emission from both the main chamber and environment chamber.

Accomplishments

- Construction of the environment chamber is finished, and in service for materials test in exhaust gas spiked with 50 ppm of SO_2.
- Long term exposure test of alloys at 5000 h and 3000 h was finished.
- Gas sampling unit is augmented to monitor both the main chamber and the environment chamber.

Future Direction

- This unique test facility is ready for long-term exposure test for next generation of high-temperature alloys.

Introduction

The objective of the project is to develop a unique rig at ORNL to evaluate the exhaust emission and assess the degradation of structural materials of turbines and microturbines when conventional and nontraditional fuels are used.

Conventionally, microturbines burn natural gas to generate electricity. With the recent increase in natural gas prices and the developing interest in using "green"/renewable fuels, many operators are considering the use of "opportunity fuels" to run turbines. Opportunity fuel is a loose term used to describe fuels generated from landfill, waste treatment, biomass, or other sources. These gases have many impurities which can accelerate degradation of turbine components and result in emission of undesired species into the atmosphere. Although there is considerable interest expressed in use of these "opportunity fuels", relatively little is known about the nature of the impurities, the potential effects of these impurities on the degradation of microturbine/turbine components, and the composition and properties of the exhaust gas.

Turbines operate more efficiently at higher temperatures. This puts a high demand on the durability of the components and parts. The ORNL Fuel-Flexible Turbine Environment Test (FFTET) Rig is designed to perform the following tasks for a given type of fuel:

- Measure the temperature and gas species at various locations inside the turbine
- Evaluate materials degradation by placing coupons inside the turbine
- Measure the SOx, NOx, CO/CO2, etc in the exhaust
- Evaluate the degradation of candidate turbine/microturbine structural materials by exposing samples in an exhaust gas stream that is heated to the desired test temperature and spiked with toxic species or components that may accelerate corrosion

The FFTET Rig is specially designed and will consist of three modules.

1. Microturbine specially modified for materials testing
2. Gas sampling and analysis unit
3. Test module for exposure of samples in a controlled temperature stream of spiked exhaust gas

Approach

In collaboration with Capstone Turbine Inc. in 2001, ORNL acquired a modified 60kw microturbine to construct the microturbine recuperator test facility (MRTF). By 2005, after running the microturbine at temperatures 165^{o}C higher than the stock models for eight thousand of hour, the microturbine was near the end of its service life [1]. Instead of simply replacing with a new engine, the Fuel-Flexible Turbine Environment Test (FFTET) Rig was constructed with added capabilities of gas sampling and a fully controlled environment chamber in which amount of gaseous spieces can be added to simulate exhaust gas of opportunity fuel or an accelerated corrosion environment. Fig. 1 presents a photo of the Rig, in which the environment chamber is wrapped in white heating tapes. The environment chamber can host four sample holders (shown in Fig. 2). Each can hold four pieces of coupons separated by ceramic spacers. Temperature of four holders decreases slightly as its location becomes further away from the aft dome, from 623^{o}C, 598^{o}C, 602^{o}C, down to 570^{o}C.

Results

The Gas Sampling Unit and Emission Data

The gas sampling unit can monitor the NO/NOx, $CO/CO_2/O_2$, SO_2, and hydrocarbon species. The exhaust gas is extracted from a gas sampling port, and then fed into three California Analytical Instruments (Orange, CA) analyzer and an Ametek Western Research Series 9000 Analyzer. The gas lines are wrapped in heating tapes and can be maintained at 190^{o}C. All of the units have both analog and digital outputs, can be accessed from a network, and have fully adjustable ranges. The gas sampling unit can alternatively monitor the emission from the main chamber and environment chamber. Currently it is set to switch between the two locations every 20 minutes.

Figure 1. The Test Rig with removable aft dome, five sample ports, (custom-built 65 kW microturbine), an environment chamber wrapped in white heating tapes, and equipped with gas analyzers.

Figure 2. Sample holder used in the environment chamber.

Plots of gas emission from the main chamber are presented in Fig. 3.

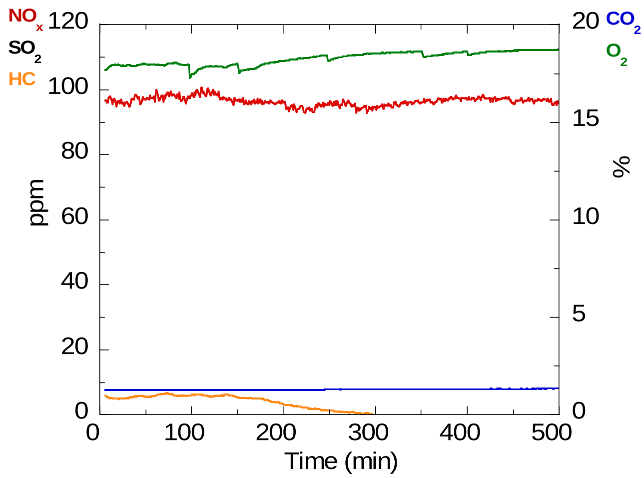

Fig. 3. Typical gas emission from the Microturbine (main chamber). No detectable SO_2 emission.

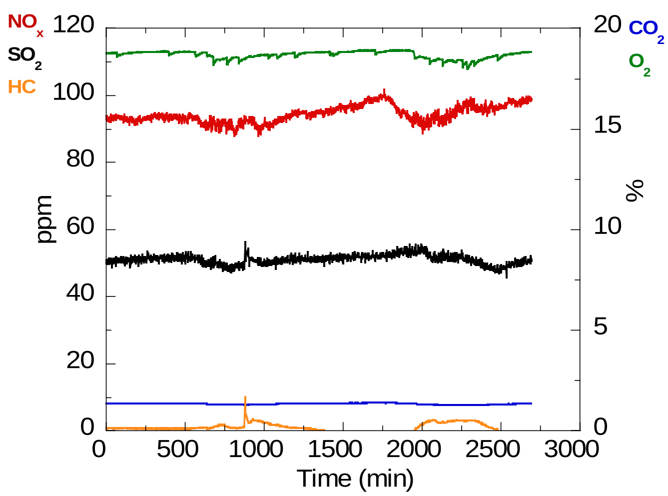

Fig. 4. Gas emission from the environment chamber. Note the SO_2 emission in black.

Materials Test Results

Materials that finished the long-term exposure tests inside the microturbine are listed in Table I. Materials being tested in the Environment Chamber are tabulated in Table II. All the samples listed in Table I have been removed from the holder. Mini tensile bars were machined and uniaxial tensile test was carried out. Scanning electron microscopy (SEM) was undertaken to evaluate the cross-sectional samples.

Table I. Material tested inside the microturbine (main chamber)

Material	Time (h)	Testing mode
2025-5mils	5000	Static
2025-3.2mils	3000	Static
2025-3.2mils	5000	Static
AL625	5000	Static
AL625-INTT	5000	Intermittent*

* The intermittent test lets a sample holder dwell inside the microturbine for 1 h and have it out for 1 h.

Table II. Materials Tested in Environment Chamber

Materials	Time (h)
HTUPS 4-3	500
HTUPS 12-2	500
FNC 31-2	500
SS347	500
HR120D	500
AL-625	500
AL-2025-3.2mils	500

Conclusions

Based upon the success of the MRTF, construction of the Fuel-Flexible Turbine Environment Test Rig was completed: 1) the custom-built C65 engine was in service for materials test; 2) construction of the environment chamber is finished and in service for materials test; 3) gas sampling unit was able to monitor the emission from the microturbine as well as the environment chamber. Early results have proven that the Test Rig has met all expectations. These test results will greatly facilitate the alloy development for many DOE's EERE programs.

References

1. Lara-Curzio E., Maziasz, P. J., Pint B. A., "Test Facility for Screening and Evaluating Candidates Materials for Advanced Microturbine Recuperators," ASME Technical Paper GT 2002-30581, 2002.

Acronyms

FFTEF-Fuel-Flexible Turbine Environment Test Facility

ORNL-Oak Ridge National Laboratory

MRTF-Microturbine Recuperator Test Facility

HC-hydrocarbon

DOE-Department of Energy

EERE-Energy Efficiency and Renewable Energy

4.2.7 - Siloxane Mitigation for NG Reciprocating Engines

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Objective

- Use thermochemical modeling to describe the formation of silica from representative landfill gas compositions
- Explore possible mitigation schemes for controlling or preventing silica formation without inlet gas cleanup

Approach

- Use FactSage thermochemical calculational package to compute equilibria under projected engine combustion conditions

Accomplishments

- A thermochemical database for combustion containing siloxanes was developed
- The parameter space of 500 K to 2200 K at 4, 35, and 75 bar was explored for stoichiometric and 150% stoichiometric air ratios
- In general, higher temperatures and pressures suppress silica formation, however, silica will inevitably form on engine components that are at more moderate temperatures

Introduction

Siloxanes are volatile silicon compounds formed in landfills as the result biological processes on silicone-containing products such as shampoos, silicone elastomers, toothpaste, among others. Combustion engines using landfill gas for fuel thus suffer from the formation of silica in the combustion environment which is abrasive to components and can severely limit life. Thermochemical modeling will be used to describe the formation of silica from representative landfill gas compositions. Areas of pressure-temperature-composition will be identified where silica will and will not form. The thermochemical model will then be used to explore possible mitigation schemes for controlling or preventing silica formation within the combustors without requiring inlet gas cleanup systems.

Approach

The FactSage® thermochemical calculational package will be used to compute equilibria under projected engine combustion conditions. Thermochemical data will be supplied by the accompanying SGTE database, supplemented with data from the literature. In particular, hydrated silica species are missing from the database yet accurately measured thermochemical values are available from recent published work.

Accomplishments

A thermochemical database for a combustor environment containing siloxanes was developed based on an assessment of gas compositions provided in the literature. Standard database thermochemical values were used as well as additional silicon-containing gaseous species data obtained from recent work on silicon carbide and nitride corrosion performed at NASA. A typical landfill gas gas composition was generated, including siloxane concentration, and used in thermochemical calculations. The parameter space 500-2200K at 5, 35 and 75 bar was explored for stoichiometric and 150% stoichiometric air ratios. Plots of major gas content and solid silica amounts were prepared showing the formation of silica under the various conditions. Figure 1 is an example of the calculated results showing the stability of SiO_2 at lower temperatures whereas above 1100-1200K all silicon species are in the gas phase. In general, higher temperatures and pressures serve to suppress silica formation, although it is apparent that at the more moderate component surface temperatures in engines that silica will inevitably form.

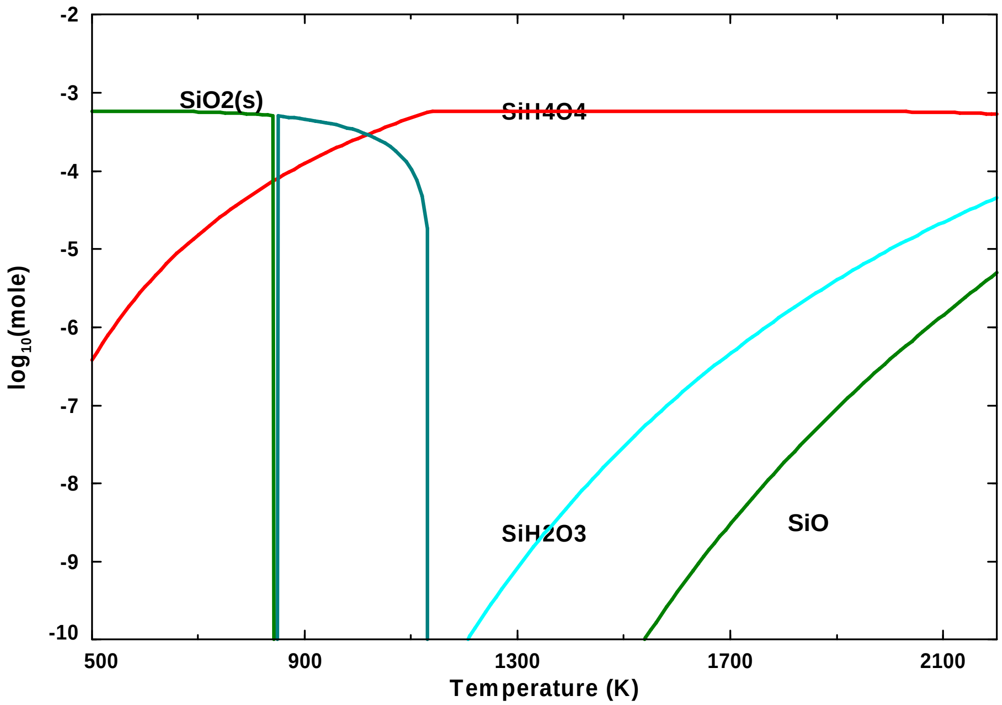

Fig. 1. Plot of the quantities of silica and gaseous silicon species computed at equilibrium from a representative landfill gas composition and stoichiometric air as a function of temperature at 75 bar.

4.2.8 - Advanced Materials for Reciprocating Engine Components

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Objectives

- Identify alloy/processing/coating options for improved NG engine exhaust valve capability and durability.

Approach

- ORNL and TRW conducted preliminary testing and characterization of coated specimens, screened for at 800°C in air + 10% water vapor to assess the potential of such alloy/coating combinations to enable commercial production of trial upgrade valves.
- Limited DOE funding caused Waukesha to initiate a Work-For-Others (WFO) project to extend the water vapor oxidation testing at 800°C to provide longer-term data to determine the benefits of such coatings for enhancing exhaust valve capability and reliability.

Accomplishments

- Oxidation tests begun in FY2006 indicated several coatings might have benefits after 500h, and very limited funding in FY2007 extended that data to 1000h before testing paused. Some coatings were clearly better than the others for imparting significant resistance to moisture-enhanced oxidation relative to bare Ni-based superalloy metal.
- Complete DE 2007 Milestone: Complete preliminary oxidation testing to identify best coatings for resistance to moisture enhanced oxidation. Evaluate the Ni-based alloys with best strength after aging. Recommend best alloy/coating combination for valve trial scale-up. (September 30, 2007). The initial part of this milestone was completed in Oct. 2006, after 1000h testing, and was the basis for Waukesha initiating the WFO project in March, 2007.

Future Directions

- Waukesha and TRW will continue to work together and privately fund commercial scale-up work that follows the WFO ORNL/Waukesha project.

Introduction

Higher power density and efficiency, and lower emissions demand higher in-cylinder pressures and temperatures for NG reciprocating engines. Such conditions can shorten the lifetime and cause failures of critical components, like exhaust valves. In 2006, TRW-Automotive, Waukesha Engine-Dresser, and ORNL engaged in a collaborative project to address the potential to create exhaust valves with more reliability and higher temperature limits through manipulating valve design, applying coatings, and optimizing processing for Ni-based superalloy strength at high temperatures. Limited funding curtailed activities, but funding was provided in FY2007 to finish the coatings portion of these efforts.

Approach

Aging of various commercial Ni-based superalloys used for exhaust valves at 1400°F and above to 5000h was completed. TRW began tensile testing of those aged materials after 1000h last quarter. Oxidation testing at in 10% water vapor at 800°C to 1000h was completed earlier in FY2007, for discs of bare metal and with various commercial oxidation-resistant coatings. Waukesha Engine, Dresser, started and funded a Work-for-Others proprietary project at ORNL to extend the oxidation testing of coated specimens, and to complete the tensile testing of materials aged for 5000h at 1400°F and above, which is currently in-progress and has been extended.

Results

All tensile properties measurements on unaged superalloy specimens in various as-processed conditions was completed previously. All aging at ORNL of various Ni-based superalloys rods processed and heat-treated to represent the condition of valves to 5000h at temperatures of 1400°F and above were completed earlier this year, and all aged materials were sent to TRW for mechanical testing. TRW began mechanical testing of materials aged for 1000h last quarter.

ORNL began oxidation testing of disks of several different Ni-based superalloys with a variety of commercial coatings at 800°C in air + 10% water vapor began at the end of FY2006, and continued into FY2007, until funding was exhausted. One particular coating showed promising resistance to water-vapor enhanced oxidation after 1000h exposure, relative to bare metal. The oxidation testing was restarted later in FY2007 and continued under a WFO project funded by Waukesha Engine, Dresser at ORNL.

References
None

FY2007 Awards/Patents
None

FY 2007 Publications/Presentations
None

Acronyms

WED – Waukesha Engine - Dresser

ORNL – Oak Ridge National Laboratory

TRW – TRW Automotive

4.3.2a,b – DG Thermal Recovery and Integration Research at University of Maryland

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Objective

- The objective of the Integrated Energy Systems Program is to assist with development and deployment of highly efficient Combined, Cooling, Heating and Power Systems. IES focuses on technologies that have broad utilization potential such as cooling, dehumidification, humidification, water heating, steam heating, drying, and shaft power from heat energy. Key program elements are packaged/modular IES development, DG thermal recovery research, IES field evaluations and end-use integration, and analytical tools/validation.

Approach

- ORNL provides in-house research in support of the industrial subcontracts. The thrust of the ORNL research has been to integrate components into systems. ORNL works with the University of Maryland to integrate systems into Buildings. ORNL also develops and maintains screening tools, provides analytical support, and provides technical guidance to our industrial partners.

Accomplishments

- The close-out plan for the University of Maryland project was drafted and the ORNL subcontract was modified to include the close-out activities.
- The draft research report for calendar year 2006 was completed.

Future Direction

- This is the final funding year for this program. No future work is being planned under the Office of Electricity.
- Planning on future research directions is being completed with industry and with the Office of Energy Efficiency and Renewable Energy.

Introduction

The objectives of the integration research being conducted at ORNL and at the University of Maryland are:

- Demonstrate the benefits of integrated CHP systems in commercial building applications
- Identify and help resolve problems that occur when combining different components into an integrated system
- Identify, develop and demonstrate system improvements
- Provide educational opportunities

This project will be completed in 2007, with the following work activities:

- Completion of testing of the newly designed low-flow conditioner components for liquid desiccant dehumidifier [work to be done in partnership with NREL]
- Completion of testing of the newly installed Broad absorption chiller with internal cooling tower
- Development of course material on absorption chiller systems operation and integration into CHP Systems for Buildings

Approach

ORNL works closely with the project team at the University of Maryland to analyze system data, to prepare presentations on test results and lessons learned, to write peer-reviewed technical papers, to provide project updates to DOE, to update the U of M website, and to find opportunities to disseminate lessons learned to the public. ORNL will facilitate cooperation and test plan development with other DOE national labs.

Results

Testing of the prototype low-flow conditioner liquid desiccant system, developed by AIL in conjunction with NREL, was completed last fall. Under similar outdoor air conditions, the prototype AIL low-flow conditioner has comparable performance with the original Kathabar conditioner. The outdoor air humidity ratio has considerable effect on AIL conditioner performance. With 75kW engine load, when humidity ratio increases 25%, dehumidification level increases 30% and total cooling capacity increases by 12%. The effect of outdoor air temperature also could not be ignored. With a 50kW engine load, when humidity ratio decreases 4% and temperature increases 7.6%, dehumidification level increases 12% and total cooling capacity increases 40%.

A final report, including lessons learned, has been drafted and is undergoing final review.

Conclusions and Recommendations

The project partnership between ORNL and the University of Maryland has been successful. The project receives high marks at the peer review meetings sponsored by DOE.

4.3.2c.d – DE Integration Lab and Analysis

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Objective

- Oak Ridge National Laboratory (ORNL) investigates emerging technologies, identifies R&D opportunities and, in consultation with the Department of Energy (DOE) Program Manager, selects the technologies to be developed and conducts supporting in-house research.

Approach

- ORNL played a key role in the development and technical transfer of this unit by providing testing and analysis of components/system in the ORNL Thermally-Activated Heat Pump (TAHP) environmental chambers and by providing design recommendations and control strategies for future designs.

Accomplishments

- Final report on the performance of GEDAC #16 was submitted to our industry partners Southwest Gas, Team Consulting LLC, and Blue Mountain Energy.
- A draft manuscript on the performance of GEDAC #16 has been prepared for submission to the 2008 ASHRAE Summer Meeting (peer reviewed transaction).
- 2007 Energy Solutions Center (ESC) Partnership Award For Innovative Energy Solutions for the GEDAC (gas-engine driven heat pump rooftop unit) working with our industry partners Southwest gas, Team Consulting, and Blue Mountain Energy.

Future Direction

- Next generation unit (GEDAC #23 with R410A as the refrigerant) has been modified based on the results of the performance evaluation of GEDAC #16 particularly the demand defrost method. This unit is currently under evaluation in the ORNL TAHP Environmental Chambers.

Introduction

Thermally activated technologies (TATs) can be directly fired or operated using waste heat in combined heat and power applications. TATs have a long history and have seen generations of service both in direct-fired systems (where fossil fuels are used directly) to produce chilled water for air conditioning or in refrigeration and dehumidification as well as in equipment using steam or hot water to provide these services. Further advances in efficiency, size, and cost will result in greater use of TATs and in progress toward national energy and environmental goals. This is particularly true in the development of TATs that are powered by recovered waste heat.

TATs represent a diverse portfolio of equipment that uses heat for heating, cooling, humidity control, thermal storage, or shaft/electrical power. TATs are the essential building blocks for integrated energy systems (IES) that can help maximize energy savings and economic return. Thermally activated systems also offer customers reduced seasonal peak electric demand and enable future electric and gas grids to operate with more level loads.

DOE's TAT development activities in recent years have focused primarily on absorption technology and desiccant technology. Desiccant equipment has been successfully applied for many years in industrial applications or where humidity control is critical. New desiccant technology is being adapted to meet the emerging comfort and indoor environmental quality needs of commercial and institutional buildings. It is expected that, in the next 1-3 years, U.S. industries will begin commercialization of a natural gas-fired small commercial absorption chiller and residential heat pump now under development as part of this program. DOE and ORNL are cooperating in a national partnership to support final product development and commercialization.

In Japan, many hundreds of thousands of small natural gas-driven heat pumps have been sold (typically 50,000 to 80,000 annually). Although very reliable and energy efficient, the Japanese products are not suited for normal U.S. commercial applications and are not suitable for typical U.S. high temperature applications.

Approach

This activity is to start with the basic technology used in the best Japanese gas-driven heat pumps (the engine) and develop gas-engine driven heat pumps suitable for U.S. drop-in commercial rooftop applications (by far the single largest product segment). Initial evaluations include:

- baseline (emissions, efficiency, and fuel consumption)
- development of several heat transfer components for U.S. applications
- vibration and noise (minimize in design)
- engine intake and exhaust system
- controls (fuel/engine management and complete heat pump system controls)
- parasitic load reduction (starting system and transformer)
- development of single packaged rooftop configurations.

Evaluation of the "next generation" packaged gas-fired heat pump rooftop unit (GEDAC #16) was conducted at the ORNL Thermally Activated Heat Pump (TAHP) Environmental Chambers. Significance of ORNL work: (1) private industry partner did not have access to a suitable psychrometric chamber for the evaluation of performance and emissions and (2) ORNL has years of experience working with the chemical industry in developing and testing alternative refrigerants, modify the prototype at ORNL, and evaluate the modified prototype.

Results

Evaluation of an integrated 10-ton gas-driven heat pump unit (GEDAC #16 rooftop unit) was conducted in the ORNL TAHP Environmental Chambers. Previous results from the ORNL evaluation were used by industry partner in developing this "next generation" integrated packaged system (GEDAC #16). The packaged unit was installed in the larger room (outdoor chamber with 15 ft by 18 ft footprint) with supply/return air from the smaller room (indoor chamber with 15 ft by 12 ft footprint). Figure 4.3.2c.d.1 shows GEDAC #16 in the ORNL TAHP Environmental Chambers. This unit was operated over a wide range of ambient conditions including the operating conditions for standard rating and performance tests [1-3]. Table 4.3.2c.d.1 shows these operating conditions. It should be noted that the evaluations were conducted at high and intermediate speeds of the engine.

Figure.1. GEDAC #16 in the ORNL TAHP Environmental Chambers

More than one hundred cooling and heating tests were conducted on GEDAC #16 at various ambient conditions in a controlled environment (TAHP Environmental Chambers). These included cooling tests up to 125ºF and heating tests down to 17ºF. The cooling mode was conducted in the range of 67ºF to 120ºF at intermediate speed of 1900 rpm and 67ºF to 120ºF at high speed of 2250 rpm. The heating mode was conducted in the range of 17ºF to 62ºF at intermediate speed 1900 rpm and 17ºF to 47ºF at high speed of 2250 rpm. The data was available on the web via password protected Web Control and Automated Logic Controller (ALC). In addition, a web camera was installed to monitor the frosting pattern on the outdoor coil of this unit. Both of these devices have been proven successful for remote monitoring.

Performance GEDAC #16 with 3 Row Indoor Coil

GEDAC #16 was initially evaluated in heating and cooling modes with the original indoor coil (3 row design). Results showed a gas Heating COP of 1.63 at 47ºF rating condition with capacity of 142,584 Btu/h at high speed of 2250 rpm. Gas cooling COP of 1.14 and capacity of 112,896 Btu/h (9.4 RT) were obtained at high speed and 95ºF rating condition which is slightly below the COP goal of 1.2 with capacity of 120,000 Btu/h (10 RT).

Performance GEDAC #16 with 4 Row Indoor Coil

The original indoor coil (3 row design) was replaced with a modified design (4 row design) to improve the performance of the GEDAC #16. This change resulted in an increase in the capacity (heating mode) at 47ºF rating condition. The capacity increased by approximately 14% to more than 160,000 Btu/h at high speed. The gas COP at 47ºF rating condition exceeded the goal of 1.6 at both high and intermediate speeds.

The cooling capacity at 95ºF rating condition was also increased by approximately 4% at high speed (from 112,896 to 118,322 Btu/h) and 8% at intermediate speed (from 101,818 to 109,760 Btu/h). Gas COP in cooling mode also exceeded the goal of 1.2 (1.22 at high speed and 1.41 at intermediate speed) at 95ºF rating condition.

Performance of GEDAC #16 with Single Fan

Computational Fluid Dynamics (CFD) modeling results showed a decrease of approximately 4% in capacity and 5% in air flow (potential energy savings) by using a single fan instead of two fans. Figure 4.3.2c.d.2 shows the air flow and heat transfer results of the CFD modeling. Based on the results of the CFD modeling that showed potential energy savings by using one fan instead of the two fans for the outdoor coil, the two outdoor fans of GEDAC #16 were replaced with a single fan. These evaluations have also been completed in both cooling and heating modes. Results showed no significant difference in the performance (Figures 4.3.2c.d.3 and 4.3.2c.d.4) and the total power used by the GEDAC unit (Figures 4.3.2c.d.5 and 4.3.2c.d.6). Therefore the design selection criteria should include initial cost, redundancy provided by having a second fan, and better staging capability provided by two smaller fans during part-load operation.

Evaluation of the Defrost Cycle

Defrost cycle was also evaluated at 35ºF outdoor dry-bulb (DB) temperatures. GEDAC is currently using time cycle for the defrost cycle. Results suggest that this timed defrost may cause a number of unnecessary defrost cycles which reduces the energy efficiency of GEDAC #16. The plans are to investigate a demand defrost method. Demand defrost method could be easily integrated into a Programmable Logic Controller (PLC).

Conclusions and Recommendations

Overall GEDAC #16 unit produced the desired results in both heating and cooling modes of operation particularly with the 4 row design of the indoor coil. The gas COP at 47ºF rating condition exceeded the goal of 1.6 at both high and intermediate speeds. Gas COP in cooling mode also exceeded the goal of 1.2 at 95ºF rating condition. The next unit (GEDAC #23 with R410A as the refrigerant) has been modified based on the results of this study particularly the demand defrost method. This unit is currently under evaluation in the ORNL TAHP Environmental Chambers.

Results confirmed the CFD modeling which showed no significant difference between two fans versus a single fan for the outdoor coil. Therefore the final design decision was made to proceed with two fans based on the initial cost, capability to provide redundancy, and better staging capability for part load operation.

REFERENCES

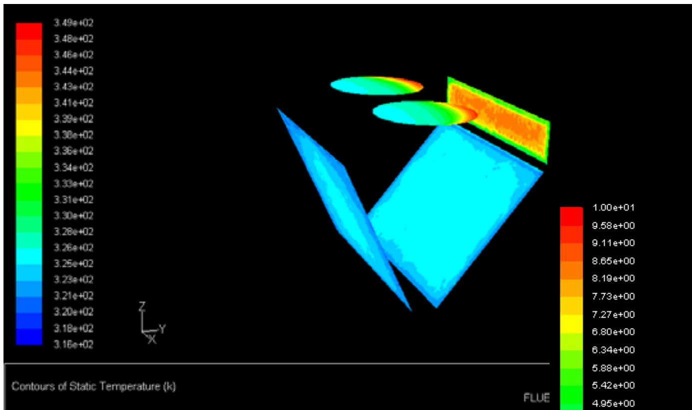
1. ANSI/ARI 210/240-94 Standard, “Unitary Air-Conditioning and Air-Source Heat Pump Equipment”, 1998.
2. ANSI/ASHRAE Standard 40-2002, “Methods of Testing for Rating Heat-Operated Unitary Air-Conditioning and Heat Pump Equipment”, 2002.
3. ANSI Z21.40.4a-1998 and CGA 2.94a-M98 Standard, “Performance Testing and Rating of Gas-Fired, Air-Conditioning and Heat Pump Appliances”, 1998.

Table 1. Operating conditions for evaluation of GEDAC #16

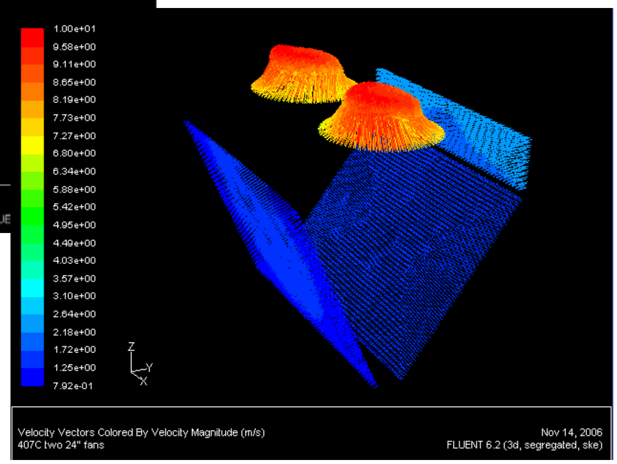
Test	INDOOR UNIT			OUTDOOR UNIT		
	Air Entering			Air Entering		
	DB (°F)	DP (°F)	WB (°F)	DB (°F)	DP (°F)	WB (°F)
COOLING TESTS						
Standard Rating Conditions "A" Cooling Steady State*	80	60.2	67	95	66.5	75**
"B" Cooling Steady State*	80	60.2	67	82	55	65**
"C" Cooling Steady State Dry Coil*	80	36.8	57***	82	55	65**
Low Temperature Operation Cooling*	67	49.8	57	67	49.8	57**
Maximum Operating Cooling Conditions*	80	60.2	67	115	55	75**
High Ambient Temperature	80	60.2	67	110	58.2	75**
Higher Ambient Temperature	80	60.2	67	120	51.3	75**
Highest Ambient Temperature	80	60.2	67	125	47.1	75**
HEATING TESTS						
Standard Rating Conditions High Temperature Heating Steady State*	70	53.5	60 (max)	47	38.7	43
High Temperature Heating Cyclic*	70	53.5	60 (max)	47	38.7	43
High Temperature Heating Steady State*	70	53.5	60 (max)	62	52.7	56.5
Low Temperature Heating Steady State*	70	53.5	60 (max)	17	9.4	15
Maximum Operating Conditions*	80			75	59.5	65

* Operating Conditions for Standard Rating and Performance Tests [1-3].
** Wet bulb temperature (WB) condition is not required
*** Wet bulb sufficiently low that no condensate forms on evaporator
Note: DB is the dry-bulb temperature and DP is the dew-point temperature.

Twin 24 Inch Axial Fans

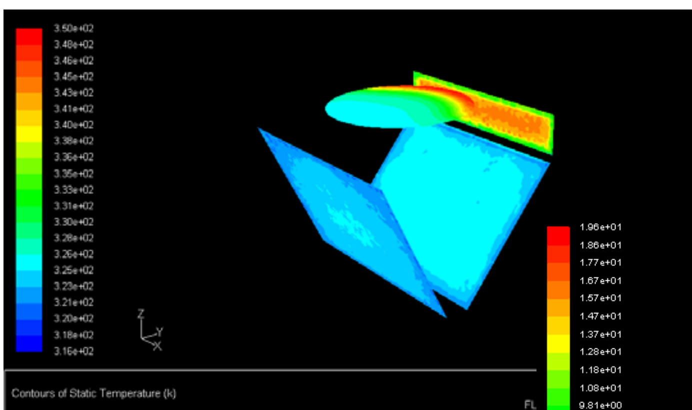


Heat Transfer Analysis

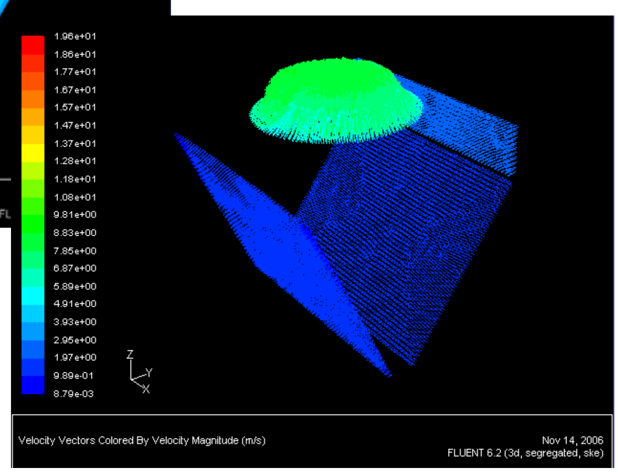


Air Flow Analysis

Single 36 Inch Axial Fan



Heat Transfer Analysis



Air Flow Analysis

Figure 2. CFD Results – Single vs Two Outdoor Fans

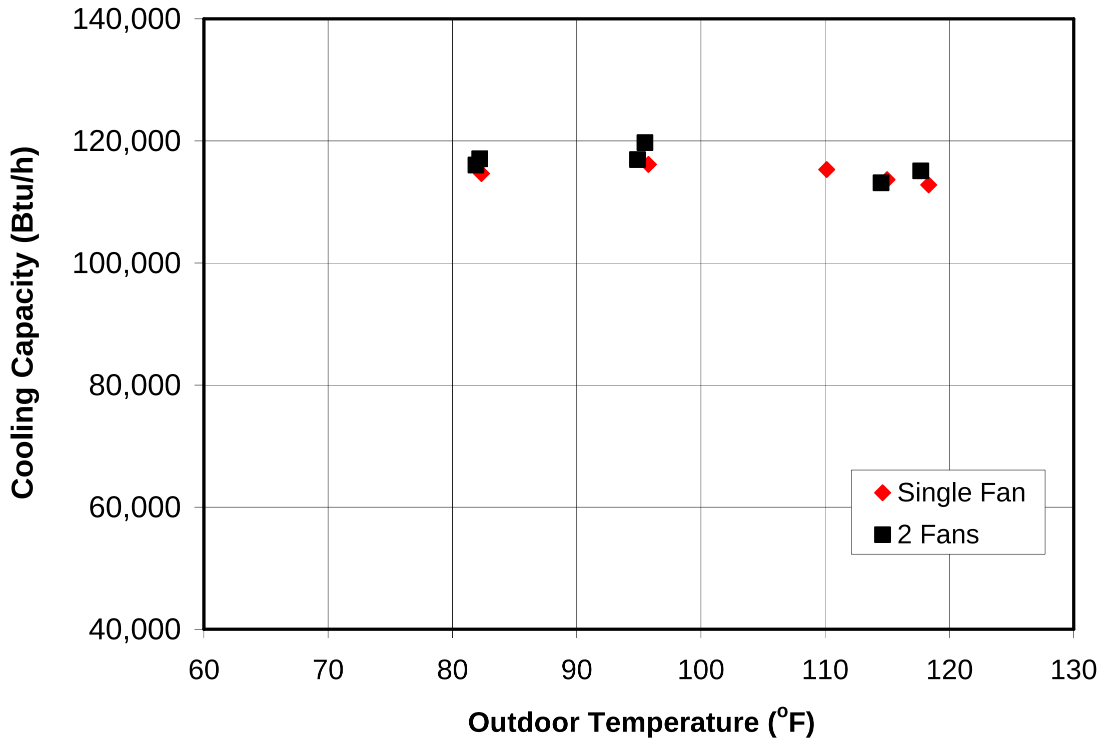


Figure 3. Comparison of Cooling Capacity – Single vs Two Outdoor Fans in Cooling Mode at High Speed

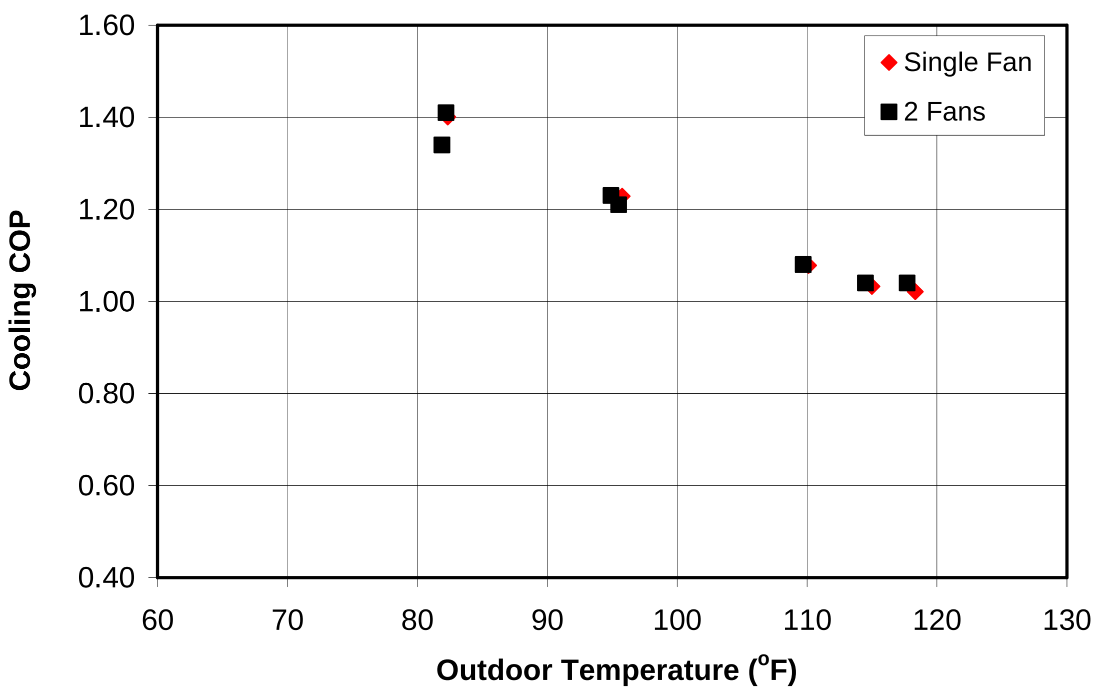


Figure 4. Comparison of Cooling COP – Single vs Two Outdoor Fans in Cooling Mode at High Speed

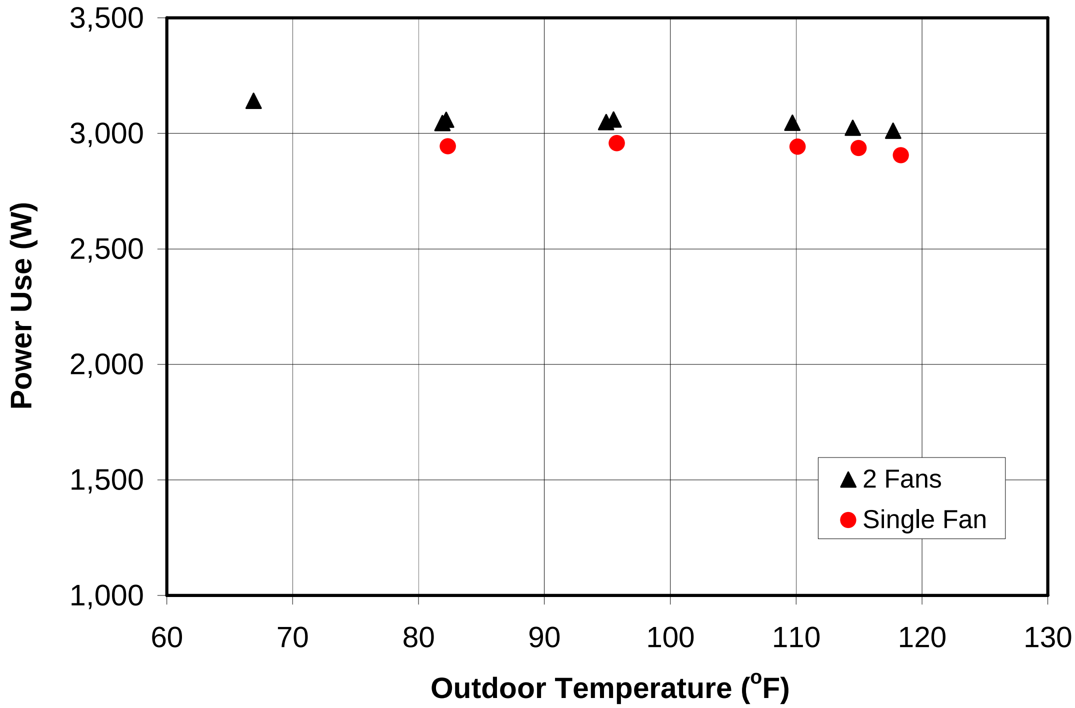


Figure 5. Comparison of Total Power Use – Single vs Two Outdoor Fans in Cooling Mode at High Speed

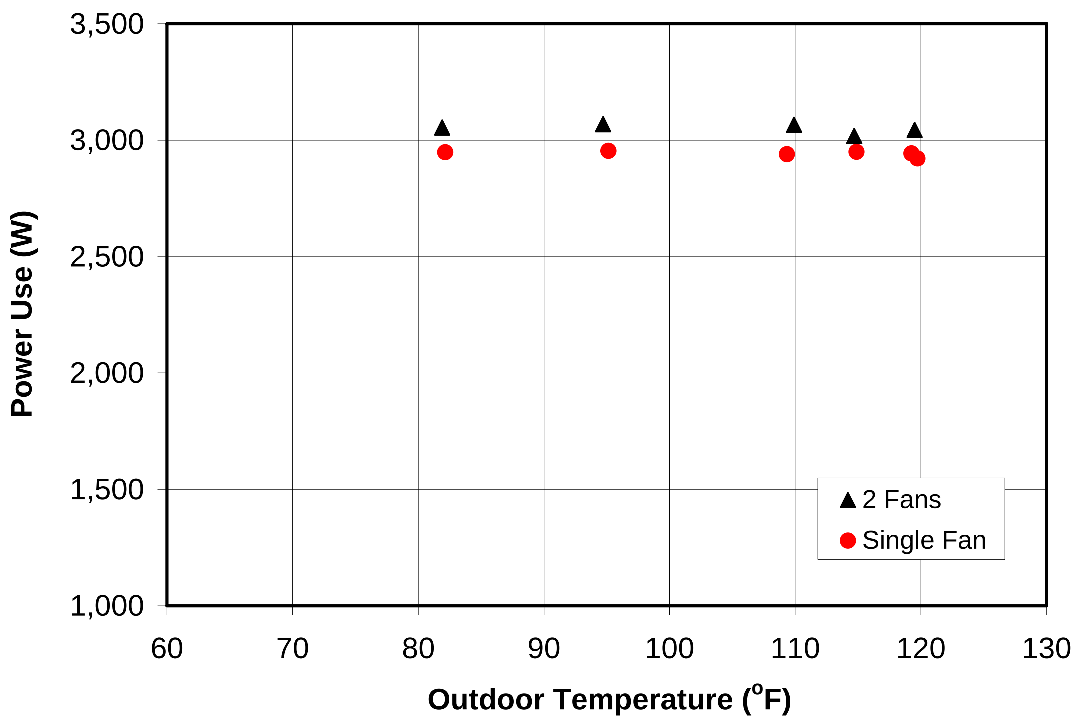


Figure.6. Comparison of Total Power Use – Single vs Two Outdoor Fans in Cooling Mode at Intermediate Speed

4.3.3 - CHP Economics/Modeling

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Objective

- Develop and improve project engineering / economic modeling tools, currently the BCHP Screening Tool and the HUD CHP Screening Tool.
- Demonstrate the use of the tools to potential users.
- Develop user manuals and provide user support as needed.

Approach

- Computerized, quick-to-use tools.
- Simplified, helpful user interfaces.
- Advanced engineering modeling and economic calculations.
- Extensive output capabilities to allow improved reporting abilities for users.

Accomplishments:

Historical for Reference

- ORNL obtained licensing rights for unlimited distribution of DoeRayMe of GARD Analytics (as long as it is free), the most advanced building energy technology screening tool engine and the technology foundation for the BCHP Screening tool.
- DoeRayMe had significant enhancements made to develop the first-generation BCHP Screening Tool (version 1.2).
- Major enhancements to the BCHP tool were made by ORNL (version 2.0).
- ORNL developed the HUD CHP tool, a simpler CHP screening tool for multifamily housing

FY 2007

- A draft User Manual for the BCHP Screening Tool was completed for Version 2.0.
- This tool was downloaded approaching 3,000 times in FY 2007.
- A version 2.1 of the BCHP tool has been developed for testing, but resources for completion are uncertain.
- Four minor updates of the HUD CHP tool were completed to increase reporting capabilities and fix some minor problems (Versions 2a, 2b, 2c, and 2d), in response to HUD testing and requests.
- The HUD tool revisions this year have been downloaded 50–100 times since late May 2007.
- Technical support continues to be provided to HUD on use of the HUD tool.
- No support requests on the BCHP Screening Tool were received.

Future Direction

- Review the DRAFT BCHP Screening Tool Manual for Version 2.0 and finalize.
- Fix some remaining technical issues in the HUD CHP tool.

- Add the capability to analyze all-electric multifamily buildings to the HUD tool if resources allow.
- Continue to provide technical support on the HUD and BCHP Screening tools.
- Evaluate whether resources can be found to finalize Version 2.1 of the BCHP tool.
- Conduct training sessions on use of the BCHP tool under other programs as resources are found.

Introduction

The BCHP Screening Tool is a computer program for assessing the economic potential of combined cooling, heating, and power (CHP) systems for commercial buildings. It was developed under Department of Energy funding by a collaborative effort between GARD Analytics of Park Ridge, Illinois and Oak Ridge National Laboratory in Oak Ridge, Tennessee. GARD Analytics delivered a fully-functional version of the program in October 2003 which has subsequently been modified by ORNL to incorporate graphical interfaces for data input and output.

Version 1.2 of the BCHP Screening Tool was developed based on the DoeRayMe program of GARD Analytics and was an extensive enhancement of DoeRayMe. The DoeRayMe technology is distributed by Oak Ridge National Laboratory (ORNL) free of charge under license from GARD Analytics. DoeRayMe is a one-of-a-kind piece of software developed to make significant improvements to the user interface and screening analysis capabilities for building energy measure parametric calculations.

The BCHP Screening Tool is structured to perform parametric analyses between a baseline building, typically a conventional building without a CHP system, and up to 25 alternative scenarios with varying selections for building mechanical systems and operating schedules.

The BCHP Screening Tool consists of the executable program, databases for HVAC equipment, electric generators, thermal storage systems, prototypical commercial buildings, climate data, and electric and gas utility rates. The program runs DOE2.1e in the background to calculate heating, cooling, and electrical loads and the Rate Script Editor to calculate monthly and annual utility costs.

With the 70 separate groups of displayed results, a lot of results information is available. Hourly data over a year are also generated. The program also generates a schematic of energy flows for each scenario, displayed one at a time. All US TMY2 weather files are available.

The HUD CHP tool is a much simpler tool that makes quick calculations based on empirical analyses of utility data to provide almost instant results on approximate payback potential of some CHP configurations in multifamily buildings.

Accomplishments and Progress

One major effort this year was completion of a DRAFT user manual for version 2.0 of the BCHP Screening tool (129 pages).

In addition, four minor updates to the HUD CHP tool were completed in response to HUD requests and user testing.

Technical support was provided to HUD as requested. No support requests were received on the BCHP Screener.

Significant additional development on the BCHP tool has led to completion of a test version 2.1, but completion remains uncertain due to resource constraints.

Project Publications

1. The DRAFT User Manual for Version 2.0 of the BCHP tool is the only publication of note at this time.

Presentations

No presentations were made in FY 2007, but presentations are expected to be made under other programs in FY 2008 on the BCHP tool.

Presentations on the HUD tool in FY 2008 are uncertain due to resource constraints at this time.

Previous presentations were on earlier versions of the tools and are no longer applicable.

4.3.8 – Industry Collaboration, Crosscutting Activities

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Objective

- ORNL will monitor the progress of the various CHP projects and provide technical direction to the subcontractors.
- ORNL will facilitate dialogue with industry stakeholders to encourage the consideration and use of DE in high-tech applications.
- ORNL will continue to work with existing CHP design and evaluation software tools and will work with stakeholders to ensure their awareness of the tools and to assist in their use.
- ORNL will continue to assist DOE with participation at crosscutting conferences and events.

Approach

As the tasks progress, lessons learned and technical results with be compiled and disseminated to the stakeholder community. Barriers to application of DE/CHP will be identified with the intent of reducing or removing them.

Accomplishments

- A brainstorming session to capture novel concept ideas for moisture management and specifically solid desiccant systems was completed.
- Chiller testing has been completed and the unit is in route to UTRC for integration into UTRC's CHP test facility.
- A system level feasibility demonstration to characterize and quantify performance and reliability of the integrated reciprocating engine and hybrid absorption chiller CHP system selected for development has been performed.

Future Direction

- The initial business case for desiccant systems identifies integration with roof top units as being a possible product play for the future.
- Another application benefiting from this technology would be buildings that are located in climates requiring daytime cooling and nighttime heating.
- Project Review Meeting planned at UTRC for November 28, 2007.

4.3.13 – Research Survey/History of DOE Programs

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Objective

- Over the last few decades, DOE has provided considerable funding in support of development of technologies for improving energy efficiency. There have been several technical analyses completed on potential for energy savings in a variety of technology applications. Although documentation on previous work activities has been completed, it can be difficult to find the relevant work because of passing time or lack of a centralized reference list. A public searchable database was developed to assist in the recollection of previously funded projects.

Approach

- In 2006, ORNL created a database that contains over 300 reports. In 2007, the following activities were completed: an additional 75+ reports on ORNL BCHP work were included, enhanced search capabilities were added, and copyright questions were resolved.

Accomplishments

- The DOE Historical Reports Database was completed. It contains over 500 DOE research reports from 1974-2006 on electrically driven heat pumps, thermally-activated technologies, advanced appliance research, distributed energy and CHP, district heating, and a few lesser categories. The database can be found at:

http://www.ornl.gov/sci/engineering_science_technology/eere_research_reports/index.html

- Each publication represented in this on-line database has a copy of its abstract, a link to read or download an Adobe Acrobat PDF file containing the full text (except for copyrighted material), a list of key words for each document, and in many cases the full reference material needed to locate hardcopies of reports or reprints of copyrighted conference papers. All of the key words used in the website have been accumulated into an extensive key word index in lieu of incorporating a web site search function. Consequently users do not need to have Javascript enabled on their computers and the database lacks any internal "programming" and is not encumbered by browser security checks.

4.4.1a – 4.4.1b - Distributed Energy Systems Applications Integration

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Objective
One of the missions of the Distributed Energy Program is to lead a national effort to integrate DE technologies at end-user sites and to document and disseminate the findings of those efforts. Strategies to accomplish that mission include:

- Investment in a diverse portfolio of RD&D projects across complementary technologies: prime movers, thermally activated technologies, and CHP systems,
- Performance of systems integration, implementation, and outreach activities aimed at addressing infrastructure, institutional, and regulatory needs, and
- The establishment of collaborative technology transfer partnerships, including cost-shared RD&D projects.

Over the last four years, a balanced portfolio of projects in selected high-opportunity market sectors has been developed to support the above mission.

Approach
Three cost-shared solicitations have been conducted in the industrial, high-tech, and institutional market sectors. In FY 2004, the institutional market sector solicitation was issued for cost-shared projects that would utilize integrated (packaged) distributed energy systems in the specific markets of healthcare, education, hospitality, and grocery/supermarkets. All accepted projects had to have a minimum vendor cost share of 50% and had to have the potential for further replication in the marketplace without federal assistance. Out of 46 vendor proposals, eight vendors were selected for award. Two projects from that solicitation are reported here.

Accomplishments

- A full year of operating experience at a major hotel chain has produced plans to add similar combined heat and power systems to additional sites without federal support.
- A full year of operating experience at a waste heat to power project at a gas pipeline pumping station has resulted in design improvements and proven the ability to operate such a system in the challenging environment of a North Dakota winter. Additional systems are planned at this time at additional sites without federal support.

Future Activities
Two final reports will be published to facilitate technology transfer to a broader audience.

Introduction

A large portion of the existing distributed generation and the potential for future distributed generation installations is found in the industrial and commercial sectors. As a result, the foci of this effort are to identify and assess promising applications for integrated distributed energy (DE) systems and to conduct projects that validate and demonstrate the benefits of DE technologies in targeted sectors.

This activity is intended to encourage the expanded use of distributed energy technologies in applications where there is a suitable combination and coincidence of electrical and thermal demand. Descriptions of two active projects are provided below.

Ritz Carlton Hotel

This project was previously installed and a full year of monitoring was completed to evaluate the performance of a United Technology Corporation (UTC) PureComfort System at the Ritz Carlton Hotel, San Francisco, CA. As installed, the system was capable of providing up to 227 kW of net electrical power and 142 Refrigeration Tons (RT) of chilled water at a 15C (59F) ambient temperature. The total installed cost for the system without incentives was $1,040,000. The customer is satisfied with the system and has ordered two more systems for another location. In addition, the knowledge gained from this hotel installation have been directly invested in further integration of future PureComfort systems. For example, newer systems now allow the simultaneous product of hot and chilled water to enable a better match between the hotel demands and the system capacity.

The CHP System installation overcame special challenges associated with the Ritz-Carlton urban environment. The system was configured to fit in the limited space, and heavy components were safely hoisted despite the narrow alley, and highly sloped access. Proper interactions with neighbors, such as an adjacent school, facilitated obtaining permits and permissions. A safe, reliable approach to a network grid interconnection was devised and accepted by the electric utility, but with additional equipment and cost.

The CHP System operated for 8,231 hours in 2006 or 94% of all available time; 90% of these hours were at full power. The electrical energy capability of the CHP System was fully demanded by the hotel. Instantaneous CHP efficiency often exceeded 70% during June-October. However, the hotel chilling demand was limited by the low demand during cooler months and nighttime hours, and by the interaction with a parallel, pre-existing electric chiller. This interaction suppressed CHP chilling because of a high minimum electric chiller output. For brief periods when only two microturbines operated, the higher proportional use of the available CHP chilling resulted in a CHP efficiency averaging over 80% with frequent instances exceeding 90%. Over the entire test period, the reduced use of the available CHP thermal energy limited the CHP output to 52% of its capability. Within this limitation, the system delivered 1.74 GWh(e) (5,940 MMBtu) of electrical energy and 1.96 GWh(th) (6,700 MMBtu) of chilling energy, while consuming 235,000 therms (23,500 MMBtu) of natural gas fuel energy. For the year, the CHP efficiency was 53.7%.

Due to the lower than anticipated thermal usage, the annual savings during the demonstration period were only $74,000. Electric rate increases since that time have increased the savings to $120,000/year. Based on lessons learned and recent product enhancements, a future installation under similar conditions would be configured to provide simultaneous heating and cooling rather than cooling alone; this would increase the thermal utilization and provide additional savings by offsetting expensive steam heating. The projected savings for such a system would be $250,000/year, resulting in a 4.2 year payback without incentives.

UTC PureComfort System at the Ritz Carlton Hotel

Basin Electric

The goal of this project is to verify the technical and economic feasibility of capturing thermal energy from a 30 MW gas turbine driving a natural gas pipeline compressor with an Organic Rankine Cycle (ORC) machine producing 4 MW of emission-free (no fuel and virtually no emissions) electricity in the summer and 6 MW in the winter. The site selected supports an electric coop that requires power and voltage support for the grid, which includes an Indian Nation with an important hospital load. The installation was completed and operation started in the summer of 2006.

During the first year, the system achieved greater than 90% availability.

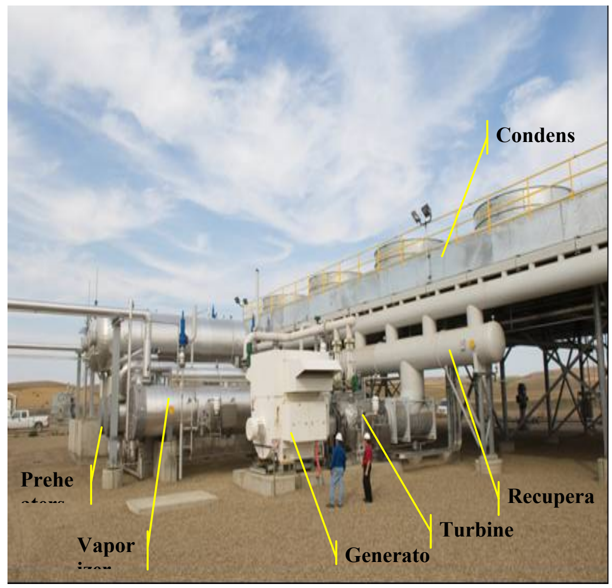
During the test period, the ORC system consistently performed between 16 and 17 percent thermal efficiency when the ORC was operating at full power.

The capital cost for the installed ORC system at compressor station #7 was about $13.75 million, which results in a rated (5.5 MW) installed cost of $2,500 / kW.

Examining the Net Present Value of this project with various contract terms (15 to 25 years in duration) over the cost of capital ranging from a low of 6% to a high of 10% for clean energy projects, we see a wide variation of positive values from $2,000,000 to $12,000,000. The internal Rate of Return (IRR) would range from a low of 5% for a 15 year contract to a high of 15% for a 25 year contract. These values do not include any federal or state subsidies for providing pollution-free electricity.

The best sign of a successful project is duplication. Ormat has already secured the rights to the waste heat for two new power plants and will continue to work towards obtaining the rights to another four new power plants. The release for construction of the new power plants is expected during 2007 with projected completion of six new sites by year end 2009.

ORC system located at compressor station #7



Publications

T. Wagner, T. Rosfjord, A. Morrow, National Account Energy Alliance Final Report for the Field Scale Test and Verification of a PureComfort® 240M Combined Heat and Power System at the Ritz Carlton, San Francisco, ORNL/TM-2007/101, August 2007

Greg Rouse, Subcontract Report: Modular Combined Heat & Power System for Utica College: Design Specification, ORNL/TM-2007/097, March 2007

4.4.3 – 4.4.6 - Distributed Energy Systems Applications Integration

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Objective

One of the missions of the Distributed Energy Program was to lead a national effort to integrate DE technologies at end-user sites and to document and disseminate the findings of those efforts. Strategies to accomplish that mission included:

- Investment in a diverse portfolio of RD&D projects across complementary technologies: prime movers, thermally activated technologies, and CHP systems,
- Performance of systems integration, implementation, and outreach activities aimed at addressing infrastructure, institutional, and regulatory needs, and
- The establishment of collaborative technology transfer partnerships, including cost-shared RD&D projects.

Over the last four years, a balanced portfolio of projects in selected high-opportunity market sectors was developed to support the above mission.

Approach

Three cost-shared solicitations have been conducted in the industrial, high-tech, and institutional market sectors. In FY 2004, the institutional market sector solicitation was issued for cost-shared projects that would utilize integrated (packaged) distributed energy systems in the specific markets of healthcare, education, hospitality, and grocery/supermarkets. All accepted projects had to have a minimum vendor cost share of 50% and had to have the potential for further replication in the marketplace without federal assistance. Out of 46 vendor proposals, eight vendors were selected for award. Remaining activities relate to completion of the demonstration and documentation phases of two projects.

Accomplishments:

- All remaining projects are nearing completion of final reports, documenting construction and operational experience.
- The distributed energy system at Eastern Maine Medical Center has produced excellent performance. Through September 23, 2007, the plant has provided 96.5% of the hospital's electricity, generating 22,463 MWh of electricity, while recovering 121,000 MMBtu of useful heat. The overall total CHP (fuel) efficiency during this period has been 77.5 percent

Future Direction:

Complete documentation of performance on remaining projects and close subcontracts.

Introduction

A large portion of the existing distributed generation and the potential for future distributed generation installations is found in the industrial and commercial sectors. As a result, the foci of this effort has been to identify and assess promising applications for integrated distributed energy (DE) systems and to conduct projects that validate and demonstrate the benefits of DE technologies in targeted sectors.

Demonstration projects, begun in FY04, were designed to encourage the utilization of integrated packaged systems in the healthcare, education, hotel, and grocery sectors. Descriptions of the remaining active projects are provided below.

Eastern Maine Medical Center

ORNL integrated a team that included Eastern Maine Medical Center (EMMC), in Bangor, Maine, Vanderweil Engineering, and Cianbro. The team designed and installed a Solar Turbines gas turbine to generate 4.4 MW of electricity, 24,000 lb/hour of steam, and drive a 500 ton absorption chiller for the hospital. The CHP system responds to the following concerns: high energy costs, fuel use diversity, the need for additional chilled water capacity, the need to deliver services under any climatic condition, utility reliability, diverse thermal heating load profile, and emissions compliance. The project began full-service operation on October 16, 2006. Through September 23, 2007, the plant has provided 96.5% of the hospital's electricity, generating 22,463 MWh of electricity, while recovering 121,000 MMBtu of useful heat. The overall total CHP (fuel) efficiency during this period has been 77.5 percent. Operations data are being collected by CDH Energy, and performance statistics are available for review on the web at http://www.emmccogen.org. As plant operations did not start until October 2006, a final report including a full year of operating data, per the contract, will not be available until the first quarter of FY08.

East Hartford High School

A final project summary on the East Hartford High School project, a 240 kW UTC PureComfort system operational in FY06, was completed.

Madera Hospital

A project by RealEnergy to place a distributed energy system at the Madera Community Hospital did not proceed due to continuing delays by the host hospital site. The project has been terminated.

Pepperell High School

The Pepperell High School CHP/active-desiccant field demonstration, field performance verification project in Lindale, Georgia is a unique integration of islanded IC engine power generation with thermally activated, desiccant, building ventilation and humidity control. Participants collaborating in the project are DOE, ORNL, SEMCO Corporation, Deutz Corporation, CM Engineering, and Floyd County Schools. The IES concept of this project is to use the electrical and thermal power provided by a 215 kWe Deutz, packaged, IC-engine cogeneration system to operate four SEMCO Revolution™ active-desiccant/vapor compression rooftops as grid independent, dedicated, outdoor air systems supplying up to 18,000 cfm of fresh ventilation air to this new 1500 student high school. CHP/IES system installation and start up were completed in September 2006. Operational data has been collected in FY07, and a final report will be issued in the first quarter of FY08.

4.5.12 – Evaluation of CHP Market Potential as it Relates to Renewable Portfolio Standards

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Objective

The objective of the ORNL CHP activity is to promote CHP installations into the public and private sectors by focusing on the issues of CHP awareness, regulatory and institutional barriers, and CHP economic feasibility. In regards to CHP awareness, there is a tremendous need to educate citizens, business executives, and public policy makers on the merits of clean, efficient energy generation using CHP. In regards to regulatory and institutional barriers, there are CHP systems that are commercially viable today but that developers have trouble getting installed because of roadblocks in siting, permitting, and interconnecting. This work complements ORNL Projects under Integrated Energy Systems and End-Use Systems Integration.

Approach

ORNL issued a solicitation at the end of FY 2002 for CHP-related projects. The objective of the solicitation was to support activities that facilitate and encourage the use of CHP technology in the U.S. The statement of work for the solicitation was developed in response to the "Consensus Action Items from the CHP Roadmap Process" issued in June 2001, which supports the National Energy Plan. As a result of the solicitation, ORNL issued 18 subcontracts in support of the CHP Roadmap. ORNL is synthesizing the data and tools developed under these contracts and is disseminating the information to the CHP application centers and stakeholders. The subject project on renewable portfolio standard with Resource Dynamics continues into FY08 under FY07 carryover funding.

Accomplishments:

- The following white paper "Project Considerations for Distributed Generation using Opportunity Fuels" has been completed and was issued in April, 2007.
- The report "Potential Impact of Renewable Portfolio Standards on Biomass Combined Heat and Power Applications" has been completed and was issued in April, 2007.
- The following white paper was drafted for comment, "Barriers to CHP with Renewable Portfolio Standards."

Future Direction

- In FY07, funding for this activity was completed. ORNL is closing out the completed projects.
- Planning on future research directions is being completed with industry and with the Office of Energy Efficiency and Renewable Energy.

Introduction

This project consisted of several tasks: Collect and summarize opportunity fuels information for fuels that already are or could be used in CHP applications, Evaluate CHP Technology Options, and Analyze Potential Market Impacts and Develop Recommendations. This work was completed in FY05 with publication of the final task report, which can be found on the DOE DE website.

In FY06, one task was added to the contract: Satisfying of Renewable Portfolio Standards with Opportunity Fuels and CHP. In this effort, a state-by-state analysis of the impact of state level renewable portfolio standards was performed, using state target dates and impacts as well as emerging values of renewable energy certificates (RECs). This analysis built off of the Phase I work. It looks at the potential capacity from opportunity fuels that would satisfy the state renewable portfolio standards, based on availability of fuel, economics of opportunity fueled CHP, and prospects for wind and solar renewables.

Results

The report "Project Considerations for Distributed Generation using Opportunity Fuels" was completed. This white paper outlines the differences between the each of the four primary opportunity fuels (biomass gas, anaerobic digester gas, landfill gas, and solid wood waste) and their natural gas and coal counterparts, highlighting any special considerations that must be made for opportunity fueled distributed generation (DG) projects. The information was collected from research on opportunity fuels, as well as interviews with manufacturers and discussions with project developers and operators. In addition, whenever possible, actual cases with project experience are used as examples to illustrate how these differences can affect real-world DG applications. The first section of this paper discusses the differences in fuel properties, such as composition, heat rate, pressure and flow rate. The next section addresses the contaminants typically found in these fuels, and their potential effect on prime mover systems and DG projects in general. Then, considering the differences in the fuels and the contaminants they contain, the necessary modifications and additional maintenance for prime mover equipment is analyzed. In the final section of the memorandum, the current market considerations for opportunity fuels are examined, including how the purchase of specialized equipment, fuel treatment systems, warranties, and O&M contracts can affect businesses.

The report "Potential Impact of Renewable Portfolio Standards on Biomass Combined Heat and Power Applications" has been completed. This report focuses on the potential impacts of biomass combined heat and power (CHP) on 15 leading state's RPS. Anaerobic digester gas from wastewater treatment and farms, landfill gas, and solid and gaseous biomass are included as biomass. They are labeled "opportunity fuels" because they are not widely used in this country, but they have the potential to be an economically viable source of power generation for certain applications. Each leading state considers these four opportunity fuels as renewable biomass fuels. Based on their RPS and biomass prospects, the leading states are: Arizona, California, Colorado, Connecticut, Illinois, Maine, Maryland, Massachusetts, Minnesota, Nevada, New Jersey, New York, Pennsylvania, Texas and Wisconsin.

4.5.16 – Coordination of Regional CHP Application Centers
4.5.17 – Project Direction and Technical Support

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Objective

The objective of the ORNL CHP activity is to promote CHP installations into the public and private sectors by focusing on the issues of CHP awareness, regulatory and institutional barriers, and CHP economic feasibility. In regards to CHP awareness, there is a tremendous need to educate citizens, business executives, and public policy makers on the merits of clean, efficient energy generation using CHP. In regards to regulatory and institutional barriers, there are CHP systems that are commercially viable today but that developers have trouble getting installed because of roadblocks in siting, permitting, and interconnecting. ORNL is synthesizing the data and tools developed under Section 4.5.12 and is disseminating the information to the CHP application centers and stakeholders.

Approach

- In 2000, ORNL worked with to the University of Illinois at Chicago to develop the first CHP Regional Application Center (RAC). The Midwest RAC was a pilot program with the goal of developing the process and protocols for such an activity. Based on the success of the pilot program, DOE, through a competitive procurement process, has started 7 more CHP RACs, covering each of the 50 United States. ORNL coordinates the activities of DOE's 8 CHP Regional Application Centers.
- ORNL is utilizing the RACs as a means to disseminate results of the 18 subcontracts issued under the CHP outreach and communications activities; see subtask 4.5.12. In FY07, funding for this activity was completed. ORNL is closing out the completed projects.
- OE partnered with EERE's Industrial Technology Program to provide funding for sustaining the RACs through FY08.

Accomplishments:

- Completed a letter report on CHP RAC accomplishments, lessons learned and metrics in April 2007.
- Held a RAC face-to-face meeting in May, 2007, in Golden, Colorado.

Future Direction

- Planning on future research directions is being completed with industry and with the Office of Energy Efficiency and Renewable Energy.

Introduction

ORNL is completing work on the 18 subcontracts awarded under the CHP Outreach, Marketing and Communications Solicitation. ORNL continues to work with Power Equipment Associates to coordinate RAC activities. OE partnered with EERE's Industrial Technology Program to provide funding for sustaining the RACs through FY08. Planning on future research directions is being completed with industry and with the Office of Energy Efficiency and Renewable Energy.

Results

- The CHP Roadmap Workshop was held in Seattle, Washington, September 13-15, 2006. The purpose of the meeting was to revisit the progress of doubling CHP capacity by 2010 and to identify an Action Plan for CHP for the coming year. The 2006 Workshop was held in conjunction with the National Association of State Energy Officials (NASEO) Annual Meeting. In preparation for the meeting, the 2006 Action Agenda: 2006 Combined Heat & Power Action Plan: Positioning CHP Value: Solutions for National, Regional and Local Energy Issues was prepared by ORNL, in conjunction with Discovery Insights and Energy & Environmental Analysis. The final peer-reviewed version of the following report was completed: Combined Heat and Power Action Plan - 2007, Created at the October 2006 7th National CHP Roadmap Workshop, held in Seattle, Washington.
- The following report was published: ORNL/TM-2006/592, *2006 Update of Business Downtime Costs*.
- The following summary technical report was received from project partner Energy Solutions Center: *Evaluating the ASERTTI Long Term Monitoring Protocol at Arrow Linen.* The twelve month data evaluation campaigns at both the Higgins Brick plant and the Arrow Linen facility were completed. Work will now focus on the preparation of a draft and final case history report for both sites.
- The following report was issued by Subcontractor Energy and Environmental Analysis*: Environmental Regulatory Barriers to Combined Heat and Power*.
- A presentation titled: *U.S. Department of Energy and Oak Ridge National Laboratory - Partnering for a More Efficient, Secure Energy Future*, was given on May 22, 2007 to the Brunswick Local Redevelopment Authority for Naval Brunswick, Brunswick, Maine.
- A presentation titled: *Distributed Generation & Cooling, Heating and Power for Energy Security*, on December 13, 2006, to Army Installation Energy Security & independence Conference, Greensboro, North Carolina
- A CHP RAC face-to-face meeting was held on May 24-25, 2007 in Golden, Colorado. The agenda for the meeting included: U.S. DOE RAC budget update, Regional roundtable discussion, Metrics, U.S. DOE Industrial Technologies Program update, RAC ITP efforts, EPA CHP Partnership, HUD update, FEMP update, Best practices/lessons learned from target market workshops, and U.S. DOE EERE PM Technology Deployment efforts.
- A compilation of Metrics for CHP RAC progress over through the history of the program has been compiled and provided to DOE.

4.5.18 – CHP Regional Application Center Technical Support
4.5.19 – Provide Support to HUD on an "As-Needed" Basis

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Objective

- The objective of the ORNL CHP activity is to promote CHP installations into the public and private sectors by focusing on the issues of CHP awareness, regulatory and institutional barriers, and CHP economic feasibility. ORNL is synthesizing the data and tools developed under Subtask 4.5.12 and is disseminating the information to the CHP application centers and stakeholders.

Approach

- ORNL is providing technical assistance in performing screening and optimization calculations on an as-needed basis to the CHP Regional Application Centers. ORNL will train CHP Regional Application Center staff on the use of the BCHP screening tool.

- ORNL also provides technical support to Bob Groberg at Housing and Urban Development (HUD) on an as-needed basis. Current work includes recommendations on the accuracy of the CHP calculator based on for the Cogen Manual for Multi-Family Housing, Appendix A. Additional work will include collaboration with HUD, and HUD "partners", in identifying and applying the best tools for evaluating CHP in multi-family housing. Among others, these partners include Sebesta Blomberg & Associates of Arlington, Virginia and Dougherty and Associates of Alexandria, Virginia who are under contract to HUD to evaluate combined heat and power for multifamily housing. A data template and utility data files will be produced for use with the BCHP Screening Tool to assess its potential for use in studying combined cooling, heating, and power in multifamily housing.

Accomplishments

- Version 2a of the HUD CHP Screening Tool was provided to the CHP Regional Application Centers for comment and suggestions.
- The DRAFT Users Manual for Version 2 of the BCHP Screening Tool was completed and is undergoing review.

Future Direction

- Planning on future research directions is being completed with industry and with the Office of Energy Efficiency and Renewable Energy.

Introduction

In 2000, ORNL worked with to the University of Illinois at Chicago to develop the first CHP Regional Application Center (RAC). The Midwest RAC was a pilot program with the goal of developing the process and protocols for such an activity. Based on the success of the pilot program, DOE, through a competitive procurement process, has started 7 more CHP RACs, covering each of the 50 United States.

Together with DOE and Power Equipment Associates, ORNL coordinates the activities of DOE's 8 CHP Regional Application Centers. ORNL also provides technical support to the RACs.

ORNL has a work-for-others activity with HUD for CHP screening and technical support in multi-family housing.

Approach

ORNL is utilizing the RACs as a means to disseminate results of the 18 subcontracts issued under the CHP outreach and communications activities; see subtask 4.5.12. Additionally, ORNL provides technical support, specifically related to screening analysis.

Results

- Version 2A of the HUD feasibility software has been released. This version has been upgraded to include: cooling, new screen shots, and new printout capability. It can be downloaded from the following site: http://eber.ed.ornl.gov/HUD_CHP_Guide_version_2a/)
- Bob Groberg presented Version 2A of the HUD CHP Screening tool at the CHP RAC face-to-face held in Golden in May. HUD is committed to running software on 20 sites. Targeting M-A, NE, MW, and CA. Funding for these software runs has not been identified.
- The BCHP Screening Tool is being utilized for the final design project of the Introduction to Mechanical Engineering Course at the University of Illinois at Chicago. The class has 4 groups of students working on 4 separate buildings and CHP applications. Previously, the class utilized the student version of the GTI Building Energy Analyzer.
- The BCHP Screening Tool Users Manual, Version 2, has been drafted and is undergoing technical review.

Conclusions and Recommendations

The project partnership between ORNL and the CHP RACs has been successful.

4.6.1 – 4.6.4 - DE Crosscutting, Systems Integration, and Analysis

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Objective

- Provide the foundation for informed program management decisions, including the definition of program priorities, direction, effectiveness, and strategy.
- Facilitate the deployment of advanced technologies developed under the program mantle by conveying the full extent of potential benefits and the role of DE in the energy market.
- Support cooperation and partnership with other DOE offices and other government agencies, such as the EPA, FERC, and IRS. This cooperation will meet their needs, as well as facilitating the DE program's efforts to remove deployment barriers under the control of these agencies.

Approach

- Consider Distributed Energy benefits analyses on a national, regional and local basis by preparing an analysis tool that can consider regionalized market and regulatory drivers.
- Evaluate the possible effects of plug-in hybrid electric vehicles on the grid and power production mix.
- Coordinate DOE efforts with the Mid-Atlantic Distributed Resources Initiative (MADRI), with particular emphasis on advanced metering and improving the DE business case.

Accomplishments:

- A national evaluation of multiple plug-in hybrid electric vehicles scenarios was completed.
- Coordinated the MADRI examination of the business case and advanced metering areas.
- ORNL contributed significant content to the revision of the DOE report on DE benefits required by Section 1817 of the National Energy Policy Act.
- A possible target for extensive distributed energy implementation was identified in New York City in a joint project with GTI, NYSERDA, and Consolidated Edison Co. of New York.

Future Direction:

- Examine DE benefits associated with full grid integration, including an evaluation of diversified DE reliability and power quality effects.
- Evaluate DE case studies regarding grid-integrated DE in the Consolidated Edison service area.

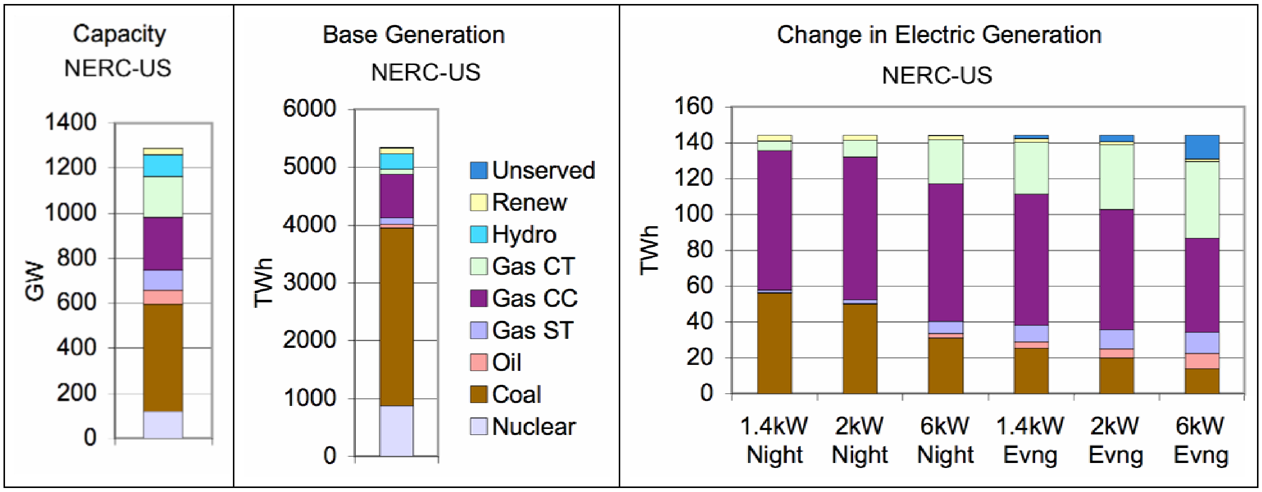
Introduction

A large number of studies have been performed over the last 30 years that describe and quantify the benefits of Distributed Energy (DE) to system owners. These benefits typically include reduced utility expenses and the provision of back-up power. However, the establishment of a broader DE program at the Department of Energy (DOE) led to a number of questions regarding the benefits of DE to society in general, as well as to other stakeholders. These broader benefits are often poorly understood and difficult to quantify. Over the past five years ORNL has studied the benefits of Distributed Energy Resources (DER) in several different areas. Case studies, quantification of market benefits to different stakeholders, an analysis of competing power sources, and an examination of DE benefits for customer-owned utilities were conducted, with reports and summary articles published for the broader industry. We have learned that broad national estimates must be supplemented with more localized studies and that defining a DE business case that is attractive to utilities can be most challenging. The most recent projects have examined the role of plug-in hybrid electric vehicles and the ability of DE to defer T&D investment on specific circuits.

Accomplishments and Progress

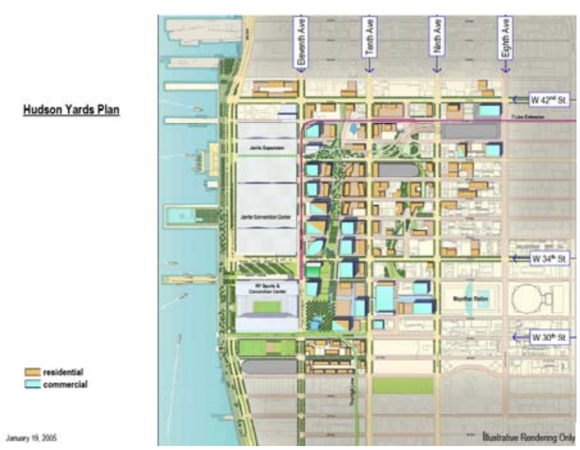
Plug-In Hybrid Electric Vehicles and the Grid: It is important to understand the ramifications of introducing a number of plug-in hybrid vehicles onto the grid. Depending on when and where the vehicles are plugged in, they could cause local or regional constraints on the grid. Prior analyses have made the ad hoc assumption that the batteries would only charge during off-peak night-time hours. However, in our society, consumer convenience is often a more important factor than optimal utility operation. This is evidenced by our current pattern of electricity use. Considering therefore, that some or all owners might elect to recharge their batteries at non-optimal times, seven scenarios were run for each NERC/EIA region for 2020 and 2030, totaling 182 scenarios. Besides a base scenario of no PHEVs, scenarios were run assuming that vehicles either plugged in starting at 5:00 pm or at 10:00 pm, and considering three charging rates. Based upon this analysis, some of the regions could require both the addition of new electric capacity along with an increase in the utilization of existing capacity. The type of generation used to recharge the vehicles will be different depending on the region of the country and timing when the PHEVs recharge.

Most regions will need to build additional capacity or utilize demand response to meet the added demands from PHEVs in the evening charging scenarios, especially by 2030 when PHEVs have a larger share of the installed vehicle base and make a larger demand on the system. The added demands with evening charging, especially at high power levels, can impact the overall demand peaks and reduce the reserve margins for the region's system. Nighttime recharge has little potential to influence peak loads, but will still influence the amount and type of generation, as shown in the following figure.



Capacity, generation and ∆generation in 2030 with PHEVs for NERC-US

T&D Deferral in New York City: Another project, a joint project with GTI, NYSERDA, and Consolidated Edison Co. of New York, examined whether DE could offer enough load relief to practically defer distribution system expansion costs, thereby reducing utility costs by an amount greater than the reduction in sales revenue associated with a DE installation. A major redevelopment project, Hudson Yards, in New York City was selected as the focus for this effort. The assessment seeks to determine whether sufficient DE, at a price attractive to customers, could be installed to avoid or reduce the planned capacity expansion for this urban area. Models have been constructed for the types of buildings planned for this area and are awaiting benchmark data from Consolidated Edison.



Rendering of Hudson Yards

Benefits Report: ORNL, a co-author of the DE Benefits evaluation called for in the Energy Policy Act, section 1817, provided reviews and comments for the final report presented to Congress.

The Mid-Atlantic Distributed Resources Initiative (MADRI), now three years old, seeks to identify and remedy retail barriers to the deployment of distributed generation, demand response and energy efficiency in the Mid-Atlantic region. MADRI was established in 2004 by the public utility commissions of Delaware, District of Columbia, Maryland, New Jersey and Pennsylvania, along with the U.S. Department of Energy (DOE), U.S. Environmental Protection Agency (EPA), Federal Energy Regulatory Commission (FERC) and PJM Interconnection. The collaborative process also includes electric distribution companies, distributed generation developers and owners, demand response companies, and other interested stakeholders. Since its inception MADRI has evolved to a point where it is now playing an instrumental role in helping to coordinate and support state efforts to shape DR policies in the Mid-Atlantic. MADRI and has also played a key role in moving DR from a back burner activity to a high priority activity with the Mid-Atlantic states. Currently each of the Mid-Atlantic states has some type of regulatory proceeding or major working group activity focused on DR.

Regional utilities have proposed significant advanced metering infrastructure (AMI) investments in Maryland, Delaware and the District of Columbia. State commissions in these states recognize that AMI could be a key enabler for demand response, but they need to understand the AMI issues before they can evaluate the utility proposals. There have been four key support efforts to states in this regard. The first has been to support PJM in its efforts to determine what role ISO's should play in coordinating with state AMI activities to ensure integration and of wholesale and retail market activities. The second has been to support Maryland's AMI working group process. The third has been to conduct AMI workshops for states to help them focus on AMI strategy options. The final activity has been to prepare a strategy paper recommending that states consider collaborating regionally on their AMI activities.

Project Publications

- Hadley, Stanton W. 2006, Impact of Plug-in Hybrid Vehicles on the Electric Grid, ORNL/TM-2006-554, Oak Ridge National Laboratory,October. http://www.ornl.org/info/ornlreview/v40_2_07/2007_plug-in_paper.pdf
- Brad Johnson, Proposed Regional Approach for Smart Grid Deployment in the Mid-Atlantic Region, August 2007.

http://www.energetics.com/madri/toolbox/vision.html

http://www.energetics.com/madri/resources.html

Presentations

1. Hadley, Stanton W. 2007, *Evaluating the Impact of Plug-in Hybrid Electric Vehicles on Regional Electricity Supplies,* Paper prepared for the Bulk Power System Dynamics and Control – VII Conference, August 19-24, 2007, Charleston, South Carolina, USA
2. PJM Demand Response Symposium, Mid-Atlantic Distributed Resources Initiative Overview, May 8, 2007, Brad Johnson.

4.7.1 – Evaluate Methods for Voltage Regulation and Analyze Techniques for Voltage Collapse
4.7.2 - Conventional Control and New Methods in Parallel

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Objectives

- Develop methods for local, autonomous control of Distributed Energy (DE) Resources to provide dynamic voltage regulation with minimal communication requirements for a distributed control system.
- Evaluate the economic and engineering feasibility of supplying reactive power locally from DE to regulate local voltage and power factor to improve the efficiency and reliability of the utility distribution system.
- Address key barriers to the local supply of reactive power so that it may be supplied without requiring the local utility to either modify the existing distribution system or perform engineering analysis of the circuit.
- Develop "engineering guidelines" for utilities to reduce the need for detailed engineering studies for the installation of DE.

Approach

- Continue development and testing of advanced control algorithms for generator and inverter-based DE technologies at the Distributed Energy Communications & Controls (DECC)" laboratory.
- Use the ORNL campus distribution system along with dynamic/static loads to evaluate how reactive power producing DE devices can operate in close electrical proximity to regulate the voltage or net power factor.
- Use power system and simulation software (SKM, PSLF and Matlab SimPower) to model and evaluate DE performance in locally controlling voltage and net power factor.
- Conduct an assessment of DE as a source of reactive power to determine reliability and economic benefits to the electric power system.

Accomplishments

- The Distributed Energy Communications & Controls (DECC)" has been established at ORNL and continues to be enhanced for evaluating non-active power, such as reactive power, from DE.
- The capability of testing 3-phase inverters for producing reactive power from DE along with a synchronous condenser (large overexcited motor) and a conventional micro-turbine has been established.
- A software and hardware framework (Matlab/Simulink and dSpace real-time system) has been established for developing and testing various control algorithms for the reactive power producing DE.

- Our two milestones for this year have been met ahead of time. On May 1, we met our first FY07 milestone of running our two reactive-power producing DE with a conventional 30kW micro-turbine. On August 28, 2007, we met our second milestone by operating our reactive power producing DE simultaneously with the micro-turbine during various voltage sag events produced by our motor startups. ***AOP Milestones***
- Seven technical papers (peer reviewed) were published and presented. Three were IEEE publications while the others were The Electricity Journal, International Conference on Electricity Distribution (CIRED), Journal of Industrial Technology, and iREP 2007 Bulk Power System Dynamics and Control VII.

Future Direction

- Determine how to better model the voltage, current and power changes due to reactive power producing DE including for unbalanced conditions, voltage sensitive loads, and real-time loading changes.
- Develop a cost goal for the local supply of reactive power from DE to determine at what cost level it would be competitive with conventional reactive power compensation.
- Continue testing of multiple DE in parallel and then in series to enhance our controls and fully evaluate interaction with multiple devices and develop engineering guidelines for DE application.
- Move the concept of reactive power producing DE from the laboratory to the field environment by working with our partners, such as Southern California Edison and their distribution circuit of the future, to implement the concept to a much larger extent (provide a large part up to all of the local dynamic reactive power) on a utility distribution circuit or circuits.

Introduction

Oak Ridge National Laboratory (ORNL) has a unique laboratory called "Distributed Energy Communications and Controls (DECC)" for studying dynamic voltage and power factor control from non-active power producing (i.e., reactive power) DE resources. This laboratory interfaces with the ORNL campus distribution system and has both rotating and inverter-based technologies along with conventional micro-turbine. Using mathematical software tools and the experiment environment of the laboratory, we are developing local, autonomous voltage regulation control for both rotating and power electronic-based DE. We are testing these control algorithms using a real-time software and hardware system in the DECC laboratory. We achieved two major milestones this year with the accomplishment of operating reactive-power producing DEs simultaneously with the conventional microturbine and also subjecting them to various dynamic voltage sag events. The controls development and testing performance shows great promise and we plan to continue our algorithm enhancement and testing schedule. Finally, we are working with our industry partners to simulate and extend the use of these DE control algorithms to the distribution system.

DECC facility

Figure 1 shows the one-line electrical diagram of the DECC Laboratory and its connection to the ORNL distribution system. ORNL is unique in that it owns and operates its own electric distribution utility for the laboratory campus and can configure the distribution system to provide optimum opportunities for testing of non-active power (including reactive power) injection effects from rotating and inverter-based DE. Real-time monitoring and programmable controls are available at the end-user laboratory level for testing and developing local controls for DE. Also, there is a real-time monitoring system for the overall distribution system via the PowerNet® System and power meters located at all of the ORNL substations. A complete hierarchy of power distribution system testing, such as load changes, startup of dynamic loads, and feeder reconfiguration, is offered by DECC via the existing end user laboratory and its linkage with the ORNL distribution system that ties in with the TVA bulk transmission system.

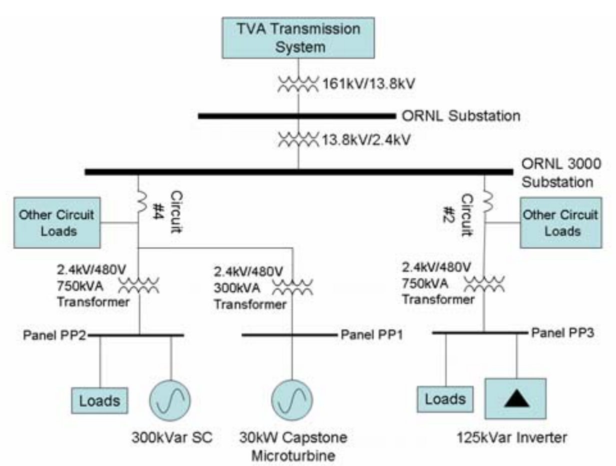

Figure 1. Electrical diagram of the DECC Laboratory and equipment.

DECC offers the capability to test technologies in a real-world distribution system and at substation environments and simulate the integration of multiple technologies on the electric grid. It provides the link between testing and simulation needed to ensure accuracy of experimental results. Additionally, renewable energy technologies, many being inverter-based like photovoltaics (PV), can be accommodated in the DECC facility. We estimate that approximately 1 MVA of inverter-based technologies could be tested in parallel at the same time.

The goal of the laboratory is to work with the power industry, manufacturers, and universities in developing local control for producing reactive power from reciprocating engines, microturbines and fuel cells using synchronous generators and inverters. Important capabilities of the laboratory include:

Testing Areas: The laboratory provides testing capability of rotating (generator or motor) and power electronic or static (inverter) based DE. Also, the laboratory has the capability to test vendor provided reactive power producing DE, such as a microturbine or reciprocating engine.

Distribution Interface: The laboratory interfaces at two different electrical locations on the ORNL distribution system. This provides the capability to test single or multiple reactive power producing DE and also their interaction. The DE devices can be connected in parallel (by using both power panels) or in series (by using only one power panel).

Substation: The reactive power compensation at the substation can be relaxed to provide a more severe testing scenario for the laboratory. Shunt capacitor banks at the substation provide power factor correction for the ORNL distribution system. The reactive power compensation can be relaxed by switching out some of these capacitor banks. Presently, the substation has 900kVar of reactive power compensation in capacitor banks in units of 150kVar.

Distribution and Power System: The laboratory interfaces with the TVA grid through the ORNL distribution system. The TVA transmission lines provide power to ORNL at 161kV and it is stepped down to 13.8kV at ORNL's substation. Secondary substations, such as the 3000 substation, which provides the electrical interface for the laboratory, steps it down further to 2.4kV. Our ownership of the distribution system allows the capability to vary loading and reconfigure the distribution feeder circuits for testing different operating scenarios at the DECC Laboratory.

Achievements

We achieved several significant milestones (on May 1 and August 28) using a unique control algorithms that we developed and tested with the simultaneous operation of three distributed energy (DE) resources (shown in Figure 2) in close proximity and connected to the ORNL electric distribution system. Two of the devices were dynamically regulating their end-use voltages using our developed control algorithm for local, independent control.

The control algorithms[1] use only a local measurement of voltage and do not require communication between DEs. Next steps include the development of independent algorithms that can be used over a wide-spread distribution network (10 miles or more) to support voltage in areas of reactive power shortage and to expand the network's margin to voltage collapse without interfering with existing utility control.

The two devices, synchronous condenser (SC) and inverter, were controlled separately, which was also unique since it didn't involve any central communications and control or the need for the two devices to talk to each other. The test was significant from the perspective of showing how conventional DE operates with "smart" DE that can dynamically control its local voltage.

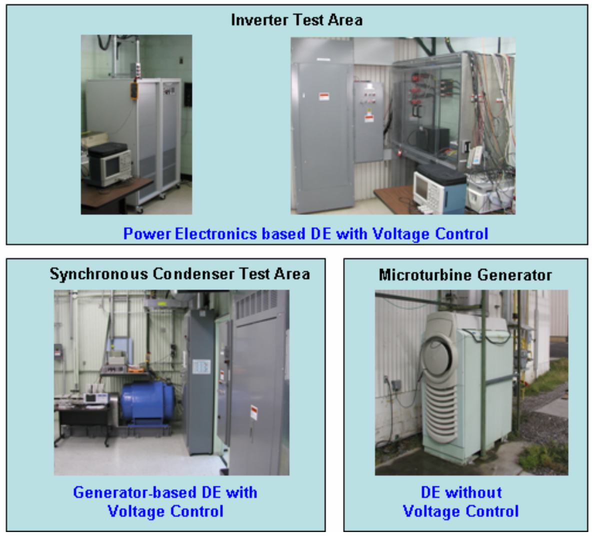

Figure 2. DECC DE Equipment that were tested simultaneously.

During the test, our 300kVar SC, which is a 250-hp synchronous motor that is overexcited, and the 30-kW Capstone Micro-turbine were running on their individual 480V power panels connected to circuit #4. Simultaneously, our 150A inverter was running on circuit #2 on its individual 480V power panel.

Figures 3 and 4 show the response of the SC and inverter to end-user voltage changes at their local power panel. They can regulate their own service voltage independently from the other. The SC can provide up to 300kVar (kVar is a kilovolt-ampere reactive, a measure of reactive power) and can easily accommodate a 5V change, as shown in Figure 3. The inverter is about one-third the size in capacity and so can accommodate a 1V sustained change, as shown in Figure 4. The tests involved changing the reference voltage for the two controllers, which is the same as what would happen with a large load connected to the same circuit being turned on or off.

The final FY07 milestone (due September 30th) for the Distributed Energy Communication and Controls (DECC) Laboratory was met ahead of schedule on August 28th. Our distributed energy (DE) devices (300kVar SC and 88kVar inverter) with dynamic voltage regulating capabilities (inject reactive power to raise voltage or absorb reactive power to lower voltage) were both operated simultaneously on different ORNL distribution circuits while independently regulating their own end-user (480V panel) voltages. We also had a 30kW conventional micro-turbine, which has no voltage regulating capability, operating on the same circuit as the SC. While the above two devices were regulating the voltage using our dynamic voltage controls, a motor (7.5hp) was started to create a momentary (~0.1s) balanced voltage sags of 2V and (~2s) unbalanced voltage sags of 1V on the inverter's panel. We measured the response of the inverter control to these fast voltage events. Also, we conduct testing in which we changed the active power (kW) dispatch of the micro-turbine from 30 (full output) to 10kW and back again while simultaneously operating the inverter and synchronous condenser. These tests provide us with valuable information on the dynamic response of the devices using our control scheme. The tests also provide a better understanding of the response to power system events and how to better implement our controls.

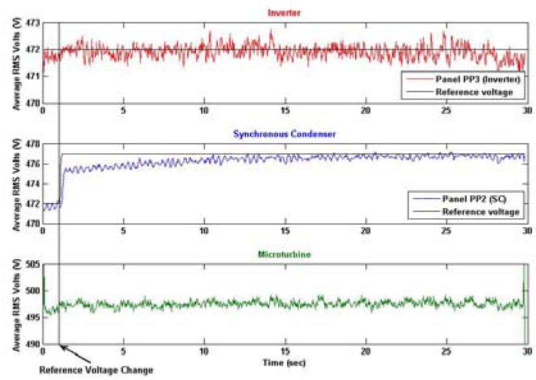

Figure 3. DE devices operating simultaneously: response of SC to 5V reference change.

DECC Path Forward

We have developed a test matrix for our path forward that considers a number of operational test scenarios for evaluating our dynamic DE control algorithms. These scenarios include (1) balanced/unbalanced voltage conditions (i.e., sags), (2) various dynamic load conditions (i.e., motor starts), (3) changing load conditions (i.e., step load changes), (4) severe abnormal conditions (i.e., when there is a fault; we will use several sizes of three-phase motors — single-phased (one phase of three-phase motor disconnected) so that they can't start — to produce severe/unbalanced voltage sags for several cycles similar to that due to a fault), and (5) changing voltage schedules for the DEs which involves the use of a voltage-band based control. Based on the results of these tests, general "engineering guidelines" will be developed along with a control methodology framework that will provide a streamlined engineering approach for utilities to implement various ancillary services using DE resources.

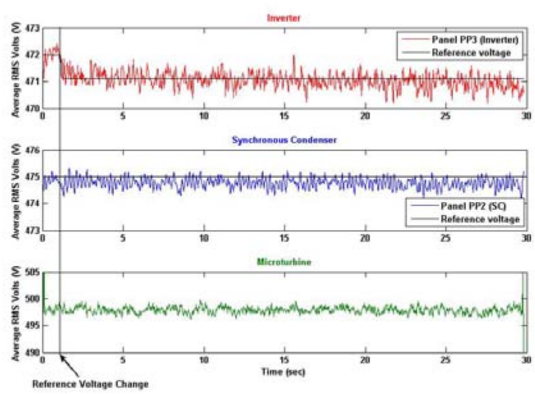

Figure 4. DE devices operating simultaneously: Response of inverter to 1V reference change.

We have started evaluating scalable, adaptive autonomous methods for voltage regulation for various DE sources operating in parallel in a distribution system with variable (small to large) impedances between the sources[1]. The methods will be enhanced so that they are readily applicable to various types of distribution systems. The methods will be simulated in steady state (using PSLF) and dynamic models (Matlab).

Key Publications

1. Y. Xu, F. Li, J.D. Kueck and D. Tom Rizy, "Experiment and Simulation of Dynamic Voltage Regulation in Multiple Distributed Energy Resources Systems", iREP 2007 Bulk Power System Dynamics and Control VII, Paper #164, August 24, 2007.
2. Y. Xu, L.M. Tolbert, D. T. Rizy and J. D. Kueck, "Nonactive-Power-Related Ancillary Services Provided by Distributed Energy Resources", Paper No. PESGM2007-001073, IEEE Power

Engineering Society General Meeting, June 2007.
3. J. Kueck, B. Kirby, T. Rizy, F. Li and N. Fall, “Reactive Power from Distributed Energy”, The Electricity Journal, Vol. 19, Issue 10, December 2006.

4.7.3 – Instrumentation and Communications Requirements using Low-Cost Methods

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Objective

- Study the scale and granularity of communication architecture requirements for distributed energy resources for the future power grid.
- Generate a report that describes more rapid, highly-distributed, and adaptive control systems that will be required for DER that respond in real-time to power system events and pricing.

Approach

- Analyze existing communication architectures in the grid to understand how to address issues like scalability, reliability, and large-scale deployment.
- Develop concise simulation to demonstrate the impact of communication network in the operation of the grid with DER elements.

Accomplishments

- The scope and the outline of a draft report that describes the adaptive control systems for DER was generated.
- The framework to simulate hi-fidelity simulation model of a demand-response scenario was developed.

Future Direction

- Develop hi-fidelity computational simulation of DER control and communication infrastructure to understand the communication requirements as a function DER penetration.
- Integrate DER elements into the IEEE 14 bus systems and understand the effect of controlling DERs over communication networks.

Introduction

The term distributed energy resources refers to a collection of technologies that are broadly characterized by small scale power generation units and price responsive loads that reside in the low voltage parts of an electric power grid. Deregulation, advances in power generation technology, a growing demand by information based businesses for highly reliable power, and interest in renewable energy resources are some of the major factors causing distributed energy resources to be adopted in significant numbers. Wind farms are leading this trend; grid connected wind farms produced approximately 13,000 Megawatts of power in 2007, a 10000 Megawatt increase from the year 2000[1]. There is a renewed interest photovoltaic technology as well; in 2007 both Google and Wal-Mart announced major solar power demonstration projects. But power generation is not the complete story. Automated demand response systems have made significant inroads in the last few years. Field trials in California, New York, and else where have demonstrated the viability of this technology, and its relative simplicity and low cost have led to rapid adoption in some parts of the country.

Modern communication technology is essential for monitoring and managing distributed energy resources. Wind farms, the most mature distributed generation technology, make use of high speed Ethernet technology to monitor and control aggregations of hundreds of wind turbines; the necessary software and communication infrastructure are often provided to wind farm operators by companies that specialize in data management and communication systems. Modern communication technology also plays a major role in automated demand response. Advanced metering technology, which is widely seen as the enabler of large scale demand response systems, is one of the major applications of the ZigBee wireless standard. But this is only the most visible part of the communication system that makes advanced metering possible; wireless technology is the last link in a large back haul network that moves data between the wireless metering network and the utility's operation and control computers.

Even though there is little working experience with large distributed energy systems, it is widely acknowledged that monitoring and coordinated control will be essential to successfully operate a power grid that contains numerous distributed energy resources. Wind farms are the first example of this, and other distributed generation conglomerates will likely encounter technical problems that a fast monitoring and control network can solve. Demand response test beds have demonstrated the utility of a modern communication network for improving the responsive of controllable loads. The public Internet is a favorite implementation technology for demand response test beds, but it is unclear if this solution is practical for very large demand response systems. This is a particularly vexing question as utilities expand their use of advanced metering technologies to enable demand elasticity.

This report examines the communication requirements that will emerge as distributed energy resources are integrated into the electric power grid. The report broadly considers distributed generation and demand response to fall under the rubric of distributed energy resources and we consider three specific instances of their application: large numbers of price responsive loads in a real time power market, aggregated generation resources connected directly to the power distribution system, and a futuristic scenario that has massive numbers of distributed generation and responsive load units integrated into an Internet-like electric power grid. Analyses focus on the capacity of the data network that will be required to support a particular scenario; we do not propose specific technical solutions that may be brought to

[1] According to the American Wind Energy Association, http://www.awea.org

bear, but the feasibility of a solution will be demonstrated, where applicable, in terms of existing technology.

Method of Analysis

In the absence of a defined monitoring and control strategy, we can make only a coarse estimate of the communication resources requirements in terms of network capacity that will be necessary to effectively use a set of distributed energy resources. With this in mind, distributed energy resources can be characterized by four main traits:

1. power output, which is the maximum amount of power that the device can produce assuming it is available for immediate use
2. physical response time, which is the time required to physically bring the device to its maximum output level
3. control data requirement, which is the average number of bits in a control message and
4. monitor data requirement, which is the average number of bits in a status message.

The first two items, power output and physical response time, are electromechanical properties of the machine. The last two items are dictated by the communication protocol that is used to monitor and control a device.

These device parameters can be used to calculate several performance metrics for monitoring and control of a set of distributed energy resources. The *control information delay* that occurs when P units of power are requested from a set of uniform distributed energy resources is

control information delay =

*network data rate * control data requirement * number of resources =*

*network data rate * control data requirement * P / power output per unit*

The significance of this delay relative to the device's physical response time is the *control information quality* given by

control information quality = physical response time / control information delay.

This metric describes the impact that control delays have on the perceived device responsiveness. For example, if a micro-turbine can reach full power in 1 minute but it requires 5 minutes for the turbine to receive the control message, then the control quality is poor; the device can not be used to its full potential. On the other hand, a control message delay of only 5 seconds is small relative to the micro-turbine startup time, and so the control delay does not significantly affect use of the device.

The *DER monitoring frequency* for a uniform set of distributed energy units with a total power output of P is the maximum rate at which the system can be sampled:

grid monitoring frequency =

*network data rate / (monitor data requirement * number of units) =*

*network data rate / (monitor data requirement * P / power output)*

This is just the rate at which the distributed energy resources can be observed with a given amount of network capacity; it does not include switches, relays, etc. that might also need observation.

In this analysis, we assume that the time required for a message to move from its source to its destination is accurately modeled by number of message bits divided by the network throughput. This implies that the base latency of the communication channel is small relative to the throughput restriction. This is a reasonable assumption when moving large quantities of data over short time frames through common types of communication devices (e.g., through an Ethernet network, ATM network, or radio link). We also assume that point to point connections are the main form of communication and are available in the required quantities. Broadcast medium, for the purposes of determining communication requirements, effectively combine physically distinct distributed energy resources into a single communication endpoint.

Given a desired performance metric for a particular makeup of distribute energy resources it is possible to estimate the required network capacity for control

control network capacity =

> *control information quality * control data requirement * P / (power output * physical response time)*

and monitoring

monitoring network capacity =

> *grid monitoring frequency * monitor data requirement * P / power output*

These two requirement formulas reflect the intuition that the network capacity must grow with the number of distributed energy resources, the size of the control and monitoring messages, and the rate at which we want to interact with the set of distributed energy resources. In particular, given a fixed aggregate power level, large numbers of small power output devices will impose a greater communication capacity requirement than a small number of high power output devices[2].

One example will suffice to demonstrate how the network data rate can be translated into a requirement for real communication hardware. Suppose a 1 MW distributed energy resource aggregate consisting of 100 small micro-turbines with 1 minute physical startup times requires a control information quality of 2 (i.e., an actual startup time of 1 minute 30 second). The control messages are 100 bits long. The corresponding network capacity requirement is a paltry 333 bits per second. If, instead, the system was realized with 1000 micro-turbines and required a control quality of 200 (i.e., an actual startup time of about 1 minute) then the corresponding network capacity requirement is 333,000 bits per second, the equivalent capacity of about 5 telephone voice circuits connecting 56k bps modems (this, of course, ignores the connection setup and tear down time required to make 200 phone calls with each line). Communication protocol overheads could bloat 100 bits of actual information to as much as 1000 bits increasing the network data rate requirements from 333 bits per second to 3330 bits per second in the first case and 3,330,000 bits per second in the second case; the latter being equivalent to a small home or office network.

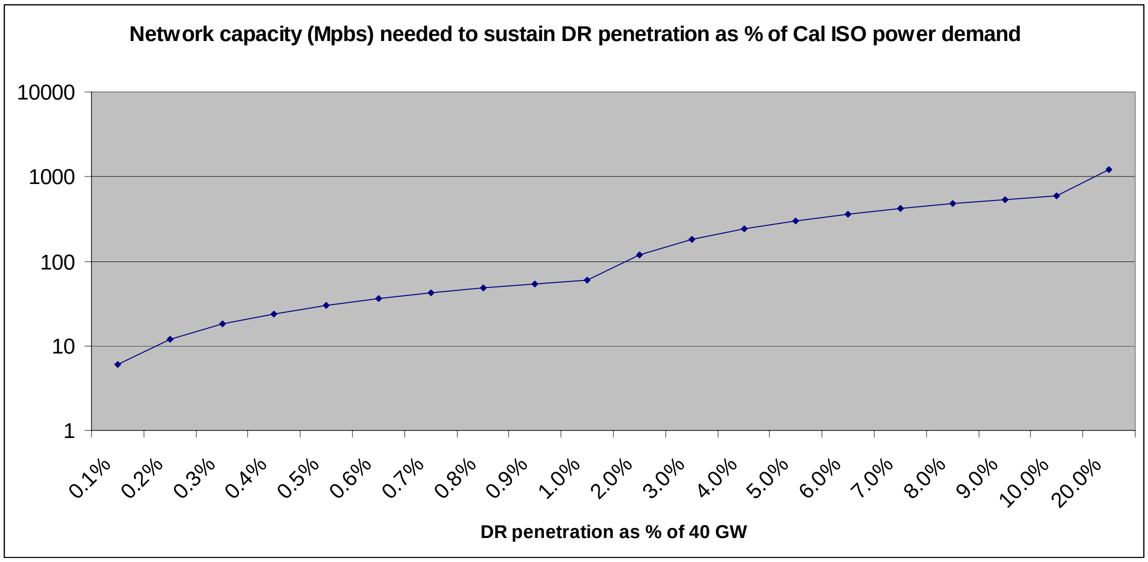
The communication requirements derived by this analysis method are likely to underestimate the actual data exchange needs; it is difficult to account for communication capacity losses due to protocol overhead, network congestion, and other effects without specifying particular usages scenario and network topologies. Simulation can be used to produce more accurate, scenario specific performance estimates.

Scalability of the CEC demand response experiments

The CEC has funded small scale field trials of demand response technology. The results of these trials are documented in a series of CRC reports[3]. These exercises include a small number (less than 12) of large commercial facilities (e.g., supermarkets and large office buildings) that receive a

[2] This economy of scale in communication requirements for large power plants vice small DERs is observed in several other aspects of power generation such as power production efficiencies and maintenance and fueling costs. See *Distributed Power Generation: Planning and Generation* by H. Lee Willis and Walter G. Scott, published by Marcel Dekker, Inc. 2000.

[3] A series of reports can be found at http://drrc.lbl.gov/drrc-pubs1.html. The numbers presented here are taken from “Machine to Machine (M2M) Technology in Demand Responsive Commercial Buildings” written by David S. Watson, Mary Ann Piette, Osman Sezgen, Naoya Motegi, and Laurie ten Hope and published in the Proceedings of the 2004 ACEEE Summer Study on Energy Efficiency in Buildings, Aug. 2004.



simulated price control signal through the Internet. In the CEC experiments, Web Service technology, based on the SOAP messaging protocol, is used to deliver price information to the site energy management computers. New price data is transmitted to each site every 1 to 5 minutes. On average, each site is able to offer 69 kW of load relief in response to unfavorable price signals. The small scale of the CEC experiments does not strain the available communication resources, but they are essential to the systems effective operation.

A large scale demand response system similar to the one described in the CEC sponsored report could require substantial network capacity. On the order of 10^3 overhead bits are required by the SOAP messaging protocol. One message every 2.5 minutes requires on the order of 10 bits/sec of network capacity. Each site provides, on average, 69kW of power. To control P kW of power with an information control delay of 2.5 minutes requires $1.5 * 10^{-4} * P$ [bits / sec] of network capacity. Power demand reported by California ISO peaks at about 40,000 MW. Figure xx shows the communication requirement as a fraction of 40,000 MW, corresponding roughly to the communication capacity required to support a given percentage of demand response penetration into the Cal ISO market (i.e., fraction of load controllable via price signals).

The capacity requirements illustrated here are well within the technical capabilities of modern communication networks, but not trivially so. A metropolitan area network built with readily available Ethernet technologies would be sufficient, in principle, to support the demand response communication sub-system in a large city. The network would connect demand response enabled businesses, homes, and industrial facilities with power providers to create an automated, real time power market. If a suitable (and available) network was not already in place, then it would need to be designed, installed, and appropriate resources made available for maintenance and operation. Metro-area networks could be connected via the Internet if coordinated power management is required across the state (this, however, may also require an appropriate data dissemination scheme to avoid clogging connections between metropolitan areas).

Future Directions

Develop hi-fidelity computational simulation of DER control and communication infrastructure (along with generation, distribution) to understand the communication requirements.

4.7.4 - Fault Current Detection and Mitigation

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Objective

- Develop fault current detection and limiting circuits to protect power electronic converters that are part of a utility interface with distributed energy in the event of an internal fault in the power converter.
- Limit the contribution to utility system fault currents by grid-connected distributed energy resources.

Approach

- A summary of present fault current detection and limiting techniques used by utilities and power electronic manufacturers will be conducted.
- A method or methods to quickly (less than 1 ms) detect internal faults in a power electronic converter will be determined. Limiting the fault current such that the power electronic device will not sustain damage will also be part of the protection circuit.
- Integrate the protection techniques into a power electronics converter circuit and test for different fault scenarios such that damage to the current is prevented and fault current contributions to the utility are limited.

Accomplishments:

- A white paper was written which summarized the fault current detection and limiting techniques presently available.
- A fault current detection and limiting circuit to protect IGBTs was built and tested. The circuit worked for two types of fault – fault under load (FUL) and hard switched fault (HSF).
- An inverter model has been developed in PSIM along with MATLAB/SIMULINK for the controls.

Future Direction:

- Integrate circuits for FUL and HSF fault detection into a single circuit.
- Determine algorithms to limit the fault current contributions by DE when a nearby fault is on the grid.
- Investigate if DE can support local voltage without making major contributions to fault current.

Introduction

A method is needed to limit the flow of fault current from DE to the grid. Current must not be injected from DE into a fault on the distribution or transmission system because the utility circuit breakers may not be rated to interrupt the additional current. The penetration of DE may greatly increase for some distribution circuits in the future, which would also increase the available fault current. Therefore, faults must be detected and the DE current limited. The challenges with such an interface are:

- Accurate and rapid analysis of any overcurrent.
- Rapid determination whether sudden current demand is due to load starting up or a fault.
- Rapid current limiting in the event of a fault.

Conventional fault detection methods rely on sensing and analysis of current imbalance, overcurrent, ground current, fault impedance, etc. Current imbalance is a common characteristic of many common faults. Another relatively new method is arcing fault detection. A unique aspect of arcing fault detection is that it may require several cycles of monitoring to positively identify the arc because the arc is not continuous, it sputters. Another difficulty with arcing fault detection is that the overcurrent magnitude may not be high; in fact, it may be less than the interrupting rating.

Balanced three phase faults are unusual, but these must be rapidly distinguished from a load start. The underlying concern is that the utility distribution circuit breakers are, in some cases, incapable of interrupting additional fault current contribution.

A method must be developed to guarantee that the fault current will be limited, regardless of the fault type. Information will be gathered on fault signatures for various types of faults and signatures for large load starts. Once this information is obtained, algorithms will be produced for rapid fault identification. Prototype detection hardware and software can be developed.

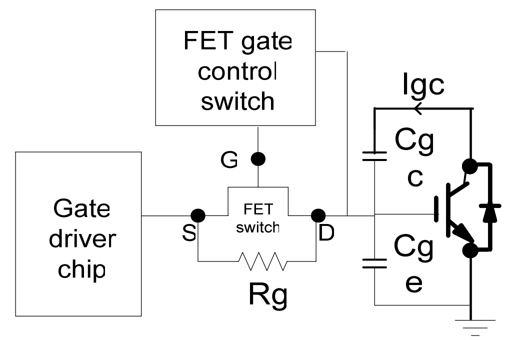


Figure 1. Schematic of the protection circuit for fault under load (FUL).

Accomplishments and Progress

Fault current detection/limiting gate drive

At device level, faults can be characterized as over-current, short circuit, open circuit faults etc. Short circuit faults are most critical to the device. A power device has an inherent short circuit withstanding time, and the main design goal of protection circuits is to detect the fault and protect the device from failure within this time. The two main short circuit fault types are Hard Switched Fault (HSF) and Fault under Load (FUL).

Figure 1 shows the schematic of the fault current detection and fault current limiting circuit under fault under load (FUL). Fault current detection is achieved by sensing the gate-emitter voltage, Vge, across the device (IGBT). The threshold gate voltage can be varied by adjusting the reference voltage. The fault detection and fault limiting time is less than 0.7 us. The FET switch stays on until the gate voltage is higher than the set threshold value.

Figure 2 shows the schematic of the fault current detection and fault current limiting circuit under HSF. The circuit was built using commercially available IC chips. The fault current detection is

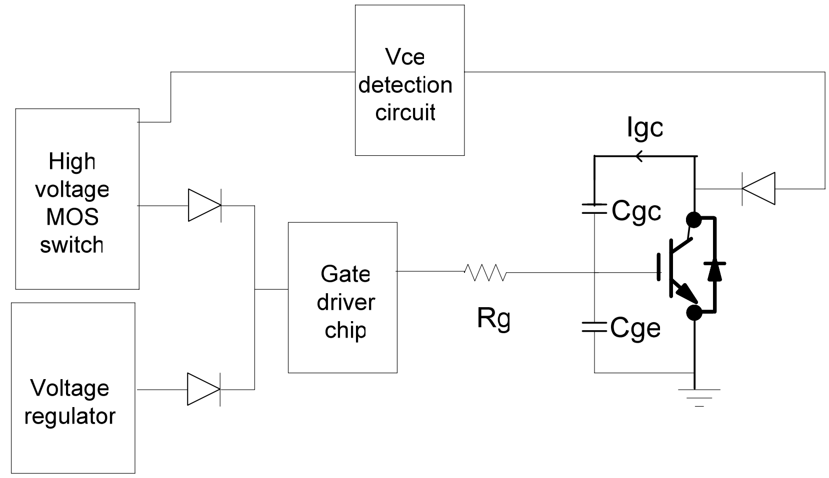
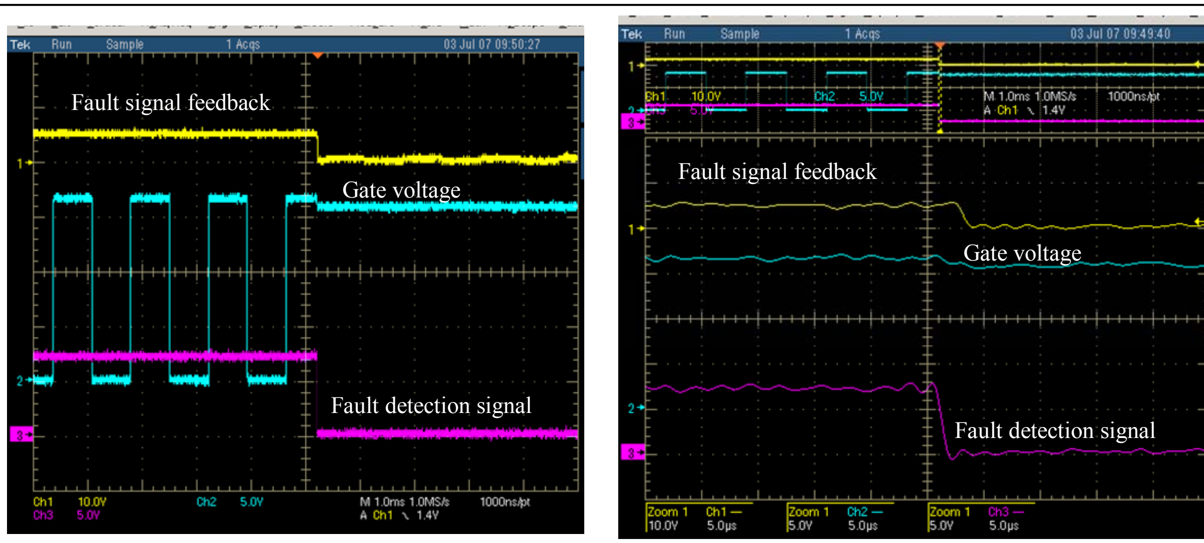


Figure 2. Schematic of the protection circuit for hard-switched fault (HSF).



(a) (b)

Figure 3. Test results of the protection circuit for HSF. (a). Normal view, (b). Zoomed view.

achieved by sensing the collector-emitter voltage, Vce, across the device.

The circuit has a blanking time capability which can be adjusted by varying the RC time constant between the gate turn-on signal and the detection signal. The blanking time prevents nuisance trips because of transient currents. The circuit has the flexibility to be adjusted for a particular on-state voltage drop between (0-7 V).

The output stage of the gate driver circuit is capable of handling 14 A of peak current. The circuit can be adapted for higher gate currents by implementing a complementary transistor pair at the output stage of the gate driver.

The waveforms in Figure 3 show the fault detection signal, the gate voltage waveform and the fault signal feedback to the controller. The fault across the device is simulated using a preset voltage across the fault detection circuit, which in the actual device is the on-state voltage drop corresponding to the short circuit current. The gate voltage is clamped to a desired preset voltage as soon as the fault is detected. There is a delay between the fault detection signal and the fault signal output. However, the gate voltage starts to decrease even before the fault signal is active. This change in the gate voltage reduces the peak fault current immediately after the fault. The gate voltage is clamped to the preset voltage until the controller commands the turn-off the gate signal.

The time needed for the gate voltage to be clamped is determined by the short circuit withstanding capability of the device. The protection circuit also has the undervoltage gate protection feature which will protect the device from damaging itself because of excessive losses.

Summary of fault current detection and limiting techniques

A literature study was done to identify the type of device faults and to study the techniques to detect, limit fault current through the device and protect. A 30-page white paper was written which discussed the following topics:

- Faults and their consequences in the grid and for power electronics
- Various fault detection algorithms and their usefulness
- Characteristics and coordination of fault current limiting fuses with surge arrestors
- Fault current sensing and limiting by power electronics

For system level fault control several detection, limiting and mitigation techniques have been discussed briefly followed by a detailed study of the characteristic of current limiting fuses and their coordination with surge arresters.

New relays are normally numerical relays. They are built around a microprocessor in which the relay characteristic is digitally implemented. The analog measurement signals are converted to digital signals for a microprocessor to perform signal evaluation. This development of a fast microprocessor has led to the possibility to implement highly sophisticated relay characteristics within the microprocessor.

This white paper further analyzes the suitability of various fault current limiting circuits available in the market for improving the performance of power electronics used in equipment present in a power system like converters, STATCOM, etc. The device reviewed for this study was an Isolated Gate Bipolar Transistor (IGBT) which was chosen because of its widespread use in modern power electronic converters.

Several fault detection algorithms have been summarized in the white paper. Artificial intelligent techniques including a novel signal processing technique can provide a shorter detection time and reasonable sensitivity. In case of an arcing fault, it would be better to detect the arcing fault by detecting the light from an arc in order to reduce a clearing time. With light arc fault detection, the device could detect arcing fault within 1 ms after fault inception.

Superconducting current limiting might be used to limit the fault current lower; however, it will likely be costly.

To maintain the power quality of the system, a current limiting fuse (CLF) can be used along with a surge arrester. The CLF showed better performance than expulsion type fuse in terms of response time and maximum current allowed.

Inverter model

A three-phase full-bridge inverter model and a multilevel converter consisting of cascaded H-bridges was developed in PSIM with its associated control model developed in MATLAB/SIMULINK. The combination of these two software platforms will aid in the development of algorithms to detect faults and test the speed of their response and what effect they may have on the utility system.

4.7.5 − Develop and Assess Specific Tariff Mechanisms

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Objectives

- Study a range of customer types in the PG&E territory to see what reactive power needs may be filled by customer-owned DER.
- Develop and assess various tariff mechanisms that encourage customers to sell reactive power to the distribution system.

Approach

- Meet with various customers and system operators in the PG&E territory to determine the cost and value of supplying reactive power from customer-owned DER.

Accomplishments

- The initial results of this study are encouraging and indicate that a tariff of ~$12/kVAR would provide the incentive for customers to supply reactive power that would benefit the distribution company.
- A 33-page draft report has been prepared that concludes that local dynamic reactive support would significantly reduce loses, increase transmission capacity, and improve reliability.

Introduction

Two kinds of power are required to operate an electric power system: real power, measured in watts, and reactive power, measured in volt-amperes reactive or VARs. Reactive power supply is one of a class of power system reliability services collectively known as *ancillary services*, and is essential for the reliable operation of the bulk power system. Reactive power flows when current leads or lags behind voltage. Typically, the current in a distribution system lags behind voltage because of inductive loads like motors. Reactive power flow wastes energy and capacity, and causes voltage droop. To correct this lagging power flow, leading reactive power (current leading voltage) is supplied to bring the current in phase with voltage. When the current is in phase with voltage, there is a reduction in system losses, an increase in system capacity, and a rise in voltage.

Reactive power can be supplied from either static or dynamic VAR sources. Static sources are typically transmission and distribution equipment, such as static Var compensators or capacitors at substations, and their cost has historically been included in the revenue requirement of the Transmission Operator (TO), and recovered through cost-of-service rates. By contrast, dynamic sources are typically generators capable of producing variable levels of reactive power by automatically controlling the generator to regulate voltage. Dynamic sources at the distribution level would be very useful in helping to regulate local voltage. Local voltage regulation would reduce system losses, increase circuit capacity, increase reliability, and improve efficiency. Reactive power is now available from any inverter based equipment such as photo voltaic, fuel cells, microturbines and adjustable speed drives. However, the installation is usually only economical if reactive power supply is considered during the design and construction phase.

Approach

Researches from ORNL have been working with Pacific Gas and Electric and the California Independent Service Operator (CAISO) on a study for the local supply of dynamic reactive power from customers to provide a voltage regulation service. Two trips to Pacific Gas and Electric were made. On the last trip, we met with three sample customers to discuss possibilities for the local supply of dynamic reactive power for voltage regulation. The customers are a shopping center, a steel rolling mill, and a university. Siemens has prepared a budgetary cost estimate for a common bus with an active front end for the shopping center. S and C Electric is preparing a budgetary cost estimate for a distributed VAR controller for the rolling mill. We are going to propose an inverter with a power factor of 0.8 for the university.

Results

A 33 page draft report has been prepared that summarizes the work done to date. In this report, we find that if the inverters of photovoltaic systems or the generators of combined heat and power systems were designed with capability to supply dynamic reactive power, they could do this quite economically. In fact, on an annualized basis, these inverters and generators may be able to supply dynamic reactive power for about $4 per kVAR. The savings from the local supply of dynamic reactive power would be in reduced losses, increased capacity, and decreased transmission congestion. The net savings may be as much as $20 per kVAR on an annualized basis. Thus the distribution company could economically purchase a dynamic reactive power service from customers for perhaps $12/kVAR. This practice would provide for better voltage regulation in the distribution system, and would provide an alternate revenue source to help amortize the cost of photovoltaic and combined heat and power installations.

Conclusions

The local dynamic reactive support would significantly reduce losses, increase transmission capacity, and improve reliability.

4.7.6 - Modeling of Reliability of High Temperature Packaging of SiC

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Objective

- Study the inner architecture of a power electronic device to eventually enable representative thermal and thermomechanical analyses.
- Adapt established design sensitivity software and methods to power electronic devices.
- Identify candidate material constituents whose substitution will reduce thermomechanical stresses in a power electronic device.

Approach

- Dissect a silicon-containing power electronic device (Powerex 100A-1200V IGBT), section it, and use the dimensions of the subcomponents for input in a finite element analysis model.
- Combine the use of established probabilistic design and lifetime prediction methods, microstructural-scale finite element analysis, micromechanical characterization, and sensitivity analyses methods, and adapt them to the analysis of potential SiC-containing power electronic devices.
- Identify which subcomponents have a material that cause high stress development and suggest alternative materials that would reduce that.

Accomplishments:

- Identified that the coefficient of thermal expansion (CTE) of a copper baseplate in a 100A-1200V Powerex IGBT dictates the magnitude of the thermomechanical stresses of all the other subcomponents.
- Concluded that copper substitution with another electrically conductive material with lower CTE and high thermal conductivity will likely improve reliability of the IGBT.

Future Direction:

- Model stresses and predict reliability of a protypical SiC-power electronic device containing alternative subcomponent materials.

Introduction

SiC-based power electronics can enable module size and weight reductions, operating temperatures of up to 400°C, loss factor reductions of an order of magnitude, and increase power capabilities by two orders of magnitude. Even though SiC has very attractive electrical capabilities for power converters, it remains a brittle ceramic (i.e., a class of material in which a deterministic approach to structural design does not work) that would be subjected to thermomechanical stresses during device manufacturing and high temperature service - conditions that can limit or decrease device operation and lifetime. The present subtask combines the use of established probabilistic design and lifetime prediction methods, microstructural-scale finite element analysis, micromechanical characterization, and sensitivity analysis methods and adapts them first to the analysis of lifetime and design optimization of Si-containing power converter devices (e.g., IGBTs), and then extend them to analogous SiC-containing devices.

Accomplishments and Progress

A conventional finite element analysis (FEA) model of an idealized cross-section of a Powerex 1200V/100A IGBT was constructed, see Figs. 1-3. These IGBTs are not capable of operating with junction temperatures above 125-150°C because their diodes are silicon (Si). Such a FEA model enables the consideration of the substitution of Si diodes with silicon carbide (SiC) diodes and the interpretation of how the thermomechanical stress field changes due to property changes of the various subcomponents within the IGBT.

Thermal boundary conditions were imposed on the silicon diode and silicon IBGT, and also on the bottom cooling plate, and the resulting steady-state thermal gradient is shown Fig. 4.

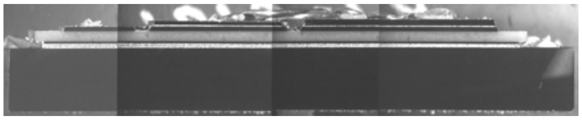

Figure 1. Polished cross-section of a Powerex 100A-1200V IGBT. This cross-section guided most of the finite element analysis conducted in this year's work.

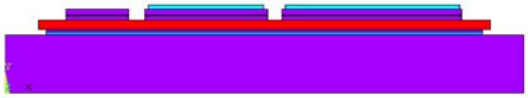

Figure 2. Finite element model of the constituents comprising the 100A-1200V IGBT.

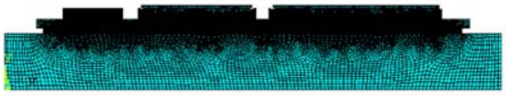

Figure 3. Finite element mesh of the IGBT.

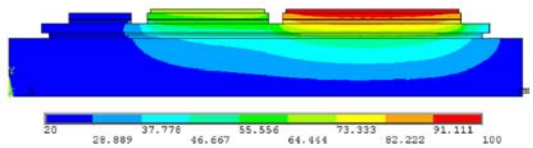

Figure 4. Resulting thermal gradient when the (silicon) IGBT and diode are self-heating and the base plate is concurrently cooled. Shown values are in Celsius.

The resulting First Principal stress field caused by the thermal gradient in Fig. 4 and the various and mismatched coefficients of thermal gradients of all the constituents comprising the IBGT were examined. For brittle materials, it is the First Principal tensile stress that leads to their prospective mechanical failure; namely, the mechanical reliability of the silicon (or the SiC when it is used to replace Si) and ceramic insulator in the DBC is sensitive to these stresses.

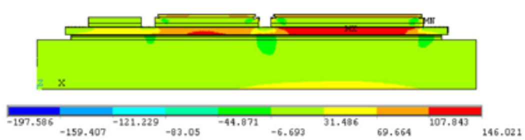

Figure 5. Resulting First Principal stress field from the thermal profile shown in Fig. 4. Shown values are MPa (6.95 MPa = 1000 psi).

Lastly, probability design sensitivity analysis was performed on the model described in Figs. 2-5. It performed a Monte Carlo simulation on 22 different independent parameters (e.g., material properties and dimensions of the various constituents) and ranked them as having the biggest effect on First Principal tensile stress in both the silicon diode and IGBT and the ceramic insulator in the DBC.

Regarding stress development in the silicon semiconductors, the PDS results listed the silicon's elastic modulus as being the most dominant property. Silicon in this instance obviously *needs* to be used, so it cannot be substituted with another material (SiC will cause the stress to be even higher because its elastic modulus is larger than that of Si). The parameter having the next largest effect is the CTE of the copper in this IGBT. Copper has the potential to be substituted with some other metal, so a replacement material having a lower CTE will act to lower the applied stress in the silicon semiconductors. Other factors affect the stress development in the silicon, including the thermal conductivity of the silicon, the thermal conductivity of the insulating ceramic, and the thermal conductivity of the copper; however, the CTE of the copper is the most dominant. The other 17 parameters (of the 22 considered) had insignificant effect on the stress in the silicon.

Similar PDS analysis was performed to examine which parameters had the largest of stress development in the insulating ceramic in the DBD, and again, it was the CTE of the copper that was dominant. Because of the similar result, it was certainly concluded that seeking an alterative to copper that has a lower CTE should improve the reliability of this 100A-1200V IGBT.

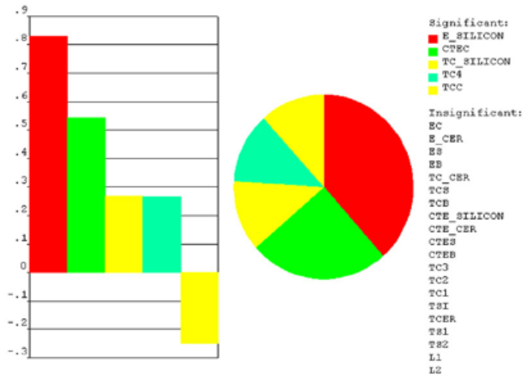

Figure 6. Results of PDS analysis. The elastic modulus of the silicon has the biggest effect on the stress development in it. Being that nothing can be done about that because silicon needs to be used, the CTE of the copper is the next important (changeable) factor affecting stress development.

Project Publications

None

Presentations

None