System Study of Rich Catalytic/Lean burn (RCL®) Catalytic Combustion for Natural Gas and Coal-Derived Syngas Combustion Turbines

Final Report

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ABSTRACT

Rich Catalytic/ Lean burn (RCL®) technology has been successfully developed to provide improvement in Dry Low Emission gas turbine technology for coal derived syngas and natural gas delivering near zero NOx emissions, improved efficiency, extending component lifetime and the ability to have fuel flexibility. The present report shows substantial net cost saving using RCL® technology as compared to other technologies both for new and retrofit applications, thus eliminating the need for Selective Catalytic Reduction (SCR) in combined or simple cycle for Integrated Gasification Combined Cycle (IGCC) and natural gas fired combustion turbines.

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INTRODUCTION

EXECUTIVE SUMMARY

Rich Catalytic/Lean burn (RCL®) combustion is a novel near-zero NOx emissions gas turbine combustion technology developed by Precision Combustion, Inc. (PCI) under a DOE Small Business Innovation Research program.

Following successful early development and combustor trials, this system study was established to explore the use of the RCL combustion system in natural gas- and coal-derived syngas-fueled power generation gas turbines. To help provide information for policy decisions and a roadmap for development, the system study provides (1) an assessment of the RCL technology and its operating map, (2) an assessment of the fit of the technology with existing DLE technology, and (3) an analysis of benefits and costs. These results are summarized below:

In summary, RCL technology was found to offer substantive improvement to Dry Low Emissions (DLE) technology for achieving near-zero emissions from gas turbine combustion of natural gas and of coal-derived syngas. Integrating the RCL technology into modern gas turbines offers to simultaneously advance DOE objectives in the areas of:

- **Near-zero NOx emissions** (<3 ppm NOx for natural gas combustion, and the same (0.01 lb/mm BTU, or <3 ppm) for syngas combustion), without post-combustion controls or ammonia. This also translates into the capability to achieve a targeted emissions level with less nitrogen dilution.
- **Improved efficiency**
  - Avoiding post-combustion controls, and
  - enabling higher firing temperatures
- **Extending gas turbine component lifetimes and service intervals** (by reducing combustion dynamics), and
- **Fuel flexibility** (including ultra-low emissions with natural gas, high reactivity hydrogen-containing fuels such as coal-derived syngas and refinery fuel gas, and low BTU fuels). The extension of this flexibility to burning pure hydrogen in nitrogen with low NOx is now being explored, with promising early results.

The study predicts a **substantial net cost savings** in using RCL technology, vs DLE with post-combustion controls as is now generally BACT in the U.S.

- **For base load merchant power gas turbines burning natural gas**
  - **$12/kW net savings in capital cost, plus an additional**
  - **$12/kW (1.3 mils/kw-hr) in net annual operating savings.**
- **For IGCC gas turbines burning coal-derived syngas**,
  - **$75/kW net savings in capital cost**
  - **$10+/kW (1 mils/kw-hr) in net annual operating savings**.

The technology is compact enough to fit to existing pressure casings, offering lowered cost integration for new machines as well as retrofit potential. Combustor module tests under large frame gas turbine conditions have demonstrated the robustness of the technology as well as stable combustion with NOx emissions as low as below 2 ppm and low combustion dynamics, in a package sufficiently compact to potentially fit into existing large frame machine combustor volumes. A smaller catalytic pilot version has been developed and tested for minimal modification to existing DLN systems.

The technology offers its benefits at lowered cost compared to DLE-SCR configurations now standard in the U.S. New RCL catalytic module component cost for natural gas-fired large frame machines is expected to be in the $4/kW range, vs SCR capital cost of $20/kW and an undetermined savings in avoided DLE components. With greater life cycle cost impact, RCL operating costs are projected at 0.2 mils/kw-hr, vs 1.5 mils/kw-hr for DLE+SCR. The above costs are estimated for natural gas-fired turbines; cost savings for smaller machines and for syngas-fired machines are expected to be higher. In addition, improved combustion stability offers increased low emissions turndown, a key flexibility feature offering both added revenue and cost advantage to power generators.

An RCL retrofit package is also predicted to offer savings to the installed base power generator. Retrofit of installed turbines even without current SCR systems would offer substantial reduction in emissions with modest net reduction in operating costs due to improved combustion dynamics. Retrofit of installed turbines with installed SCR systems would enable the SCR to be mothballed and offer substantially reduced net operating costs (>1.0 mils/kw-hr).

<ins>Relevancy</ins>: RCL technology offers a near term opportunity to advance DOE objectives by providing an energy-efficient in-engine near-zero emissions solution:

- Eliminating the need for SCR in combined cycle or simple cycle, for IGCC and natural gas fired combustion turbines
- Enabling simple cycle and small turbine near-zero emissions, encouraging CHP/distributed power
- Improving efficiency due to the avoidance of SCR and improved combustion stability
- Reducing combustion dynamics, enabling improved RAMD
- Reducing power generation turbine capital and O&M costs
- Retrofittable to the installed base
- Capable of fuel-flexible operation, including with natural gas/liquid fuels, and applicable to ultra-low NOx syngas combustion.

In summary, RCL technology offers substantial public benefit as well as supporting the accomplishment of key DOE goals. Next steps include the need for more development toward (1) the syngas combustion goal, (2) full scale multimodule combustor trial, and (3) engine field trial. There are currently active R&D programs on the technology, with DOE support, at multiple gas turbine OEMs participating in the Fossil Turbine program as well as at PCI. While these development programs continue to require ongoing DOE support, they offer a path forward to implementing the technology in the nation's power generation combustion turbines.

1. BACKGROUND

Power generation is a prime driver of the U.S. economy. Fuel-efficient, low cost gas turbines are targeted to supply most new U.S. central station power needs between now and 2020. DOE policy in this area seeks high efficiency with near-zero emissions. The DOE Fossil Turbine program is focused upon achieving increased efficiency and near-zero emissions from coal-derived fuels, in systems seeking fuel-flexible operation.

In the last ten years, gas turbine operators have had to comply with increasingly strict exhaust emissions regulations. Oxides of nitrogen (NOx) are exhaust constituents of great concern and can act as smog precursors. U.S. environmental policy relating to power generation turbines has led to broad usage of lean premix (LP) combustion systems as well as broadening requirement for post-combustion controls directed to NOx and HAPS emissions. LP and post-combustion technologies have been successful in lowering emissions. However, combustion dynamics arising from lean operation have limited operability and the push to extend turbine component life and reliability, while the increasingly-dominant Selective Catalytic Reduction (SCR) post-combustion control reduces system efficiency and has increased electricity costs by on the order of 1-2 mils. Driven by NOx concerns, SCR is now BACT for large combined cycle turbines and is increasingly becoming required also for large simple cycle machines. The requirement for use of SCR on smaller machines is also spreading. This trend is expected to continue.

DOE has provided support over time to the development of Rich Catalytic/Lean burn catalytic combustion. This has been shown a promising catalytic combustion technology offering to resolve combustion dynamics limitations, avoid the need for SCR post-combustion control, and provide system-level reduction in electricity costs. The technology was originally developed under a DOE Small Business Innovation Research program by the contractor (PCI), and involves use of a rich catalytic reactor integrated to a lean combustion zone (summarized as Rich Catalytic/Lean burn, or RCL®). The initial SBIR was followed up by other DOE exploratory development support, with results supporting this as a leapfrog technology offering low single digit ppm NOx emissions clean and efficient combustion for gas turbines, with unusually broad fuel flexibility. The fuel-flexibility capability includes low NOx emissions with coal-derived syngas, for which initial testing has demonstrated an ultra-low NOx potential (0.01 lb/MM BTU, or <2 ppm)

As a result, this system study was established to explore the use of the RCL combustion system in natural gas- and coal-derived syngas-fueled power generation gas turbines. In support of assessing the potential benefit and costs and to help provide a roadmap for development, the system study was directed to (1) provide an assessment of the RCL technology and its operating map, (2) assess the fit of the technology with existing DLE technology, and (3) provide a benefit/cost analysis of the technology for public policy purposes.

1.1. BACKGROUND ON RCL TECHNOLOGY

Catalytic combustion has the potential to provide the needed step change reduction in NOx emissions down to low single digit levels. The use of a catalytic reactor within the combustion system allows combustor flame temperature (and thus NOx emissions) to be maintained at levels lower than in today's combustors technology. Natural gas and syngas fuels have been the recent focus of interest, because they are currently the low-emissions fuels of choice for power-generating gas turbines.

For methane oxidation under fuel-lean conditions, however, only Pd-based catalysts are currently practical, because only they offer acceptable activity, lightoff temperature, and resistance to volatilization [1-3]. Unfortunately Pd-PdO catalyst morphology and its reactions with methane are complex, and lead to complex behaviors such as deactivation at high temperature (above about 750 C / 1380 F), hysteresis in reaction rate over heating and cooling cycles [4-7], and oscillations in activity and temperature [8-11]. Lightoff and extinction temperatures are well above 300 C (570 F) for fuel-lean methane reaction on Pd-based catalysts, thus requiring the use of a preburner in many engine applications [12-13]. For syngas combustion, hydrogen reactivity leads to early autoignition of the fuel in the catalytic channels, and consequent temperature overrun. Using of fuel lean catalytic reactor for both syngas and methane is not possible.

In addition to these catalyst challenges, commercial acceptance of catalytic combustion by gas turbine manufacturers and by power generators has been slowed by the need for durable substrate materials. Of particular concern is the need for catalyst substrates, which are resistant to thermal gradients and thermal shock [12, 14-15]. Metal substrates best fill this need, but their temperature must be limited to less than 950 C (1750 F) to assure sufficient material strength and long life. Downstream of the catalyst, combustion temperatures greater than about 1200 C (2200 F) are required for gas-phase reactions to complete the burnout of fuel and CO in a reasonable residence time (on the order of 10 ms). Thus, only a portion of the fuel can be reacted on the catalyst.

A major challenge, then, is to limit the extent of reaction within the catalyst bed such that excessive heat does not damage the catalyst or substrate, yet release sufficient heat that downstream gas-phase combustion is stabilized under ultra-low emission conditions. For systems which lean-premix fuel and air upstream of the catalyst, the degree of reaction can be limited by chemical reaction rate upon the catalyst, or by channeling within the reactor such that only a limited fraction of the fuel contacts the catalyst. In all cases, however, it is imperative that gas-phase reactions do not occur within the catalyst-bed, since this implies a loss of reaction limitation and ultimate over-temperature and failure of the catalyst bed. Preventing such gas-phase reactions is especially challenging in applications to advanced, high-firing temperature turbines, where fuel/air ratios in the catalyst-bed are well within the flammability limits.

Fuel-Rich Catalyst Systems

An alternative means to limiting the extent of reaction is to operate the catalyst fuel-rich. In this scenario, there is insufficient oxygen to fully oxidize all fuel in the catalyst bed, and the extent of reaction is therefore limited even if gas-phase reactions occur. To use a fuel-rich catalyst bed in a catalytic combustion system, additional air is introduced downstream of the catalyst so that combustion completion can occur fuel-lean. Based on this concept, fuel-rich catalytic reactors were tested by NASA and contractors for liquid fuel applications, and showed good soot-free performance [16-17]. An examination of fuel-rich catalysis on a variety of liquid fuels was also conducted at Yale University under support from NASA [18]. Like the NASA results, this work showed soot-free catalyst performance on a range of fuel types, including a surrogate jet fuel. United Technologies Research Center [19] also investigated fuel-rich catalytic reaction of liquid fuels, to reduce downstream thermal NOx generation by removing some heat of reaction prior to gas-phase combustion.

For these applications, ultra-low NOx emissions (< 3 ppm) had not previously been considered feasible because of the possibility for autoignition during mixing with additional combustion air downstream of the catalyst. Even for natural gas fuel, previous systems have not permitted mixing of raw catalyst effluent with additional combustion air. For example, Acurex tested a two-stage natural gas combustion system having a fuel-rich catalyst stage followed by inter-stage heat extraction [20]. Additional combustion air was introduced only after heat extraction, and prior to a final fuel-lean catalytic combustion stage.

However, because the temperature exiting the catalyst can be limited (by fuel-rich oxygen limitation of reaction), we have found that it is possible to mix catalyst effluent with additional combustion air without incurring autoignition [21]. This is possible because significant improvement in combustion stability is imparted to the downstream fuel-lean combustion even at catalyst effluent temperatures well below the instantaneous autoignition temperature of the effluent. PCI has developed an integrated catalytic reactor / mixer based upon this concept, to provide for lean-premixed combustion downstream of a fuel-rich catalytic reaction stage. We call this system Rich-Catalytic Lean-burn (RCL) combustion.

EXPERIMENTAL

Rich-Catalytic Lean-burn (RCL) Combustion

A schematic of the RCL system is shown in Figure 1.1.1. As shown, the combustion air stream is split into two parts upstream of the catalyst: one portion is mixed with all of the fuel and contacted with a catalyst, while a second portion is used to backside cool the catalyst. At the exit of the reactor, the catalyzed fuel/air stream and the cooling air are rapidly mixed to produce a fuel-lean, reactive mixture prior to final combustion.

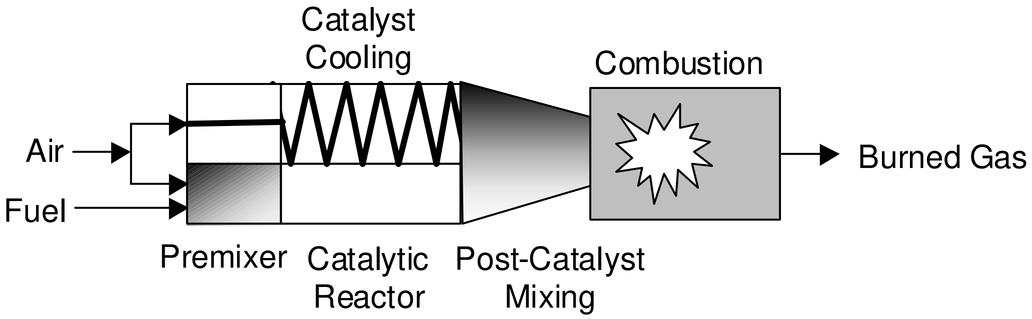

Figure 1.1.1. *Schematic of RCL system. A fuel-rich fuel/air mixture contacts the catalyst, while heat is extracted into a cooling air stream. The cooling air stream and the catalyzed stream are rapidly mixed downstream of the catalyst, but prior to final combustion, to create a fuel-lean fuel/air mixture for the low-NOx burnout zone.*

A simple drawing in Figure 1.1.2 shows implementation of the RCL system. The RCL reactor is fabricated from multiple tubular elements (tubes), shown in blue in Figure 1.1.2, each having catalyst coating on its outside surface. Each tube is inserted through a sealing plate at its upstream end, and the entire tube bundle with sealing plate is then positioned inside a reactor housing. Thus, as shown in Figure 1.1.2, cooling air (without fuel) impinges on the sealing plate and passes only through the inside of the tubes. The fuel-rich fuel/air mixture enters the reactor housing downstream of the sealing plate and flows only over the outside of the tubes. Catalytic reaction occurs when the fuel/air mixture contacts the tubes' catalyst-coated outside surfaces. The catalyst effluent and the cooling air only come in contact downstream of the catalyst-coated tubes.

For combustion of fuels, the reactor housing is extended some distance downstream of the catalyst-coated reactor, to provide a space for post-catalyst mixing of cooling air with catalyst effluent, prior to final gas-phase combustion.

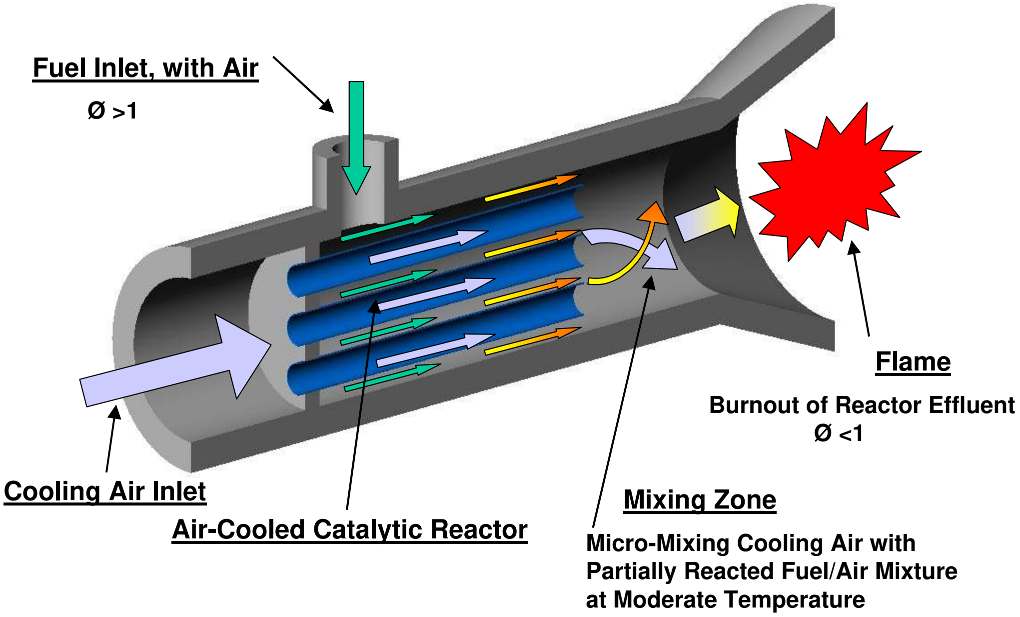

Figure 1.1.2. *Simple drawing showing construction of RCL catalytic reactor from tubular elements, having catalyst coating on the outside surfaces only. Cooling air passes through the center of the tubular elements, and mixes uniformly with catalytically reacted effluent prior to final gas-phase combustion.*

In the RCL system the catalyst cooling stream remains free of fuel at all times, precluding failure by flashback or auto-ignition to the cooling stream. At the same time, the fuel-rich mixture contacting the catalyst has insufficient oxygen to completely oxidize all of the fuel, thus limiting the extent of catalyst-stage reaction and enabling limitation of the catalyst-stage operating temperature to a safe value.

Fuel-rich operation of the catalyst also provides significant catalyst advantages, including wide choice of catalyst type (non-Pd catalysts are active to methane and syngas under fuel-rich conditions), improved catalyst durability (non-oxidizing catalyst environment), and low catalyst lightoff and extinction temperatures. Catalyst extinction temperature is particularly low, and is generally less than 200 C (400 F) for the precious-metal catalysts used in the work reported here (that is, once the catalyst has been lit off, the catalyst remains lit at inlet air temperatures as low as 200 C / 400 F). Lower values have been achieved for syngas fuel application. (A more complete discussion of fuel-rich versus fuel-lean catalyst behavior for methane oxidation is given by Lyubovsky et al. [27].)

The RCL system thus provides significant operational advantages. Most notably, the RCL™ reactor requires no preburner, is immune to issues of auto-ignition and flashback, and provides long catalyst life (as a result of the non-oxidizing fuel-rich catalyst environment), while providing ultra-low NOx (< 3 ppm) performance.

In summary, the RCL approach to catalytic combustion provides the following advantages:

- No preburner – space, cost and durability advantage.
- Integrated compact premixer using simple existing technology.
- Compact - capable of fitting to existing engine envelopes.
- High firing temperature operation ideal for F-class applications.
- Robust operation, avoiding catalyst failure by flashback/autoignition.
- Long life due to fuel-rich catalyst environment and moderate wall temperatures.
- Simple control system.

The RCL concept has been patented with government use rights granted to the DOE.

2. RCL OPERATING CHARACTERISTICS AND OPERATING MAP

PCI has tested the RCL catalytic reactor at pressures from 1 to more than 15 atm, in both sub-scale and full-scale tests, providing design data over a wide range of operating conditions. Ultra-low emissions performance for the RCL combustion system has also been confirmed in full-scale full-pressure rig tests, and in testing of a modified industrial gas turbine engine over a range of loads. This work to date provides a solid foundation for developing an "operating model" of the RCL combustion system, to enable design and performance prediction for RCL applications to new machines.

2.1. RCL PERFORMANCE DATA

In considering potential applications for RCL combustion, several key performance parameters are always of interest. Measured values for these parameters are given in this section. The following parameters are of most interest:

From *full*-scale full-pressure rig tests to date:

- RCL combustor emissions and turndown
- RCL combustor noise levels
- RCL system pressure drop
- Catalyst operating temperatures

From *sub*-scale full-pressure rig tests to date:

- Catalyst lightoff and extinction temperatures
- Catalyst durability
- Alternate fuel capability

In addition to these performance criteria, engine operational issues are also of interest, including method for engine start and catalyst lightoff, fuel staging needs, complexity of required controls, and transient capability such as load shifting and load rejection. To begin addressing these issues, PCI and Solar Turbines have operated a modified Saturn engine using RCL combustion; these results are also presented here.

2.1.1. Full-Scale Test Data

Full-scale full-pressure tests have been performed in cooperation with Solar Turbines, at their combustion test facility. For this purpose, a single full-scale (3-inch diameter) RCL reactor was fabricated. A schematic of the complete RCL combustor assembly, including premixer, catalytic reactor, and downstream combustor liner as tested at Solar is shown in Fig. 2.1.1.

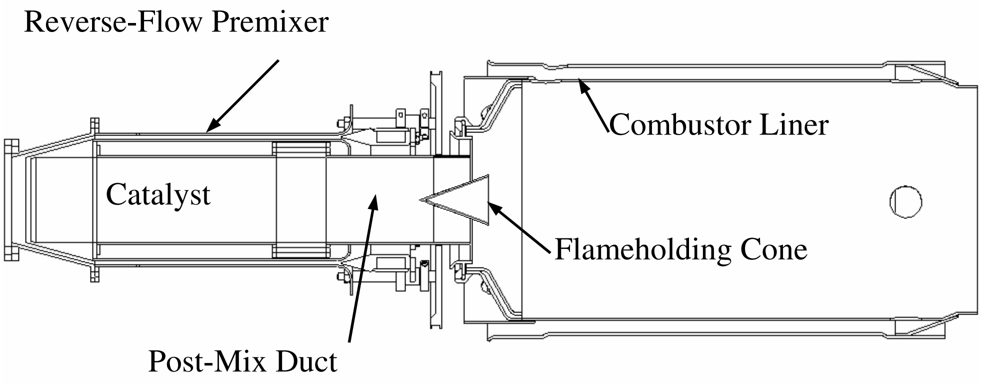

Figure 2.1.1. *Assembly of RCL catalytic reactor with combustor liner in Solar Turbines' high-pressure combustion test facility. Bulk flow is from left-to-right.*

RCL Combustor Emissions and Turndown

The RCL combustion system depicted in Figure 2.1.1 was used to measure RCL emissions performance and turndown. NOx and CO emissions from RCL combustion testing are plotted in Figure 2.1.3 as a function of adiabatic flame temperature at the combustor exit, after addition of some leakage air into the combustor. NOx and CO emissions are reported after correction to 15% O_2 on a dry basis. UHC emissions are reported on a wet basis, corrected to 15% O_2. Combustor residence time was approximately 30 ms for these tests.

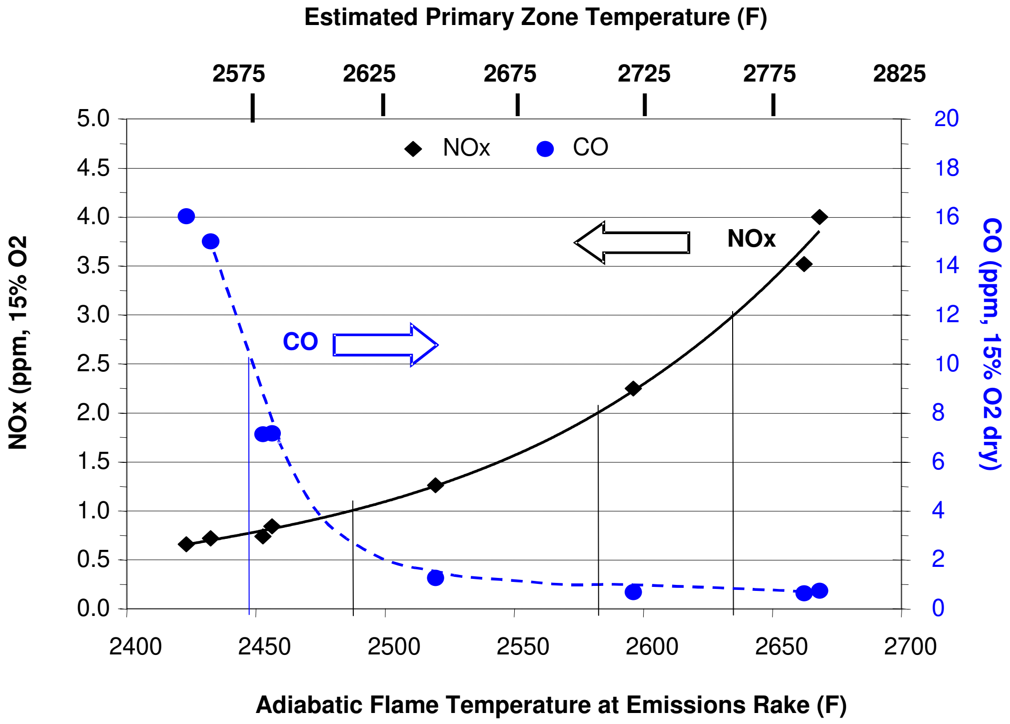

Figure 2.1.3. *NOx and CO emissions, as a function of adiabatic flame temperature at emissions rake. Data obtained at 16 atm pressure.*

As shown in Figure 2.1.3, the RCL combustion system achieves ultra-low emissions over a wide operating window of approximately 110 C (200 F) variation in flame temperature, with CO below 10 ppm and NOx below 3 ppm (and as low as 1 ppm). Unburned hydrocarbons (UHC) remain less than 2 ppm at all conditions shown in Figure 2.1.3. These results demonstrate the potential for wide engine load turndown with ultra-low-emissions.

RCL Combustor Noise Levels

Combustion-driven pressure oscillations (noise) were also monitored during full-scale combustion tests at Solar, and remained less than 2.4 kPa (0.35 psi) peak-to-peak (less than 0.15% peak-to-peak of mean combustor pressure) at all conditions tested, indicating quiet operation. Low levels of combustion noise are expected, since gas-phase energy release in the combustor (the driving force for combustion noise) is reduced when a portion of the fuel is catalytically reacted prior to gas-phase combustion. For the high-pressure rig combustor at Solar, peak noise occurs in the 295 to 320 Hz range; peak noise in this range is plotted in Figure 2.1.4 for RCL combustion at adiabatic flame temperatures from about 1310 to 1470 C / 2390 to 2680 F (based on emissions rake O_2 and CO_2 concentrations).

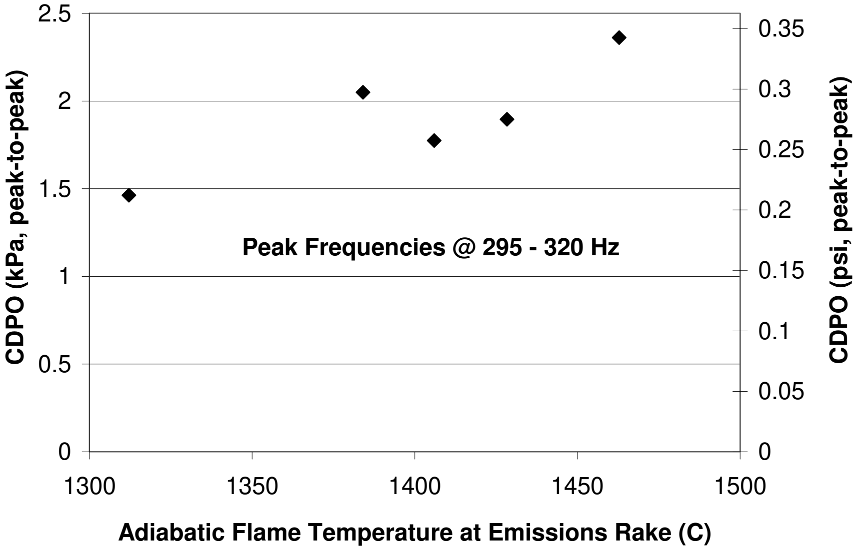

Figure 2.1.4. *Combustor-driven pressure oscillations (CDPO) for RCL combustion, at flame temperatures from about 1310 to 1470 C (2390 to 2680 F).*

RCL System Pressure Drop

Pressure drop through the RCL reactor is a primary determiner of reactor size for any given application. For the 3-inch diameter reactor tested at Solar, pressure drop through the entire combustion system is about 3.5% of combustor inlet pressure, at combustor test conditions as shown in Figures 2.1.2 to 2.1.4. This pressure drop includes both the RCL reactor loss and losses in the downstream combustor (pressure drop across flameholder, dump loss at combustor inlet, fundamental combustion loss, etc.). We estimate that losses in the downstream combustor account for about 0.5% pressure drop, with the remaining 3% attributable to the RCL reactor in Solar's rig. Additional pressure loss data has been obtained for an updated full-scale RCL reactor, intended to provide reduced pressure drop. Based on preliminary test data, this new RCL reactor will give about 2% pressure drop at similar test conditions. Pressure drop will be discussed in more detail in Section 2.2, when we discuss prediction of RCL performance (RCL operating map).

Catalyst Operating Temperatures

Figure 2.1.2 shows steady-state catalyst surface temperatures plotted against adiabatic flame temperature at the full-scale RCL injector exit, as tested at Solar. As shown in Figure 2.1.2, catalyst surface temperature increases only slightly as fuel flow is reduced, and all catalyst surface temperature measurements remain below 780 C (1430 F) over the complete range of operating conditions tested (1440-1700 C / 2620-3090 F range in adiabatic flame temperature).

RCL catalyst temperatures do not vary significantly with fuel/air ratio because reaction rate (heat release) upon the catalyst surface is controlled by oxygen flow (air flow) under fuel-rich conditions, and because heat removal (heat transfer) from the catalyst is also determined primarily by air flow. Fuel flow has little effect on reaction rate and little effect on heat removal rate. This insensitivity of catalyst temperature to fuel/air ratio is advantageous in allowing combustor and turbine operation over a wide range of flame temperatures (including flame temperatures well above the low-NOx-emissions range), making the RCL system suitable even for advanced high-firing-temperature machines.

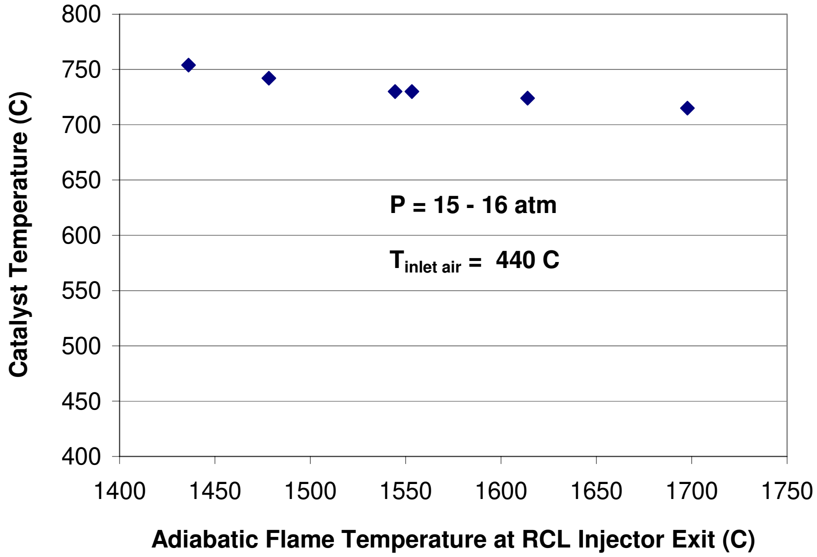

Figure 2.1.2. *Catalyst surface temperature as a function of adiabatic flame temperature at full-scale RCL reactor exit, at 15 atm pressure.*

2.1.2. Sub-Scale Test Data

Catalyst testing under controlled conditions is best conducted at sub-scale, where smaller-size equipment allows for accurate flow metering and control. Thus, accurate values for catalyst lightoff and extinction temperature are obtainable, and catalyst durability tests can be conducted for thousands of hours under constant conditions. Sub-scale testing is also useful for evaluating new concepts, such as use of alternative fuels.

Catalyst Lightoff and Extinction Temperatures

Catalyst lightoff and extinction tests have been performed under well-controlled experimental conditions at sub-scale for pressures from 9 to 15 atm. For natural gas fuel having one or two percent ethane, PCI's catalysts typically light off in the vicinity of 300 C. For natural gas fuel with greater than two percent ethane (or higher-order hydrocarbons) lightoff can occur at inlet temperatures below 280 C. This is shown in Figure 2.1.5 below, which indicates a lightoff temperature between about 260 and 280 C for natural gas fuel, at 15 atm pressure. In Figure 2.1.5, inlet gas temperature, catalyst surface temperature, and gas temperature exiting the module (following mixing of the catalytically reacted stream with the catalyst cooling air stream, but prior to gas-phase combustion) are plotted as a function of time in minutes. Lightoff occurs when the heat of reaction results in an increase in catalyst operating temperature and catalyst exit temperature as compared to the gas inlet temperature.

Following catalyst lightoff, the inlet air temperature can be reduced well below the initial lightoff temperature without extinguishing the catalyst. Thus, once lit (active), the catalyst remains lit (active) down to inlet temperatures approaching ambient. Following the catalyst lightoff event depicted in Figure 2.1.5, the inlet air temperature was reduced to less than 200 C, but catalyst activity was not diminished. This is shown below in Figure 2.1.6, which plots the same parameters as Figure 2.1.5, now after several hours of durability testing following the initial lightoff. Here, still at 15 atm pressure and with the same flow of natural gas fuel, catalyst activity was maintained until the fuel was shut off at an inlet air temperature less than 200 C.

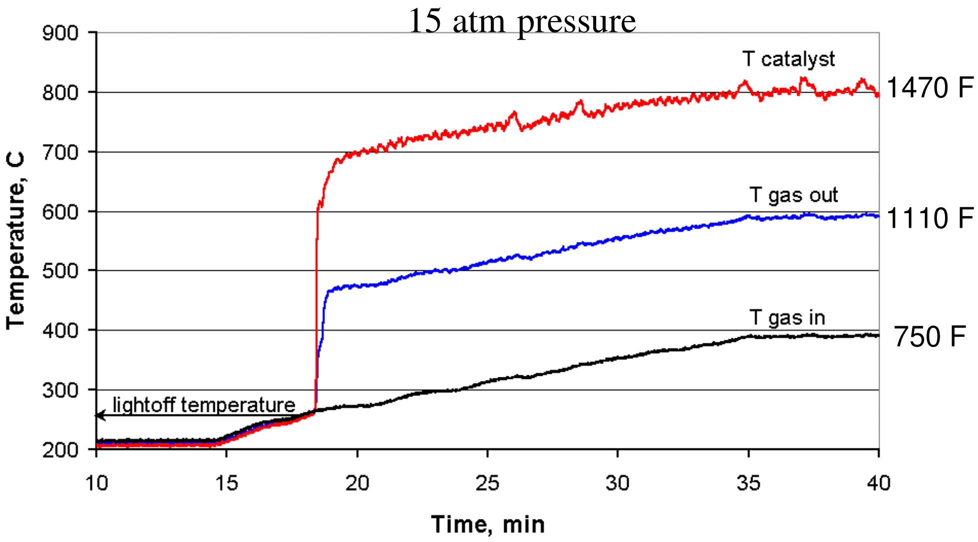

Figure 2.1.5. *Catalyst lightoff in a sub-scale high-pressure (15 atm) RCL reactor operating on natural gas fuel. Inlet gas temperature ("T gas in"), catalyst surface temperature ("T catalyst"), and gas temperature exiting the module ("T gas out") are plotted as a function of time in minutes.*

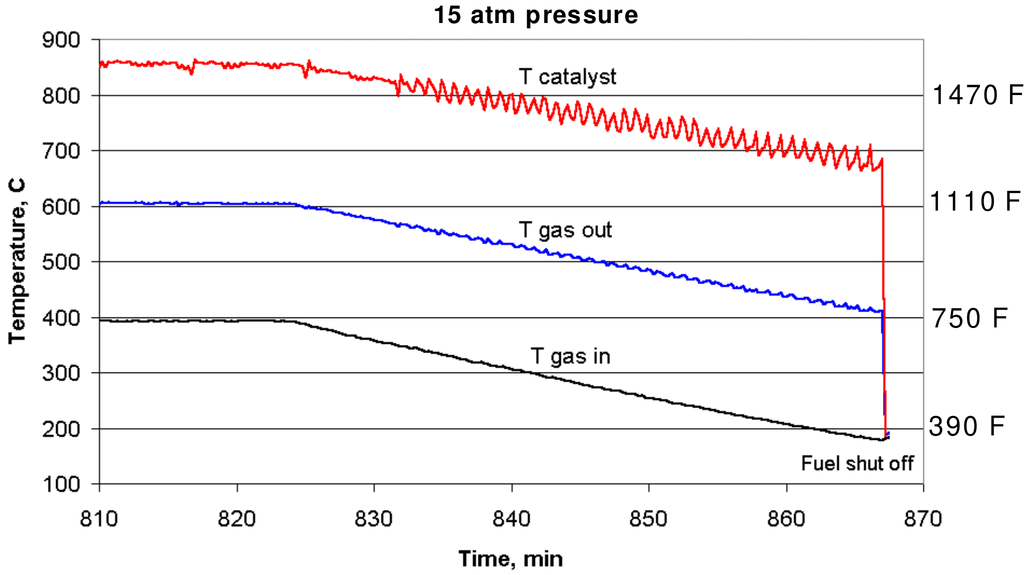

Figure 2.1.6. *Catalyst extinction does not occur until the fuel is shut off at an inlet air temperature less than 200 C. Data were obtained for the same sub-scale high-pressure (15 atm) RCL reactor for which data were shown in Figure 5.1.1. Again, inlet gas temperature ("T gas in"), catalyst surface temperature ("T catalyst"), and gas temperature exiting the module ("T gas out") are plotted as a function of time in minutes.*

Catalyst Durability

RCL long-term durability goal for engine application is targeted for 25,000 hours life. At PCI, durability testing both steady state and transient is ongoing to identify the life limiting component and the corresponding failure mode. Through reactor enhancement and material upgrade, we expect to meet our 25000 hours goal. Based on the extensive durability testing we predict the present hardware configuration will meet our initial market entry of 8,000 hours life.

Multiple sub-scale catalyst and mechanical tests have been performed to evaluate RCL reactor durability. The RCL reactor has been run for more than 1000 hours, and has shown no measurable loss of performance during this period (Figure 2.1.7). Thermal cycle testing on the catalyst support (washcoat) has also been performed, to ensure adhesion to the metal substrate. In addition, the metal substrate itself has been tested for resistance to oxidation for more than 1000 hours, and the reactor braze joints have been pull-tested and inspected after 1000 hours of operation.

Catalyst durability tests were performed at 9 atm pressure. Gas samples were analyzed in a gas chromatograph periodically throughout the test period. Gas sample analysis, and the gas temperature exiting the module, confirmed that the catalytic reactor showed no measurable loss in fuel conversion or gas temperature exiting the module during the more than 1000 hours of testing. Catalyst surface temperatures during the test are plotted in Figure 2.1.7, and also constant performance after the initial 100-200 hour break-in period.

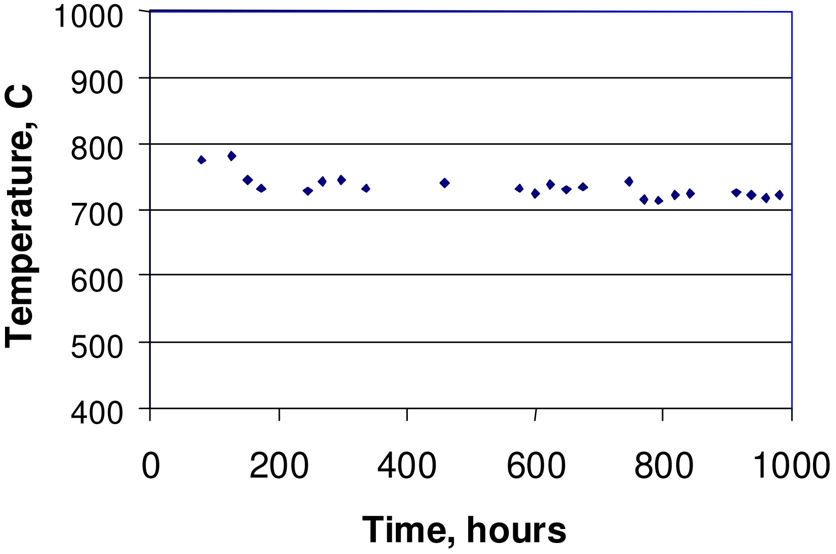

Figure 2.1.7. *Catalyst surface temperatures remain constant during 1000-hour catalyst durability test.*

Catalyst washcoat adhesion has been tested in a Thermal Cycle rig (Figure 2.1.8) for more than 600 cycles, to simulate thermal cycling during engine "trips" or shutdown events. In this test, each thermal cycle is comprised of heating to a peak temperature of 100°C, 150°C or 200°C above the design condition followed by rapid cooling to ambient temperature. A cooling rate of 200-300 C/sec is achieved in the Thermal Cycle rig. Samples are examined after cycle test completion for evidence of washcoat delamination. Results show that all samples are acceptable after completion of the test; the only effect observed is the loss of three very small spots of catalyst at the 200°C above design peak temperature test condition. The general conclusion is that the washcoat/substrate combinations are very resistant to delamination due to thermal shock, and can survive more than the expected number of trip events during the life of the reactor.

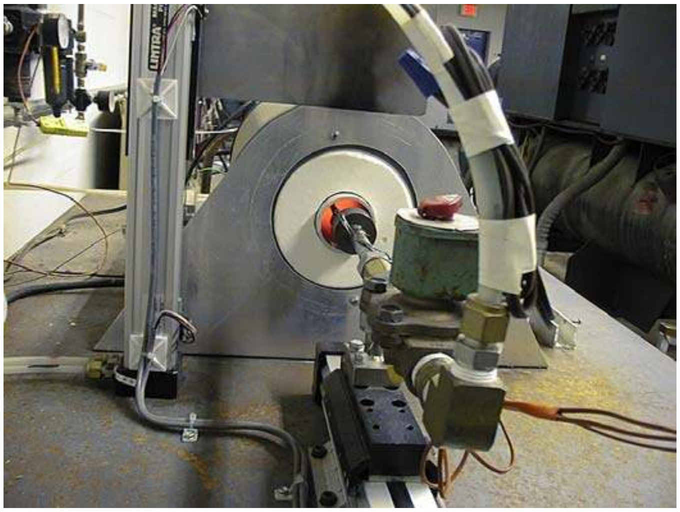

Figure 2.1.8. *Photographs of Thermal Cycle test rig for testing washcoat adhesion. Subscale reactor samples are heated in furnace and then rapidly cooled at 200 - 300 C / sec. Current washcoat is adherent beyond 600 thermal cycles (simulated engine trips).*

Metal substrates have been aged for 10,000 hours in a wet environment at a temperature 50 C above the peak design temperature, and have shown acceptable oxidation rates with the baseline substrate for our targeted first field trial reactor durability (8000 hours at initial market entry). The cooling-air side of the substrates used in the catalyst durability tests are also inspected at the completion of each high-pressure catalyst durability test. Braze samples are also examined at completion of each catalyst durability test, and have shown no signs of oxide penetration with a good indication of braze material integrity. Braze material pull tests have also been performed, and show good strength and integrity. In the RCL reactor braze material is only used at the reactor's cold upstream end, at the combustor inlet temperature; thus, excellent long life performance of the braze material is expected.

Required hot end component life for large power generation machines ranges from 12000-25,000 hours, with a development target of 25,000 hours. Based on durability testing to date, a shift to an available higher oxidation resistant substrate together with related coatings development to ensure adhesion will be sufficient for the RCL system to achieve a target 25,000 hour life. In the cost/benefit section of this report, this higher cost configuration is the baseline that is assumed for costing purposes.

Alternate Fuel Capability

Sub-scale RCL tests have also been performed using alternative (non-natural-gas) fuels. In particular, liquid fuels have been tested (gasoline and Diesel No. 2 fuel) with performance similar to that obtained using methane or natural gas. No changes were made to the reactor or combustor for operation on different fuels. For diesel fuel, however, a prevaporizer was added upstream of the reactor. Two different pre-vaporizers were developed: initially we used a first-generation prevaporizer to directly heat diesel fuel, after adding less than 10% N_2 (by weight) to assist in atomization; PCI later improved prevaporization by using a second-generation prevaporizer, wherein steam was mixed with diesel fuel to maintain vaporization. The latter was considered ideal for co-generation applications. Note that liquid fuel tests were generally performed at 6-8 atm pressure, based on limitations of the fuel prevaporizers.

Figure 2.1.9 compares catalyst lightoff for gasoline and natural gas fuels at 7 atm pressure. As seen, lightoff occurs at a similar inlet air temperature for the two fuels, and catalyst temperature rises to a similar steady-state operating value after lightoff for the two fuels.

Catalyst lightoff and extinction temperatures for diesel fuel were tested at 6 atm pressure using the first-generation prevaporizer, as shown in Figure 2.1.10. For this test, temperature of the pre-vaporized fuel was between 350 and 380 C before mixing with air. For catalyst lightoff, inlet air temperature was ramped up from about 345 C until definitive lightoff occurred at about 360 C inlet air temperature, as indicated by a rapid increase in catalyst temperature. Prior to this event, some reaction occurred along the length of the reactor, as evidenced by catalyst temperatures nearly 75 C higher than the inlet temperature (e.g. 420 C versus 350 C). After lightoff, inlet air temperature was ramped down until sudden loss of activity (catalyst extinction) occurred at about 200 C inlet air temperature. Note that the catalyst extinction temperature (200 C) was well below the catalyst lightoff temperature (360 C). This was true for all fuel types tested under fuel-rich catalyst conditions.

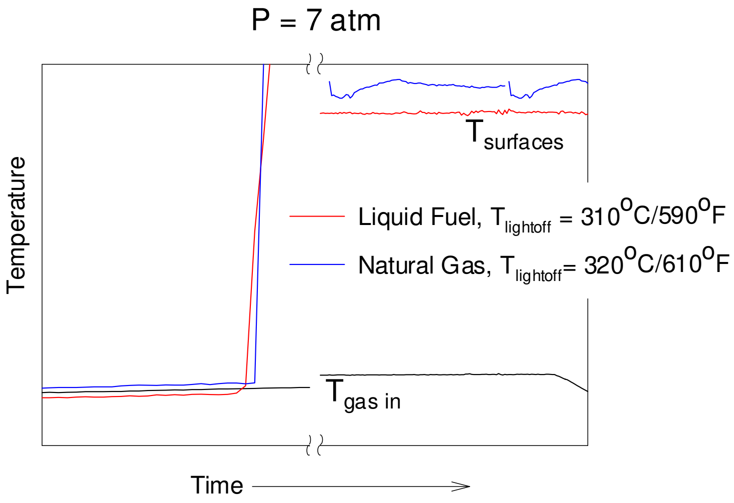

Figure 2.1.9. *Catalyst temperature as a function of time, for operation on two different fuels: gasoline versus natural gas. Catalyst surface temperatures are shown in color (red for gasoline, blue for natural gas), while inlet air temperature is shown in black. Note that catalyst lightoff occurs at a similar inlet air temperature for both fuels.*

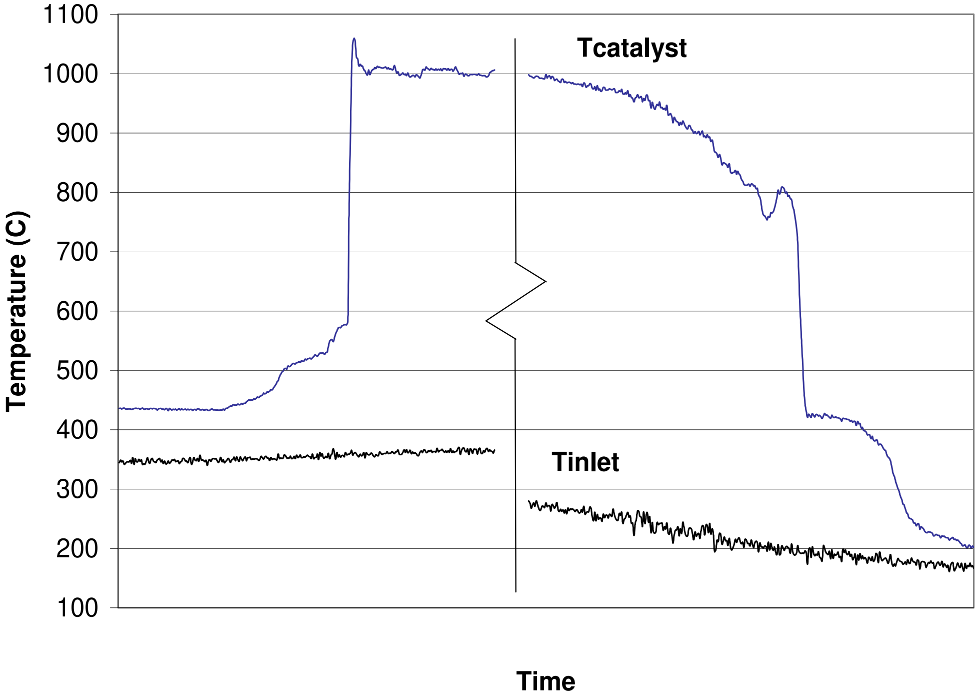

Figure 2.1.10. *Catalyst lightoff and extinction temperatures for diesel fuel. Tests were performed with first-generation prevaporizer, at 6 atm pressure. "Tinlet" represents air temperature entering the reactor, and "Tcatalyst" represents catalyst surface temperature.*

Steady-state catalyst temperature data ("T surface") are shown as a function of the reactor's overall equivalence ratio in Figure 2.1.11, for diesel fuel operation using the second-generation prevaporizer. Diesel fuel operating data were obtained at the pre-vaporizer's maximum operating pressure of 6 atm, and at 430 C inlet temperature. Average gas temperature exiting the reactor ("T gas out") is also shown. Note that "T gas out" and overall equivalence ratio are both defined after mixing of catalyst effluent with catalyst cooling air.

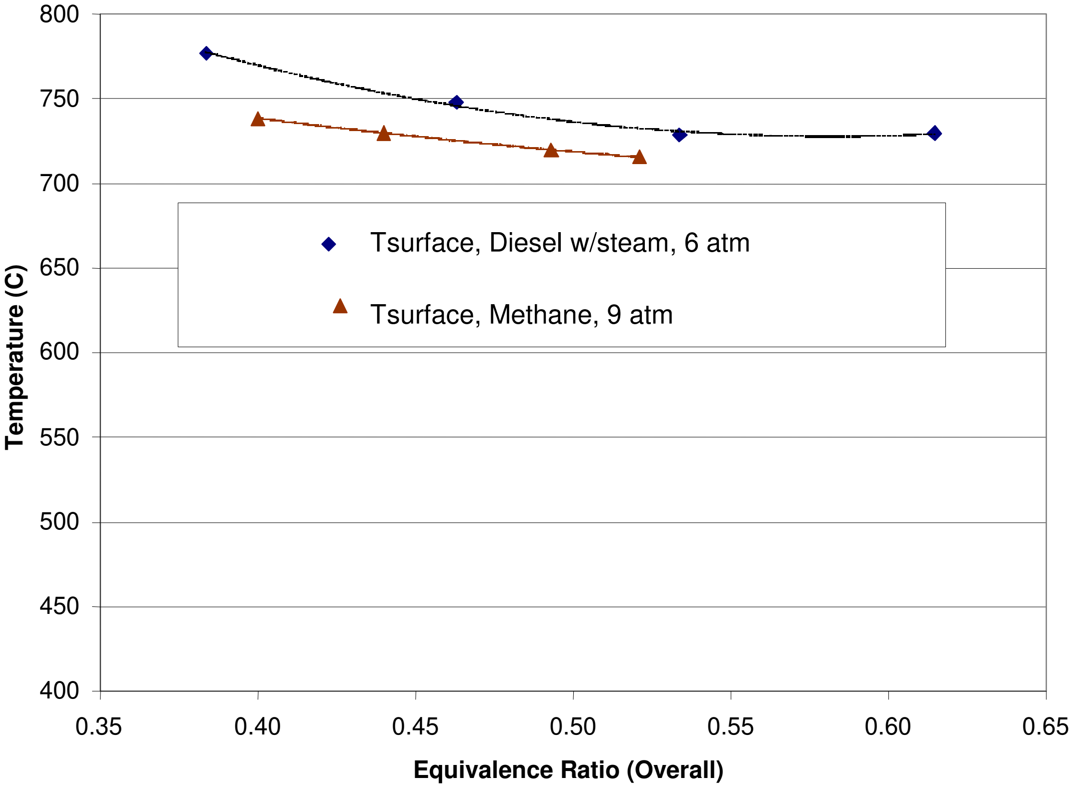

Figure 2.1.11. *Catalyst performance with diesel fuel versus methane, for second-generation pre-vaporizer (~5:1 steam:fuel ratio by weight) operating at 6 atm pressure and 430 C inlet air temperature. Compare to methane tests at 9 atm and 440 C inlet temperature.*

As shown in Figure 2.1.11, catalyst operating temperatures are insensitive to operating condition (overall equivalence ratio) for both methane and diesel fuels, and in general very similar catalyst performance was obtained for both fuels.

As stated earlier, RCL catalyst temperatures do not vary significantly with fuel/air ratio because reaction rate (heat release) upon the catalyst surface is controlled by oxygen flow (air flow) under fuel-rich conditions. Thus, the oxygen available for reaction (the limiting reactant under fuel-rich conditions) is the same at all test conditions, with the result that heat release and temperatures in the catalyst bed are insensitive to equivalence ratio, and are very similar for both methane and diesel fuels despite a wide difference in reactivity between these two fuels.

NOx emissions from RCL combustion have also been measured with liquid fuels, as well as gaseous fuel, in a 9 atm sub-scale combustion test rig. For these tests, gas-phase burnout of all fuel occurred in a lean-premixed mode downstream of the catalyst, in a combustor lined with a 2-inch inside-diameter ceramic insulator. Emissions samples were obtained at about 30 ms residence time.

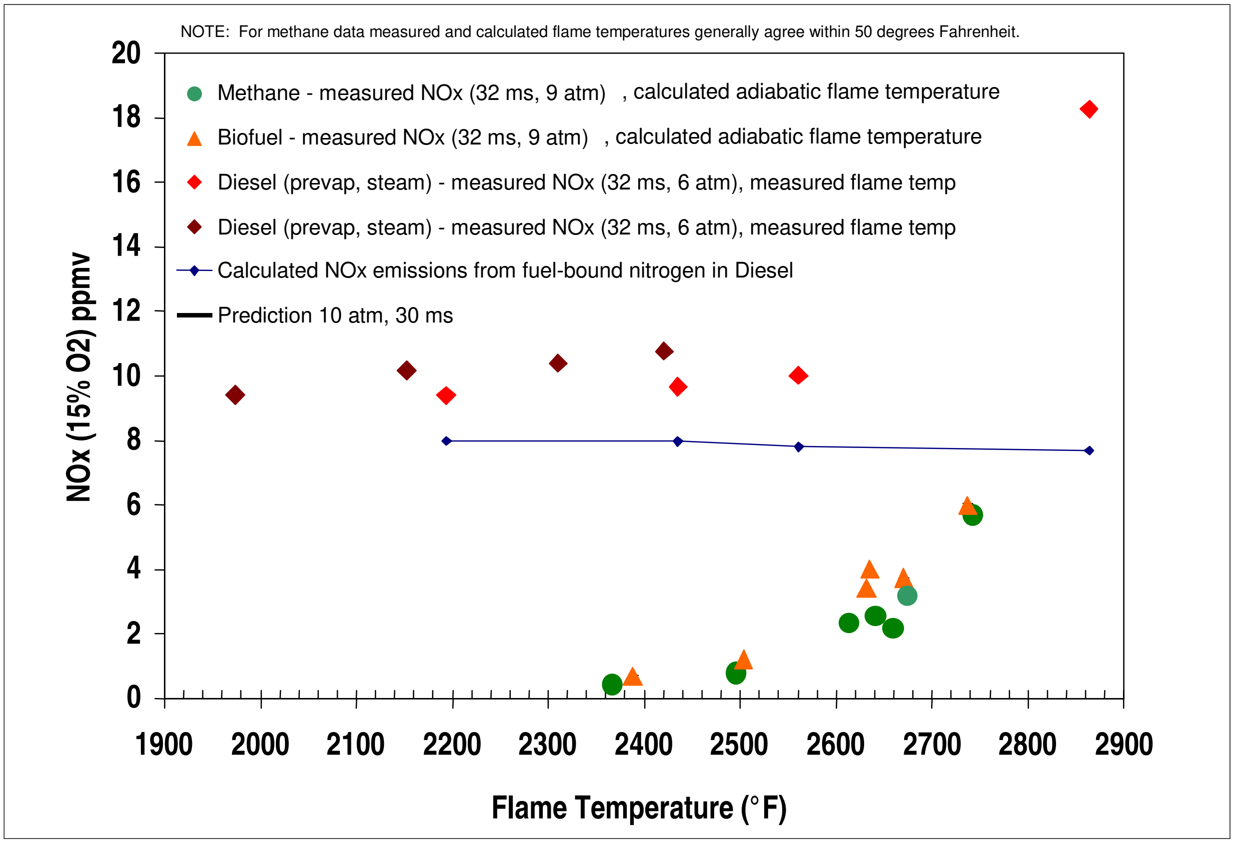

Figure 2.1.12. *NOx emissions for three fuel types (methane, biomass landfill gas, and Diesel No. 2 fuel). For all data points, CO/UHC emissions were less than 2 ppmv. For the Diesel No. 2 fuel, fuel analysis indicated that 8.1 ppmv NOx would be emitted as a result of fuel-bound nitrogen alone.*

NOx emissions are shown in Figure 2.1.12 three fuel types: methane, simulated bio-mass landfill gas (essentially diluted methane), and Diesel No. 2 fuel. Here, NOx emissions are measured on a dry basis and are corrected to 15% excess O_2. NOx emissions are shown as a function of maximum measured flame temperature (via type S thermocouple) for each data point. For all data points obtained, CO and unburned hydrocarbon (UHC) emissions were less than 2 ppmv.

For methane and bio-mass landfill gas fuels, NOx emissions were below 3 ppm for measured flame temperatures below 2600 F. For diesel fuel, NOx emissions were about 10 ppm for measured flame temperatures below 2600 F. This compare to 8.1 ppm expected based on fuel-bound nitrogen alone. Thus, about 2 ppm NOx is likely formed by prompt (non-thermal) mechanisms at low flame temperatures (below 2600 F). At higher flame temperatures, NOx increases due to thermal formation mechanisms for all three fuels, as shown. The low NOx levels at low flame temperature indicates that well-mixed fuel-lean combustion was achieved downstream of the catalyst for all three fuels: methane, bio-mass landfill gas, and diesel.

2.1.3. Engine Operating Experience To Date (RCL-Equipped Saturn Engine)

Four RCL injectors were installed in a modified (single can combustor) Solar Turbines Saturn engine, to assess controls compatibility and transient operation in an engine environment, including engine start, acceleration, and load variation. In addition, steady-state operating data were obtained, including NOx and CO emissions at the engine exhaust. The engine test also provided a basis for evaluating RCL reactor robustness in an engine environment, over a range of operating conditions and demands (including start, acceleration, and load).

Test Engine Specifications and Configuration

The test engine was a modified version of a two-shaft recuperated Saturn T1200 engine, nominally rated at 750 kW (1000 hp) after modification. This engine was selected as a test bed because its external combustor configuration was amenable to modification. For the tests reported here, the recuperator was removed, but the compressor discharge scroll and turbine inlet scroll were retained, allowing a single side-mounted combustor can to be installed.

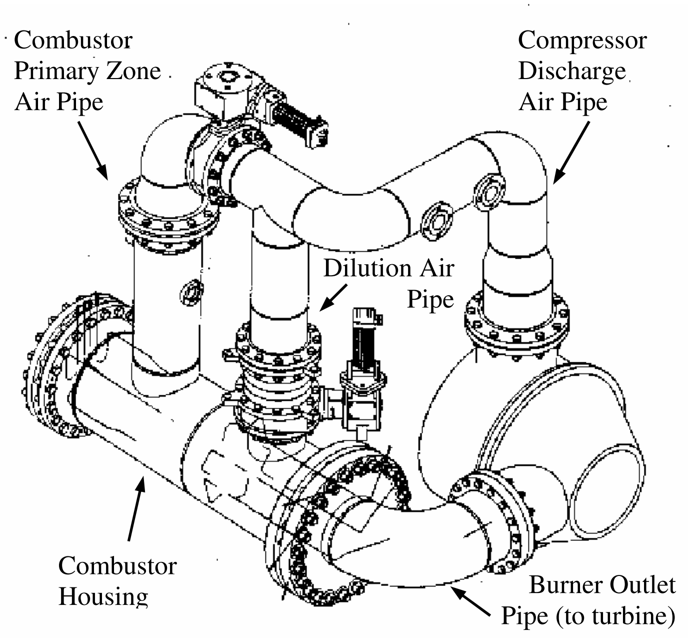

Figure 2.1.13. *Side-mounted combustor configuration in modified Saturn engine, showing variable airflow control valves in primary zone air pipe and dilution air pipe.*

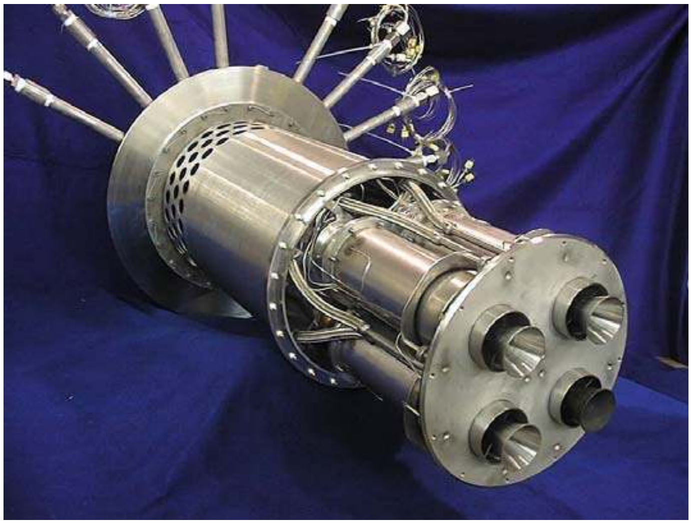

Figure 2.1.14. *Photograph of four-RCL-injector assembly, prior to installation in Saturn engine.*

The overall combustor configuration is shown in Figure 2.1.13. Note that variable airflow butterfly valves were fitted in the combustor primary zone air pipe and the dilution air pipe, to allow combustor air to be varied for best emissions at any given fuel flow (engine load). Also note that a preburner was located in the combustor primary zone air pipe below the butterfly valve, to temporarily increase catalyst inlet air temperature to about 350 C (660 F) to ensure catalyst lightoff. The preburner was turned off after catalyst lightoff, and before engine emissions were measured.

All fuel and air entered the combustor through the four RCL injectors (neglecting leakage air). The combustor liner was backside cooled with dilution air, before the dilution air entered the hot gas path 60 cm (24 inches) downstream of the combustor's upstream end (the round plate through which the post-mix ducts are inserted, visible in Figure 2.1.14, forms the combustor's upstream end). The combustor liner itself was cylindrical and 38 cm (15 inches) in diameter. At full Saturn engine load, and assuming 0.6 kg/s (1.3 pps) airflow through each RCL injector for ultra-low-emissions operation, combustor residence time is about 35 ms.

Engine Operating Procedure

Engine start-up data are shown in Figure 2.1.15, with annotations, giving a graphical depiction of the start-up procedure. Note that there are three fuel circuits: a preburner fuel stage, which received about 25 kg/hr (55 pph) fuel during catalyst lightoff, and two RCL injector fuel stages, which together received up to about 275 kg/hr (600 pph) fuel at load. RCL fuel stage A supplied fuel to the top two injectors, while RCL fuel stage B supplied fuel to the bottom two injectors.

At cold crank conditions (29% gas producer shaft speed, Ngp) the preburner was ignited and adjusted to 260 C (500 F) outlet temperature, below the catalyst lightoff temperature. As seen in Figure 2.1.15, the small preburner fuel flow provided little motive power to the engine and negligible increase in engine speed. Next, while still at 29% Ngp, fuel was introduced to the RCL injectors and combustion was ignited by a torch igniter in the main combustor. With the starter motor still engaged, fuel flow was ramped up as the engine accelerated to 65% Ngp. At 65% Ngp the starter motor was disengaged and the engine controller added fuel to maintain a constant idle speed of 65% Ngp (no load). Preburner outlet temperature remained at 260 C (500 F), and the catalysts remained inactive.

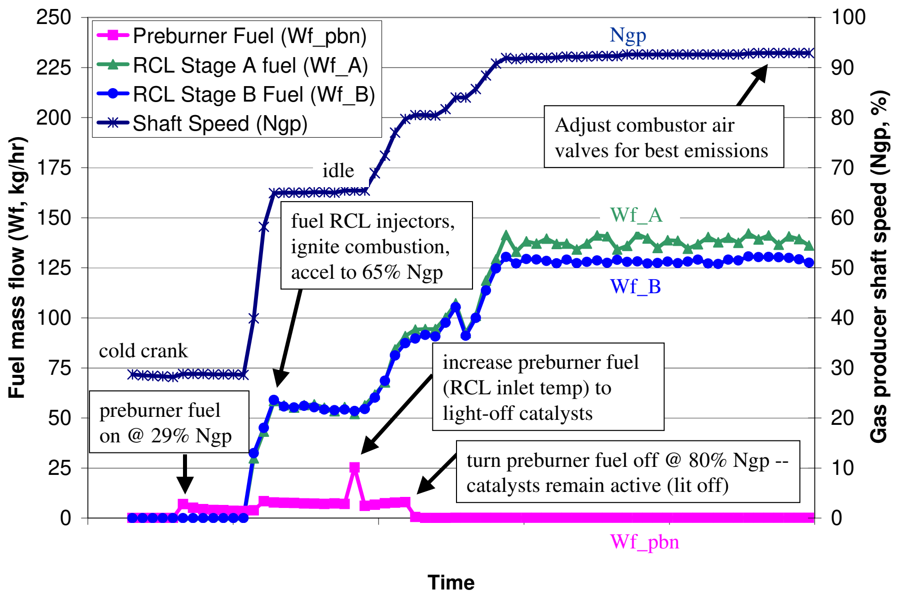

Figure 2.1.15. *Saturn engine start-up data, obtained using RCL combustion, showing engine acceleration, catalyst activation by preburner (followed by preburner shutoff with continued catalyst activity), and loading of engine.*

Preburner temperature was then increased to about 350 C (660 F) to ensure catalyst lightoff. Engine speed was increased to 80% Ngp, the preburner was turned off, and the catalysts remained active. Engine speed was then increased to 90% and the variable airflow valves were adjusted to obtain optimum emissions. The valves served to vary the airflow to the RCL injectors thus allowing control of NOx and CO emissions. Emissions data were taken as engine speed was reduced in increments of about 1% Ngp. The airflow valves were adjusted for best emissions at each speed.

Engine controls were based on a Saturn T1202R design and used a state of the art Allen-Bradley microprocessor console to run the logic. For the RCL combustor engine tests, catalyst temperatures were not used in the fuel control algorithm. Instead, fuel control was performed according to standard DLN methods (primarily monitoring engine speed versus set point), with the addition of a preburner fuel control during initial start and catalyst lightoff. This was possible because catalyst temperature is insensitive to fuel/air ratio under fuel-rich conditions, as shown in Figure 2.1.2 for the single-injector rig tests. In addition, the RCL catalyst is air-cooled by a large fraction of the total combustion air, and reactions on the catalyst are limited by available oxygen (fuel-rich); thus, the catalyst is resistant to flashback, autoignition, and overheating damage, and can operate safely without active temperature control.

Engine Performance with RCL Combustor

With RCL combustion, Saturn engine NOx emissions averaged 2.1 ppm with less than 10 ppm CO over an achievable engine operating range (82% to 89% Ngp), as shown in Figure 2.1.16. Over this engine operating range, UHC emissions remained below 3 ppm, and combustion-driven pressure oscillations (CDPO) remained less than 0.7 kPa (0.1 psi) peak-to-peak (less than 0.15% peak-to-peak of mean combustor pressure).

At 89% Ngp, combustor inlet air (compressor discharge air) was at 5.0 atm and 223 C (434 F). At 82% Ngp, combustor inlet air was at 3.9 atm and 191 C (376 F). For all data points shown in Figure 2.1.16 the preburner was turned off, the catalyst remained active at the available compressor discharge temperatures (as low as 191 C / 376 F), and NOx emissions remained below 3 ppm.

Measured power output ranged from 237 kW (318 hp) to 453 kW (607 hp) over the 82% to 89% Ngp operating range, or about 32% to 61% load based on a 750 kW (1000 hp) nominal power rating for this modified engine. Engine load was delivered to a water dynamometer.

Engine operation was limited to the 82% to 89% speed range. At less than 82% Ngp the compressor was at its surge condition, and the compressor bleed valve was opened to prevent surge. This reduced the airflow to the RCL modules thus increasing NOx emissions. At speeds greater than 89% Ngp operation was limited by locally hot temperatures within the scroll ducting downstream of the combustor. This limitation was not attributable to the RCL combustion technology but to inadequate mixing of combustor dilution air. Improving the test rig dilution mixing was deemed unnecessary to document the controllability of the RCL system.

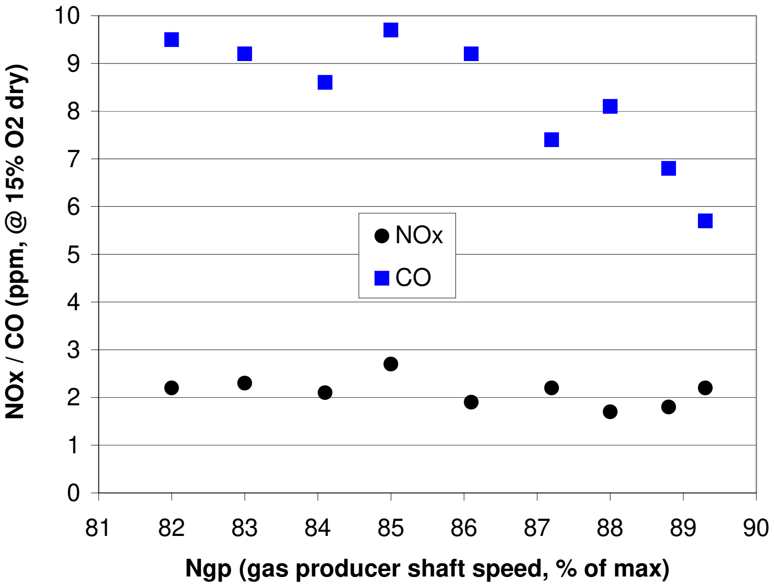

Figure 2.1.16. *RCL combustor emissions during Saturn engine operation, showing ultra-low NOx and CO emissions over an achievable engine operating range of 82% to 89% speed.*

Table 3 summarizes the Saturn engine operating data at the low-end and high-end of the achievable operating range. In general, the results show good combustor performance (low emissions and low noise) even at very low inlet temperatures. In addition, the Saturn engine operation shows the feasibility of engine start-up, acceleration, and operation at load using RCL combustion with simple engine controls. The engine was successfully started, accelerated, and powered at load by fuel injected through the four catalytic reactors, using conventional engine instrumentation and controls without instrumentation input from the catalyst.

Engine Speed	**82% Ngp**	**89% Ngp**
NOx Emissions	2.2 ppm	2.2 ppm
CO Emissions	9.5 ppm	5.7 ppm
CDPO (noise)	< 0.7 kPa pk-pk	< 0.7 kPa pk-pk
Power Output	237 kW / 318 hp	453 kW / 607 hp
Nominal Load	32%	61%
Comb. Inlet Pressure	3.9 atm	5.0 atm
Comb. Inlet Temp.	191 C / 376 F	223 C / 434 F

Table 3. *Saturn engine operating data at low-end and high-end of achievable operating range. Note catalyst activity and ultra-low-emissions achieved at inlet temperatures as low as 191 C (376 F).*

2.2. RCL OPERATING MAP

In applying RCL combustion to different engines and different engine families, overall measures of performance are important, and evaluation of potential barriers are important as well. Thus, for design of a new system we desire to predict both final output (size, pressure drop, combustor turndown and emissions, and catalyst life) and internal behavior (fuel/air flow and mixing requirements, component temperatures, and autoignition risk). Formally, we list each of the critical parameters, and we assign a value based on analysis. Tools for analysis include operating curves based on experimental data (such as presented in Section 2.1) and engineering models including CFD prediction.

The RCL operating map can be divided into 5 groups of Inlet, Premixer, Reactor, Postmix and Combustor. There are generally 16 parameters, which are used to characterize the overall RCL system:

- Inlet: Pressure, Temp, Pressure drop
- Premixer: Equivalence ratio, Unmixedness
- Catalytic Reactor: Catalyst length, $A_{effective}/A_{frontal}$, Split, S/V, Velocity, Exit Temp
- Postmix: Residence Time, Unmixedness, Exit Velocity
- Combustor: Residence Time, Adiabatic Flame Temp

Table 2.2.1 below lists these primary parameters with the ranges tested to develop a valid operating map for the RCL application. We have assigned values for RCL combustor operation in two different F-class machines (GE's 7FA engine and SWPC's W501F engine), based on approximate combustor operating conditions as presented in Section 3.1.1 and 3.1.2 of this report, and based on preliminary design assumptions for construction of the RCL reactor (i.e. consistent with our current design practice and experience base). Determination of these values constitutes an operating map for the RCL system in each given application. The check mark √ under each OEM represents that each parameter is within the exiting RCL operating map.

Table 2.2.1. *Summary of RCL Operating Map based on Reactors/Combustors Tested.*

Parameters	***Ranges Tested***	***GE 7FA***	***SWPC 501F***
INLET			
Inlet Pressure	1 - 17 atm	√	√
Inlet Temperature	190 – 600C (microturbines)	√	√
Combustor Press. drop	2 – 7%	√	√
PREMIXER			
Equivalence Ratio	1.5 (low load) – 15 (Start-up)	√	√
Premixer Unmixedness	<5% rms for low NOx	√	√
CATALYTIC REACTOR			
Catalyst length	CONFIDENTIAL	√	√
Effective area / frontal area	CONFIDENTIAL	√	√
Air split to catalyst vs. cooling	CONFIDENTIAL	√	√
Reactor superficial velocity	CONFIDENTIAL	√	√
Surface/volume ratio	CONFIDENTIAL	√	√
Exit mixed gas temperature	550 – 700C	√	√
POSTMIX			
Residence time-no autoignition	1 – 3 msec	√	√
Unmixedness	<5% rms for low NOx	√	√
Exit velocity	CONFIDENTIAL	√	√
COMBUSTOR (Backside cooled)			
Combustor residence time	15 – 35 msec	√	√
Calculated adiabatic flame temp.	3ppm NOx: 2400 – 2650F Safely tested up to: 3200F	√	√

2.3. PREDICTION OF EMISSIONS PERFORMANCE AT F-CLASS CONDITIONS

Analysis suggests that NO_x emissions of less than 2 ppm are achievable for GE's 7FA engine with PCI's RCL® combustion system. Specifically, NO_x less than 2 ppm is achievable for primary zone flame temperatures up to 2875F, a temperature higher than the primary zone flame temperature of 2760- 2800F for the 7FA engine. The key to achieving these low NO_x emissions is use of the RCL combustion system, which enables stable combustor operation requiring a significantly smaller percentage of fuel/air mixture participating in the central recirculation zone

(CRZ). Most of the combustor NO_x is produced in this CRZ, and by decreasing the amount of fuel/air mixture in this zone, NO_x can be significantly reduced.

Analysis

The purpose of this analysis is to assess the NO_x potential for application of PCI's RCL technology for natural gas in GE's 7FA combustor. In the analyzed configuration a small portion (in the range of 5 – 10%) of the fuel flow is combusted non-catalytically in the central recirculation zone. The analyzed RCL combustion system for GE's F class engine is shown in Figure 2.3.1.

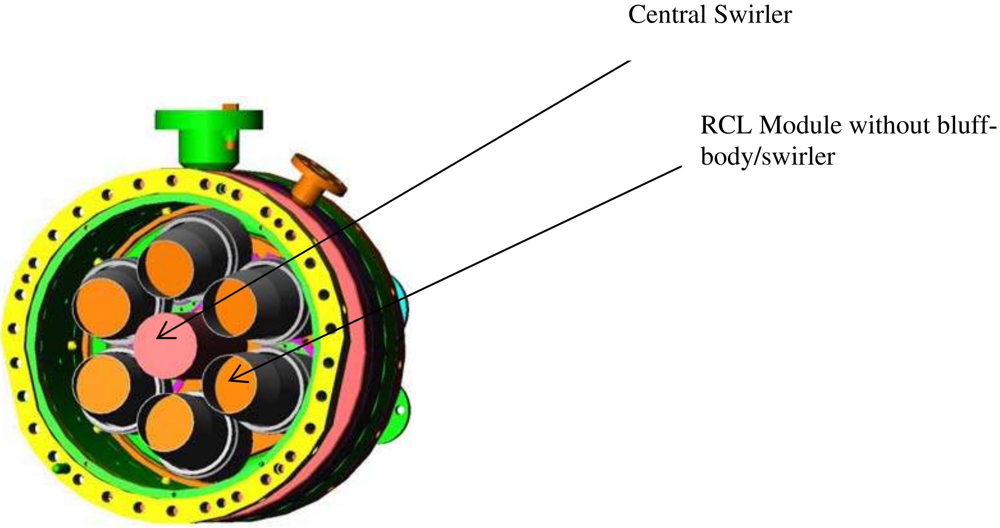

Figure 2.3.1: Combustor arrangement proposed for GE's F class machine

In this combustion system configuration for GE's F class engine, 6 RCL modules surround a central swirler. In this design, the central swirler is used to create a central recirculation zone for anchoring the central flame. However, the fuel/air mixture exiting the RCL reactors plug flow through the combustor. In this configuration fuel and air split in the swirler may range from 5 – 10%. This type of configuration will be referred hereafter as "**Low-CRZ**". Because of inherent stability provided by the RCL reactor due to pre-reaction of the fuel, a recirculation zone downstream of each RCL nozzle is not necessary.

In contrast to configuration 1, configuration 2 (which is not shown) uses seven RCL modules for each combustor, with each RCL module having a bluff body (cone/swirler) at the end of the postmix section prior to flow entering the combustor. The differences between the two configurations are that configuration 2 has a bluff body/swirler at the end of each RCL module and no central lean premix swirler. A recirculation zone is created downstream of each RCL module for configuration 2, because of the use of the bluff body (cone)/swirler.

To assess NO_x emissions potential for both the configurations, reactor models, along with GRI mechanism version 3.0 for methane combustion was used. Figure 2.3.2 shows the reactor model used for Low-CRZ combustor configuration. We observe from Figure 2.3.2 that 90% of the fuel flow passes through the catalytic reactor and then enters the PFTR (plug flow tubular reactor), without participation in the central recirculation zone. The rest (10%) of the fuel and air mixture enters the CSTR, signifying the fuel/air mixture that enters the combustor through the swirler. After 0.5 msec of residence time, the mixture exiting out of the CSTR mixes with the products exiting the catalytic reactor and then enters the PFTR reactor. In the combustor, this represents the entrainment of products from the re-circulation zone by the jet exiting the RCL catalytic reactor. The PFTR portion of the reactor model signifies the burnout zone of the combustor.

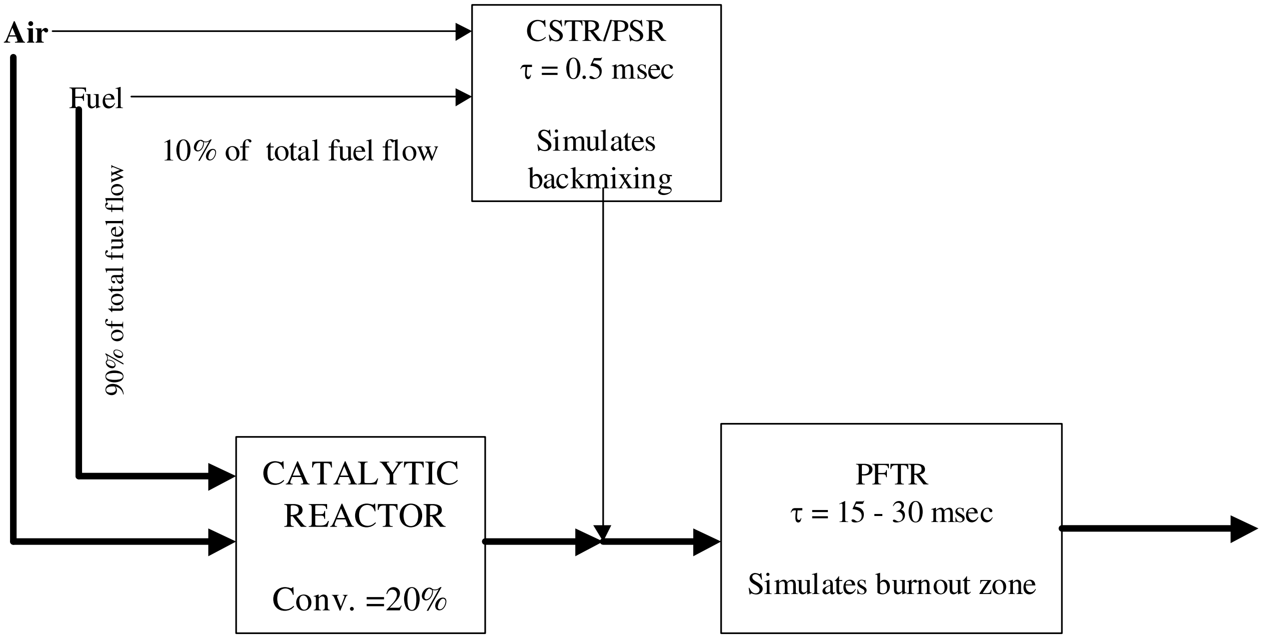

Figure 2.3.2: Reactor model to describe Low-CRZ combustor configuration 1

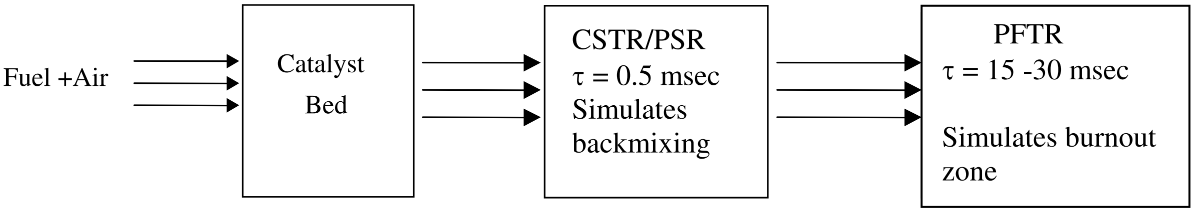

Figure 2.3.3:- Reactor model used to describe combustor configuration 2

Figure 2.3.3 shows the reactor model for configuration 2. The fuel and air mixture first enters the catalytic reactor and then enters the CSTR reactor followed by the PFTR reactor.

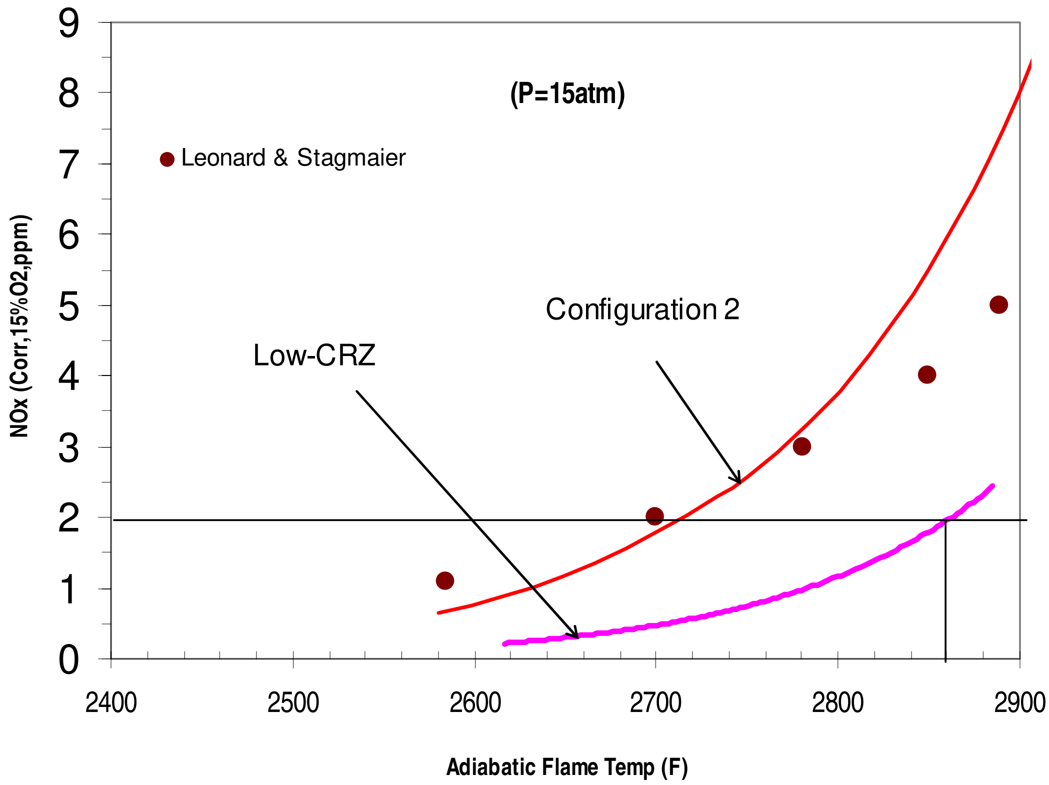

Figure 2.3.4: Prediction of NO_x by simpler reactor model for different combustor configurations

Figure 2.3.4 shows the NO_x predictions for both combustor configurations 1 and 2 along with experimental data of Leonard & Stagmaier, 1994 [30], who obtained the NO_x data from sector testing of GE's LM6000 combustor. This combustor configuration used swirlers to create vortex breakdown.

The predictions show significant advantage of NOx emissions especially at higher flame temperature for c Low-CRZ configuration over configuration 2. The decrease of NO_x emissions for combustor Low-CRZ configuration can easily be explained by the non-participation of a significant portion of the flow in the recirculation zone, modeled as CSTR. In summary Low-CRZ configuration can achieve NO_x less than 2 ppm for adiabatic flame temperatures up to 2875 ^oF versus a 2 ppm flame temperature of 2725 ^oF for configuration 2. The data suggest that NO_x less than 2 ppm can be achieved comfortably for a primary zone temperature of 2760 ^oF for an FA (GE) class engine, and potentially for the FB.

In conclusion, flame stability augmentation by use of the RCL combustion system allows significant NO_x emissions benefit for a combustor in which the fuel/air mixture percentage in the recirculation zone is reduced. More specifically this RCL approach could enable NOx emission less than 2 ppm for GE's 7FA engine, and potentially low single digit NO_x for the 7FB engine.

Comparison of Prediction Results with Experimental Data

Figure 2.3.3 shows a comparison of the experimental prediction with the experimental data obtained during testing of a full-scale RCL combustion system at T70 conditions at Solar Turbines' single injector testing facility. The testing was conducted in an regular Taurus 70 liner and was not optimized to take advantage of RCL technology. The data points, NOx (solid diamonds) and CO (solid circles), with lines drawn through them show the emissions as function of adiabatic flame temperature calculated from emission measurement at the emission rake. Also shown in the same figure, is the model prediction for a overall combustor residence time of 30 msec. The test data was obtained from the combustor also had a nominal residence time of 30 msec. We observe reasonable quantitative agreement between the model and the experimental data and it appears experimentally higher NOx was observed than that was predicted. However it should be noted that the adiabatic flame temperature plotted in Figure 2.3.3 is taken at the measurement rake plane. This experimental temperature was calculated with a number of cooling and leakage flows included that remained unmixed and did not participate in the flame front. Thus, the experimental curve as plotted should be translated an unspecified amount to the right, the maximum bound of which is calculated to be 243 ^{o}F.

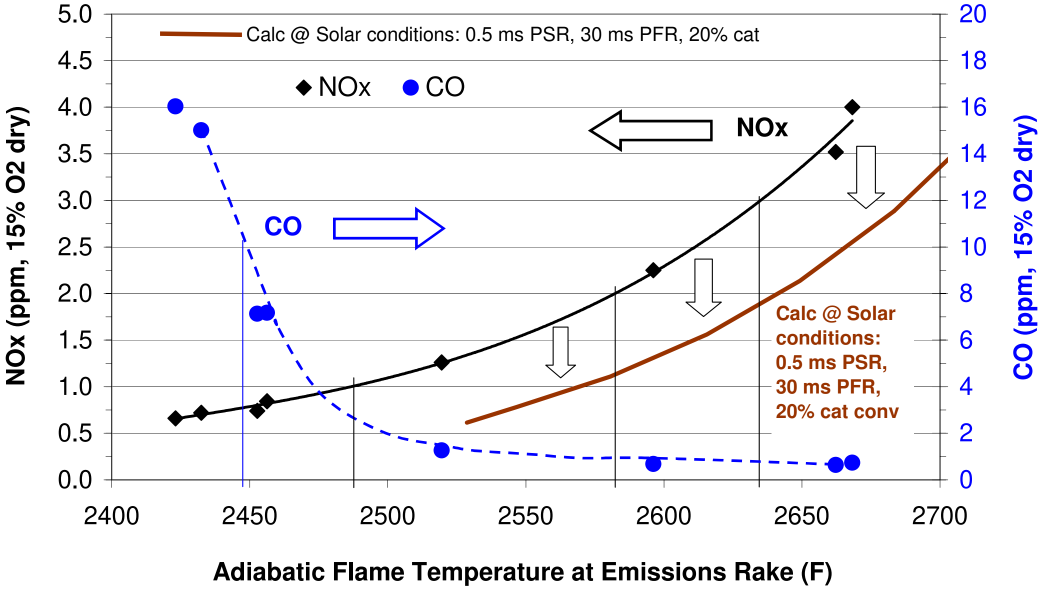

Figure 2.3.3. *Comparison of experimental data to the model prediction.*

This experimental uncertainty of 243 ^{o}F is much larger than the difference of approximately 80^{o}F (@ 2 ppm level) between the experimental data and the prediction shown in Figure 2.3.3. Thus the experimentally observed NOx emissions is quantitatively well predicted by the model.

3. RCL TECHNOLOGY FIT WITH EXISTING DLN MACHINES

3.1. ENGINE MANUFACTURER F-CLASS ENGINE DATA

For power-generating gas turbines, the highest firing temperatures are found on the largest machines, where the required technologies are cost effective as a result of improved machine efficiency. Thus, F-class firing temperatures are offered for large frame engines manufactured by both General Electric Power Systems (GEPS) and Siemens Westinghouse Power Corporation (SWPC). (Alstom offers an alternative technology using sequential combustion at slightly lower firing temperatures which we will also discuss below.) Note that F-class engines currently provide the highest power output in each engine frame size (neglecting applications in which internal engine parts require steam cooling, i.e. G- and H-class machines), since increase in firing temperature is generally accompanied by increase in pressure ratio and mass flow (compressor modification) for optimum performance.

A summary table of current F-class machines is given in Table 3.1.1 below. Table 3.1.1 also includes Alstom's similar frame-size engines using sequential combustion, and Siemens's annular-combustion engines ("A" designation). Note that Table 3.1.1 excludes GE's "FB"-class turbines, which operate at higher firing temperatures than the low-emissions F-class turbines of other manufacturers (e.g. more than 100 F higher than GE's "FA"-class turbines).

Table 3.1.1. *Summary of current F-class utility-scale gas turbine engines (from recent publications).*

Manufacturer	**Engine**	**Duty**	**Simple Cycle Power**	**Firing Temp (TRIT)**	**Pressure Ratio**	**Exhaust Mass Flow**	**Exhaust Gas Temp (EGT)**
General Electric[1-2]	6FA	50/60 Hz	76 MW	~2400 F	15.6	447 pps	1120 F
	7FA	60 Hz	172 MW	2420 F	15.5	952 pps	1116 F
	9FA	50 Hz	256 MW	~2400 F	15.4	1375 pps	1129 F
Siemens Westinghouse[3-7]	V64.3A	50/60 Hz	67 MW	2175 F	15.8	421 pps	1092 F
	W501F	60 Hz	187 MW	2420 F	16	1015 pps	1094 F
	V94.3A	50 Hz	265 MW	2250 F	17.0	1420 pps	1084 F
Mitsubishi Heavy Industries[8]	M501F	60 Hz	185 MW		16		
	M701F	50 Hz	270 MW		17		
Alstom[9]	GT24	60 Hz	179 MW	2290 F	30	862 pps	1184 F
	GT26	50 Hz	262 MW	2290 F	30	1239 pps	1184 F

[1] GE information from GE pamphlet published in 2002: "Gas Turbine and Combined Cycle Products," available at http://www.gepower.com/corporate/en_us/assets/gasturbines_heavy/prod/pdf/gasturbine_2002.pdf.

[2] GE 7FA TRIT from GE Report number GER-4194, "The 7FB: The Next Evolution of the F Gas Turbine."

[3] V64.3A TRIT: "Evolution of the V64.3A Gas Turbine," Diesel & Gas Turbine Worldwide, June 2001.

[4] V94.3A TRIT: "Advanced Burner Development for the VX4.3A Gas Turbines," ASME Paper No. 2001-GT-0077.

[5] V64.3A/V94.3A pressure ratio, mass flow, and exhaust temperature: Gas Turbine Forecast, May 2002.

[6] W501F TRIT and pressure ratio: "The 2001 Powerplant Award -- Klamath cogen counters California Calamity," POWER Magazine, May/June 2001.

[7] W501F mass flow and exhaust temperature: Gas Turbine Forecast, October 2002.

[8] M501F and M701F pressure ratio: "M501F / M701F Gas Turbine Uprating," ASME Paper No. 2001-GT-0553.

[9] Alstom information from Alstom web sites for GT24 / GT26 information and technical data: http://www.power.alstom.com/servlet/ContentServer?pagename=OpenMarket/Xcelerate/View&inifile=futuretense.ini&c=Page&cid=978628276564; and http://www.power.alstom.com/servlet/ContentServer?pagename=OpenMarket/Xcelerate/View&inifile=futuretense.ini&c=Page&cid=978628276564&pfid=400457.

As seen in Table 3.1.1, for all manufacturers the largest machines operate at 50 Hz (3000 rpm) and can generate well over 200 MW simple cycle power. In the 60 Hz US market, where large machines operate at 3600 rpm, machine size is slightly reduced to give equivalent rotor tip speeds. Thus, power output from 60 Hz machines is somewhat less, generally in the range of 170 MW simple cycle power for F-class machines. Smaller machines operate at higher speeds and can be geared for either 50 or 60 Hz electric power generation.

For all current F-class machines (Table 3.1.1), exact mass flow through the machine at varying loads is controlled by variable inlet guide vanes (IGVs). This provides multiple benefits, including control of exhaust gas temperature for combined cycle applications, and extension of low-emissions turndown range (by control of combustor airflow). The IGVs are also used to improve low-speed compressor surge characteristics (in combination with compressor bleed) and to adjust machine performance during variations in ambient temperature. Some machines are also equipped with variable guide vanes (VGVs) for the first several compressor stages (e.g. Alstom GT24, Siemens V84.3, and GE's H-class engines). This is of interest for catalytic combustor design since it allows some control of airflow through the combustor, for improved low-emissions turndown and operability.

The following sub-sections of this report provides greater detail for the engines of most immediate interest for RCL combustion (e.g. ultra-low-emissions market).

3.1.1. General Electric Power Systems (GEPS) F-Class Engines

GE Power Systems manufactures five different F-class type machines. Three of these are FA-class (6FA, 7FA, and 9FA), and two are FB-class (7FB and 9FB). The FA-class machines operate at a nominal turbine rotor inlet temperature (TRIT) of 2,400 F, while the FB-class machines operate at a nominal TRIT of 2,500 F. Using GE's Dry Low-NOx (DLN) combustor technology, NOx emissions below 9 ppm can be achieved at FA-class firing temperature, while the higher-firing-temperature FB-machines deliver somewhat higher emissions.

The 7FA 60 Hz machine is of most interest for low-emissions applications in the U.S. 7FA baseload operating conditions are listed in Table 3.1.2 below, as published by GE (see reference 1 from Table 3.1.1):

Table 3.1.2. *Baseload operating conditions for GEPS 7FA engine (simple-cycle operation).*

Engine	Output (MW)	Heat Rate (kJ/kWh)	Pressure Ratio	Mass Flow (pps)	Exhaust Temp (F)	Number of Combustors
GE 7FA	171.7	9936 (36% eff)	15.5:1	952	1116	14

For low-emissions operation GE's H-class machine, developed under the DOE-ATS program, is also of interest. By using closed-loop steam cooling of the first-row stator vanes, upstream of the first rotating turbine blades, the H-machine's TRIT was increased by about 200 F (as compared to FA-class machines) without an increase in combustor outlet temperature. Thus, low NOx emissions similar to the FA-class engines can be achieved with improved engine efficiency.

Table 3.1.3. *Baseload operating conditions for GEPS 7H engine.*

Engine	Output (MW)	Heat Rate (kJ/kWh)	Pressure Ratio	Mass Flow (pps)	Exhaust Temp (F)	Number of Combustors
GE 7H	--	--	23:1	1230	--	12

7H baseload operating conditions are listed in Table 3.1.3 above, as published by GE (GE Report number GER-3935A). Note that because steam-cooling is required, the H-class engines are only available for combined-cycle operation. Thus, simple-cycle output and efficiency are not listed. Also note that temperature drop across the first-row stator vanes is about 80 F for GE's H-class machines, as compared to about 280 F for GE's FA-class machines (GE Report number GER-3935A).

Nominal combustor operating conditions can be calculated from the published engine data, assuming a typical 90% efficiency for the compressor. Thus, for the 7FA engine, compressor discharge temperature (combustor inlet temperature) will be approximately 745 F on a standard day (59 F) at 15.5 pressure ratio ($\gamma_{\text{air}} \sim 1.4$). Based on the published 2420 F turbine rotor inlet temperature (TRIT) and the 280 F temperature drop across the first-row stator vanes, combustor outlet temperature is about 2700 F. Combustor airflow can also be calculated. Assuming that roughly 10% of the total air is used to cool the turbine blades, disks, and intermediate stators, then 13% of the total air is used for cooling of the first-row stator vanes (to give the 280 F temperature drop). This leaves about 77% of total air for combustion. Based on total engine exhaust flow and 14 combustors, airflow per combustor is about 52 pps (neglecting fuel mass flow). This 52 pps represents an approximate value, since actual cooling air requirements for the turbine are not known (not published).

Based on the above assumptions, we can tabulate approximate combustor operating conditions at full load for the 7FA engine, as shown in Table 3.1.4 below. Fuel flow is calculated from engine heat rate and power output (using the lower heating value for methane fuel). Air and fuel flows are for a single combustor (one of fourteen total on the 7FA engine). Note that a calculation of combustor outlet temperature from the fuel and air flows in Table 3.1.4 yields 2720 F (in good agreement with the 2700 F number based on published data), corroborating that combustor airflow is about 52 pps.

Table 3.1.4. *Calculated (approximate) combustor operating conditions for 7FA engine.*

GE 7FA Load	Pressure	Combustor Airflow	Combustor Inlet Temperature	Combustor Outlet Temperature	Fuel Flow (Methane)
100%	15.5 atm	52 pps	745 F	2700 F	1.50 pps

The 7FA operating conditions are well-suited to RCL combustion, as will be discussed in detail in Section 3.2 below. Briefly, the combustor inlet temperature is well above the fuel-rich catalyst lightoff temperature for an RCL reactor, such that a preburner is not required; the combustor outlet temperature is well within the range where ultra-low NOx emissions are achievable; and the 15 atm pressure allows for a compact catalytic reactor.

3.1.2. Siemens Westinghouse Power Corporation (SWPC) F-Class Engines

The W501F (60 Hz) frame-size F-class engine is sold by Siemens Westinghouse. The 501-series engine was originally developed by the Westinghouse Electric Company, before the merger with Siemens KWU. Variations of the basic 501 frame engine are also sold by Fiat and Mitsubishi. For the 50 Hz market, Siemens Westinghouse sells the Siemens-developed V94.3A engine, as well as the smaller, geared V64.3A engine for the 50/60 Hz market (see Table 3.1.1).

For the U.S. market, the W501F engine is of most interest, and its baseload operating conditions are tabulated in Table 3.1.5 below:

Table 3.1.5. *Baseload operating conditions for SWPC W501F engine (simple-cycle operation).*

Engine	Output (MW)	Heat Rate[1] (kJ/kWh)	Pressure Ratio	Mass Flow (pps)	Exhaust Temp (F)	Number of Combustors[1]
W501F	187	9633 (37% eff)	16:1	1015	1094	16

[1] Heat rate and number of combustors from Gas Turbine Forecast, October 2002.

The W501F engine uses a 4-stage turbine. Thus, as compared to the 7FA engine (3-stage turbine), cooling air requirements per stage are less (smaller size stages). Temperature drop across the first-row stator vanes, due to stator cooling air entering the flow, is therefore less than the 280 F drop reported for the 7FA engine. Assuming, roughly, that the cooling-air requirement and temperature drop scale inversely with the number of stages, we would expect about a 210 F drop in the W501F engine's first-row stator vanes. Thus, for the same TRIT, the combustor outlet temperature in the W501F engine is less than in the 7FA engine, providing a NOx advantage if combustion stability requirements can be met (as, for example, by the use of an RCL catalytic combustion system).

Approximate combustor operating conditions can be calculated for the W501F engine, based on the published engine data and an assumed 210 F temperature drop across the first-row stator vanes. Thus, again assuming a typical 90% efficiency for the compressor, compressor discharge temperature (combustor inlet temperature) for the W501F engine will be approximately 755 F on a standard day (59 F) at 16:1 pressure ratio ($\gamma_{air} \sim 1.4$). Based on the published 2420 F turbine rotor inlet temperature (TRIT) and the assumed 210 F temperature drop across the first-row stator vanes, combustor outlet temperature is about 2630 F. To calculate combustor airflow, again assume that roughly 10% of the total air is used to cool the turbine blades, disks, and intermediate stators. For the assumed 210 F temperature drop across the first-row stator vanes, 10% of the total air would then be required for cooling of the first-row vanes. This leaves about 80% of total air for combustion. For a total engine exhaust flow of 1015 pps and 16 combustors, airflow per combustor is about 51 pps (neglecting fuel mass flow). As before, this 51 pps represents an approximate value, since actual cooling air requirements for the turbine are not known (not published).

The calculated, approximate full load W501F combustor operating conditions are tabulated in Table 3.1.6 below. Fuel flow is calculated from engine heat rate and power output (using the lower heating value for methane fuel). Air and fuel flows are for a single combustor (one of sixteen total on the W501F engine). Note that a calculation of combustor outlet temperature from the fuel and air flows in Table 3.1.6 yields 2640 F, in good agreement with the 2630 F number based on the published TRIT and the assumed 210 F temperature drop across the first-row vanes.

Table 3.1.6. *Calculated (approximate) combustor operating conditions for W501F engine.*

W501F Load	Pressure	Combustor Airflow	Combustor Inlet Temperature	Combustor Outlet Temperature	Fuel Flow (Methane)
100%	16 atm	51 pps	755 F	2630 F	1.39 pps

The W501F combustor operating conditions are quite similar to the 7FA operating conditions, and again are well-suited to RCL combustion, as will be discussed in more detail in Section 3.2 below. Briefly, the combustor inlet temperature is well above the fuel-rich catalyst lightoff temperature for an RCL reactor, such that a preburner is not required; the combustor outlet temperature is well within the range where ultra-low NOx emissions are achievable; and the 16 atm pressure allows for a compact catalytic reactor.

3.2. RCL APPLICATION TO F-CLASS ENGINES

In the sub-sections below, we discuss RCL applications to current F-class engines, based on the combustor operating conditions presented in Section 3.1 above. Approximate, calculated full load combustor operating conditions (from Section 3.1) are summarized in Table 3.2.1 below, for reference during the following discussions.

Table 3.2.1. *Summary of calculated (approximate) full load combustor operating conditions.*

Engine	Pressure	Combustor Airflow	Combustor Inlet Temperature	Combustor Outlet Temperature	Fuel Flow (Methane)
7FA	15.5 atm	52 pps	745 F	2700 F	1.50 pps
W501F	16 atm	51 pps	755 F	2630 F	1.39 pps

PCI's design goal for all manufacturer's engines is to fit the RCL system within the existing engine and combustor casing. Because the RCL premixer and reactor are compact, as compared to alternative fuel-lean catalyst technologies, and because a preburner is not required for F-class engines, it is generally possible to meet this goal. The RCL system also requires minimal modification to the engine control system: as discussed in Section 2.1.3, an RCL-equipped Saturn engine was operated without control-system monitoring of catalyst temperatures; instead, fuel control was performed according to standard DLN methods (primarily monitoring engine speed versus set point). It is therefore also a design goal, in all manufacturer's engines, to use existing DLN engine controls, with only minimal modification as required if fuel staging sequences and transient event fuel flows (e.g. startup, load shedding, etc.) are changed.

In general, the RCL modules specifically designed for each manufacturer's engine will replace the existing swirler (injector) and premixer space. Each RCL module contains an integrated premixer, catalytic reactor, and post-catalyst mixing duct. The exit of the post-catalyst mixing duct delivers the fuel-lean fuel/air mixture to the combustor's primary zone. Other than combustor cooling air, no additional fuel or air is added downstream of the catalyst. Combustion stability (and noise), turndown, and emissions performance are improved as a result of heat release in the RCL catalytic reactor, providing an effectively higher inlet temperature and reduced fuel burn requirement to the combustor.

3.2.1. RCL Application to Can-Combustor F-Class Engines (7FA and W501F)

Basic Considerations and Layout

Both large-frame 60-Hz F-class machines manufactured in the U.S. (the 7FA and the W501F) use can-annular combustion chambers. The combustion system in GE's 7FA engine consists of 14 can-annular combustion chambers, each canted at an angle of roughly 20-degrees from the rotor axis. Similarly, the combustion system in SWPC’s W501F engine consists of 16 can-annular combustion chambers, each canted at an angle of roughly 40-degrees from the rotor axis. For each combustor (in both engines), a cylindrical combustor casing (pressure vessel) extends forward from the engine shell at this cant angle, to contain the upstream portion of the combustor and the fuel injection assembly. Thus, the combustion system is fully accessible from outside the engine, and is amenable to inspection, servicing, and retrofit, and is therefore also amenable to installation and servicing of a catalytic combustor.

In can combustion systems of this type, fuel and air are injected parallel to the combustor centerline, from the combustor’s upstream end. For Dry Low-NOx (DLN) systems, there are generally several swirlers/injectors mounted in a circular-type arrangement. For example, GE’s DLN-2.6 combustor design (Vandervort [29]) consists of six "PM" (premixed) fuel injectors/swirlers. One of the six swirlers is located on the combustor centerline, with the remaining five spaced equally around it.

For RCL combustion, some or all of the OEM’s swirlers/injectors can be replaced with RCL reactors injecting premixed, catalytically pre-reacted fuel and air into the combustor. A configuration which combines many of the advantages of RCL combustion with DLN flame stabilization is shown in Figure 3.2.1. Here, the DLN-2.6 system is modified such that the center PM injector remains as a non-catalytic, highly-swirled DLN-type injector, while the remaining five injectors are replaced with RCL reactors. This provides a central flame anchor zone (the non-catalytic swirler) while still catalytically pre-reacting the majority of fuel entering the combustor, for maximum catalytic benefit in terms of combustion stability and turndown, and reduced combustion noise.

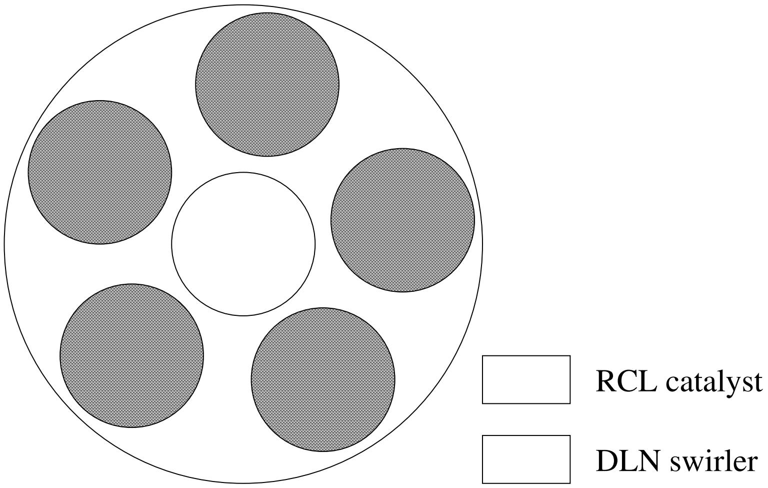

Figure 3.2.1. *Possible configuration for RCL combustion system in can-type combustor. View is aft looking forward (facing into flow), from combustor exit. Central DLN swirler is non-catalytic, and provides a recirculation zone for flame anchoring within the combustor. The central swirler can also be used for engine start.*

The central non-catalytic swirler can also be used for engine start if operated alone, without fueling of the RCL modules. Thus, all fuel to the combustor can pass through the central swirler at engine start, ensuring that fuel/air ratios in the flame anchor zone are within flammable limits at all engine conditions, including start. The size of the central swirler will be determined in part by start-up needs, to ensure combustion stability when the central swirler is operated alone, but will also be determined by the desire to maximize fuel and air flowing through the RCL modules (to provide maximum catalytic benefit).

If there is insufficient frontal area to accommodate multiple RCL modules in each combustor can (based on the RCL size required to meet combustor pressure drop requirements), a single annular RCL module can be used, with a central swirler placed inside the annulus. This uses the empty space that would otherwise exist between modules. An example of this type of arrangement is pictured below (Figure 3.2.2), as disclosed by Siemens Westinghouse in U.S. Patent No. 6,415,608. Note that the Siemens Westinghouse variation uses six flat-sided sectors to create the annulus, resulting in a hexagonal-type shape.

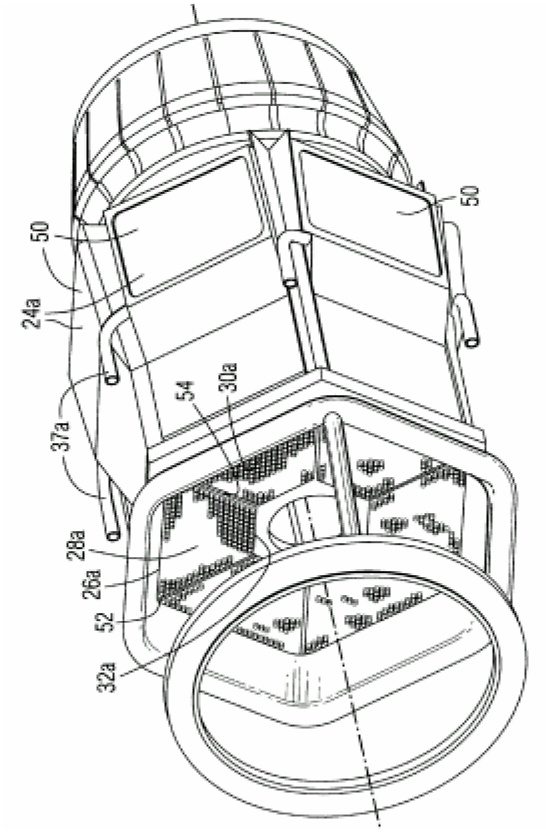

Figure 3.2.2. *Annular RCL modules surrounding central non-catalytic swirler, as depicted in Siemens Westinghouse patent (U.S. Patent No. 6,415,608). Note use of six flat-sided segments or sectors to create full annulus.*

As compared to the annular RCL module design, the use of multiple RCL modules in place of existing DLN-type swirlers/injectors has several advantages. First, by simply replacing existing swirlers/injectors, modifications to the existing combustion hardware are less extensive, making this arrangement more amenable to retrofit applications. Second, the use of multiple RCL modules allows greater flexibility of fuel staging, allowing improved combustion performance (e.g. pattern factor, combustion efficiency, etc.) during startup and part-load operation, and allowing tuning of the combustor to quiet combustion dynamics if needed. The greatest disadvantage to use of multiple RCL modules (other than space constraints) is probably fabrication cost.

The RCL combustion system can also be operated without swirl, although an alternative flame anchor means is then required (the RCL's catalytic reactor is intended to improve combustion stability, but is not intended to induce auto-ignition). For example, a flameholding body can be placed downstream of the post-catalyst mixing zone in one or more RCL modules. This was the method of flame anchoring used during RCL combustion tests at Solar, including both high-pressure single-injector rig tests and Saturn engine testing. For the Saturn engine, a separate flameholding cone was placed downstream of each of the four RCL modules. Each cone was held in place by four thin, streamlined struts attached to the post-catalyst mixing duct walls. The cones were hollow, shaped to a 20-degree half-angle, and about 2.5 inches in diameter at their base. The use of a flameholding cone is effective in anchoring combustion; however, the cone is less effective than a swirler in expanding the injected fuel/air flow into the combustor volume. In addition, the cone is located well downstream of final fuel/air mixing and is in close proximity to the primary combustion zone: it therefore suffers from the potential for overheating damage unless provisions are taken to provide air cooling.

Frontal Area Requirements

Now consider the frontal area required for application of RCL combustion to the 7FA and W501F engines. In all cases, we assume that 1.5% pressure drop through the RCL reactor is acceptable, and we calculate required size on this basis. Note that this 1.5% loss is through the catalyst only, and does not include downstream dump losses in the combustor, fundamental pressure loss due to downstream combustion, or engine flow losses upstream of the reactor. Thus, total combustion system pressure losses are higher, and typically exceed 3-4% for most engines. Actual combustor pressure drop data is not published, however, and is not available.

For the 7FA full load combustor conditions shown in Table 3.2.1, and assuming 1.5% pressure drop through the RCL reactor, a frontal (cross-sectional) area of 135 in^2 (13.2-inch diameter circle) is required if all fuel and air for a single combustor pass through the RCL reactor(s). For the W501F full load combustor conditions, and again assuming 1.5% pressure drop, a frontal (cross-sectional) area of 130 in^2 is required (12.8-inch diameter circle). If the RCL reactors were made annular about a central swirler, these required diameters would likely decrease somewhat, since some flow would be diverted to the less-restrictive (more open) non-catalytic swirler.

Catalyst Performance, including Lightoff and Extinction

The combustor inlet temperatures for the 7FA and W501F engine at full load are well above the lightoff temperature for fuel-rich methane reaction on the RCL catalyst. However, for a cold day (-25 F), combustor inlet temperature at full load falls to about 550 F for the 7FA engine and about 560 F for the W501F engine (again assuming 90% compressor efficiency). This is marginal for catalyst lightoff, and is near the expected catalyst lightoff temperature. For cold day operation, therefore, it may be desirable to provide a means for reducing compressor efficiency to give higher combustor inlet temperatures (via bleeds, guide vane adjustment, etc.), or to provide a means for preheating of the engine or combustor inlet air. Alternatively, the catalyst lightoff temperature can be lowered by doping the fuel with a low-lightoff temperature fuel such as hydrogen.

Regardless of the lightoff means, once the catalyst has been lit off it will remain lit off at temperatures well below 400 F, so that the lightoff means can be almost immediately discontinued (i.e. compressor efficiency can be returned to normal, preheaters can be shut off, or fuel doping can be discontinued) and the catalyst will remain lit at essentially any engine load. For example, the RCL catalyst remained lit during all Saturn engine loads tested, including operation at 3.9 pressure ratio and 376 F combustor inlet temperature (82% Ngp engine speed).

Emissions Performance

For the approximate 2700 F combustor outlet temperature of GE's 7FA engine, the NOx model presented in Section 2.3 predicts between 2 and 3 ppm NOx emissions, depending on the residence time of the stirred (back-mixed) flow which provides flame anchoring, and the residence time of the plug flow burnout zone. One advantage of catalytic combustion is that the improved flame stability allows a smaller flame anchor zone, and allows burnout in a shorter length (less fuel to burn in the gas phase). Thus, for RCL combustion it may be possible to modify the combustor to deliver 2ppm NOx at a 2700 F burner outlet temperature. For retrofit applications, however, where modifications are less, NOx emissions of about 3 ppm may be achievable.

The somewhat lower combustor outlet temperature in SWPC's W501F engine (approximately 2630 F) allows NOx emissions at even lower levels. In fact, the NOx model presented in Section 2.3 shows NOx emissions below 2 ppm at 2630 F flame temperature for all residence times considered. Thus, reduced stator cooling air requirements provides a measurable NOx benefit. Improvements in stator and turbine materials, as well as cooling technologies (air or steam) may therefore be used in the future to reduce NOx emissions without penalty to machine performance in terms of power output or efficiency (without altering the machine's TRIT).

3.2.2 RCL Application to Annular-Combustor F-Class Engines

Siemens (Germany) and Alstom are manufacturers of F– class engine with annular combustor. Pratt-Whitney’s FT-8 engine also uses an annular combustor. In the case of annular configuration, we have developed an RCL combustor for Solar Turbine’s Taurus 70 engine, which uses a similar annular combustion system. This engine is mainly used for mechanical drives (industrial) and is a more compact engine than an F class engine. The RCL combustion system that we have been developing replaces each DLN nozzle with an RCL module, and these RCL modules are distributed circumferentially. To fit RCL modules in the combustor, slight modification of the combustor liner within the pressure vessel is required. RCL technology for this engine provides the opportunity to reduce NOx emission to less than 3 ppm.

Based on our ongoing experience of developing this combustion system, we believe developing annular combustion system for F class machine involves scaling up the RCL module to permit much higher flow rates of fuel and air. As the F class machines are much larger in size than the Taurus 70 engine, accommodating these larger modules inside the annular combustor will be not as challenging. Since the operating pressure and flame temperature in annular combustor for F class machine will be quite similar to that of the Taurus 70 machine (approximately 17 atm and 2700 °F RCL primary zone flame temperature), the emission performance will be similar.

4. SYNGAS AND ALTERNATIVE FUELS IN RCL COMBUSTION

As discussed in Section 2.1, the RCL reactor has been tested on a range of fuels, including gasoline and Diesel No. 2 fuel, with similar performance to that obtained on natural gas. The primary issue for operation on heavy liquid fuels is prevaporization. Reactor performance is not sensitive to the fuel's reactivity, because reaction rate (heat release) upon the catalyst surface is controlled primarily by oxygen flow (air flow) under fuel-rich conditions, and not by fuel flow or reactivity. Performance on different type fuels will therefore be similar when heat release per atom of oxygen reacted is similar, and when the fuel's mass and thermal capacity is negligible in the fuel/air mixture. This is generally the case for hydrocarbon fuels.

For coal-derived syngas fuel, heat release per atom of oxygen reacted is similar to hydrocarbon fuels, but the large volume of fuel is not negligible. Thus, while RCL reactor performance for syngas fuel can be made similar to that obtained on hydrocarbon fuels, the design must consider the large volume of fuel.

In addition, lean-premixed combustion for syngas fuels has not been considered acceptable, because the high concentration of hydrogen leads to increased risk for flashback and flameholding in regions upstream of the combustor. Thus, it has generally been considered preferable to burn syngas fuels in a non-premixed mode, with NOx control accomplished by dilution of the fuel stream with water and/or nitrogen. This introduces combustion stability issues, however, such that low single-digit NOx emissions have not yet been achieved for syngas fuel. One solution to the combustion stability problem is to catalytically react some portion of the syngas fuel prior to gas-phase combustion, effectively providing a higher inlet temperature to the combustor.

4.1. RCL APPLICATION FOR SYNGAS FUEL

The RCL technology developed for natural gas uses the fuel flexibility of RCL^{TM} catalytic reactor in a combustion system for syngas fuel. Based on 10atm laboratory testing at PCI, RCL operation with syngas fuel was successfully demonstrated. NOx emissions were generally near 0.01 lbs/MMBtu (corresponding to 2.0 ppm NOx corrected to 15% O_2 dry). The emissions levels were achieved at scaled (10 atm, sub-scale) baseload conditions corresponding to Tampa Electric's Polk Power Station operation on 100% syngas (no co-firing of natural gas).

Tests were performed in PCI's sub-scale 10 atm high-pressure test rig, using PCI's two-stage (catalytic / gas-phase) combustion process for syngas fuel. In this process, the first stage is a catalytic reactor, wherein a fuel-rich mixture contacts the catalyst and reacts while final and excess combustion air cool the catalyst. The second stage is a gas-phase combustor, wherein the catalyst cooling air mixes with the catalytic reactor effluent to provide for final gas-phase burnout and dilution to fuel-lean combustion products.

Currently, NOx emissions from conventional coal-fired power plants vary widely, from about 0.4 to 2.0 lbs/MMBtu depending on burner type. Low-NOx coal burners can reduce these emissions by roughly half, with the lowest NOx emissions achieved being 0.10 lbs/MMBtu with sub-bituminous coal. But ultra-low NOx emissions, to compete with natural gas fired turbines, requires alternative combustion means or aftertreatment.

One promising approach is coal gasification, followed by combustion of the resulting syngas within a gas turbine engine. IGCC power plants have been proven to achieve high efficiency with low emissions, including NOx emissions guarantees of less than 25 ppmv (at 15% O2), corresponding to about 0.1 lbs/MMBtu. However, further reduction in NOx emissions, by dilution of the fuel with inert gases, faces barriers in terms of flame stability and impact on overall cycle efficiency.

Catalytic combustion is known to improve flame stability, and can also reduce NOx emissions without excessive use of diluent, thus maintaining cycle efficiency. RCL catalytic combustion system is especially well suited for syngas fuels, since it is designed to operate robustly and with constant performance using a wide range of fuels.

Based on reactor testing using a syngas fuel made from a fixed blend of gases, namely 25% H_2, 35% CO, 20% N_2, and 20% CO_2 , the following observations were made:

- For fuel-rich conditions, syngas lightoff temperature is about 180 C, while extinction temperature is < 80 C.
- Start-up and transient operation is accomplished similar to actual IGCC engine. Startup was accomplished by bringing the reactor to fuel-rich conditions using methane fuel, with some diluent addition to ensure proper mixing. When necessary, a small amount of H_2 was temporarily added to light off the reactor. Once the catalyst and combustor were lit and the rig was thermally stable, syngas fuel flow was ramped up while methane fuel flow was ramped down, holding catalyst equivalence ratio approximately constant. This startup procedure was both safe and economical: it minimized the use of high-volume (costly) laboratory syngas fuel blend, and also avoided use of H_2 during transient.

High-Pressure (10 atm) Test Hardware and Experimental Setup

A sub-scale catalytic reactor for high-pressure testing with syngas fuel was fabricated at PCI, and is shown prior to final assembly in the photograph in Figure 4-1. The reactor housing is the long piece shown in Figure 4-1. Flow is from top-right to bottom-left in the photograph. During assembly an injector for syngas fuel is fitted at the upstream end of the reactor, where fuel and air mix to provide a fuel-rich fuel/air mixture to the catalyst. The large flange-like piece shown in the photograph contains the fuel plenum, and syngas fuel is delivered through the needle-like injectors shown.

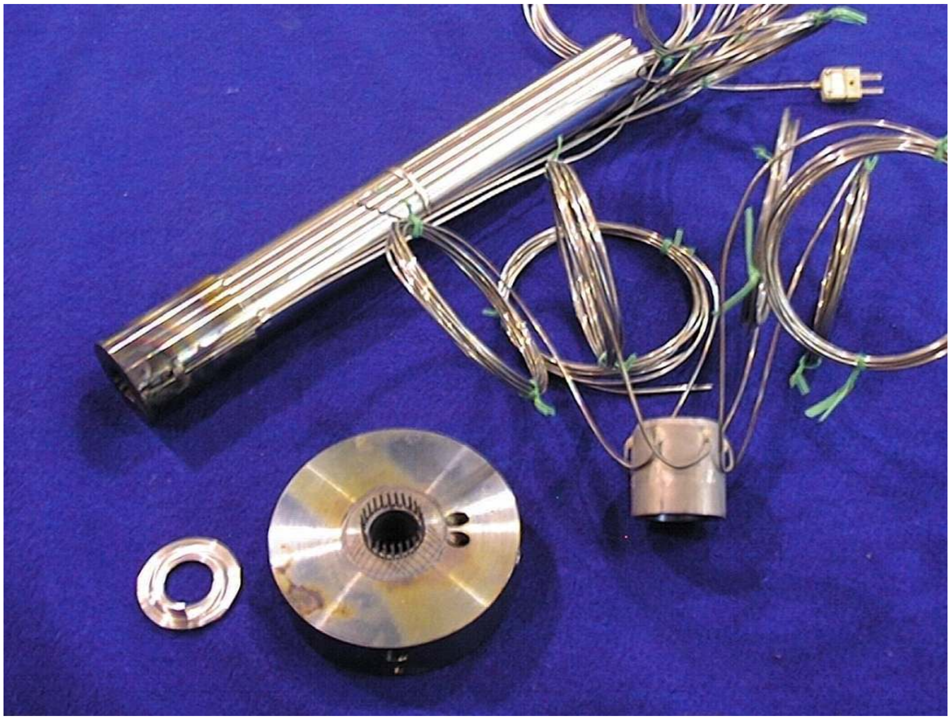

Figure 4-1. *Photograph of sub-scale catalytic reactor for syngas combustion.*

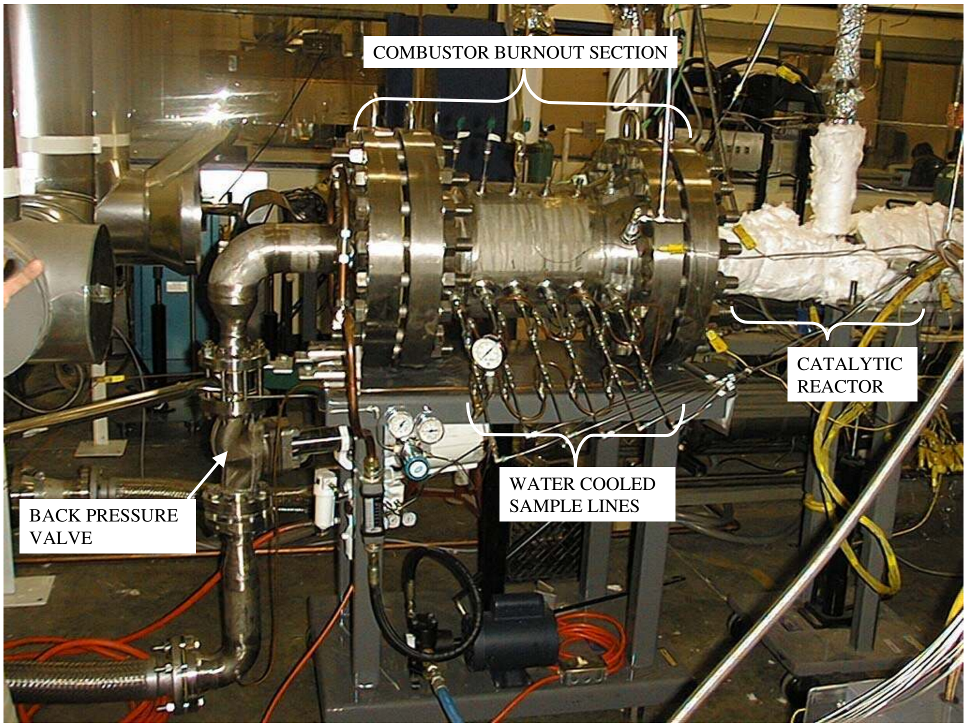

Figure 4-2. *Photograph of PCI's 10 atm sub-scale combustor rig for syngas combustion.*

The combustor burnout section is instrumented with 6 type-S thermocouples to measure flame temperatures axially along the combustor liner at 3-inch increments, and 6 gas sample extraction ports (one at each axial thermocouple location). A hydrogen torch is used to ignite gas-phase combustion. This torch remains on during rig stabilization (to ensure safe burnout of all fuel prior to the rig exhaust, even if the catalytic reactor is not yet lit off), but is turned off prior to obtaining steady-state data.

Basis for High-Pressure Test Conditions

For the high-pressure sub-scale tests, "baseline" operating conditions are based on the IGCC plant at Tampa Electric's Polk Power Station. The Tampa Polk plant operates a GE 107FA combined cycle system on syngas generated from a Texaco oxygen-blown coal gasifier. Nitrogen injection reduces the effective heating value of the fuel, for NOx control.

At the Tampa Polk plant, the syngas composition entering the combustor is shown in the first row (Row 1) of Table 4-1 below, as published in DOE's Clean Coal Technology Topical Report Number 19, "Tampa Electric Integrated Gasification Combined-Cycle Project, An Update" July 2000. Row 1 shows the composition following syngas cleanup, but before mixing with injected nitrogen in the combustor. Row 1 also shows the Lower Heating Value (LHV) of this undiluted fuel. Row 2 of Table 4-1 shows the effective syngas composition following mixing with injected nitrogen in the combustor (assuming that fuel and nitrogen mix prior to mixing with combustion air). Row 2 also shows an "Equivalent" Lower Heating Value for this diluted fuel. The Row 2 "Equivalent" Lower Heating Value was obtained from GE Report number GER-4207 ("GE IGCC Technology and Experience with Advanced Gas Turbines"), and the fuel composition in Row 2 was calculated based on dilution of the Row 1 fuel to this heating value. Note that wet sulfur scrubbing removes virtually all ammonia from the syngas prior to its entering the turbine.

Table 4-1. *Syngas composition at Tampa Electric Polk Power Station.*

Row Number	Nitrogen Dilution	H_2 (%)	CO (%)	CH_4 (%)	CO_2 (%)	N_2+Ar (%)	H_2O (%)	LHV or Equivalent LHV
1	no	38.3	42.7	0.1	14.4	4.2	0.3	240 Btu/ft^3
2	Yes	19.2	21.4	0	7.2	52	0.2	120 Btu/ft^3

Engine operating conditions for syngas fuel are not published. However, natural gas operating conditions can be used as a starting point to approximately calculate engine operating conditions. GE's 7FA engine conditions are tabulated in Table 4-2 for baseload operation on natural gas (from GE pamphlet: "Gas Turbine and Combined Cycle Products" available at www.gepower.com/corporate/en_us/assets/gasturbines_heavy/prod/pdf/gasturbine_2002.pdf.).

Table 4-2. *Baseload operating conditions for 7FA engine (natural gas, simple-cycle operation).*

Engine	Output (MW)	Heat Rate (kJ/kWh)	Pressure Ratio	Mass Flow (pps)	Exhaust Temp (F)	Number of Combustors
GE 7FA	171.7	9936 (36% eff)	15.5:1	952	1116	14

For the 7FA engine, compressor discharge temperature (combustor inlet temperature) will be about 745 F on a standard day (59 F ambient) at 15.5 pressure ratio, assuming $\gamma_{air} \sim 1.4$ and 90% efficiency for the compressor. These values are for natural gas operation, and represent an approximate condition for syngas operation (since mass flow and pressure drop through the turbine change somewhat for syngas operation).

Table 4-3. *Operating data for Tampa Polk plant, from DOE's Clean Coal Technology Topical Report Number 19, July 2000 "Tampa Electric IGCC Project, An Update."*

GE 7FA Power Output	Coal Feed to Gasifier	Carbon Content of Coal (Typical Analysis)	Hydrogen Content of Coal (Typical Analysis)	Oxygen Feed to Gasifier	Nitrogen Feed to Gas Turbine
192 MW (100%)	2,200 tons/day	73.76%	4.72%	2,171 tons/day	5,600 tons/day

Also, for syngas operation turbine rotor inlet temperature is lower than during natural gas operation. For example, GE Report number GER-4207 discusses NOx emissions for a baseload combustor exit temperature of 2550 F using syngas fuel, which is about 150 F less than the nominal 2700 F baseload combustor exit temperature for natural gas fuel (2420 F TRIT plus 280 F temperature drop across the first-stage nozzle, as published by GE). Also note that combustor airflow is affected because some compressor air is extracted for the air separation unit (ASU).

"Baseline" fuel and air flows (for the Tampa Polk plant's 7FA engine) can be calculated from data provided by DOE's publication (Clean Coal Technology Topical Report Number 19, "Tampa Electric IGCC Project, An Update" July 2000). Table 4-3 lists the relevant data.

For the carbon/hydrogen ratio listed in Table 4-3, and for the syngas composition listed in Row 1 of Table 4-1, the 2171 tons per day oxygen feed makes 2090 ft^3/s syngas, or about 150 ft^3/s of syngas to each of the engine's 14 combustors. This calculation is based on the overall (average) reaction

$$4.4\ C_{13}H_{10} + 16.3\ H_2O + 27.6\ O_2 \rightarrow 38.3\ H_2 + 42.7\ CO + 14.4\ CO_2$$

At the engine's combustors, about 5600 tons/day of N_2 is added, to bring the equivalent lower heating value of the fuel to about 120 Btu/ft^3, giving the syngas composition listed in Row 2 of Table 4-1. To achieve the 2550 F burner outlet temperature, this diluted syngas is then burned with about 48 pps air in each of the engine's 14 combustors.

***Table 4-4.** Calculated (approximate) single combustor conditions for 7FA engine (syngas fuel).*

Pressure	Combustor Inlet Temperature	Combustor Outlet Temperature	Combustor Airflow	Nitrogen Diluent Flow	Fuel Flow (Undiluted Syngas)
15.5 atm	745 F	2550 F	48 pps	150 ft^3/s	150 ft^3/s

Based on the above discussions, baseload combustor operating conditions are listed in Table 4-4, for one combustor (of fourteen total) at the Tampa Polk site. The listed conditions are calculated and approximate, but are useful in determining appropriate test conditions for RCL catalytic combustor.

***Table 4-5.** Nominal baseload sub-scale operating conditions at PCI (10 atm pressure).*

Pressure	Combustor Inlet Temperature (Air & Fuel)	Combustor Outlet Temperature	Combustor Airflow	Nitrogen Diluent Flow	Fuel Flow (Undiluted Syngas)
10 atm	750 F	2550 F	0.048 pps	0.15 ft^3/s	0.15 ft^3/s

Finally, for simplicity the "baseline" syngas fuel composition shown in Row 2 of Table 4-1 is approximated for these tests with the following composition:

***Table 4-6.** Simplified baseline syngas composition used for high-pressure tests.*

H_2	CO	CO_2	N_2	LHV
20%	20%	10%	50%	117 Btu/ft^3

High-Pressure Sub-Scale Test Results for Syngas Fuel

Emissions measurements reported here were obtained from the gas sample port located 15 inches downstream of the catalyst, corresponding to 50 ms residence time. This represents the maximum residence time expected in a low-emissions gas turbine combustor, and therefore also represents the maximum expected NOx emissions for a given operating condition. All emissions reported in ppm are corrected to 15% excess oxygen, dry.

All measurements were made with a combustor inlet air temperature of 750 F and a syngas fuel temperature of 570 F. Adiabatic flame temperatures were calculated based on fuel/air ratio as measured by the emissions analyzers (i.e. from gas samples extracted at the 15-inch gas sample probe location).

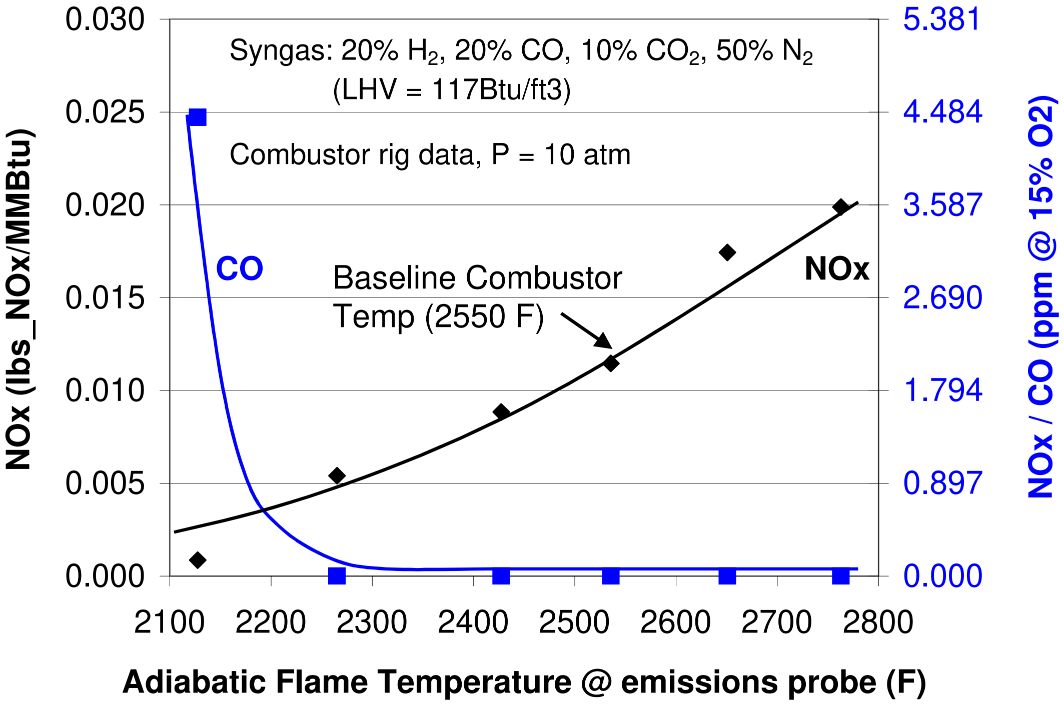

Figure 4-3. *Measured NOx and CO emissions in PCI's sub-scale rig at 10 atm pressure, as a function of adiabatic flame temperature at the emissions probe. For this data, the syngas fuel's Lower Heating Value (LHV) was 117 Btu/ft^3. For 2550 F baseline flame temperature, NOx emissions were 2.0 ppm at 15% excess oxygen, or 0.011 lbs/MMBtu.*

Figure 4-3 plots measured NOx and CO emissions as a function of adiabatic flame temperature at 10 atm pressure for a "baseline" syngas composition of 20% H_2, 20% CO, 10% CO_2, and 50% N_2, giving a Lower Heating Value (LHV) of 117 Btu/ft^3. With this fuel composition, NOx emissions were 0.011 lbs/MMBtu at the 2550 F flame temperature data point corresponding to the "baseline" IGCC firing temperature and representing operation at 100% load. Also note that for this syngas fuel composition 0.011 lbs/MMBtu is equivalent to 2.0 ppm NOx.

As the fuel/air ratio was decreased CO emissions remained near zero for flame temperatures greater than about 2250 F, permitting a 300 F turndown in flame temperature from the 2550 F baseline point, and allowing ultra low emissions operation over a wide range of loads.

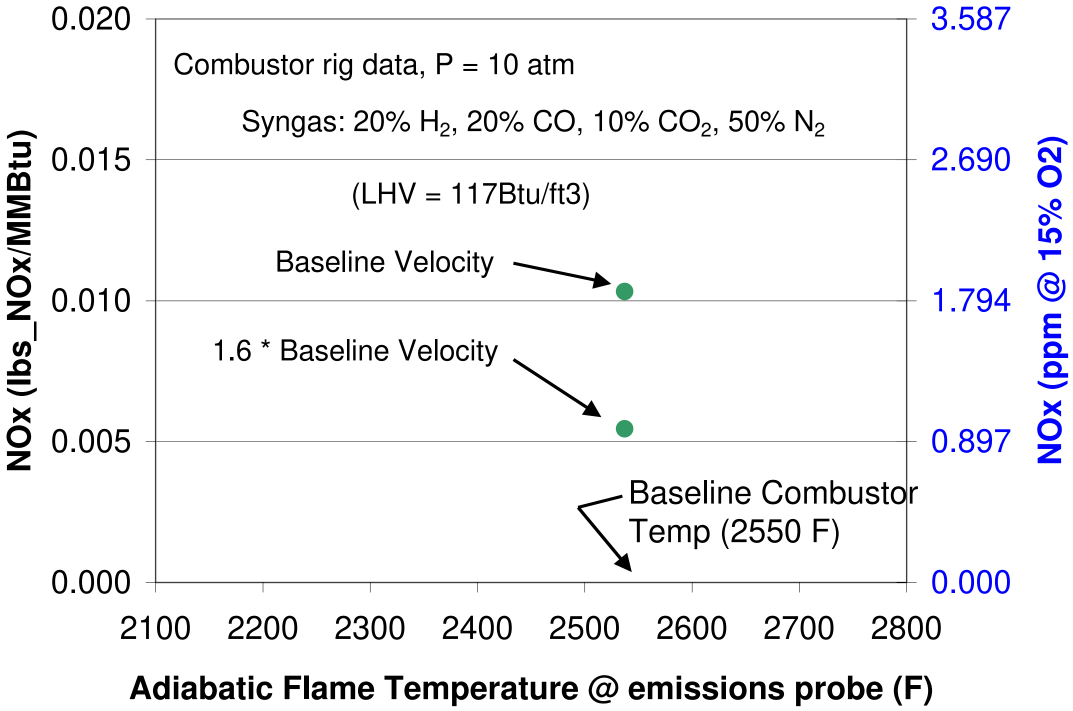

Figure 4-4. *Measured NOx emissions in PCI's sub-scale rig at two different velocities, for 2550 F baseline flame temperature. For both data points pressure is 5 atm, and the baseline syngas composition was used (LHV = 117 Btu/ft*^{3}*). As shown, NOx emissions well below 0.01 lbs/MMBtu (less than 2 ppm at 15%* O_2*) were achieved for the higher velocity condition.*

In fact, NOx emissions below the 0.01 lbs/MMBtu target were achieved during parametric testing, as shown in Figure 4-4. Here, rig pressure was reduced to 5 atm to allow operation at increased velocity without exceeding PCI's air supply capability. Two different cases were tested to determine the effect of velocity on NOx emissions. The first 5 atm case, labeled "baseline velocity" in Figure 4-4 used the same reactor velocity as used during 10 atm testing, and gave similar NOx emissions results (0.010 lbs/MMBtu) as the 10 atm case. The second 5 atm case showed a significant reduction in NOx emissions with increased velocity. At a velocity 1.6 times higher than baseline, NOx emissions dropped to 0.005 lbs/MMBtu or 1.0 ppm, well below our project target of 0.01 lbs/MMBtu. CO emissions were near zero for both data points shown in Figure 4-4.

In another parametric test, syngas composition was varied to determine the effect of fuel heating value on NOx emissions. NOx emissions for three syngas compositions are shown in Figure 4-5. Note that the right-hand vertical axis in Figure 4-5 (NOx values in ppm) is only applicable to the baseline syngas composition, as marked. For the fuel composition with lower heating value NOx emissions in ppm are slightly lower than shown (0.011 lbs/MMBtu is equivalent to 1.6 ppm).

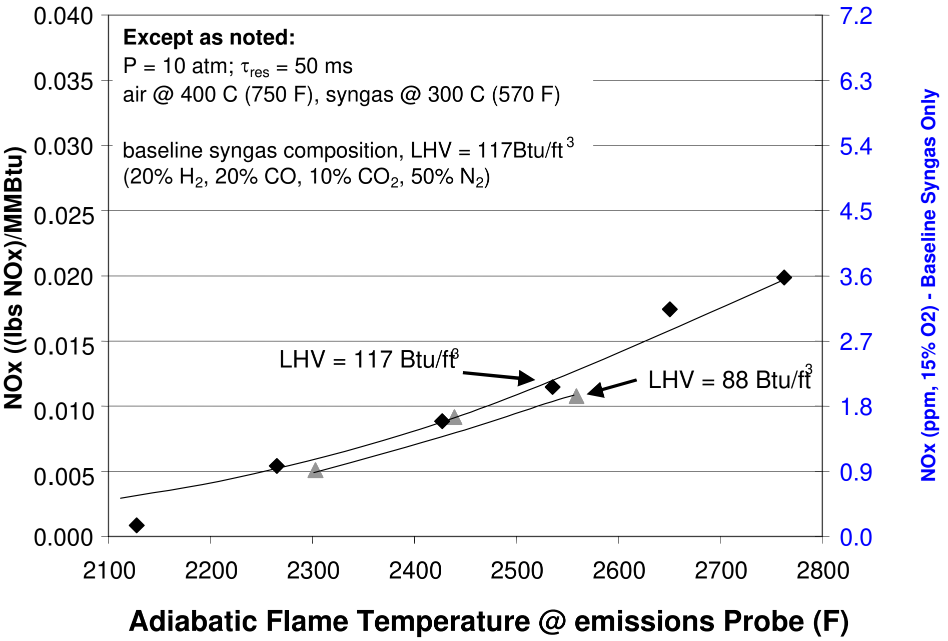

Figure 4-5. *Measured NOx emissions in PCI's sub-scale rig for three different syngas compositions having Lower Heating Values (LHVs) of 88, 117, and 147 Btu/ft^3.*

Table 4-7. *Syngas compositions for data shown in Figure 5-3, arranged by heating value.*

H_2	CO	CO_2	N_2	LHV
15%	15%	10%	60%	88 Btu/ft^3
20%	20%	10%	50%	117 Btu/ft^3
25%	25%	10%	40%	147 Btu/ft^3

As shown in Figure 4-5, reducing the syngas heating value by adding more nitrogen diluent decreased NOx emissions slightly, to 1.0 ppm. It is also worth noting that catalytic combustion allows stable operation with low emissions for the very low Btu syngas case (88 Btu/ft^3) even at flame temperatures as low as 2300 F. CO emissions were less than 5 ppm in all cases, and were very near zero for flame temperatures greater than 2200 F. The fuel compositions for the data shown in Figure 4-5 are listed in Table 4-7.

Pressure Drop and Sizing Requirements

PCI's high-pressure rig allows for two separate air supplies: one supply feeds the fuel-rich stream contacting the active catalyst, and the other supply feeds the catalyst cooling air stream which provides final combustion air for the downstream combustion zone. The two supplies can operate at different pressures, and this allows for independent and flexible control of the two streams during testing, regardless of pressure drop through the catalyst and combustion system.

4.2 Alternate Fuels Testing:

(a) Refinery Fuel

RCL combustion of a refinery fuel gas (30% H_2 and 70% CH_4) was tested in PCI's sub-scale high-pressure combustion rig. Results showed that lean-premixed combustion downstream of the catalyst was possible, with NOx emissions below 3 ppm for flame temperatures below about 2800 F. GC data from the catalyst exit indicated that H_2 was preferentially reacted in the catalytic reactor (~90% H_2 conversion vs. ~30% CH_4 conversion), resulting in low H_2 concentration downstream of the catalyst and absence of flashback.

Test Configuration and Conditions

The refinery fuel gas tests were performed using the same reactor and combustor setup used for the recent syngas fuel tests. For these tests the simulated refinery fuel gas comprised 30% H_2 and 70% CH_4, and entered the reactor without passing through a fuel heater. Some fuel heat was obtained from hot combustor rig components, however, so that the fuel plenum gas temperature measured about 175 C. Combustion air entered the reactor at about 390 C.

Tests were performed over a range of adiabatic flame temperatures, from about 2400 to 3000 F in the combustor burnout section, and at a pressure of about 10 atm. NOx and CO emissions were measured at each condition, as well as O_2 and CO_2. GC measurements were obtained at a single mid-range operation condition (near 2700 F flame temperature, representing typical low-NOx gas turbine operation).

COMBUSTION TEST RESULTS

Gas chromatograph (GC) measurements of the catalytically reacted fuel-rich mixture were obtained from gas samples extracted near the reactor's downstream end, at a condition corresponding to a combustor adiabatic flame temperature of about 2700 F. The GC results are tabulated in Table 1 below.

Table 4-8. *GC measurements from RCL reactor, at the ~2700 F combustor flame temperature condition. Catalytic sample was obtained near the reactor's downstream end port. The abbreviation "conv" in the Table means "conversion*

	H_2	CO	CO_2	N_2	O_2	CH_4	ϕ	O_2 conv	H_2 conv	CH_4 conv
Cat. Exit	1.9%	2.9%	5.2%	75.6%	1.0%	16.8%	2.7	95%	82%	33%

The measured species concentrations are listed as measured by the GC, after water removal by a chiller in the sample line. Note that all calculated values in Table 4-8 (equivalence ratio and species conversions) are based on reduced data, after the removed water has been accounted for.

The major benefit (Table 4-8) is the high conversion of hydrogen compared to the relatively low conversion of methane. Thus, hydrogen concentration in the reacted fuel-rich mixture is on the order of 1% at the catalyst exit. This concentration then decreases to well below 0.5% after mixing with catalyst cooling air. These numbers are comparable to some previous data obtained for methane-only (or natural-gas-only) reaction in the RCL reactor. Thus, based on previous experience and existing art, it seems possible that low-emissions lean-premixed combustion can be achieved for H_2 concentrations below about 0.5% in the fuel-lean combustible mixture.

NOx emissions for the RCL combustion of refinery fuel gas are plotted in Figure 4-6 below, as measured by sample extraction from a cooled probe located 15 inches downstream of the catalyst exit, corresponding to about 50 ms residence time. NOx emissions were measured below 3 ppm (corrected to 15% O_2) for flame temperatures less than about 2800 F, indicating that combustion occurs in a lean-premixed mode, without flashback to the fuel/air mixing zone at the catalyst exit. CO emissions were less than about 1 ppm for all conditions shown.

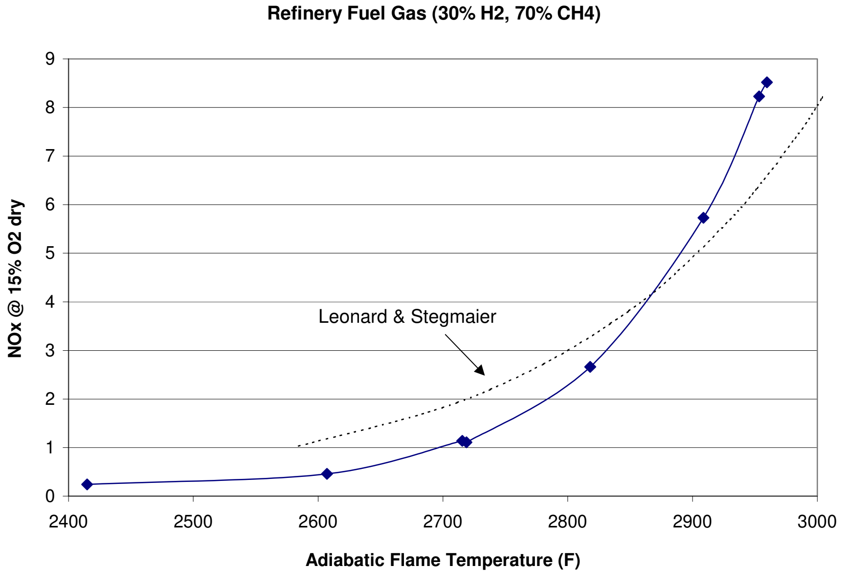

Figure 4-6. *NOx emissions, corrected to 15% O_2, as a function of adiabatic flame temperature in the downstream combustion zone, for RCL combustion of a refinery fuel gas comprising 30% H_2 and 70% CH_4.*

(b) Blast Furnace Fuel:

RCL combustion of an 82 Btu/ft^3 blast furnace gas (23% CO, 1.4% H_2, 0.6% CH_4, 22% $CO_2$and 53% N_2) was successfully tested in PCI's sub-scale high-pressure combustion rig. In practice this fuel can only be combusted with co-firing with other fuels such as methane. Results showed that combustion of this gas was extremely stable following fuel-rich catalytic reaction, even at adiabatic flame temperatures as low as 2250 F. No co-firing was required.

Test Configuration and Results

The blast furnace gas tests were performed using the same reactor and combustor setup used for the recent syngas and refinery fuel gas tests. For these tests the simulated blast furnace gas entered the reactor after being heated to about 230C/445F. Combustion air entered the reactor at about 350C/660F.

Tests were performed over a range of adiabatic flame temperatures in the combustor burnout section, from about 2250 to 2500 F (representing maximum fuel flow capability of the rig for this blast furnace gas composition), and at a pressure of about 7.25 atm. Note that the stoichiometric flame temperature for this blast furnace gas is only about 2700 F for the inlet temperatures tested. NOx and CO emissions were measured at each condition, along with O_2 and CO_2.

In general, low NOx emissions with low CO indicating stable combustion was achieved. NOx emissions for blast furnace gas operation are plotted in Figure 4-7, as measured by sample extraction from a cooled probe located 15 inches downstream of the catalyst exit. For all conditions tested, NOx emissions were measured below 1 ppm corrected to 15% O_2. CO emissions were near zero (< 1 ppm) for all conditions shown. The test data show that by partially converting some of this low Btu fuel within the RCL reactor, a more reactive and stable products are delivered into the downstream combustion zone with the resulting low emission performance. As a result, no co-firing is required to stabilize the downstream combustion flame.

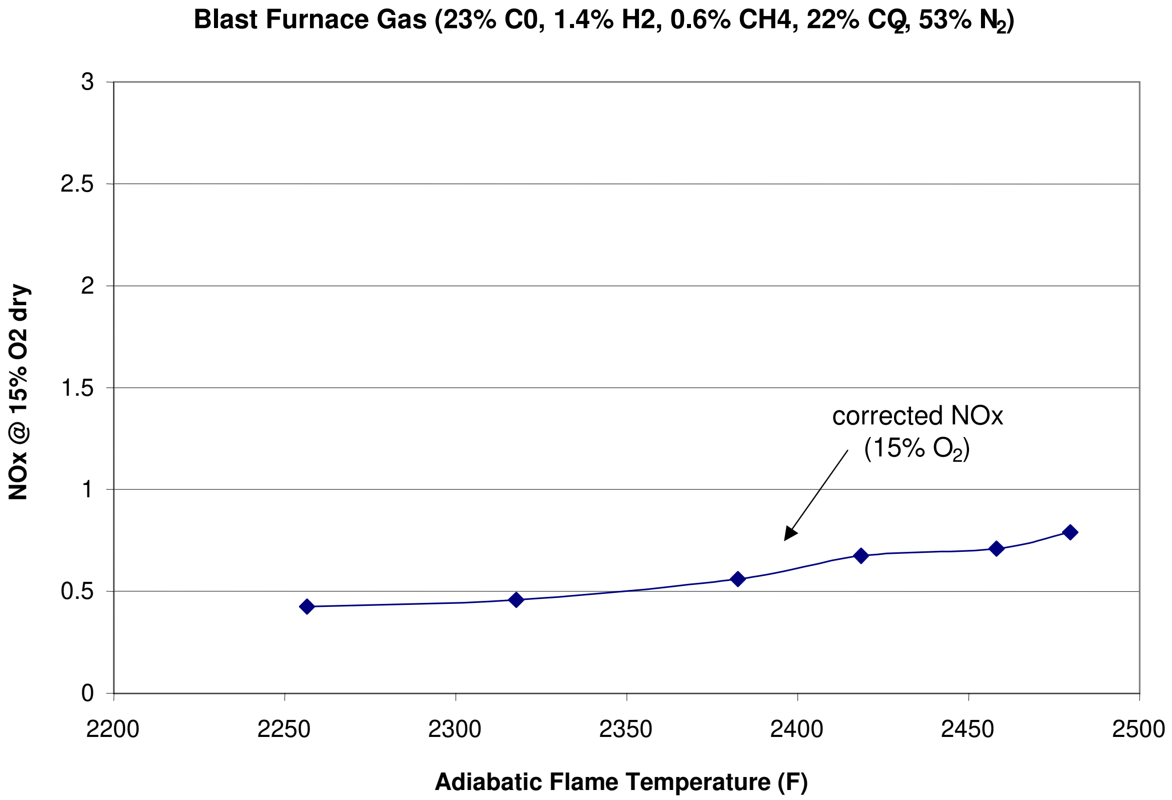

Figure 4-7. *NOx emissions, uncorrected and corrected to 15%* O_2*,, as a function of adiabatic flame temperature in the downstream combustion zone, for RCL combustion of a blast furnace gas comprising 23% CO, 2%* H_2 *+*CH_4*, remainder diluent.*

In general, the fuel flexibility feature of RCL with the advantage of preferentially converting H2 for certain fuels make the rich catalytic combustion a strong candidate for H2 fuel combustion delivering low emission. RCL reactor operates in oxygen limited environment, providing insensitivity to the type of the fuels used in the reactor. Within the reactor, H2 or higher hydrocarbon are initially oxidized and provide a tailored downstream product for combustion in the downstream flame zone.

4.3 Assessment of Potential Success and Feasibility for IGCC

The RCL testing operation with syngas fuel support an expectation that the RCL combustion system is feasible for IGCC application and offers key benefits in terms of expanded capability, lower emissions, and reduced cost such that the technology offers to advance commercialization potential of IGCC both in terms of total volume and timing.

High pressure catalytic combustion of syngas has been successfully achieved at subscale, with good catalyst performance and confirming that PCI's basic reactor design, catalysts and substrate metallurgy are applicable to syngas. Results to date support the following expectations for the RCL catalytic combustor technology:

1. Ultra-low NOx emissions
    - Achieved 0.01 lbs/MM BTU (2ppm), vs current industry standard at approximately 0.10 lb/MM BTU
    - The ability to meet DOE emissions objectives without post-combustion control using SCR, with large capital and operating savings.
    - The potential for achieving higher temperature operation at low NOx in syngas turbines, should system objectives and capabilities support this objective.
    - The ability to burn syngas with low NOx emissions with reduced nitrogen dilution requirement.

2. Ability to burn lower BTU gas that conventional combustion
    - LHV 88 BTU/ft3 gas was operable with slightly lower NOx than the baseline case.
    - Broadened applicability for IGCC where processes that now require supplemental fueling to raise BTU content can either avoid such cost or require less of it. This may also be an indication of the ability to burn less reactive mixtures.

3. Operability and size were consistent with fitting to current engines.

4. Potential for reduced-NOx operation with other hydrogen-containing fuels, including process industry byproducts (e.g. refinery gas), and hydrogen itself.

The technology offers to avoid the need for SCR (and related additional sulfur cleanup) to meet DOE emissions goals, providing cost savings as follows:

- Capital cost savings of \$20/kW SCR and \$50/kW for related sulfur cleanup. This is a significant fraction of the estimated total capital cost of IGCC power.
- Operating cost savings of 1 mils, also a significant savings. These arise from avoiding the operating costs of SCR, improved efficiency, and improved component life.
- Avoided ammonia slip

For example, for an IGCC gas turbine supplying 190 MW, we estimate capital savings at approximately \$14 million in capital and annual operating savings at \$2 million.

Also, IGCC technology faces a certain degree of market entry challenge in terms of the very limited number of actual gasification sites (prior to broad commercialization of large scale coal-based IGCC). The RCL technology offers to broaden the range of low BTU and high hydrogen industrial waste gas applications due to the lowered BTU capability and the lower cost achievement of low emissions. Especially relating to refinery applications or other industrial applications, there may be a number of potential applications where current emissions, clean-up costs, and/or post-combustion control footprint requirements together lead to no application where otherwise there could be a power plant.

RESULTS AND DISCUSSION

5. COST-BENEFIT ANALYSIS FOR RCL SYSTEM

Methodology
The net benefits of the RCL technology for F-class power generation gas turbines were identified and quantitatively estimated, and compared to the estimated net costs of implementing the technology in the engines. Estimates were provided based upon information provided without restriction by gas turbine OEMs and by information obtained in primary research of documents in libraries and on the web.
All costs and benefits are presented in current (2004) dollar terms.

RCL Costs
It is assumed that the RCL technology will be offered initially as an OEM option for specific engines, i.e. the engine will continue to be made in its non-catalytic form and the option version will be produced for customers who wish to purchased the option from the OEM.

As described below, RCL system costs for a baseload F class gas turbine are estimated at $4/kW purchase cost plus $1.57/kW operating cost per year (0.2 mils/kw-hr).

The costs of RCL technology can be examined in the following categories:
1. Capital costs of the core RCL system component. These comprise the cost of the catalytic reactor itself as well as subcomponents integrated with the reactor to implement rich premixing and to house the post-reactor flows.
2. Capital cost of system-level components required to implement the RCL component. These comprise modifications required to the combustor itself (as needed: any required combustor changes, fuel stages, control systems, etc.)
3. Avoided capital cost of DLE components no longer required when utilizing the RCL system.
4. Related O&M costs of each of the above categories, including replacement costs of the RCL component, added system-level components, and savings from avoiding DLE system components no longer required with the RCL system.

Capital costs were estimated as follows:

Cost category	Specific component	Cost/kW	Comments
RCL system component	Catalytic reactor Other subcomponents	$4 $2	Catalytic element assembly Rich premix zone walls, assembly casing, downstream zone walls, sensors
System level changes	Fuel injectors Added fuel stage Control system Pressure casing Pilot means	$0 $0 $0 $0 $0	Same as DLE None Similar to DLE Same as DLE Similar to DLE
Avoided DLE costs	Avoided premix system components	($2)	Simpler premix system
Total		$4	

Costs of the RCL system have been estimated at the component level based upon actual current PCI prototype production costs and planned pricing, adjusted for an annual volume assumption of 10 F class machines/year. With some 200 large engines being sold annually worldwide, this reflects a penetration of 5%. Additional cost reduction may be anticipated from higher volumes and from actual product and manufacturing experience. Within the total $6/kW cost for the RCL system component, the $4 for catalytic reactor/assembly costs will share economies of manufacturing scale across the entire RCL market. This $4 estimate is based upon current PCI manufacturing costs for these components, reduced by approximately 50% for the effects of planned automation to meet the planned volume. The $2 for other subcomponents will be for items being specially manufactured for each engine application, and will as a result have economies of scale related to the volume of each specific engine. This estimate is based upon PCI projections of having these subcomponents manufactured by the gas turbine supplier base. The $2 in avoided current premix system component costs is estimated based upon OEM pricing provided by power generation customers.

O&M costs of the RCL system and related required system changes is estimated as follows:

Cost category	Specific cost	Cost/kW/yr	Comments
RCL system	Operating cost	$0	Similar to DLE injectors
Replacements	Catalytic element assembly Balance of system costs	$1.33 .40	$4/mod; 25,000 hr baseload life 40,000 hr life
Property tax/ admin overhead		.24	.04 annual cost factor
Premix system	Replacement costs	(0.4)	40,000 hr life, savings @ $0.5
Total		$1.57	

IDENTIFICATION and QUANTIFICATION OF BENEFITS

Benefits and costs are analyzed separately for natural gas-fired and for coal derived syngas-fired turbines. These are quantified for a 170 MW F class base load gas turbine system. Following this section is more detailed analysis of individual benefits

Natural gas-fired combustion turbines

Benefits: Combined cycle plants burning natural gas fuel:

- near-zero NOx emissions (<3 ppm), avoiding the capital and O&M costs of SCR post-combustion controls,
- avoided PM-10 emissions from ammonia (compared to SCR post-combustion controls),
- extended low emissions turndown range,
- reduced combustion dynamics, resulting in extended hot section component life and reduced O&M cost,
- no efficiency penalty vs DLN technology,
- extended fuel quality/BTU insensitivity,
- extended low BTU capability, and
- potential future gas/liquid dual fuel capability.

These benefits were assessed based upon the results of combustor tests at F class conditions.

Benefit/Cost: Combined cycle plants burning natural gas fuel:

Sources of value	Capital Savings	Operating Gain/Yr
Avoided SCR capital/operating $	$3.8 MM	$0.8 MM
Efficiency gain from avoiding SCR		0.4 MM
No ammonia emissions		0.1 - 0.2 MM
Reduced dynamics/longer life @ 5-20% O&M		0.3 - 1.4 MM
Reduced starts/stops		0.5 MM
NOx trading credits (where available) @$2K/ton		0.15 - 0.4 MM
Retrofit enablement		* + New sales
Medium frame and industrial machines		* + Help drive DG
Fuel flexibility		*
TOTAL Value-added	**$3.8 MM**	**$2 MM - $3 MM**

**** Not Specifically Valued***

	Capital cost	Operating Cost/Yr
Cost of full RCL® system	**$0.67 MM**	**$0.2 MM**
Cost of partial RCL® system	**0.33 MM**	**0.1 MM**

Benefits: Simple cycle F-class plants burning natural gas:

- All benefits of combined cycle plants, plus
- Higher annual power generation capacity where capacity is limited by tons of NOx emissions. The estimated value of this is $680,000 - $3,400,000 annually.

Benefits: Retrofits of combined cycle or simple cycle plants burning natural gas and where no SCR installation is required:

- All operating benefits as with new plants, except no capital or operating cost savings relating to SCR
- Added benefit of being able to sell NOx credits where salable. $150,000 - $580,000/year.

Syngas-fired combustion turbines:

Benefits: Combined cycle IGCC plants burning coal-derived syngas:

- near-zero NOx emissions (0.01 lbs NOx/mm BTU, or <3 ppm NOx), avoiding the capital and O&M costs of SCR post-combustion controls,
- avoided PM-10 emissions from ammonia (compared to SCR post-combustion controls),
- avoided requirement for added sulfur control required for syngas SCR operation
- the ability to burn stably even with syngas fuels of lower BTU content
    - the ability to burn lower BTU syngas (tested down to 82 BTU/scf)
    - the ability to burn syngas stably with less nitrogen addition for a NOx target
- no efficiency penalty vs DLE technology,
- extended fuel quality/BTU insensitivity,
- fuel flexibility:
    - capability to burn natural gas with ultra-low emissions

- capability to burn stably even with low BTU industrial gas CO gas
- potential capability to burn hydrogen fuel in nitrogen with ultra-low NOx

These benefits were derived from limited subscale testing done under DOE contract at IGCC conditions as well as analytic study. The technology is at an earlier stage of development relative to syngas compared to natural gas.

Benefit/Cost: IGCC plants

Sources of value	**Capital Savings**	**Operating Gain/Yr**
Avoided SCR capital/operating $	$3.8 MM	$0.8 MM
Efficiency gain from avoiding SCR		0.4 MM
No ammonia emissions		0.1 - 0.2 MM
Avoided need for added sulfur removal	$9.3 MM	0.5* MM
Fuel flexibility	______	No Estimate
TOTAL Value-added	**$13 MM**	**$1.8 MM**
		+sulfur removal
		+fuel flexibility

***** *Uncertain Estimate***

	Capital cost	**Operating Cost/Yr**
Cost of full RCL® system	**$0.67 MM**	**$0.2 MM**
Cost of partial RCL® system	**0.33 MM**	**0.1 MM**

INDIVIDUAL BENEFITS ANALYSIS

The next section contains individual benefits analyses, with discussion and calculation of each benefit.

Benefit Analysis

Avoiding SCR Capital and Operating Costs

Value: $3.8 million saved in capital costs
$1.2 million saved in annual operating costs

Discussion: Selective Catalytic Reduction (SCR) systems are installed in the HRSG train in combined cycle gas turbine systems. These systems use catalytic surfaces and an added reducing agent (typically ammonia) to reduce NOx in the gas flow after the expansion turbine. The SCR system requires the catalyst system itself (including the basic equipment, modifications to the HRSG, controls and an ammonia storage system), as well as installation costs (direct and indirect). Operation includes operator and maintenance costs, ammonia, performance loss by the turbine (due to the added backpressure), and the costs of periodic catalyst replacement (ranging from 3 to 6 years depending upon assumptions and allowable degree of ammonia slip). Finally, the system adds to the overall indirect annual costs of the plant, including for overhead, administration, insurance and property tax.

NOx emissions from the RCL system are as low as those with DLE+SCR, leading to the RCL system avoiding the requirement for the SCR. The avoidance of ammonia emissions (2-10 ppm) makes the RCL system lower in overall emissions than the SCR. Thus, the RCL system will avoid the need for the capital and operating costs of the SCR.

Benefit calculation:
The avoided costs are estimated below. The specific costs shown are drawn from individual power plant BACT submissions that have been released to the public in the States of Washington and California. These costs have also been validated by a major gas turbine OEM.

Capital Costs	Cost	Comments
Equipment	$2,400,000	OEM estimate, also multiple BACT subms
Direct Installation	720,000	30% of Equipment, per BACT submissions
Indirect Installation	936,000	30% of Equipment, per BACT submissions
Total Capital Costs	$3,840,000	

Annual Operating Costs	Cost	Costs from OEM estimate and BACT submission
Operator/supervision	$ 88,000	
Maintenance	105,000	
Ammonia	125,000	5 ppm slip
Catalyst replacement	189,000	6 year life, incl $14K catalyst disposal
Other component replacement	125,000	
Performance loss	438,600	0.5% loss, $.06 value, 8600 hrs
Total Direct Annual Cost	$1,071,250	
Overhead	85,000	
Administrative, Insur, Prop Tax	94,000	
Total annualized operating cost	$1,250,250	Before depreciation/amort and interest

Benefit Analysis

Avoiding ammonia emissions

Value: $100,000 -$200,000 per year

Discussion: Ammonia emissions are a byproduct of the use of ammonia addition to chemically reduce NOx in selective catalytic reduction. Ammonia "slip" to the atmosphere of 2 to 10 ppm NOx is reported as a byproduct of using ammonia to reduce NOx from the 25 ppm range to 3 ppm. This slip is higher where SCR catalyst life is extended (i.e. more slip for 6 year catalyst life than for 3). Ammonia is a greenhouse gas and is a promoter/component of PM-10 particulates. Ammonia also constitutes a safety and security risk; an unexpected release would require local evacuation.

Benefit calculation:
Assume 40% conversion of ammonia to PM-10 (source: SATSOP BACT submission) and $5,000/ton value (BACT cost-effectiveness SMQAMD guide for PM-10).
Assume 50 tons/year ammonia slip from 5 ppm slip (also SATSOP)

40% x $5,000 x 50 = $100,000 per year for 3 year catalyst life
40% x $5,000 x 50 = $200,000 per year for 6 year catalyst life

Benefit Analysis

Reduced dynamics/improved operability

Value: $365,000 - $1,462,000 per year

Discussion: Combustion generated pressure oscillations, or "combustion dynamics", are a byproduct of lean premixed operation for low NOx at high temperature and close to stability limits. The resulting local variations in combustion flows leads to vibration of hot section components, narrowed operating regime, and reduced hot section component lifetimes. The pressure fluctuations are a cause of reduced reliability, are a primary cause of the requirement for more frequent inspection intervals and tuning, and can lead to substantive combustor and gas turbine failure. Reducing these oscillations would lead to

- longer combustion hardware inspection periods
- longer combustion hardware component life
- potential for reduced tuning requirements
- potential for combustor engineering simplification in terms of both combustor system and the period of time required to develop new combustors
- improved gas turbine availability and reliability

With the RCL technology offering to substantially cut dynamics, there is the potential to achieve these benefits.

Benefit calculation:
Experienced-based data was not obtained from OEMs or users relating to the effect on life or O&M costs of combustion dynamics. However, the consensus appears to be that a large fraction

of the current cost and frequency of gas turbine O&M can be ascribed to dynamics, with much work directed to its minimization and control. Based upon this, we estimate that the RCL system has a strong potential for reducing dynamics sufficiently to reduce O&M costs by 5 - 20%.

Assume O&M at 50 mils/kw-hr
5% x 50 mils x 8600 hrs x 170 MW = $365,000
20% x 50 mils x 8600 hrs x 170 MW = $1,462,000

Benefit Analysis

Reduced starts/stops

Value: $500,000 saved in annual operating costs, for start-spaced maintenance regimes

Discussion: In DLE systems, combustion stability and low emissions cannot be maintained below some part-load conditions; below this level, emissions climb significantly and operation would be outside the targeted range. If demand drops sufficiently to require operation below this targeted turndown level, the machine would instead be shut down, and would require a separate start-up process to bring the machine back on-line to producing power.

A major cost of DLE systems relates to these shutdowns and start-ups. A full hot path overhaul for an F class machine is estimated (power producer as source) to cost in the $7 million range ($3 to $10 million), with full engine cost components including fuel control valve ($200,000), fuel nozzle assembly ($1.2 million), combustor cap set ($520,000), and transition assemblies ($1.2 million). Spreading the $7 million across a recommended 1200 start cycles between full overhauls leaves an O&M cost per start of $6,000. With another $3,000 in fuel required for each start-up, and other miscellaneous costs, this indicates a cost per start in the $10,000 range.

One benefit of the RCL technology is the ability to operate at low emissions across a greater turndown range, potentially to 25% of base load. The benefit would be the ability to avoid turning off an engine, and saving the related stop/start cost cycle.

Benefit calculation:

Assuming 50 avoided starts per year, and a cost/start of $10,000, the estimated savings is $500,000 per year.

Benefit Analysis

Expanded low emissions hours (simple cycle)

Value: $680,000 - $3,400,000

Discussion: This value arises from the ability to sell greater kw-hrs of power in situations where a peaking machine is effectively emissions-limited; in effect the RCL system expands power output for a specified emissions level. Simple cycle machines are often permitted with an allowed annual emissions level (tons/year) or a total hours of operation based upon an assumed emissions/hour. Where power is in excess supply, this is not a key limitation inasmuch as more hours of operation would not normally be sought. But in times and in regions where the power demand/supply balance offers the potential for more hours of power sales from such a simple cycle machine, this emissions or hours limitation can prevent a power generator from selling additional hours of power when it would otherwise wish to.

The value of such added power sales is a function of supply and demand at the time of potential sale, and can be expressed as a margin between the sale price and the cost of production.

The benefit will range from nothing in the case where power is in general surplus supply, to high levels where time-sensitive power may be in shortage relative to demand.

Benefit calculation:

Four cases are considered:

Case 1: Modest demand price and duration	$20/MW-hr, 200 hours:	$ 680,000
Case 2: Higher demand price and modest duration	$50/MW-hr, 200 hours:	$ 1,700,000
Case 3: Modest demand price and long duration	$20/MW-hr, 1000 hours:	$ 3,400,000
Case 4: Very high demand price and low duration	$150/MW-hr, 100 hours:	$ 2,500,000

Based on these cases, the benefit is determined to be too variable to summarize. Most generically for the gas turbine OEM it offers the ability to sell either a new machine with greater sales flexibility than otherwise feasible, or to offer a retrofit kit a large increase in power sales for a machine in a region of high demand/supply.

In other cases (typically involving smaller machines) a gas turbine system with the RCL technology may be able to avoid regulatory review for emissions if its total emissions are below a cutoff level.

Benefit Analysis

NOx trading credits (where available)

Value: $580,000 per year for base load operation, but only if the low NOx is not part of the certification (effectively for retrofits) and the machine is in the trading zone

Discussion: The NOx trading zone is expanding, expected to include 23 states by 2007. In cases where the targeted NOx level is not simply part of a certification but instead represents a voluntary reduction, there is the opportunity to sell the excess tons of NOx avoided.

Benefit calculation:
Assuming NOx values of $2,000 - $3,000 per ton,
F class baseload emissions of 25 tons per ppm of NOx for full year operation,
A 5 month NOx season (May - September), and
A NOx credit of 22 ppm (25 ppm - 3 ppm)

This produces a baseload credit of $580,000/year.
This produces a peaker credit of $160,000, assuming 1000 hours of annual operation (and all peaker sales during the NOx season)

Benefit Analysis

Avoiding cost of added sulfur clean-up (IGCC only)

Value: $55/kW capital cost avoided, $500,000 ($3/kW) operating cost avoided

Discussion: Currently, in order to avoid poisoning an SCR system in an IGCC syngas plant, additional sulfur removal is required beyond that otherwise required by regulation at this time. This removal is very expensive inasmuch as it seeks to remove the last amounts of sulfur from thestream. Given the RCL technology capability to achieve ultra-low NOx emissions without an SCR unit (and with sulfur tolerance), implementing the RCL technology is predicted to also remove the consequential requirement and cost for the added sulfur removal.

Benefit calculation:

We have been provided an estimate of the capital cost for the added sulfur removal as $55/kW. There is less definition for the operating cost of this added removal; this is estimated at $500,000 per year.

Benefit Analysis

Reduced requirement for nitrogen or steam dilution (IGCC only)

Value: Capability; uncalculated

Discussion: Currently, IGCC plants use nitrogen or steam addition to the syngas stream for several purposes, including limiting NOx emissions. With the RCL technology reducing the NOx emissions for a given amount of nitrogen dilution, there is the capability to meet a targeted NOx level with less dilution. This provides a degree of engineering design freedom that could prove useful, and is of specific interest in the case of hydrogen combustion. Diluent addition adds substantially to the cost of IGCC systems, involving the cost of the diluent (e.g. cost of steam or alternative value of nitrogen pressure from the ASU) as well as added costs e.g. for further pressurization of ASU nitrogen.

Benefit calculation:

There is no benefit calculated here, but we note this as a potential capability RCL technology offers for IGCC systems.

Benefit Analysis

Fuel flexibility (beyond IGCC)

Value: Site-specific, large, notably for refineries, chemicals plants, and plants with process heating. Gains include energy efficiency gains arising from higher efficiency gas turbine combustion of process offgases (vs boiler combustion or flaring), and extended combustion system component reliability and life.

Discussion: There are sites where the ability to burn a specific fuel in stable combustion at ultra-low emissions is enabling for gas turbine operation. These are typically projected to be for industrial sites. We identified three general cases:

1. IGCC plants: The ability to burn syngas with lower BTU levels provides operating flexibility for a variety of refinery and chemical plant fuels, enabling the use of IGCC gas turbine systems with lower BTU feedstocks. In some cases, this can be enabling for use of the IGCC system (improving plant energy efficiency and resource utilization). In other cases, this can avoid the need for high BTU or hydrogen content sweetening of the low BTU fuel (offering capital savings as well as fuel savings relating to the avoided mixing apparatus and fuel cost). In all cases where the BTU content of the fuel is marginal, the RCL system's ability to operate with greater stability and lower dynamics offers improvement in O&M costs of the combustion system.

2. Refinery fuel gas: A major intermediate product of refineries is refinery fuel gas, with moderate hydrogen contents. Refinery fuel gas comprises nearly half of refinery fuel consumption. The substantial fraction that is not recycled into product is generally consumed in boilers; it requires substantial mixing with natural gas to bring reactivities to levels acceptable for use in DLE gas turbines. We have tested the RCL system with simulated refinery fuel gas (as described in the technology section above), confirming that an RCL combustion system can burn refinery fuel gas with ultra-low NOx. Developing RCL gas turbine fuel flexibility for burning refinery fuel gas with ultra-low NOx offers a much higher value use than in boilers. This could become an exported fuel source for petrochemical and chemical industry cogen with costs potentially below natural gas and in any case providing a domestic alternative to natural gas and a potential opportunity for increased refinery electricity production (refineries generally purchase substantial external electricity for their operations).

Additionally, we are told by a major oil refiners' engineers that the capital cost of an SCR for an natural gas-fired F class machine in one of their refineries is estimated at in excess of $10 million, with operating costs somewhat higher than our estimates. (The added costs relate to the space-constrained nature of a refinery together with added controls and other features.) The nature of emissions at a refinery (or a chemicals plant) is that emissions can be capacity-limiting, i.e. total refinery output is constrained by the regulatory restrictions on total refinery emissions. As a result, the value of reduced emissions at a refinery can be substantially above that at a merchant plant, plus there is the improvement in energy efficiency that is advanced by the refinery operating at higher capacity levels.

3. Blast furnaces: At the other extreme of fuel characteristic are gases such as blast furnace gas, a low BTU gas with very low reactive content (typically primarily CO). Such gas generally requires sweetening with higher BTU gases containing hydrogen species. As with refinery fuel

gas, the RCL system was able to burn simulated blast furnace gas stably even with low BTU content (e.g. 80 btu/scf range). The opportunity is to burn this gas without BTU enhancement in a high value application such as a gas turbine, with the potential to operate with greater combustion stability and resulting improvement in combustion system life and O&M costs. A specific application of interest would be for power at blast furnace sites, e.g. in China.

Benefit calculation:

The benefit calculation is site-specific here. Enabling IGCC system operation with tail gasses in general provides a site-wide improvement in energy efficiency and resource utilization. For refinery fuel gas, we note the substantial fuel flow that could benefit from higher-value conversion in a gas turbine, plus the substantial capital cost savings vs an SCR system. For blast furnace gas, the savings are in terms of reduced requirement for BTU augmentation to achieve gas turbine efficiency operation plus the potential for reduced O&M costs arising from the greater combustion stability.

Benefit Analysis

Application to Industrial Machines and Distributed Generation

Value: Enabling for sales

Discussion: A major benefit offered by RCL technology is to enable distributed generation (DG) gas turbines to achieve the same low emissions levels as large central station plants. With DG gas turbines by their nature often being placed in locations of high population density, the ability of DG turbines to have emissions as clean as they can be may prove critical to the spread of distributed generation in efficient gas turbines.

RCL costs scale roughly proportional to the size of the machine (i.e. the cost/kW for a small machine (e.g. $8/kW for a 7 MW Solar Taurus 70) is not much larger than the $4 cost/kW for a large F class machine. SCR costs, on the other hand, climb significantly on a per kW basis as gas turbines get smaller, with the cost/kW of an SCR for a 7 MW Solar Taurus 70 estimated at approximately $130/kW vs $20/kW for a 170 MW F class machine. This very high cost of post-combustion controls for smaller gas turbines substantially restrains their penetration into regions where emissions controls are placed, especially as reciprocating engines are finding their cost of implementing SCR is relatively low.

Benefit calculation:
Enabling for sales in areas where SCR is required.

CONCLUSION

6.1. PROJECT SUMMARY AND RECOMMENDATIONS

RCL technology was found to offer substantive improvement to Dry Low Emissions (DLE) technology for achieving near-zero emissions from gas turbine combustion of natural gas and of coal-derived syngas. Integrating the RCL technology into modern gas turbines offers to simultaneously advance DOE objectives in the areas of:

- **Near-zero NOx emissions** (<3 ppm NOx for natural gas combustion, and the same (0.01 lb/mm BTU, or <2 ppm) for syngas combustion), without post-combustion controls or ammonia. This also translates into the capability to achieve a targeted emissions level with less nitrogen dilution.
- **Improved efficiency**
  - Avoiding post-combustion controls, and
  - enabling higher firing temperatures
- **Extending gas turbine component lifetimes and service intervals** (by reducing combustion dynamics), and
- **Fuel flexibility** (including ultra-low emissions with natural gas, high reactivity hydrogen-containing fuels such as coal-derived syngas and refinery fuel gas, and low BTU fuels). The extension of this flexibility to burning pure hydrogen in nitrogen with low NOx is now being explored, with promising early results.

The study predicts a **substantial net cost savings** in using RCL technology, vs DLE with post-combustion controls as is now generally BACT in the U.S.

- **For base load merchant power gas turbines burning natural gas**
  - **$12/kW net savings in capital cost, plus an additional**
  - **$12/kW (1.3 mils/kw-hr) in net annual operating savings.**
- **For IGCC gas turbines burning coal-derived syngas**,
  - **$75/kW net savings in capital cost**
  - **$10+/kW (1 mils/kw-hr) in net annual operating savings**.

The technology is compact enough to fit to existing pressure casings, offering lowered cost integration for new machines as well as retrofit potential. Combustor module tests under large frame gas turbine conditions have demonstrated the robustness of the technology as well as stable combustion with NOx emissions as low as below 2 ppm and low combustion dynamics, in a package sufficiently compact to potentially fit into existing large frame machine combustor volumes. A smaller catalytic pilot version has been developed and tested for minimal modification to existing DLN systems.

The technology offers its benefits at lowered cost compared to DLE-SCR configurations now standard in the U.S. New RCL catalytic module component cost for natural gas-fired large frame machines is expected to be in the $4/kW range, vs SCR capital cost of $20/kW and an undetermined savings in avoided DLE components. With greater life cycle cost impact, RCL operating costs are projected at 0.2 mils/kw-hr, vs 1.5 mils/kw-hr for DLE+SCR. The above costs are estimated for natural gas-fired turbines; cost savings for smaller machines and for syngas-fired machines are expected to be higher. In addition, improved combustion stability offers increased low emissions turndown, a key flexibility feature offering both added revenue and cost advantage to power generators.

An RCL retrofit package is also predicted to offer savings to the installed base power generator. Retrofit of installed turbines even without current SCR systems would offer substantial reduction in emissions with modest net reduction in operating costs due to improved combustion dynamics. Retrofit of installed turbines with installed SCR systems would enable the SCR to be mothballed and offer substantially reduced net operating costs (>1.0 mils/kw-hr).

6.2 RELEVANCY:

RCL technology offers a near term opportunity to advance DOE objectives by providing an energy-efficient in-engine near-zero emissions solution:

- Eliminating the need for SCR in combined cycle or simple cycle, for IGCC and natural gas fired combustion turbines
- Enabling simple cycle and small turbine near-zero emissions, encouraging CHP/distributed power
- Improving efficiency due to the avoidance of SCR and improved combustion stability
- Reducing combustion dynamics, enabling improved RAMD
- Reducing power generation turbine capital and O&M costs
- Retrofittable to the installed base
- Capable of fuel-flexible operation, including with natural gas/liquid fuels, and applicable to ultra-low NOx syngas combustion.

In summary, RCL technology offers substantial public benefit as well as supporting the accomplishment of key DOE goals. Next steps include the need for more development toward (1) the syngas combustion goal, (2) full scale multimodule combustor trial, and (3) engine field trial. There are currently active R&D programs on the technology, with DOE support, at multiple gas turbine OEMs participating in the Fossil Turbine program (GEPS, Pratt & Whitney, and Siemens Westinghouse), as well as at PCI. While these development programs continue to require ongoing DOE support, they offer a path forward to implementing the technology in the nation's power generation combustion turbines.

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8. List of Acronyms

CDPO	COMBUSTION-DRIVEN PRESSURE OSCILLATIONS
CRZ	central recirculation zone
eff	efficiency
GC	gas chromatograph
LHV	lower heating value
Npg	gas producer shaft speed
PFTR	plug flow tubular reactor
PSR	perfectly stirred reactor
SCR	selective catalytic reduction
TRIT	turbine rotor temperature
UHC	Unburned hydrocarbon