

**Industrial Gas Turbine Engine Catalytic Pilot Combustor -
Prototype Testing**

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ABSTRACT

PCI has developed and demonstrated its Rich Catalytic Lean-burn (RCL[®]) technology for industrial and utility gas turbines to meet DOE's goals of low single digit emissions. The technology offers stable combustion with extended turndown allowing ultra-low emissions without the cost of exhaust after-treatment and further increasing overall efficiency (avoidance of after-treatment losses). The objective of the work was to develop and demonstrate emission benefits of the catalytic technology to meet strict emissions regulations. Two different applications of the RCL[®] concept were demonstrated: RCL[®] catalytic pilot and Full RCL[®].

The RCL[®] catalytic pilot was designed to replace the existing pilot (a typical source of high NO_x production) in the existing Dry Low NO_x (DLN) injector, providing benefit of catalytic combustion while minimizing engine modification. This report discusses the development and single injector and engine testing of a set of T70 injectors equipped with RCL[®] pilots for natural gas applications. The overall (catalytic pilot plus main injector) program NO_x target of less than 5 ppm (corrected to 15% oxygen) was achieved in the T70 engine for the complete set of conditions with engine CO emissions less than 10 ppm. Combustor acoustics were low (at or below 0.1 psi RMS) during testing. The RCL[®] catalytic pilot supported engine startup and shutdown process without major modification of existing engine controls. During high pressure testing, the catalytic pilot showed no incidence of flashback or autoignition while operating over a wide range of flame temperatures.

In applications where lower NO_x production is required (i.e. less than 3 ppm), in parallel, a Full RCL[®] combustor was developed that replaces the existing DLN injector providing potential for maximum emissions reduction. This concept was tested at industrial gas turbine conditions in a Solar Turbines, Incorporated high-pressure (17 atm.) combustion rig and in a modified Solar Turbines, Incorporated Saturn engine rig. High pressure single-injector rig and modified engine rig tests demonstrated NO_x less than 2 ppm and CO less than 10 ppm over a wide flame temperature operating regime with low combustion noise (<0.15% peak-to-peak). Minimum NO_x for the optimized engine retrofit Full RCL[®] designs was less than 1 ppm with CO emissions less than 10 ppm.

Durability testing of the substrate and catalyst material was successfully demonstrated at pressure and temperature showing long term stable performance of the catalytic reactor element. Stable performance of the reactor element was achieved when subjected to durability tests (>5000 hours) at simulated engine conditions (P=15 atm, T_{in}=400C/750F.). Cyclic tests simulating engine trips was also demonstrated for catalyst reliability. In addition to catalyst tests, substrate oxidation testing was also performed for downselected substrate candidates for over 25,000 hours.

At the end of the program, an RCL[®] catalytic pilot system has been developed and demonstrated to produce NO_x emissions of less than 3 ppm (corrected to 15% O₂) for 100% and 50% load operation in a production engine operating on natural gas. In addition, a Full RCL[®] combustor has been designed and demonstrated less than 2 ppm NO_x (with potential to achieve 1 ppm) in single injector and modified engine testing. The catalyst/substrate combination has been shown to be stable up to 5500 hrs in simulated engine conditions.

TABLE OF CONTENTS

Title Page	1
Disclaimer	2
Abstract.....	3
Table of Contents	4
Executive Summary	5
Nomenclature.....	7
Introduction.....	8
Rich Catalytic Lean-burn System.....	9
Technical Results	18
Solar T70 RCL [®] Catalytic Pilot.....	18
Single Injector Catalytic Pilot Testing.....	18
Multi Injector Catalytic Pilot Testing – Loop Engine Set.....	27
Multi Injector Catalytic Pilot Testing – Full T70 Engine Set	29
Full RCL [®] Injector	34
Single Injector Full RCL [®] Testing- Saturn Conditions	35
Multi Injector Full RCL [®] Testing - Saturn Engine Set.....	36
Single Injector Full RCL [®] Testing for Engine Integration- T70 Conditions.....	41
Durability Testing Results	49
Conclusions	56
References	57

EXECUTIVE SUMMARY

PCI has developed and demonstrated its Rich Catalytic Lean-burn (RCL[®]) technology for industrial and utility gas turbines to meet DOE's goals of low single digit emissions. The technology offers stable combustion with extended turndown allowing ultra-low emissions without the cost of exhaust after-treatment and increasing overall efficiency (avoidance of after-treatment losses). The objective of the work was to develop the catalytic technology and demonstrate the emission benefits of this technology to meet strict emissions regulations. This report discusses the results of PCI's Rich Catalytic Lean-burn (RCL[®]) combustor with natural gas fuel for low emission power generation application, under contract with DOE. The testing results demonstrate effectiveness and engine retrofitable design concepts that provided low single digit emissions of NO_x and CO in testing and application in production engines. Parallel development of two variants of the RCL[®] combustor technology was performed. For applications with less stringent NO_x requirements (less than 5 ppm corrected to 15% O₂) an RCL[®] catalytic pilot replacing current high NO_x producing pilot technology was developed. For stricter NO_x regulations (less than 3 ppm) a Full RCL[®] combustor design replacing existing DLN injectors was developed. Both concepts achieved lower than target emission levels in testing with minimal impact on engine operation, including acoustics.

PCI has successfully developed and demonstrated a low emissions **RCL[®] Catalytic Pilot** in a T70 engine in collaboration with Solar Turbines, Incorporated. The pre-reaction within the pilot provided enhanced reactivity to pilot flame, thereby reducing the need to use higher temperatures to stabilize the combustor primary zone. This concept synergistically combined the best features of catalytic combustion and conventional aerodynamically stabilized DLN combustion technology. A set of catalytic pilot cartridges (fabricated by PCI) were installed in the T70 engine with the main injector swirlers (fabricated by Solar Turbines, Incorporated) and tested. This engine testing showed no incidence of flashback or autoignition while operating over wide range of combustion temperatures. The catalytic reactor lit off at a temperature of approximately 325°C (598K/617°F) and was operated at 100% and 50% load conditions. NO_x emissions were less than 2.5 ppm for 100% and less than 3 ppm for 50% load conditions at 15% O₂ accompanied with low acoustics. The maximum catalyst surface temperatures were below material limits. Similar results were observed for high pressure (17 atm.) single injector testing and loop engine testing (8.5 atm.). These results demonstrate that a catalytic pilot burner replacing a diffusion flame or partially-premixed pilot in an otherwise DLN combustor can enable operation at conditions with substantially reduced NO_x emissions.

PCI also developed a **Full RCL[®]** concept that can replace the existing DLN swirler/injector module providing minimum NO_x production. This Full RCL[®] module was tested at industrial gas turbine conditions in a Solar Turbines, Incorporated high-pressure (17 atm) combustion rig and in a modified Solar Turbines, Incorporated Saturn engine. Single injector high pressure testing demonstrated ultra-low emissions of NO_x less than 2 ppm and CO less than 10 ppm with natural gas fuel. NO_x of less than 3 ppm and CO less than 10 ppm were achieved over a 110°C/230°F operating range in flame temperature, including a NO_x production of less than 1 ppm at about 1350°C/2450°F flame for the single injector test. Combustion noise for this test was less than 0.15% peak-to-peak. The modified Saturn Solar Turbine engine tests demonstrated NO_x emissions less than 2 ppm over the allowable operating range for this modified engine, with CO

less than 10 ppm and low combustion acoustic. Analytical studies of engine retrofittable Full RCL[®] catalytic module designs were performed to achieve similar performance. These designs were further tested at Solar Turbines' high pressure single injector test facility. Minimum NO_x emissions for engine retrofit capable designs were less than 1 ppm with CO emissions less than 10 ppm.

Subscale durability testing of the substrate and catalyst material was successfully demonstrated at engine pressure (15 atm.) and temperature (400C/750F) conditions to show long term stable performance of the catalytic reactor element. Catalyst/substrate system durability tests greater than 5000 hours with different catalytic formulations were successfully performed at simulated engine conditions of pressure of 15 atmospheres and inlet air temperature of 400°C/750°F. These tests determined long term catalytic element candidates. Cyclic tests simulating engine trips, start-up and shutdowns were also demonstrated for long term catalyst reliability. In addition to tests focused to improve catalyst performance and durability, substrate oxidation testing was also conducted. These tests were performed for the downselected substrates for over 25,000 hours at static conditions and the oxidation characteristics were analyzed. Based on these tests the best substrate for the operating conditions was used for durability testing.

At the end of the program, an RCL[®] pilot system has been developed and demonstrated to produce NO_x emissions of less than 5 ppm (corrected to 15% O₂) in a production engine operating on natural gas. In addition, a Full RCL[®] combustor has been designed and demonstrated less than 2 ppm NO_x (with potential to achieve 1 ppm) in single injector and modified engine testing. In addition, the catalyst/substrate combination has been shown to be stable to at least 5500 hrs.

NOMENCLATURE

CO	Carbon Monoxide
DOE	Department of Energy
DLN	Dry Low NO _x
EDS	Energy Dispersive Spectroscopy
GC	Gas Chromatograph
IR	Infra Red
JANAF	Joint Army, Navy, Air Force
LBO	Lean Blow-Out
LP	Lean Premixed
NASA	National Aeronautics and Space Administration
MW	Megawatt
NO _x	Oxides of Nitrogen
PCI	Precision Combustion, Inc.
PPM	Parts Per Million
PSR	Perfectly Stirred Reactor
PZ	Primary Zone
RCL [®]	Rich Catalytic Lean-burn
RMS	Root Mean Square
SCR	Selective Catalytic Reduction
SEM	Scanning Electron Microscope
SoLoNO _x	Solar Low NO _x
XRD	X-ray Diffraction

INTRODUCTION

In recent years, gas turbine operators have had to comply with increasingly strict government emissions regulations that are forcing both industrial and utility turbine manufacturers to improve engine designs [Vandervort, Davis]. The exhaust constituents of greatest concern are oxides of nitrogen (NO_x) that can act as smog precursors. In this quest to achieve lower emissions, lean-premixed combustion technology is preferred by both the industrial and utility engine manufacturers. Lean-premixed combustion technology has demonstrated the ability to achieve NO_x concentrations as low as 5-9 ppm corrected to 15% O_2 at F-class conditions or 5 ppm at E-class conditions during operation with natural gas. [Stuttaford, Vandervort, Snyder, Davis].

At low- NO_x operating conditions, however, flame temperatures are reduced and flame stability issues arise. In addition, combustion of uniform, premixed fuel/air mixtures, with little additional combustor air, can lead to combustion-induced pressure oscillations (noise). To mitigate these combustion instability issues with lean-premixed flames, gas turbine manufacturers frequently use higher temperature pilot/flames to impart stability to the main combustion process. One of the techniques used is of either a diffusion flame pilot or a partially premixed pilot [Kendrick, Prade, Snyder]. Traditionally the pilot is another fuel injector in which a small portion of the fuel is combusted in a diffusion flame or partially premixed mode. The rest of the fuel is combusted in a lean-premixed flame while the pilot maintains the stability of this main flame. In addition to providing stability at baseload, the pilot also provides combustion stability during engine start-up, load ramping, transients and fuel transfer operation. Depending on the design of the combustor, 2-10% of the fuel can be used for the piloting at baseload. If more fuel is used for piloting, more NO_x is produced due to the higher temperatures associated with pilot flame. Thus with such a conventional pilots, DLN combustors can operate close to the overall lean limit and achieve 9-25 ppm NO_x . Nevertheless the reliance on a high NO_x pilot can be a barrier to further NO_x reductions.

Catalytic combustion has the potential to provide the needed step change reduction in NO_x emissions down to low single digit levels. The use of a catalytic reactor within the combustion system allows combustor flame temperature (and thus NO_x emissions) to be maintained at levels lower than in today's lean-premixed combustors. Methane and natural gas fuels have been the recent focus of interest, because natural gas is currently the low-emissions fuel of choice for power-generating gas turbines [Pfefferle, Dalla Betta, Kraemer, Carroni, Smith].

For methane oxidation under fuel-lean conditions, however, Pd-based catalysts are currently practical, because they offer acceptable activity, lightoff temperature, and resistance to volatilization [Lee, Dalla Betta, Forzatti]. 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 [Farrauto, McCarty, Rodriguez], and oscillations in activity and temperature [Dalla Betta, Furuya, Ozawa, Kuper]. In addition, lightoff and extinction temperatures are well above 300 C (570 F) for fuel-lean reaction on Pd-based catalysts, thus requiring the use of a preburner in many engine applications [Kolaczkowski, Fant].

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 [Kolaczowski, Hayes, Johansson]. 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) is 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. The development status and challenges for application of full catalytic combustion to large utility engines and smaller industrial engines has been discussed in detail by Laster, Fant, and Dalla Betta.

RICH CATALYTIC LEAN-BURN (RCL[®]) SYSTEM

Overview:

A practical and robust approach of integration of catalytic combustion for low emission gas turbine is to limit the extent of reaction by operating 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 [Rollbuhler, Brabbs]. An examination of fuel-rich catalysis on a variety of liquid fuels was also conducted at Yale University under support from NASA [Kraemer]. 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 [Colket] also investigated fuel-rich catalytic reaction of liquid fuels, to reduce downstream thermal NO_x generation by externally removing some heat of reaction prior to gas-phase combustion. Some of the tasks described in this report were conducted under another program and were included for continuity and completeness.

RCL[®] Design Concept:

The RCL[®] system is shown schematically in Figure 1. As shown, the combustion air stream is split into two parts upstream of the catalyst. One part is mixed with all of the fuel and contacted with the catalyst, while the second part 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. Note that the catalyst is cooled only by primary combustion air, so that no heat is extracted from the system. By passing all of the fuel over the catalyst, the catalyst cooling stream remains free of fuel, precluding failure by flashback or autoignition 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. This approach avoids both soot formation as discussed in the literature [Rohlbuhler, Brabbs] and the high temperatures, which in non-catalytic RQL (Rich-burn/Quench/Lean-burn) designs lead to high NO_x formation. In the RCL[®] system, fuel-rich reaction occurs at moderate temperatures on the catalyst surface. The catalyst also allows fuel-rich reaction outside the gas-phase flammability limits in the temperature range of 700 °C to 900 °C (1530 °F to 1650 °F). This allows the partially reacted mixture to be cooler than the product of the rich section of a RQL system (which operates at the rich flammability limit). As a result there is a long auto-ignition delay time which allows mixing to fully complete without auto-ignition.

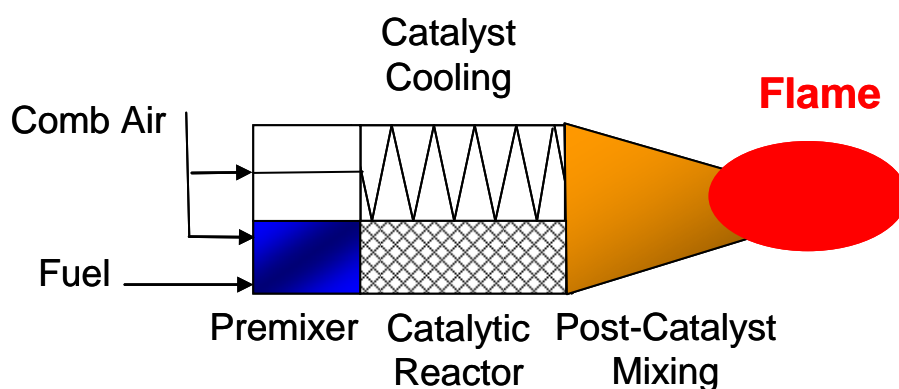


Figure 1. Schematic of the Catalytic Reactor

In addition, fuel-rich operation of the catalyst provides significant catalyst advantages, including wide choice of catalyst type (non-Pd catalysts are active to methane 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).

Lyubovsky et. al conducted experiments at PCI for methane oxidation on alumina-supported Palladium(Pd), Platinum(Pt), and Rhodium(Rh) catalysts under both fuel-rich and fuel-lean conditions. Catalyst activity/lightoff was measured in a micro-scale isothermal reactor at temperatures between 300 and 800 °C. Non-isothermal (near adiabatic) temperature and reaction data were also obtained in a full-length (non-differential) sub-scale reactor operating at high pressure (9 atm) and constant inlet temperature, simulating reactor operation in catalytic combustion applications.

Under fuel-lean conditions it was observed that Pd catalyst was the most active, although deactivation occurred above 650 °C, with reactivation upon cooling. Rh catalyst also deactivated above 750 °C, but did not reactivate. Pt catalyst was active above 600 °C. Fuel-lean reaction products were CO₂ and H₂O for all three catalysts. The same catalysts tested under fuel-rich conditions demonstrated much higher activity. In addition, a 'lightoff' temperature was found (between 450 and 600 °C), where a stepwise increase in reaction rate was observed. Following 'lightoff' partial oxidation products (CO, H₂) appeared in the mixture and their concentration increased with increasing temperature. All three catalysts exhibited this behavior. This was attributed to different intermediate species adsorbed on the catalyst surface. Following lightoff the surface is covered by oxygen when reacting fuel-lean mixtures, and covered by CO and H species when reacting fuel-rich mixtures. Greater activity under fuel-rich conditions provides reduced catalyst lightoff and extinction temperatures for catalytic combustion systems. Absence of adsorbed surface oxygen minimizes catalyst loss through

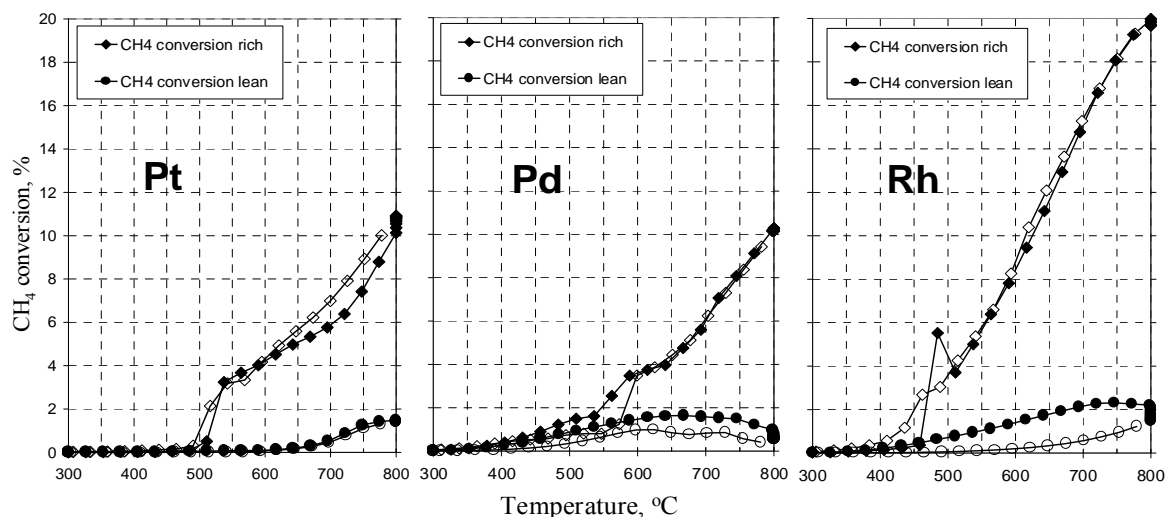


Figure 2. Catalyst activity for methane oxidation under fuel-rich and fuel-lean conditions. Same weight loading of the catalysts. Filled symbols – heating cycle, empty symbols – cooling cycle.

volatilization as precious metal oxide. A comparison of methane conversions for all three catalysts, under both fuel-rich and fuel-lean conditions, is shown in Figure 2 [Lyubovsky]. The solid symbols represent data obtained during the heating cycle, and the open symbols represent data obtained during the cooling cycle. It was found that for all tested catalysts methane conversion was much higher under fuel-rich conditions than under fuel-lean conditions.

It was shown that a fuel-rich catalytic reactor can stabilize lean-premixed combustion downstream of the catalyst, with ultra-low NO_x emissions, and without auto-ignition issues. Catalyst temperature is insensitive to equivalence ratio, allowing wide variations in inlet fuel/air ratio (tolerant to fuel/air unmixedness). Under adiabatic conditions the catalyst remains active at temperatures below 120°C , allowing operation without a preburner. In addition, the extent of catalytic reaction (heat release) is limited by available oxygen in the fuel-rich mixture, giving a level of reactor robustness that is not possible in fuel-lean catalyst systems using flammable mixtures.

RCL[®] Design Characteristics:

For natural gas fuels, it was found that it is possible to mix catalyst effluent with additional combustion air without incurring autoignition [Pfefferle]. 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. Autoignition delay time is plotted in Figure 3 for a representative natural gas composition (94.9% CH_4 , 3.1% C_2H_6 , 0.65% C_3H_8 , 0.3% C_4H_{10} , 0.1% C_5H_{12} , 0.1% C_6H_{14} , 0.05% C_7 and higher-order hydrocarbons, and 0.8% diluent) mixed with air at 0.5 equivalence ratio, 15 atm pressure, and varying temperature. The delay times were calculated using the correlation of Spadaccini and Colket, and approximately represent the delay time of catalyst effluent after heating by catalytic reaction (vitiation is neglected here). For temperatures below 700°C (1290°F) the autoignition delay time is greater than 25 ms, and for temperatures below 650°C (1200°F) the delay time is greater than 75 ms. These delay times are far greater than the

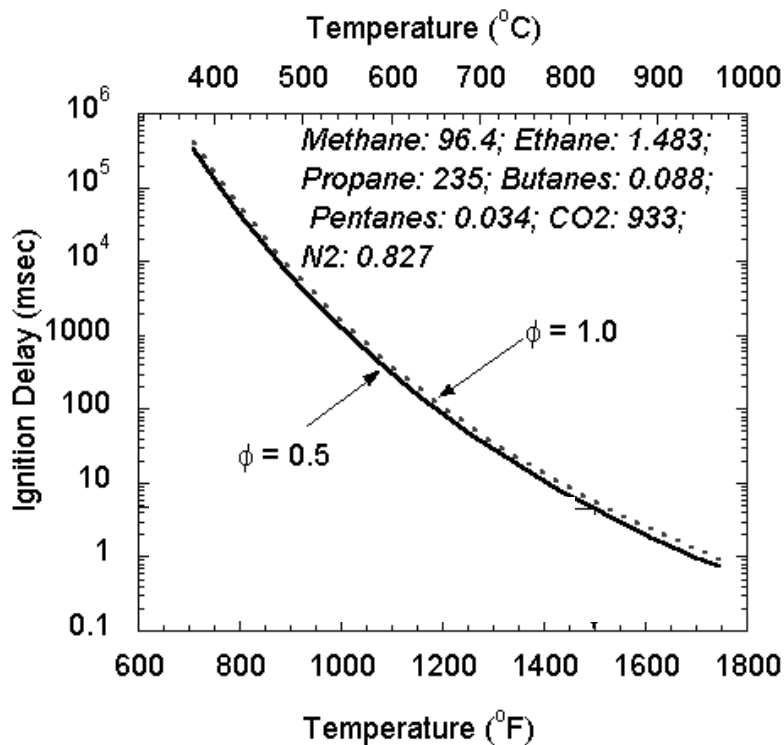


Figure 3. Prediction of Auto-ignition Delay at 16 atm Using Spadaccini's Correlation

2 to 5 ms residence time required to mix catalyst effluent with final combustion air for RCL reactors, and are also greater than the typical 10-20 ms residence time of gas turbine combustors.

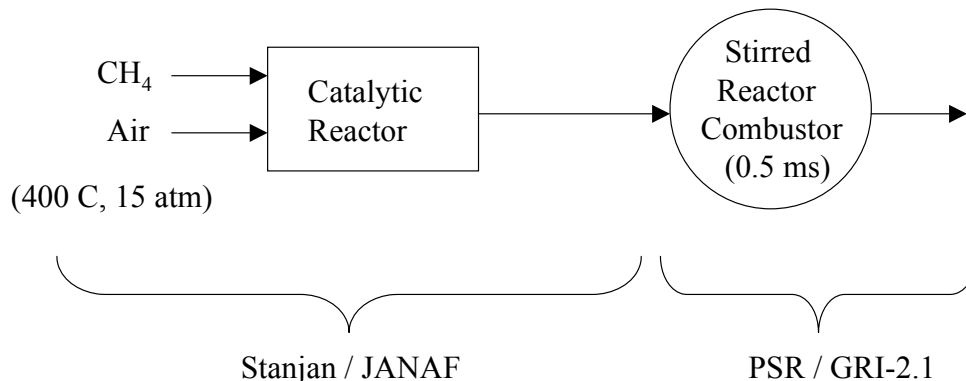


Figure 4. Schematic of simple stirred-reactor model for calculating effect of catalytic pre-reaction on combustion stability (lean blowout).

Figure 4 shows a simple stirred-reactor combustion model that demonstrates combustion stability to be significantly improved when catalytic pre-reaction heats the combustor inlet gases to temperatures in the range of 700C/1290F (well below the instantaneous autoignition temperature). Here, methane and air enter a catalytic reactor at 400C (752 F) and 15 atm pressure, and are partially reacted to provide an increased inlet temperature to a perfectly stirred reactor (PSR) having 0.5 ms residence time for gas-phase combustion reactions. The Stanjan equilibrium calculation code [Reynolds] and the JANAF thermodynamic data base [Chase] were used to calculate inlet temperature and composition to the stirred-reactor for varying degrees of reaction over the catalyst, and for varying methane/air equivalence ratios, assuming full oxidation products only (no CO or H₂) and zero heat loss [Glaborg, Frenklach].

For each different inlet temperature to the stirred reactor, PSR calculations were initially performed for high equivalence ratio, well above lean blowout. This result was then used as a restart (initial guess) for a PSR calculation at an incrementally lower equivalence ratio, and the process was repeated until the lean blowout point, where reactions in the PSR are extinguished, was found. In this manner, the curve in Figure 5 was generated, showing the gas temperature ("flame" temperature) within the PSR reactor at imminent blowout as a function of gas temperature entering the PSR reactor. Note that a 400 C (752 F) inlet temperature to the catalytic reactor is assumed, so that increased inlet temperature to the PSR reactor implies greater catalytic pre-reaction, and greater vitiation of the fuel/air mixture at the PSR inlet.

As seen in Figure 5, increased inlet temperature improves combustion stability and reduces the lean blowout limit: for example, with catalytic pre-reaction providing 700 C (1290 F) inlet temperature to the PSR, combustion reactions are sustained at a temperature that is 55 C (100 F) lower than the minimum stable combustion temperature without catalytic pre-reaction. At the same time, the 25 ms autoignition delay time at 700 C (1290 F) permits complete mixing of fuel-rich catalytic reaction products with final combustion air, allowing ultra-low NO_x emissions from a well-mixed and stable lean combustion zone downstream of the catalyst.

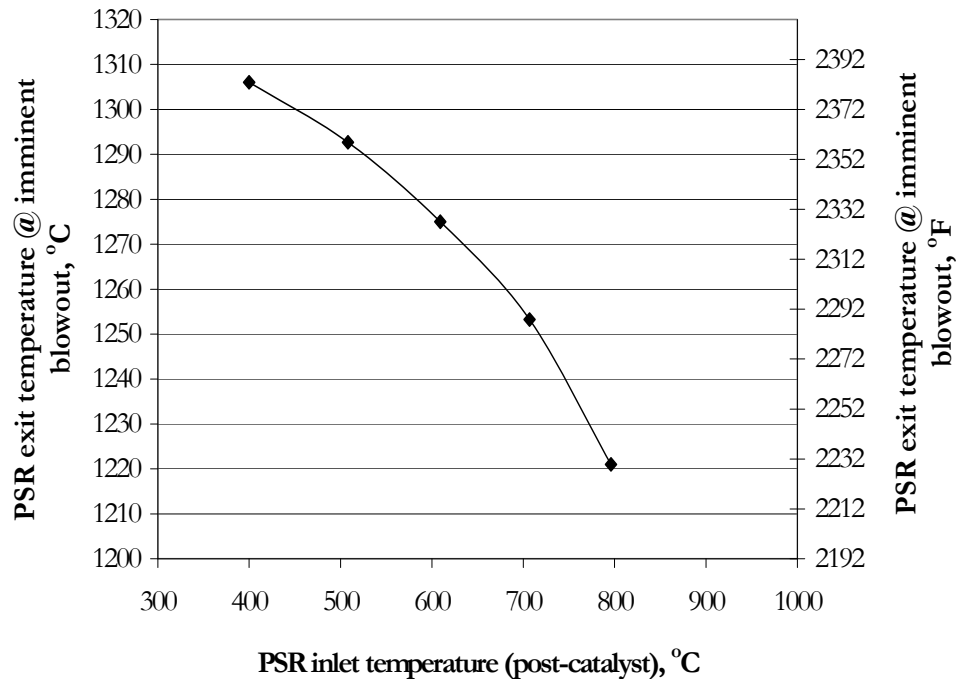


Figure 5. Gas temperature ('flame' temperature) within PSR reactor at imminent blowout, as a function of PSR inlet temperature (catalyst exit temperature)

RCL[®] Pilot:

An alternative concept to a Full RCL[®] combustion system, instead of replacing the entire DLN combustor, only the pilot is replaced by a rich catalytic system. This concept focuses on replacing the highest temperature zone of a DLN combustor with catalytic combustion technology. The motivation for using a catalytic pilot is that the catalytic pre-reaction in the pilot provides enhanced reactivity to the gas mixture exiting the pilot and thereby eliminate the need to use higher temperature flames to sustain and stabilize the combustion of the primary premixed fuel air mixture. Since the catalytic pilot is designed to replace an existing pilot, the catalytic pilot is potentially applicable for both new engines and retrofit applications with reduced hardware modification and cost. The concept combines the features of increased stability through pre-reaction of catalytic combustion and proven conventional aerodynamically stabilized combustion technology. At low equivalence ratios, which are required for low NO_x operation of the combustor, the main swirler flame depends on the catalytic pilot flame for its stability and the pilot's flame depends on the catalytic pre-reaction for its stability. Depending on design and load condition of the engine, the equivalence ratios of the main swirler flame and the pilot flame can be different.

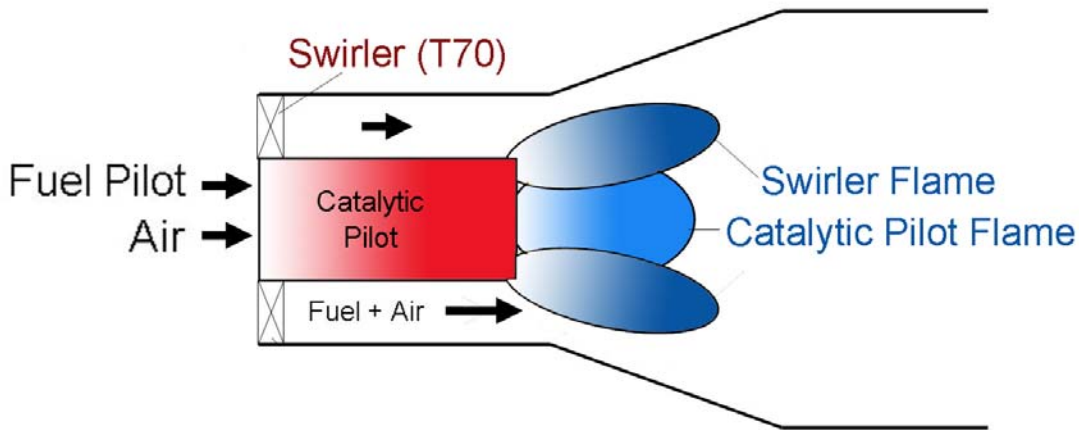


Figure 6. Schematic of the RCL[®] Pilot Concept within a Lean Premixed Injector (Swirler + Pilot)

Figure 6 shows a sketch of the catalytic pilot concept and how it integrates within a main injector for a lean premixed combustion system. Typically the full injector consists of an annular swirler with a central pilot. A portion of the fuel/air mixture passes through the catalytic pilot and prereacts within the catalytic reactor before a pilot flame is stabilized downstream of the reactor. The rest of the fuel and air mixes prior to and passes through the swirler portion of the injector with a swirl stabilized flame anchored by the catalytic pilot flame. At the low equivalence ratios required for low NO_x operation of the combustor, the main swirler flame depends on the catalytic pilot flame for stability, and the pilot's flame depends on the catalytic pre-reaction for its stability as shown in Figure 7. Depending on design and load condition of the engine, the equivalence ratios of the main swirler flame and the pilot flame can be different.

Angled View



Side View

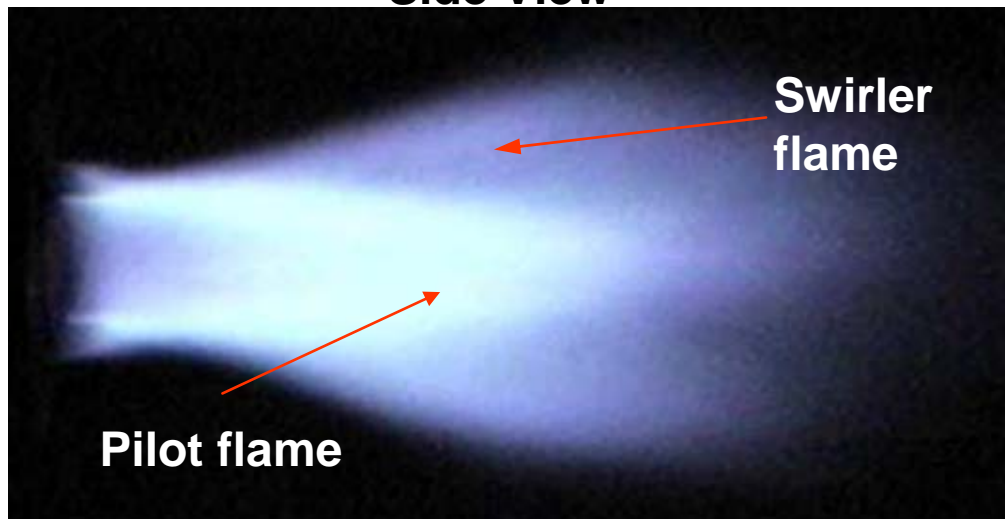


Figure 7. Views of the pilot and injector flame demonstrating stable and robust combustion

Full RCL[®]:

The Full RCL[®] is designed to retrofit into the available injector space by replacing the complete injector volume by the RCL[®] module. The RCL[®] injector is followed by a swirler that helps stabilize the flame in the downstream region. Thirty percent of fuel energy released

in the reactor hence reducing the energy released in downstream gas-phase causing reduced acoustics. Higher chemical reactivity and more stable combustion can be achieved due to increased fuel conversion. This leads to a higher inlet temperature entering the flame zone leading to increased turndown. The Full RCL[®] can be installed in the engine with minor modification. The Full RCL[®] has the advantage of ultra-low single digit emissions and improved turndown as discussed earlier.

Advantages of RCL[®] Technology:

This rich catalytic, lean-burn technology is ideal for gas turbines by providing:

- Low temperature lightoff: Advanced gas turbine engines provide combustor inlet temperatures greater than necessary to light off a catalyst operating rich thus eliminating the need for preburner.
- Low temperature required to maintain catalytic reaction: Once the reactor achieves lightoff, the catalyst is active to very low inlet temperatures, i.e. the extinction temperature is much lower than the light off.
- No preignition or flashback danger in the catalytic reactor: Potential for flashback in system is eliminated in three ways. First, the backside cooling flow has no fuel therefore flame is impossible. Secondly, while fuel and air are mixed upstream of the rich catalytic section, this mixture is maintained outside the limits of rich gas phase combustion eliminating flame initiation and propagation through the bed. In addition, due to smaller volumes of fluids to be mixed (reduced air) mixing can occur much faster reducing residence time of regions with flammable mixtures. Finally, oxygen is consumed along the length of the reactor, so when the rich reactor flow reaches the end of the catalytic elements, the majority of the oxygen is consumed. This low oxygen region provides a barrier preventing flames from propagating from the postmix region into the reactor bed.
- Tolerance to Unmixedness: Under a rich catalytic regime, the reactor temperature is less sensitive to variations in the fuel/air ratio as will be discussed later. This allows a greater allowable variation (unmixedness) of the fuel/air distribution and allows the reactor to be overfueled during start-up and acceleration regimes of the engine without dangerous temperature variations in the reactor. The stoichiometric contour that occurs during fuel start and shutdown is controlled through minimizing reactor residence times and through back side cooling minimizing temperature excursions.
- Fuel Flexibility: Because available oxygen limits catalytic reactor fuel oxidation, not fuel reactivity, the combustor can burn higher reactivity fuels (e.g. those containing higher hydrocarbons and hydrogen) in premix without early autoignition and flashback.
- Improved catalyst durability: Fuel-rich operation reduces catalyst volatilization and substrate oxidation, enhancing catalyst life.

TECHNICAL RESULTS

SOLAR T70 RCL[®] CATALYTIC PILOT

SINGLE INJECTOR CATALYTIC PILOT TESTING

To verify and demonstrate the low NO_x potential of the catalytic pilot for industrial engines, a pilot was fabricated for a single injector that was used in Solar Turbines' T70 turbine. The T70 is an industrial engine with a design rating of 7.2 MW @ 1394 K (1121°C/ 2050 °F) Turbine Rotor Inlet Temperature [Hoshizaki]. The engine has twelve injectors (swirler + pilot) arranged circumferentially around an annular combustor liner.

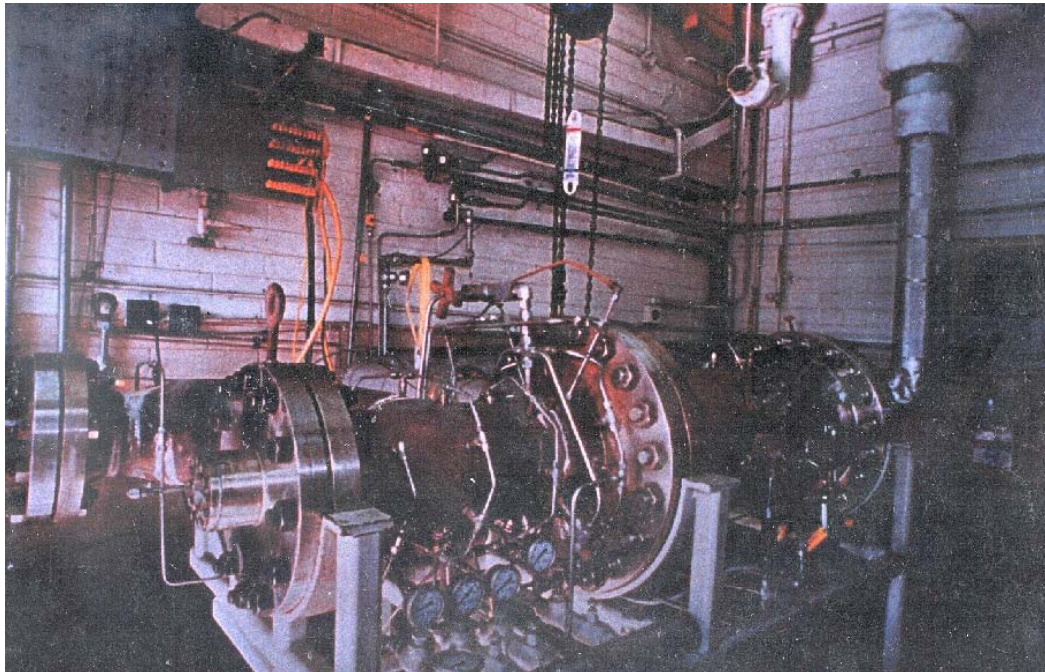
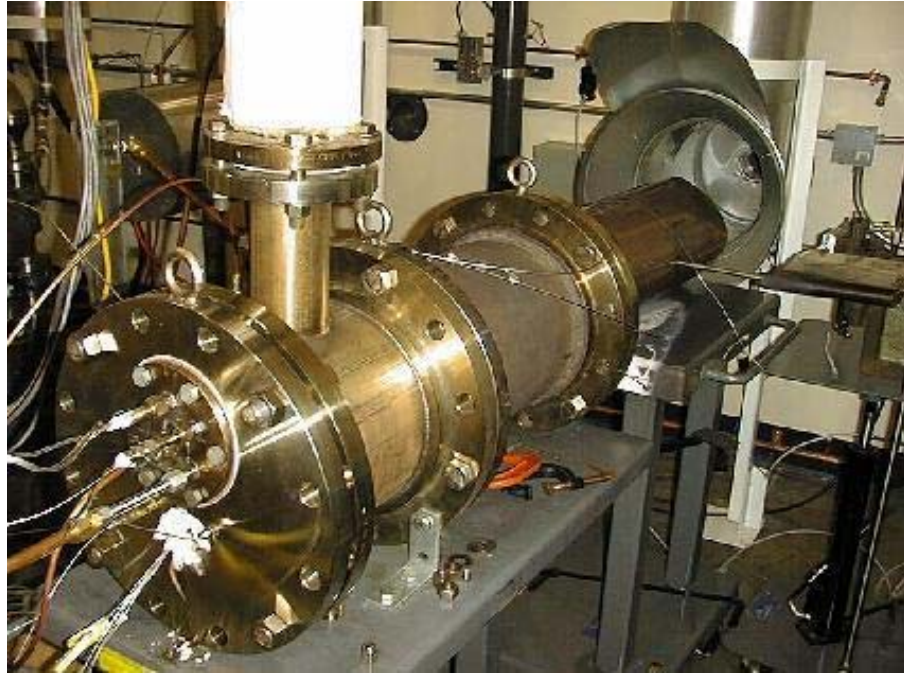


Figure 8: Photograph of modified T70 premixed fuel/air injector hardware, with RCL[®] Pilot

Figure 8 shows a hardware picture of the catalytic pilot integrated inside a T70 injector. The catalytic pilot replaced the existing partial premixed pilot without modification to the surrounding injector geometry. The catalytic pilot is installed on the injector centerline within the swirler hub. The orientation of the injector in the photograph shows the mounting flange at upper left, and swirler and catalytic reactor exits at lower right. The modified T70 injector assembly was integrated with an augmented backside cooled (ABC) combustor liner [Smith]. Approximately 50% of the combustion system airflow enters the liner through the catalytic pilot and injectors. The remaining 50% of the air is used to cool the liner and enters the combustion zone (liner) either through the dome cooling holes in the liner at the front or through dilution holes in the post-primary combustion zone.

Single Injector Test Facilities

Two different test facilities were used during the evaluation of the catalytic pilot performance as discussed in the following sections.



**Figure 9: (a) Top Panel: Single injector atmospheric pressure test facility at PCI,
(b) Bottom Panel: Single injector high pressure test facility at Solar Turbine**

Atmospheric Pressure Test Facility at PCI:

The integrated assembly of the modified T70 injector and the ABC liner configuration was first tested at PCI, in an atmospheric pressure rig (Figure 9(a)). Testing was conducted both for the catalytic reactor only and for the catalytic pilot and injector together. These tests were conducted at the simulated baseload condition of T70 engine. This implies that the pilot and injector were run at the same flow velocities in the atmospheric pressure rig as they would at baseload condition in an engine. The velocities through the component were identical to their values at baseload when the inlet temperature used at atmospheric condition was same as that of the baseload.

High Pressure Test Facility at Solar Turbines:

After completion of testing at atmospheric pressure conditions at PCI, the modified injector assembly was tested at Solar Turbines' high-pressure single injector test facility; a photograph of the facility is shown above in Figure 9(b). Solar Turbines' single-injector test facility is capable of flowing heated air (maximum inlet air temperature of 650 C / 1200 F) at a rate of 3.6 kg/s (8 pps) and a pressure of 2.1 MPa (300 psig). Air entering the rig is split into two streams. One stream (primary zone air) flows through the injector and reacts with the fuel while the other stream (dilution air) is used to cool the combustor and is then mixed with combustion products downstream of the primary zone. The percentage of inlet air entering the primary combustion zone is determined by the effective flow area of the combustor liner (including cooling and dilution air holes) versus the effective flow area of the injector. The test facility permitted independent control of the airflow, natural gas (CH₄: 95.82%, C₂H₆: 1.8%, C₃H₈: 0.32%, C₄H₁₀: 0.13%, CO₂: 0.89%, N₂: 1.0) flows to the catalytic pilot and swirler, and total pressure of the system. At this facility, the modified injector was tested at close to full load (limited by available air flow) and half load conditions, which are shown in Table 1 below.

Table 1- Nominal T70 Full Load Combustor Operating Conditions [Karim, 2003]

Baseload Inlet Temperature	705 K (432°C/810 °F)
Baseload Inlet Pressure	1.7 Mpa (250 psia)
Baseload Pressure Drop	4.0%
Halfload Inlet Temperature	636 K (363°C/ 687 °F)
Halfload Inlet Pressure	1.02 Mpa (153 psia)
Halfload Pressure Drop	3.5%

High Pressure Single Injector Test Results

Results obtained for high pressure of 15 atm. operation are discussed below. During the several days of operation at Solar Turbines' high-pressure facility no autoignition or flashback in the catalytic pilot was observed.

Catalyst Lightoff:

Lightoff of the reactor occurred when the inlet air temperature reached approximately 325°C (598K/617°F) in the 15 atm. high pressure rig. As the catalyst lights off, it becomes sufficiently active that fuel was oxidized and heat release occurred on the surface. The gas in the catalytic reactor was heated by the convection of heat from the catalyst surface. Due to

resistances in heat transfer mechanisms; the exit gas temperature was less than the maximum surface temperature. The measured lightoff temperature of 325°C (598K/617°F) was substantially lower than the 450°C (723K/842°F) lightoff temperature reported in the literature for catalytic combustion of natural gas using fuel lean catalysis [Beebe, 1995]. This lower lightoff temperature is a direct consequence of using fuel rich oxidation in the catalytic reactor and has shown no dependence on pressure.

During startup, the catalytic pilot can be used as a non-catalytic fuel stage to provide 50% to 60% of the fuel for the combustor thereby creating a rich primary zone. Since compressor exit air temperature will be lower than the lightoff temperature for the reactor, no reaction will occur inside the catalytic reactor. The unreacted fuel air mixture exiting the catalyst will then be combusted in the downstream liner (combustor) section along with the fuel/air mixture from the swirler albeit with higher emissions. Once the combustor ramps up and the compressor discharge temperature, reaches the lightoff temperature of the reactor, fuel oxidation in the reactor starts to occur. This catalytic reaction provides further stability to the overall combustion process. The higher fuel-rich equivalence ratios which will result from such a fuel split are within the safe operating range of the reactor, since higher fuel rich equivalence ratios produce less heat. When 50% load is reached, fuel flow to the pilot is readjusted for operating in the low NO_x regime.

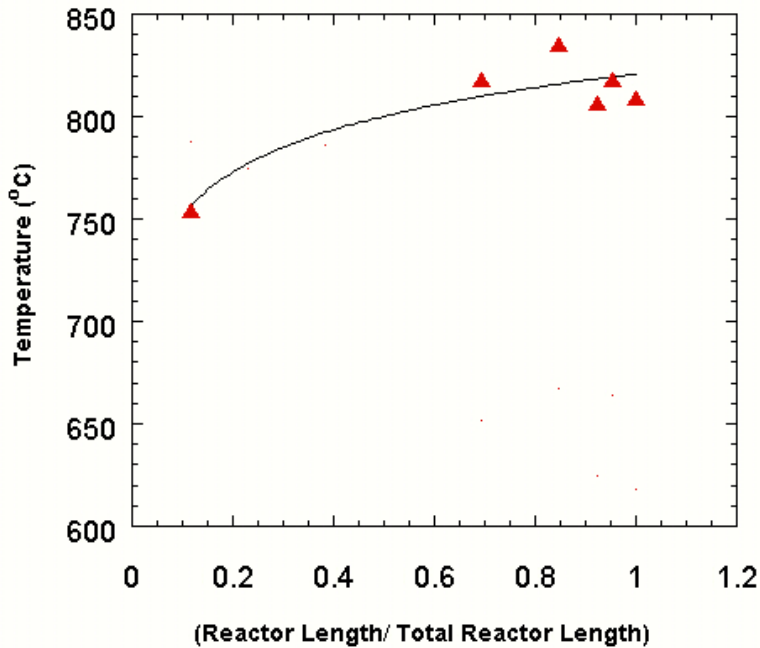


Figure 10: Catalyst surface temperature at 15 atm. pressure

Surface Temperature of the Catalyst:

Figure 10 shows catalyst surface temperatures at a pressure of 15 atmospheres as function of non-dimensional reactor length. The maximum catalyst surface temperature was below 850°C,

a temperature much lower than the reported maximum surface temperature for fuel lean catalytic combustion (Dalla Betta, 1999). This reduced temperature operation decreases catalyst volatilization, and sintering, which are factors judged potentially life limiting for catalytic combustors and permits the use of metal for catalyst substrate.

The maximum catalyst surface temperature was similar to the maximum surface temperature during atmospheric operation. As a consequence of this, catalytic reactor operation at atmospheric pressure gives a good estimate to the maximum temperature at high pressure.

Emission Results:

Due to air flow limitation in the high pressure rig, emission data were collected at 15 atm. instead of 17 atm, which is the baseload pressure for T70 engine. As discussed earlier in the “Single Injector Catalytic Pilot” section, the modified T70 injector was integrated with an ABC liner and installed in the high pressure rig. As shown in Table 2, the replacement of the standard diffusion pilot with the catalytic pilot increased the air split to the pilot to 12.2% from 3.3%.

Table 2- Air Splits in the Combustor [Karim, 2003]

Catalytic Pilot Configuration		Standard Pilot Configuration	
Catalytic Pilot	12.2%	Pilot	3.3%
Swirler	40.6%	Swirler	45.0%
Liner (dome cooling)	12.2%	Liner (dome cool.)	13.4%
Liner (dilution holes)	35.0%	Liner (dilution holes)	38.3%

All emission results discussed below are in terms of pilot and swirler equivalence ratios and front end adiabatic flame temperatures (calculated based on pilot and swirler air and fuel flow) rather than primary zone flame temperatures, which are difficult to measure because of entrainment of dome cooling air and liner dilution air.

Figure 11 shows the sensitivity of NO_x emission to catalytic pilot equivalence ratios at a pressure of 15 atm. The symbols show the experimental data obtained after correction to 15% O_2 in a dry sample, and the lines represent trend lines drawn through the data points with constant swirler equivalence ratio. For a constant swirler equivalence ratio (Φ_{swirler}), emission data were first collected with the highest pilot equivalence ratio ($\text{NO}_x < 20$). Then gradually the pilot equivalence ratio (Φ_{pilot}) was dropped until blow-off occurred or CO exceeded 20 ppm. CO exceeded 10 ppm in only the first two data points ($\Phi_{\text{pilot}} = 0.55, 0.61$) from the lowest swirler equivalence ($\Phi_{\text{swirler}} = 0.61$) ratio series shown in Figure 11. CO was lower than 10 ppm at all other data points shown in Figure 11. From figure 11 it can be observed that for higher swirler equivalence ratio less piloting is necessary and blowoff occurred at lower pilot equivalence ratio. This is expected and the increased stability is achieved at the expense of higher NO_x emission. Below Φ of 0.65, NO_x dependence on the pilot equivalence ratio was linear. Figure 11 also shows that the best NO_x emission ($\text{NO}_x < 5$ ppm) can be obtained for this configuration of modified T70 injector and ABC liner when the swirler equivalence ratio is between 0.5 to 0.65 and the pilot equivalence ratio is between 0.55 to 0.65. Thus the modified injector showed a wide operability range. If the fuel to the catalytic pilot was shut-off while operating at these low swirler equivalence ratios (0.5-0.65), blow-off would occur. This indicated that the catalytic pilot provided stability to the main flame.

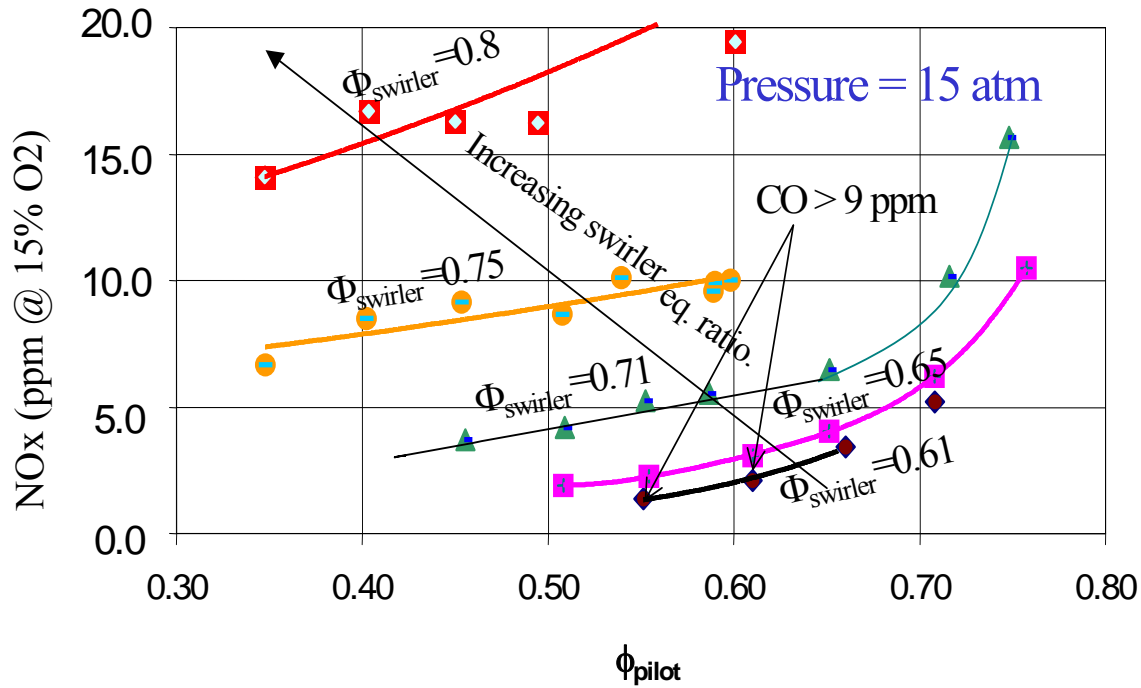


Figure 11: NO_x emission dependence on catalytic pilot equivalence ratio

Figure 12 shows the same emission data (CO and NO_x) of Figure 11 when plotted as a function of front end temperature of the combustor. The front end temperature was calculated based on the air flows to the pilot, and injector, and fuel flows to the swirler and pilot. Note that the calculated front end temperature does not take into account any reverse flow dilution

air (liner cooling) or dome cooling that may participate in the combustion process occurring in the primary zone of the combustor. As such, the temperature shown in the x-axis is not the primary zone temperature during combustion. Comparison of these data with data from lean-premixed combustion of Kendric and Snyder suggest that the primary zone temperatures may be 200C/360F lower than the calculated front end temperature shown in the abscissa of Figure 12.

The symbols represent measured emission data (closed symbols represent NO_x data and open symbol represents CO data) after correction and the solid line is an exponential trend line drawn through the NO_x data set. Figure 12 also shows the operating temperature for this modified configuration at 100% load to be around 1950 K (1677 °C/ 3050 °F). It was observed that with this modified configuration less than 5 ppm NO_x was achieved for the operating condition. Also, less than 5 ppm NO_x was also achieved in the front end temperature range of

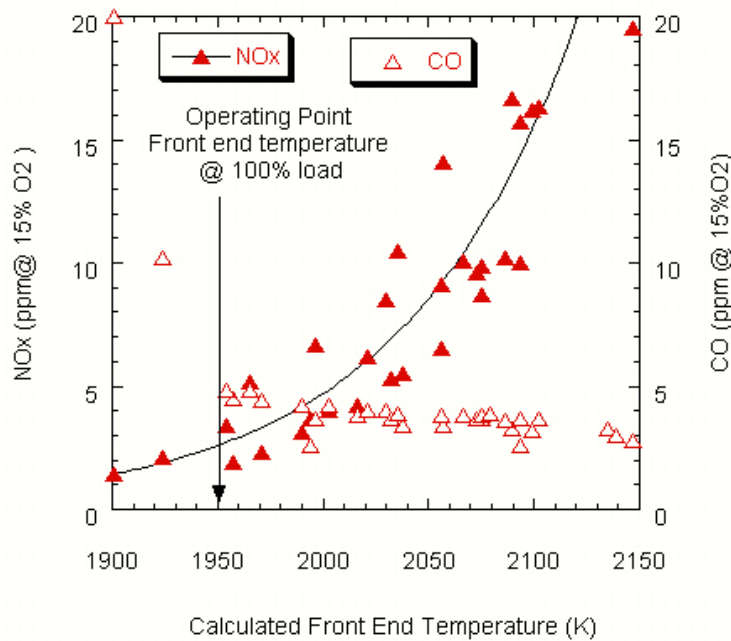


Figure 12: Measured NO_x and CO emission for the modified T70 injector at close to 100% load condition

1900 – 2000 K (1627-1732 °C/ 3000- 3150 °F). In diffusion flame pilot tests with a similar (same effective area) swirler, NO_x emission of 15 ppm resulted for an operating front end temperature of approximately 2140 K (1868 °C/3394 °F). Clearly, the use of larger air split for the catalytic pilot, (flow-splits shown in Table 2) has permitted operating at lower front end operating temperature and thereby decreased NO_x.

Figure 12 also shows that at a front end temperature of 1960 K (1687 °C/3070 °F), measured NO_x values of 1.9 ppm and 5.2 ppm were observed. This discrepancy in NO_x data is due to the use of very different pilot and swirler equivalence ratios for the two cases. If these data are

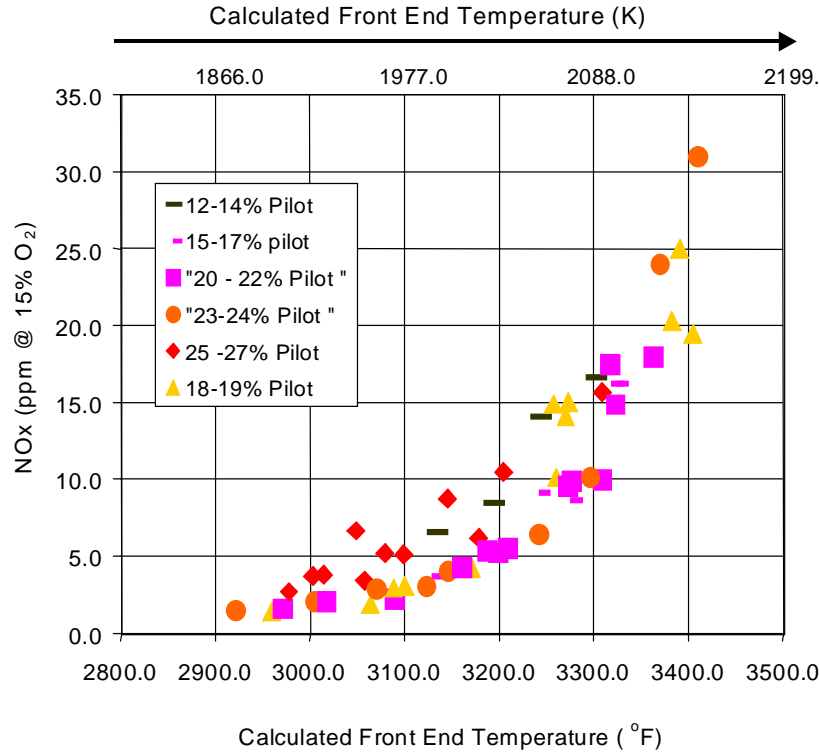


Figure 13: NO_x emission (100% load) as function of front end temperature with percent pilot as parameter

compared to the data of Figure 11, it can be observed that a NO_x level of 1.9 ppm was observed for swirler and pilot equivalence ratios of 0.65 and 0.51 respectively, whereas for the higher NO_x case Φ_{swirler} and Φ_{pilot} were 0.61 and 0.71 respectively. The use of a higher pilot equivalence ratio was responsible for the increase in NO_x. Thus there is an optimum percent of pilot fuel flow above which increasing the percentage has detrimental effect on NO_x emission. This can be observed in Figure 13, which shows the emission data plotted as function of front end temperature with percent pilot as a parameter. The data shows that 18-20 percent pilot to be the optimum percentage for lowest NO_x emission. It can also be observed from Figure 13 that for a lower percent pilot of 12%, blow-off occurred at a higher front end flame temperature of approximately 3100 °F. In addition to the testing at close to 100% load condition, emission data were also obtained at 50% load condition. The 50% load condition is shown in Table 1. The catalytic reactor of the pilot was active even when the inlet temperature was dropped to the 50% load inlet temperature of 363 °C (636 K /687 °F). The pressure of the system was also brought down to a pressure of 153 psia, which is the inlet pressure for T70 engine at 50% load condition. Figure 14 shows data similar to Figure 12 but for 50% load condition. In an effort to control emission over the entire operating range, lean-premixed combustion systems are frequently designed to maintain constant flame temperature as the engine changes power level. Thus for an operating point of 1950 K, which is the same as that

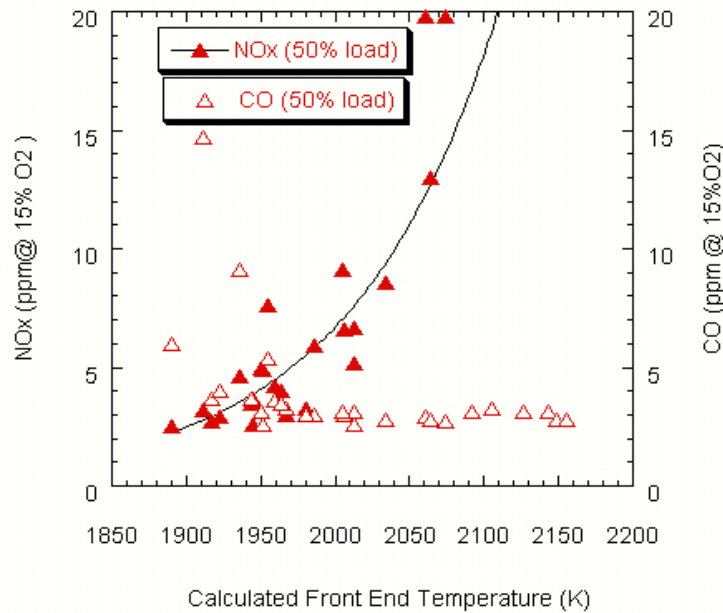


Figure 14: Measured NOx and CO emission for the modified T70 injector at 50% load condition

of the 100% load condition, it can be observed from Figure 13, that emissions less than 5 ppm are achievable.

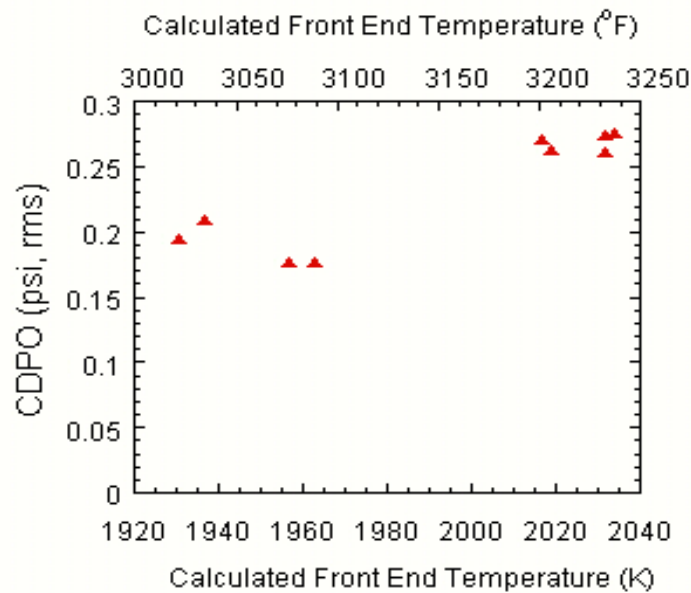


Figure 15. Dynamics plot for single injector

Combustion Noise:

During the testing of the modified T70 single injector at Solar Turbines' facility, pressure fluctuations in the combustor were recorded. The magnitude of the pressure fluctuations never exceeded 0.5 psi (RMS) during testing including 100% and 50% load conditions as shown in Figure 15.

MULTI INJECTOR CATALYTIC PILOT TESTING -LOOP ENGINE SET

Results for single injector high pressure 17 atm. testing showed low emissions, good flame stability, and low acoustics as discussed in the earlier sections. Based on the promising single injector performance data, it was decided to test a full set of twelve injectors in a loop engine followed by production T70 engine testing. In order to conduct testing of a full set of hardware a set of T70 SoLoNO_x injectors with RCL[®] pilots was tested in the loop engine. Engine light-off, acceleration to idle, catalyst light-off and operation at full load were achieved with the catalytic pilots. Emissions measurements were made at various engine loads with different levels of pilot.

Engine Hardware:

A set of fourteen catalytic pilots cartridges were manufactured by PCI (twelve for testing (Figure 16(a) with two spares). Each cartridge was instrumented with two Type K thermocouples to measure catalytic bed temperatures. The pilots were then integrated with the T70 swirlers (Figure 16(b)) and single injector (swirler + catalytic pilot) testing of four randomly chosen injectors were performed. The results from these randomly tested single injectors were similar to the initial results obtained and reported earlier.



(a)



(b)

Figure 16: Catalytic Pilots for T70 Engine Testing
(a) Twelve Instrumented Catalytic Pilot Cartridges
(b) Catalytic Pilots Integrated with T70 Swirlers

Loop Engine Test Results

A set of production T70 injectors was used to shake down the loop facility with the T70 combustion rig. These tests helped to establish the engine bleed schedule, and other operating requirements to run the engine at combustor exit temperatures representative of the T70. The operation of the recuperator was also tested so that T70 combustor inlet temperatures could be

achieved. Operation of the engine with the catalytic pilots followed a control scheme similar to that used for the production injectors. The catalyst lit-off within the baseload operating temperature. Once catalyst light-off was achieved, the engine was brought to full load using approximately 23% pilot flow.

Emissions measurements were made at three different loads for a range of pilot flows. Figure 17 shows NO_x emissions plotted against Adiabatic Flame temperature for different pilot flows. It is anticipated that operation of the T70 engine near the design pilot fraction of 15%, if possible, would lead to lower NO_x emissions than seen in the loop tests.

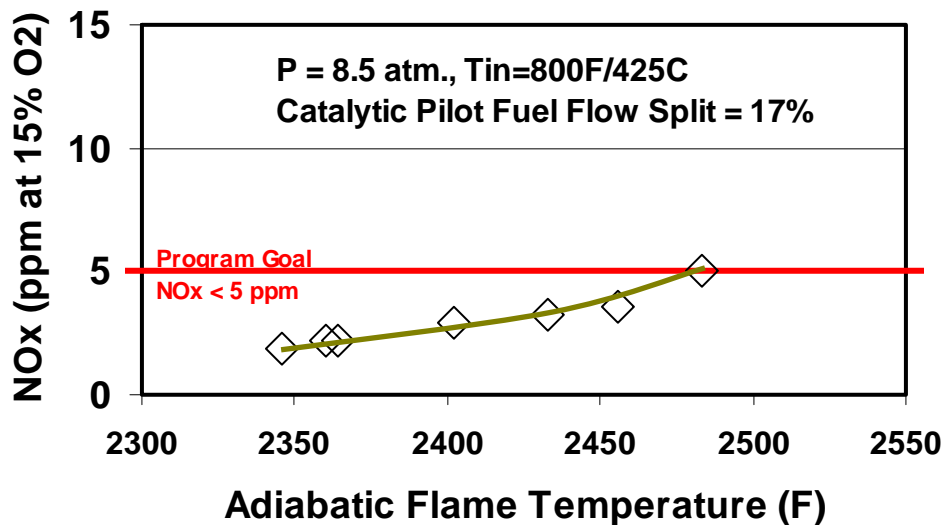


Figure 17: Loop Engine testing demonstrating < 5 ppm NO_x emissions

Measured NO_x emissions (2 –5 ppmv @ 15% O₂) were similar to those measured in the single injector high pressure test rig. The loop test demonstrated the low NO_x potential of the catalytic pilots, and a T70 engine test is planned for Q3 2007. These tests demonstrated that the combination of the catalytic pilot with the DLN swirler did not negatively impact the radial temperature profile, the pattern factor, engine startup and shutdown capability. In comparison to the stock partially premixed flame pilot, the catalytic pilot required a higher fuel split during startup. After approval, the twelve catalytically piloted injectors were installed in a production T70 engine and performance was tested.

MULTI INJECTOR CATALYTIC PILOT TESTING -FULL T70 ENGINE SET

High pressure single injector and loop engine test with the 12 modules provided promising results with low emissions and stable flame performance. Based on these results, PCI and Solar Turbines, Incorporated decided to move forward to conduct full scale T70 engine testing. The results of this testing are discussed below.

As part of the approval process for installation of the catalytic pilot injectors into the production T70 engine, it was determined that the length of the pilot flame before catalyst

lightoff was outside the engines accepted tolerances. After catalyst lightoff, the flame became much shorter and was well within engine specifications. Several options were considered for reducing flame length during initial startup, including modification of fuel/air splits to the pilot. After testing of options in atmospheric and pressure test facilities, it was found that a hardware design modification to the post-mix region of the catalytic pilot resolved the excessive flame length issue with minimal impact on catalyst performance or engine startup. This modification was made to the full engine set of catalytic pilots and full engine testing continued.

Startup Performance:

Startup of the engine occurred without significant variation in startup procedure than a standard piloted engine. The lightoff characteristics of the catalytic reactor at engine startup are shown in Figure 18. The data plotted is the transient data for engine performance test start up with the combustor inlet air temperature and the catalytic surface temperature of three of the twelve injectors plotted as a function of time. During prior testing, a number of the

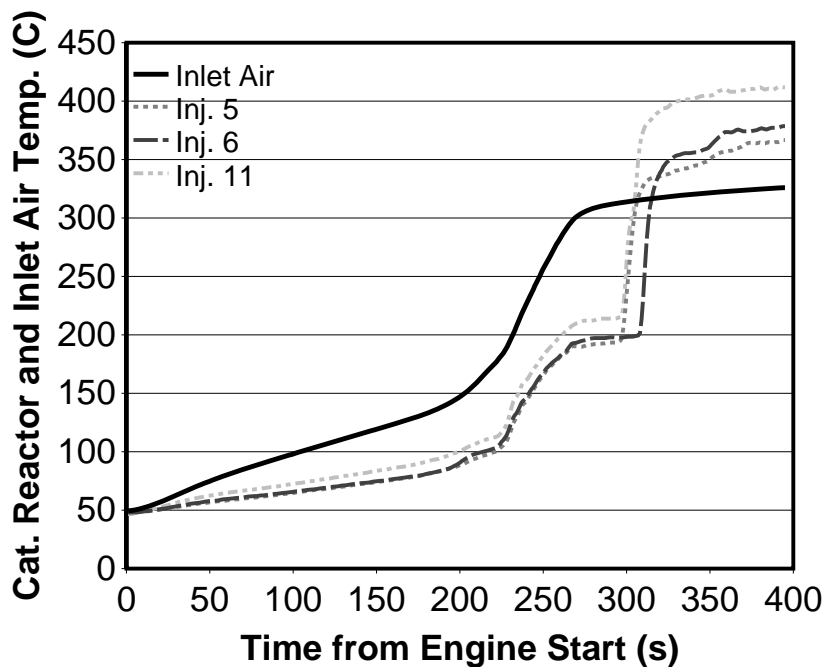


Figure 18. Combustor inlet air and catalytic reactor temperature indicating lightoff at 325°C / 620°F inlet air temperature during engine testing

thermocouples monitoring reactor temperatures were damaged and thus were replaced. Due to the reactor geometry, the replacement thermocouples could not be attached directly to the catalytic elements, but were threaded into the fuel-rich reactor. This would allow determination of presence of catalytic activity (i.e. lightoff), however exact reactor temperatures were difficult to measure. Injector to injector variation of temperature measurements was high because of the uncertainty of the location of the sensor tip. Prior to lightoff, the reactor temperature was reduced compared to the combustor inlet air temperature due to thermal lag of the combustor and reduction in gas temperature due to mixing of the incoming air with lower temperature fuel. It can be observed from Figure 18 that lightoff of

the reactor occurred when the inlet air temperature reached approximately 325°C (600 K /617°F). The measured RCL[®] reactor lightoff temperature is substantially lower than the 450°C (730 K/842°F) lightoff temperature reported in the literature for catalytic combustion of natural gas using fuel-lean catalysis [Beebe, 1995]. The catalytic reactor heated up to a steady-state condition (constant temperature difference between catalyst surface temperature and inlet air temperature) in less than two seconds indicating rapid lightoff. This behavior is similar to what was observed during single injector testing by Karim et. al. In addition, the twelve injectors lit-off nearly simultaneously, showing tolerance to injector to injector variation in fuel/air ratio variation. The injector to injector variation in catalytic reactor temperature after lightoff was likely due to imprecision in the insertion location of the thermocouples in the catalytic reactor or due to fuel/air ratio variation in the catalytic pilot.

Full Load Pilot Fuel Split Variation:

To optimize for reduced NO_x production by the catalytic pilot, the percent of the overall fuel

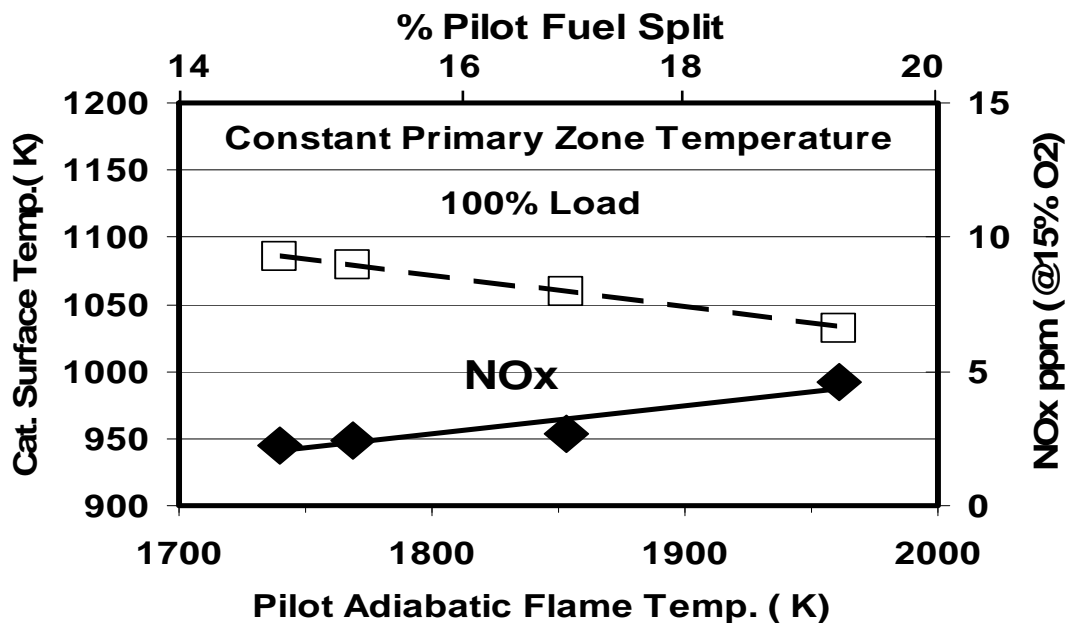


Figure 19. Catalytic reactor temperature and NO_x emissions with constant PZ temperature with variation in percentage of fuel to pilot [Baird, 2009].

flow rate to the pilot was varied (while keeping the overall injector fuel flow rate constant) while monitoring overall injector (main and pilot) NO_x emissions and catalytic surface temperature. Air flow to the pilot is geometrically controlled, thus is constant over the range of testing here. Figure 19 shows the results of this testing. With reduction in fuel flow to the pilot, catalytic bed temperatures increased (due to catalytic region operating leaner) and NO_x production reduced to very low single digit levels through reduction in pilot flame temperatures. The maximum catalyst surface temperature was well below 1120 K (850°C/1550°F), a temperature much lower than the reported maximum surface temperature for fuel-lean catalytic combustion [Dalla Betta]. The reduced temperature plus operation of the catalyst fuel-rich decreases the occurrence of potential life limiting factors such as catalyst volatilization, catalyst sintering, and substrate oxidation. In addition, the variation of catalytic

surface temperature was small across wide variation in pilot adiabatic flame temperature. This indicates catalyst reactor robustness in that large changes in operating conditions (i.e load shedding or acceleration) will have reduced impact on catalytic bed lifetime. A fuel to pilot split of approximately 15% was chosen to be the optimum based on the low NO_x emissions at reasonable bed temperatures and subsequent results will be based on this. This fuel split is higher than used for standard pilots; however the catalytic pilot has a higher air flow rate, leading to leaner operating conditions and thus lower peak temperatures. Lower NO_x emissions could possibly be achieved by reducing the fuel split further; however, catalytic temperatures would need to be closely monitored.

Emissions Performance with Load Turndown from 100% to 50% Full Load:

Figure 20 shows the emissions performance of the T70 engine with catalytically piloted injectors with a fuel to pilot percentage of 15%. The filled symbols indicate NO_x emissions while open symbols indicate CO emissions. A solid line indicates the trend of NO_x emissions. For the T70 engine, the combustor primary zone temperature is held constant with changes in load. The engine achieved low single digit (2.5 to 3.5 ppm corrected to 15% O₂) over a range of engine loads from 100% to 50% with no requirements for fuel staging. A slight increase in NO_x and CO was seen with decreased loading of the engine. As the engine load decreases, the inlet pressure and temperature to the combustor decrease, both of which potentially can have an effect on emissions, however, it was seen that, for the catalytically piloted combustor tested in this study, the change was small.

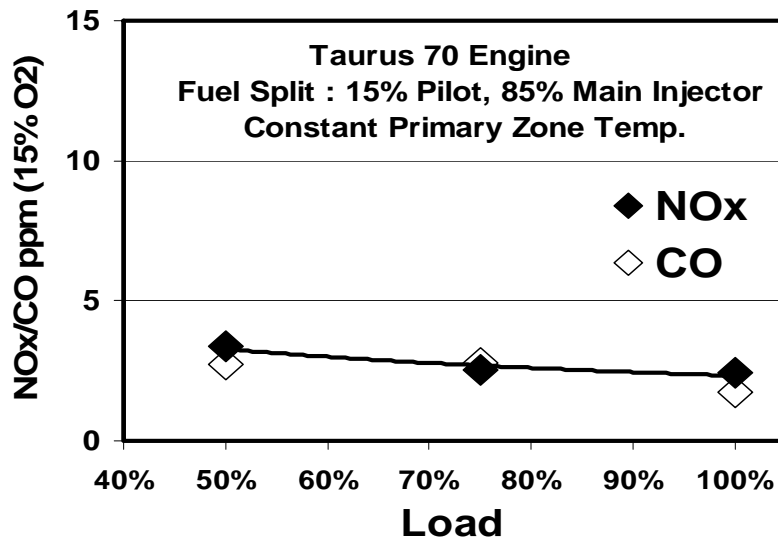


Figure 20: NO_x and CO emission with variation of engine loading showing low single digit emissions from 50% part load to full base load [Baird, 2009].

Overall Combustor Adiabatic Flame Temperature Turndown at Part Load (50%) Conditions:

In addition to the testing at baseload conditions, emission data were also obtained at 50% part load condition (Figure 21) to examine overall adiabatic flame temperature turndown for low single digit operation. This is a test to determine combustor stability. The catalytic reactor of the pilot maintained activity with decrease of the system operating conditions to the inlet

temperatures and pressures at 50% part load, further indicating the self sustaining capability of the reactor. The enhanced stability provided by the catalytic pilot allowed operation of the combustor at low adiabatic flame temperatures, allowing ultra-low NO_x emissions even at part-load without fuel staging. The combustor at 15% pilot split also had a reasonably broad range of flame temperatures with low CO (<10 ppm) emissions indicating good flame stability at 50% load. The increase in CO is due to lower flame stability allowing incomplete combustion products escaping the combustion zone. Further optimization/adjustment of the fuel percentage to pilot may broaden this turndown range.

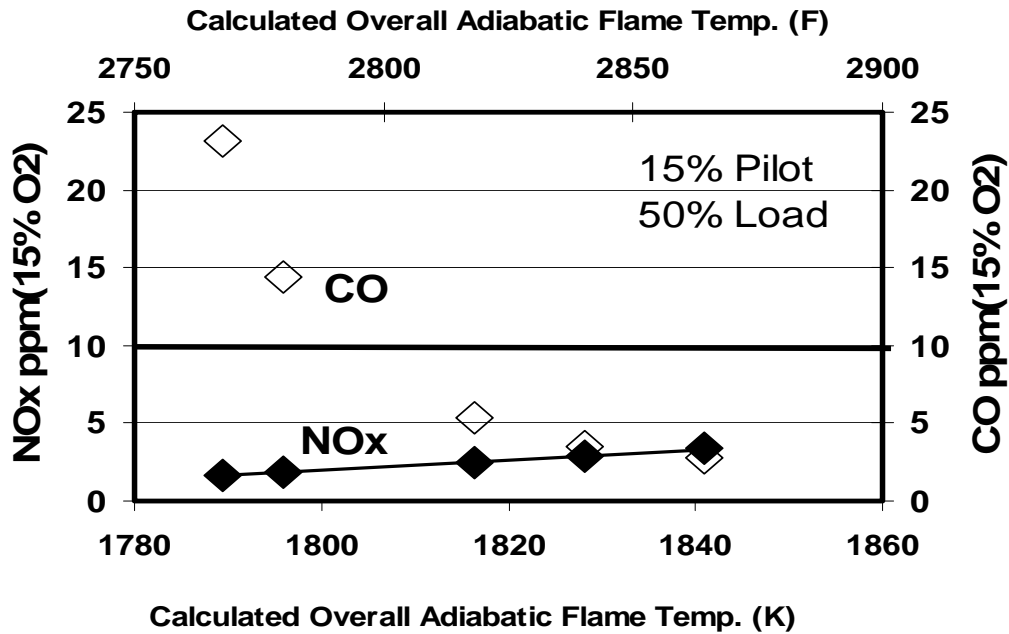


Figure 21: NO_x and CO emission with variation of calculated overall adiabatic flame temperature showing large potential low emissions turndown (Overall = Pilot +Main) [Baird, 2009].

Combustion Noise

As part of testing, acoustic levels in the engine were monitored. The magnitude of the pressure fluctuations never exceeded 689 Pa or 0.1 psi (RMS) during testing including 100% and 50% load conditions. Low acoustic emissions help ensure longer operating lifetimes of the combustor hardware by reducing acoustic driven vibrational loads.

FULL RCL[®] INJECTOR

Solar Turbines' T70 and Saturn engines were chosen for concept demonstration of the Full RCL[®]. After conducting preliminary testing T70 engine was down selected as the engine for performance demonstration and integration of the Full RCL[®] reactor. Testing was conducted at Solar Turbines' single injector simulated engine (17 atm.) test facility. Testing was conducted in a Saturn engine. Design optimization and testing of the Full RCL[®] injector for T70 engine integration was also performed.

SATURN ENGINE TESTING

Single Injector Hardware Configuration:

A 7.6-cm (3.0-inch) diameter RCL[®] catalytic reactor was fabricated for testing in Solar Turbines' high-pressure single-injector combustion test facility. Testing was performed at simulated Saturn engine operating conditions as representative of an advanced industrial gas turbine application.

For the tests reported here, the rig combustor liner was cylindrical, 20 cm (8.0 inches) in diameter, and backside-cooled. Four nominally 1.3-cm (0.5-inch) diameter holes were located at the combustor liner's downstream end, to allow the dilution air to enter the combustor after cooling it. The dilution air flow path effective area, including losses during convective cooling along the liner length, was measured at 5.2 cm² / 0.8 in² (discharge coefficients included). For comparison, the RCL[®] catalytic reactor effective flow area was approximately 11 cm² (1.7 in²), and there was an additional approximately 1.9 cm² (0.3 in²) effective flow area of leakage. Leakage occurred primarily at the combustor's downstream seal (into the post-combustion flow path), and at the injector insertion seal (grommet seal).

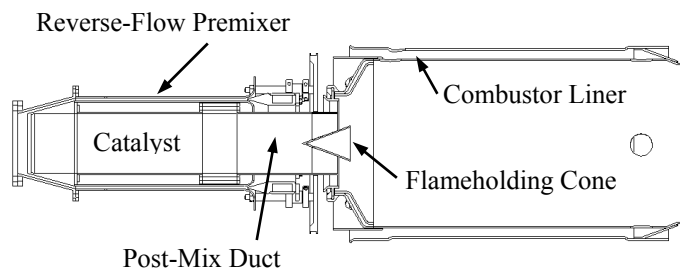


Figure 22. Assembly of RCL catalytic reactor with 20-cm (8-in.) diameter combustor liner in Solar Turbines' single injector test facility. Bulk flow

A schematic of the complete RCL[®] combustor assembly, including premixer, catalytic reactor, and downstream combustor liner as tested at Solar Turbines, Incorporated is shown in Figure 21. The catalytic reactor design is as described earlier. An annular reverse-flow premixer was fitted around the catalytic reactor, to provide a premixed fuel-rich mixture to the catalyst. Note that all fuel entered via this premixer, and all fuel contacted the catalyst. Catalyst cooling air bypassed the premixer, and entered from the left-hand side in Figure 22. Downstream of the catalyst, but upstream of the combustor, the fuel-rich mixture and the catalyst cooling air

were combined in a post-catalyst mixing duct ("post-mix" duct) to create a partially-reacted fuel-lean fuel/air mixture. The premixer, catalytic reactor, and post-mix duct together constitute what we will call the "RCL[®] injector." Conceptually, the RCL[®] injector replaces a conventional DLN premixer/swirler arrangement, such as Solar Turbines SoLoNOx injector.

As shown in Figure 22, the 7.6-cm (3.0-inch) diameter post-mix duct was fitted into a grommet seal at the upstream end of Solar Turbines' rig combustor liner, to inject the partially-reacted fuel-lean mixture into the combustor. Note that for the tests reported here, a flameholding cone was installed at the exit of the post-mix duct, just upstream of Solar Turbines' combustor liner. Thus, gas-phase combustion was anchored on the combustor centerline by the flameholding cone. The expansion (dump) of the combustor liner's dome also served to anchor combustion. In general, the catalyst is intended to improve combustion stability and turndown at the flame anchor point, but is not necessarily intended to provide gas-phase ignition. Solar Turbines' torch igniter was used to ignite gas-phase combustion during rig testing.

SINGLE INJECTOR RIG TEST RESULTS- SATURN CONDITIONS

As discussed in more detail below (next section), four RCL[®] injectors were fabricated for engine testing in a modified Solar Turbines' Saturn engine. Each injector had the same basic design and dimensions as the original single RCL[®] injector tested at T70 conditions described above. One of the four Saturn-bound RCL[®] injectors was tested in Solar Turbines single-injector test rig. The purpose of this test was to evaluate operation at low inlet temperature, prior to actual Saturn engine testing. In particular, it was desired to confirm catalyst activity (maintained lightoff) at low inlet temperature (e.g. Saturn half load combustor inlet temperature of 215 C / 420 F), and to also measure achievable combustor emissions at these low inlet temperatures.

Three operating points for the modified Saturn engine were selected for single-injector tests, as listed in Table 3. Based on one-quarter Saturn-engine fuel flow (for one of four injectors), a full load RCL[®] injector airflow of 0.6 kg/s (1.3 pps) was selected to provide ultra-low-emissions lean-premixed combustion. For part-load testing, injector airflow was scaled according to combustor inlet pressure.

Table 3. Nominal Saturn-Engine Combustor Inlet Conditions for Modified (Catalytic) Saturn Engine [Smith, 2005].

Saturn Combustor Inlet Cond.	57% LOAD	74% LOAD	100% LOAD
Temperature	215C / 415F	225C / 440F	250C / 485F
Pressure	4.85 atm	5.41 atm	6.15 atm
Emissions from Single Injector Rig	< 2 ppm NO _x < 6 ppm CO	< 2 ppm NO _x < 5 ppm CO	< 2 ppm NO _x < 2 ppm CO

Because the Saturn-engine combustor inlet temperature is below the catalyst lightoff temperature (but above the catalyst extinction temperature) the test procedure included a catalyst lightoff transient wherein the rig inlet temperature was increased to about 360 C (680 F) to ensure catalyst lightoff. To demonstrate the low catalyst extinction temperature the rig inlet air temperature was then decreased to the Saturn combustor inlet temperature (e.g. 250C/485 F for Saturn full load conditions). After lightoff the catalyst remained lit at all conditions tested, including no-preburner combustor inlet temperatures (catalyst inlet temperatures) as low as 215 C (415 F).

For each Saturn load condition tested, rig airflow conditions (flow rate, pressure, and temperature) were established and then fuel flow was varied to determine optimal emissions. This simulated, approximately, combustor tuning in the modified Saturn-engine via variable airflow valves (discussed in more detail below, next section). At selected points, fuel/air ratio at the RCL[®] injector exit was confirmed by gas sample extraction and GC analysis.

RCL[®] combustor emissions are listed in the bottom row of Table 3, for each airflow load condition tested. In general, NO_x emissions below 2 ppm were achievable with CO below 10 ppm at all inlet temperatures tested, including inlet temperatures as low as 215 C (415 F). UHC emissions were below 2 ppm for all conditions listed in Table 3.

MULTI INJECTOR FULL RCL[®] TESTING - SATURN ENGINE SET

Based on the successful single-injector rig tests, a "cluster" of four RCL[®] injectors was installed in a modified (single can combustor) 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 NO_x and CO

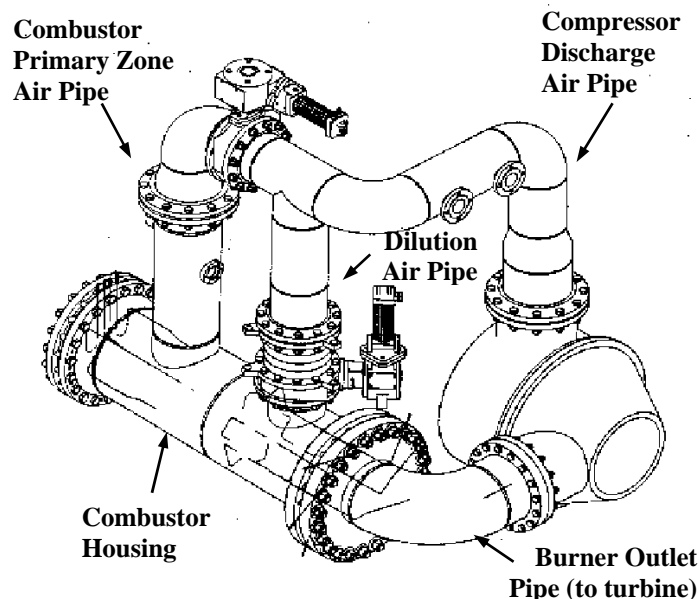


Figure 23. Side-mounted combustor configuration in modified Saturn engine, showing variable airflow control valves in primary zone air pipe and dilution air pipe.

emissions at the engine exhaust. The engine test also provided a basis for evaluating 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.

The overall combustor configuration is shown in Figure 23. 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. The multi-port gas-sampling probe was mounted in the engine exhaust stack and used to gather gas samples for emissions analysis. Gas samples were transported from the probe to the emissions analyzers through heated hoses.

The cluster of four catalytic injectors was assembled in the Saturn-engine combustor, parallel to one another in a square array as shown in the photograph in Figure 24. Each RCL[®] catalytic reactor was 7.6 cm (3 inches) in diameter. A flameholding cone was positioned at the end of

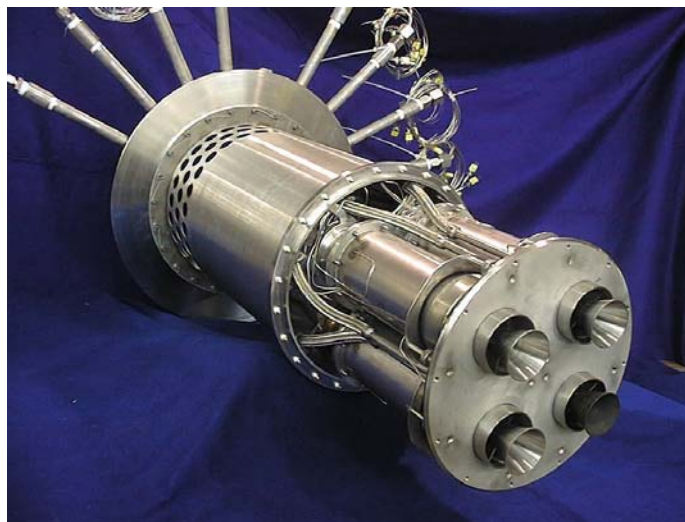


Figure 24. Photograph of four-RCL[®]-injector assembly, prior to installation in Saturn engine.

each post-mix duct, as in the single-injector rig tests described above. Each injector was also fitted with an annular reverse-flow mixer, located outside the catalytic reactor housing, as in the single-injector rig tests. Note that the perforated duct upstream of the injectors (visible in the photograph of Figure 24) was for inlet airflow conditioning, since air entered the combustor housing from the top, as shown in Figure 24. The perforated duct was hollow

(except for instrumentation and fuel lines) and did not perform any fuel/air premixing functions.

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 24, 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 25, 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

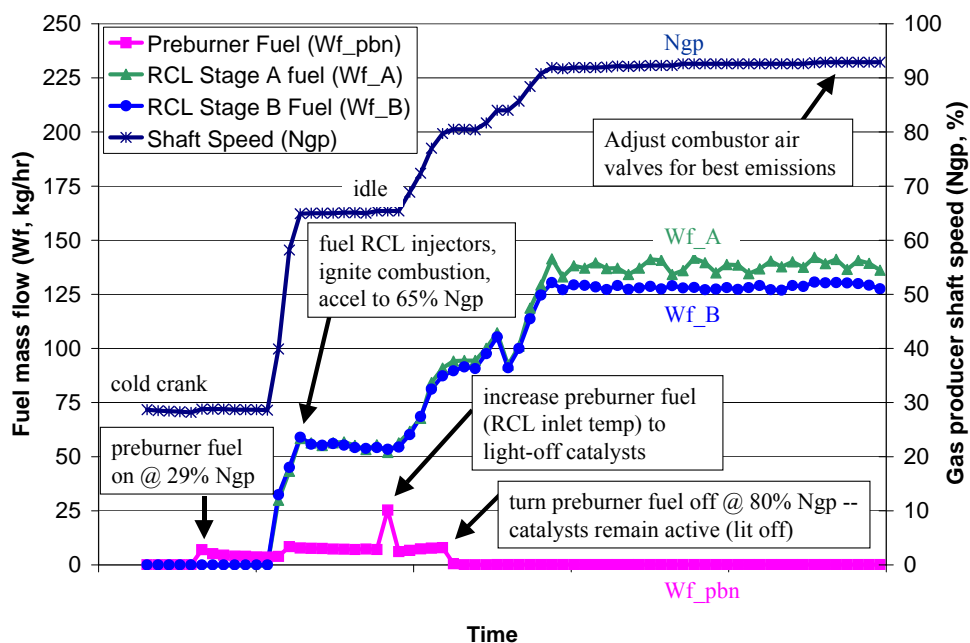


Figure 25. Saturn engine start-up data, obtained using RCL[®] combustion, showing engine acceleration, catalyst activation by preburner (followed by preburner shutoff with continued catalyst activity), and loading of engine.

two injectors. Each stage was separately adjustable, so that fuel/air ratio could be equalized for all injectors (for minimum NO_x emissions) even if airflow was asymmetric between the top and bottom injectors. Top-bottom airflow asymmetry was anticipated because primary-zone air entered the combustor casing from the top, as shown in Figure 23. GC analysis of gas samples from each of the four RCL[®] injector exits, however, showed little airflow asymmetry during engine operation.

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 25, 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.

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 NO_x 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. In addition, the 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 NO_x 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 26. 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 26 the preburner was turned off, the catalyst remained active at the available compressor discharge temperatures (as low as 191 C / 376 F), and NO_x 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 NO_x 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.

Table 4 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.

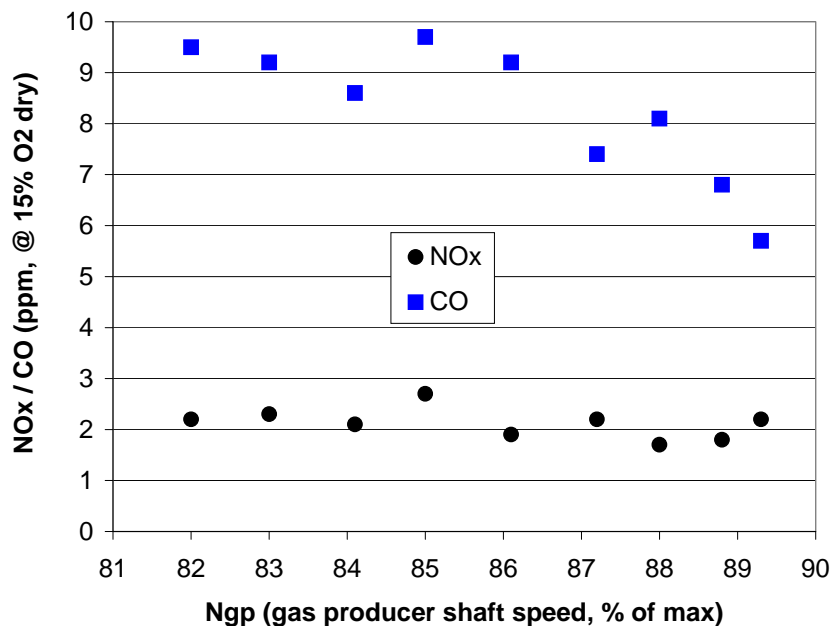


Figure 26. RCL[®] combustor emissions during Saturn engine operation, showing ultra-low NO_x and CO emissions over an achievable engine operating range of 82% to 89% speed.

Table 4. Saturn Engine Operating Data at Low End and High End of Achievable Operating Range. Note Catalyst Activity and Ultralow Emissions Achieved at Inlet Temperatures as Low as 191C (376F)

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

FULL RCL[®] SINGLE INJECTOR SIMULATED T70 TESTING FOR ENGINE INTEGRATION

Testing of high pressure single injector provided performance benchmarks for the Full RCL[®] module. In order to optimize retrofit capabilities to achieve ultra low emissions for T70 engine

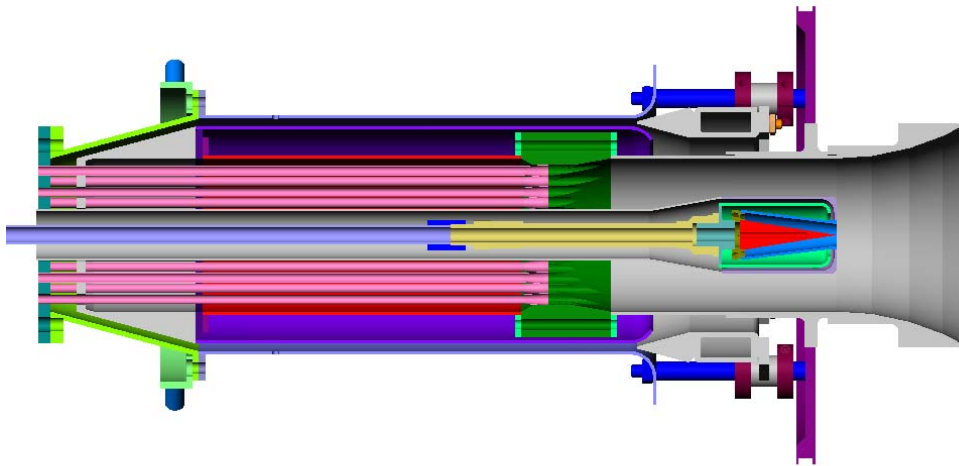


Figure 27. Cut View Section of Gen II Full RCL[®] showing the central pilot and postmix section. Flow is from left to right

design optimization of the RCL[®] reactor was performed. Integration of Full RCL[®] in Solar Turbines' T70 engine was conducted in three generations as shown below.

Gen I:

Results of Gen I testing are reported in Final Report by Etemad (2001). Under this program, the RCL[®] concept was successfully developed to address the need of advanced industrial engines to operate with low single-digit NO_x emissions. High pressure single injector testing demonstrated ultra low emissions of NO_x < 1 ppm with a 200F turndown with low acoustics of < 0.15 psi (RMS) at baseload performance. The technology offered the following additional benefits: operation without a pre-burner and with relaxed unmixedness requirements; robust operation; simple single-fuel control system; and compact size for engine integration and retrofit applications. Based on the successful full-scale combustion tests and sub-scale durability tests, the program met its stated objectives of achieving NO_x < 5 ppm and technical potential for 8000 hour catalyst durability.

Gen II:

In the second generation PCI designed and developed an advanced Full RCL[®] with dual stage fuel system for transient and start-up operation. The downstream cone flame stabilizer from Gen I was eliminated. PCI designed, fabricated, and integrated, a central pilot swirler for the Full RCL[®]. A flared section was designed at the end of the postmix for stabilizing the downstream flame. Figure 27 shows the cut section view of this design of the Full RCL[®] with the premixer, catalytic section, postmix and central pilot. Alternative design geometry is to replace the flared section with a standard swirler downstream of the Full RCL[®]. The hot gases from the exit of the RCL[®] will enter the swirler section that will further help anchor the flame at lower flame temperatures.

Atmospheric Testing at PCI:

Atmospheric testing was conducted at PCI to measure effective area, unmixedness and NO_x emissions before being installed in the high pressure rig. Figure 28 shows the NO_x emissions

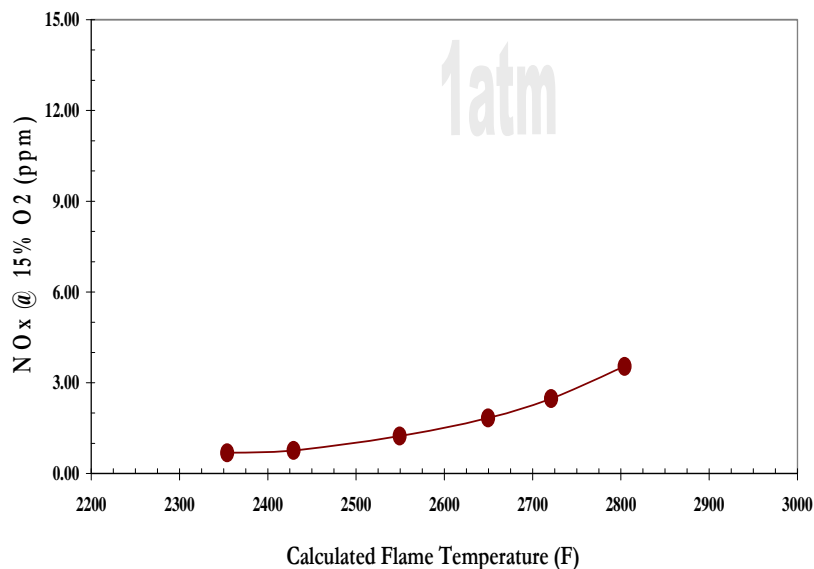


Figure 28. Atmospheric testing of Full RCL[®] showing < 2 PPM

curve for the testing conducted at PCI. Atmospheric testing was conducted by matching velocities at T70 baseload conditions with varying flame temperature. NO_x was < 3 ppm for a wide range of flame temperatures. CO was < 10 ppm for the complete testing. The catalyst bed was sized to replace a single injector in a Solar T70 engine. Effective area measurements were recorded and compared to those of the single injector T70 injector. Unmixedness was measured at atmospheric conditions and at a baseload operating equivalence ratio. The unmixedness was within limits to show low emissions performance.

High Pressure Simulated T70 Test Results

Single injector testing at simulated T70 conditions was conducted at Solar Turbines for the Gen II configuration. Baseload/halfload performance demonstration was completed and the results are as discussed in the following sections.

Lightoff Testing:

Testing was conducted at T70 ramp up conditions to conduct lightoff performance. As shown in Figure 29 reactor light off occurred around 610 °F/320 °C. This lightoff testing was consistent with the testing conducted for Gen I.

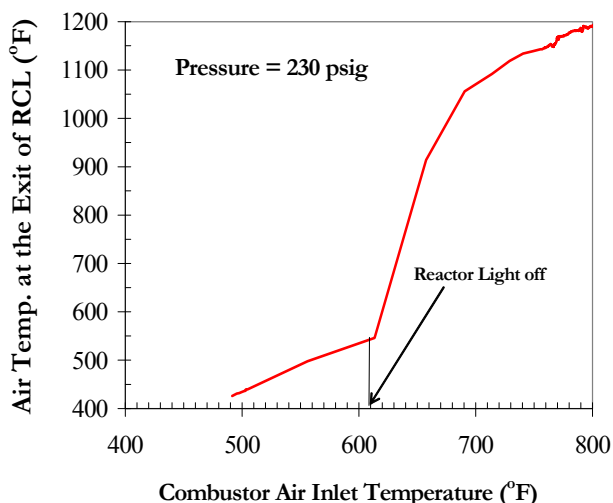


Figure 29. Full RCL[®] lightoff occurred at 610 F/325 C

Emission and Acoustics Results:

Testing was conducted at baseload and halfload under simulated T70 conditions as shown in Figure 30 and 31. Testing was conducted for different pilot flows to optimize the design conditions. NO_x emissions were insensitive to pilot variations from 0-6%. However, more than 8% pilot provided an increased turndown. NO_x emissions were <3 ppm for a wide range of flame temperatures and pilot flows with minimum NO_x as low as 0.7 ppm. The Gen II testing is also compared to Dec 2001 (Gen I) testing that showed < 1 ppm minimum NO_x levels. CO emissions were <10 ppm for the entire range of flame temperatures tested. Figure 31 demonstrates NO_x performance at halfload conditions. Low NO_x emissions and a turndown of > 200F was seen at halfload.

Figure 32 shows acoustics data obtained at 17 atm. 30% pf the energy is released in the reactor with the remainder being released in the flame zone. Very low acoustics were demonstrated

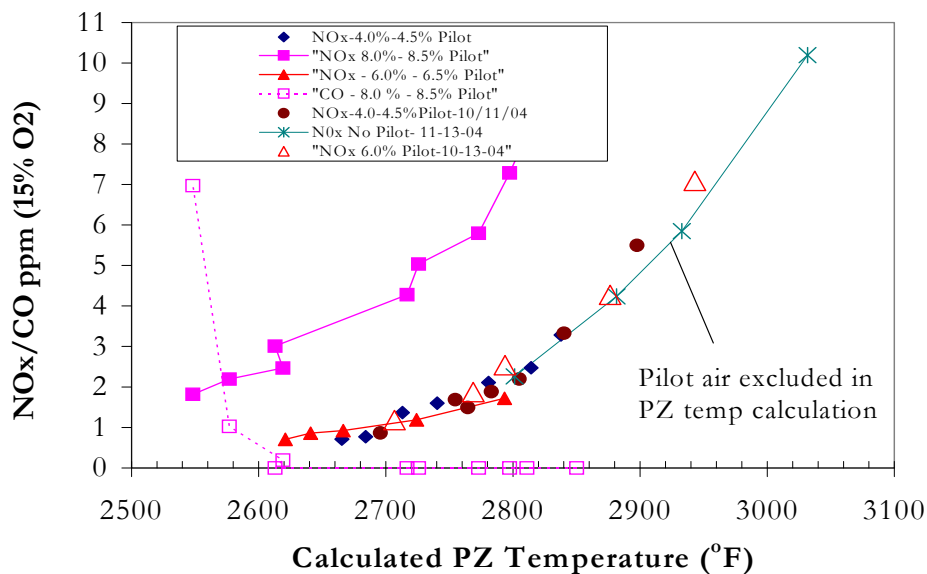


Figure 30. NOx emissions for Gen II module at different pilot conditions at baseload

for pilot fuel >4%. However, it was necessary to fuel to achieve low acoustics. Acoustic levels were within Solar Turbines' specifications and consistent with 2001 Gen I testing data.

The Gen II testing demonstrated that low single digit emissions were achieved with Full RCL[®] at baseload and half-load conditions. At baseload the RCL[®] with pilot provided 300 °F operating window for less than 3 ppm NO_x and 9 ppm CO. An increase of 100°F on the low emissions operating window from RCL[®] was achieved without pilot. The testing demonstrated

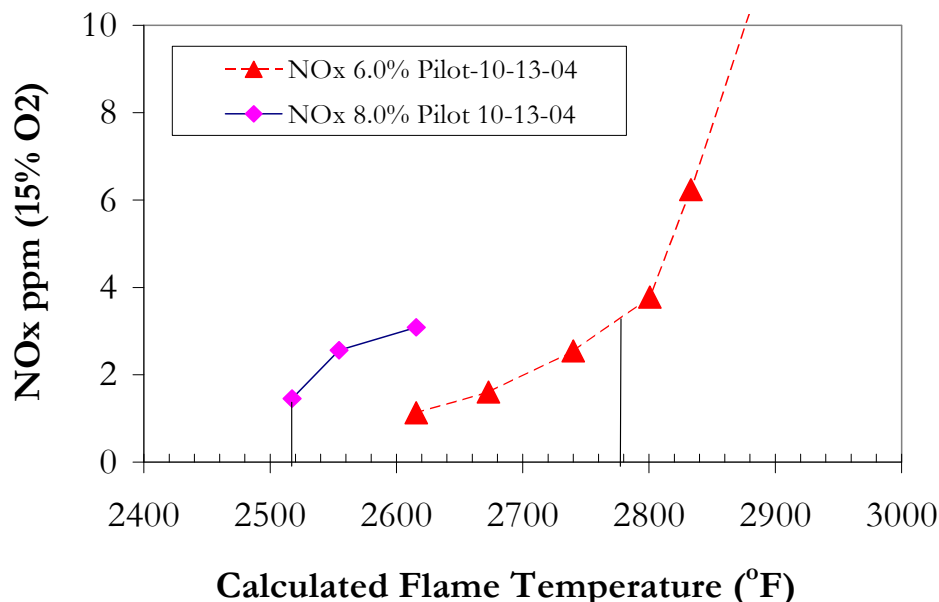


Figure 31. NOx emissions for Gen II module at different pilot conditions at halfload

that at 6.0%-6.5% pilot fuel low NO_x emissions and acoustics can be achieved. The testing also showed no major robustness issue encountered with the RCL[®] or the pilot.

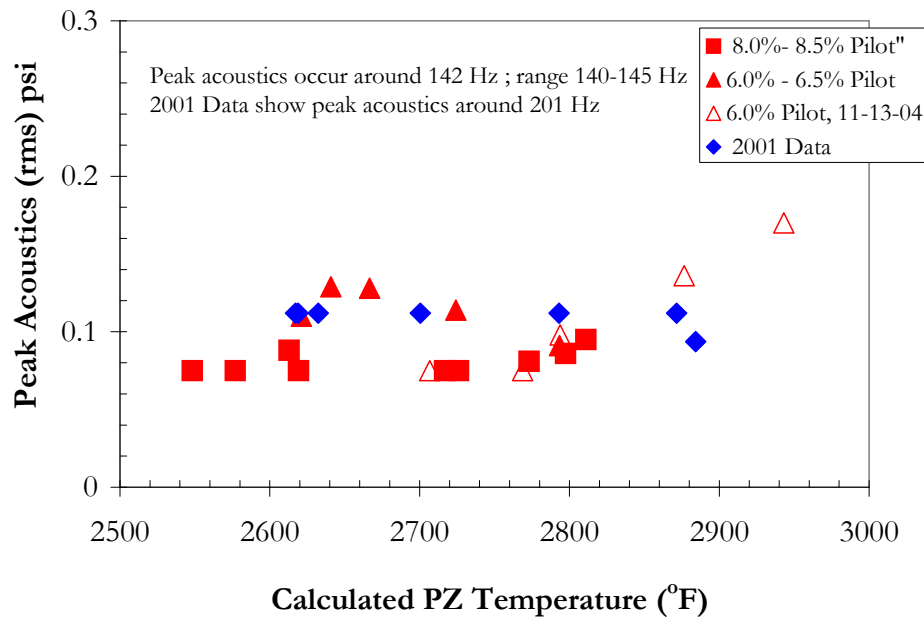


Figure 32. Acoustics for baseload for Gen II module at different pilot conditions

Gen III:

Gen II testing provided the path forward for engine integration. Three different design configurations with the pros and cons were discussed with Solar Turbines, Incorporated for integrating the Full RCL[®] in the T70 engine. Based on these discussions the recommendations were as follows –

- Reduce catalyst length for improved retrofit capability
- Optimize catalyst side air split to increase fuel side conversion
- Attempt to match catalyst surface area requirement

Based on these recommendations it was necessary to further reduce the module length, however without compromising the fuel side conversion. This meant shorter catalyst length which could effect the fuel conversion and hence postmix temperature/downstream flame stability. Analytical studies were conducted to understand the effect of the reduced catalyst on performance. Table 5 shows three different modules that were downselected for analysis and testing. Reduced catalyst volume leads to reduced fuel conversion. In order to compensate for this a higher air split was required to increase the fuel conversion in the catalytic reactor to match the downstream postmix exit temperature. This was achieved by analyzing the needed increase in the air split with respect to the fuel conversion and pressure drop in the injector.

Based on these analytical studies three catalyst designs were shortlisted for atmospheric and high pressure testing. The new three modules were fabricated by PCI with the central pilot

being fabricated by Solar Turbines, Incorporated. Figure 33 shows the hardware for the medium and short length Full RCL[®] reactor design. All these modules had Solar Turbines' fabricated swirler in the downstream section of the Full RCL[®].

Table 5. Analytical Comparison of Different Module Lengths for Engine Integration

	Medium	Short	Compact
Air Inlet. Temp. (deg F)	804.16	804.16	804.16
Pressure (psi)	247.18	247.18	247.18
Injector Length (inches)	7.5	6.0	4.0
Fuel Conversion (% of total fuel)	X	0.86X	0.6X
Post-mix Temperature (deg C)	678	646	580

Atmospheric Testing:

The medium length Full RCL[®] reactor was tested at Solar Turbines' cold flow quartz rig facility to get the effective areas of the various flow passages through the injector. The following tests were conducted for this reactor-

- Catalyst light off test
- Flame visualization
- Emissions performance

The injector was fitted with Solar Turbines T70 swirlers in the post mix zone. Figure 34 shows the lightoff temperature for a const catalytic phi. The lightoff occurs at 600F/315C inlet air temperature. Once the steady state conditions were achieved, the inlet temperature was raised to 750 F/400C. The flame was than observed for various pilot flow rates. The flame was anchored nicely at the exit of the pilot tip. Overall the flame was quite compact and nicely expanded inside the quartz rig.



Figure 33. Hardware picture of the medium and short Full RCL module

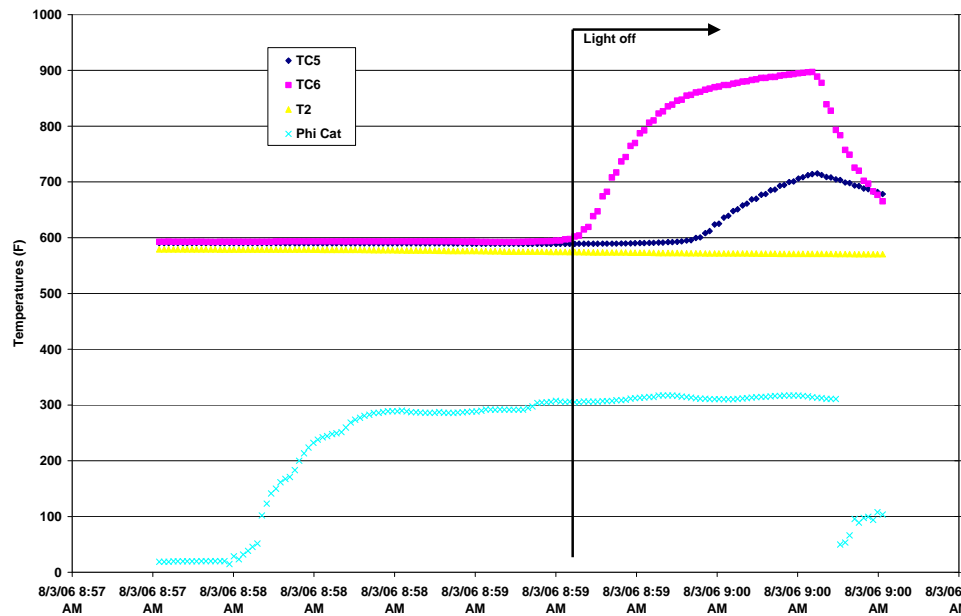


Figure 34. Full RCL[®] Catalyst lightoff at Atmospheric Conditions (Medium Length)

Figure 35 shows the emissions that were sampled at varying adiabatic flame temperatures and pilot fuel flow rates. The data shown in Figure 33 indicates that very low NO_x emissions are achievable for wide range of pilot fuel flow rates. CO was always < 10 ppm throughout testing.

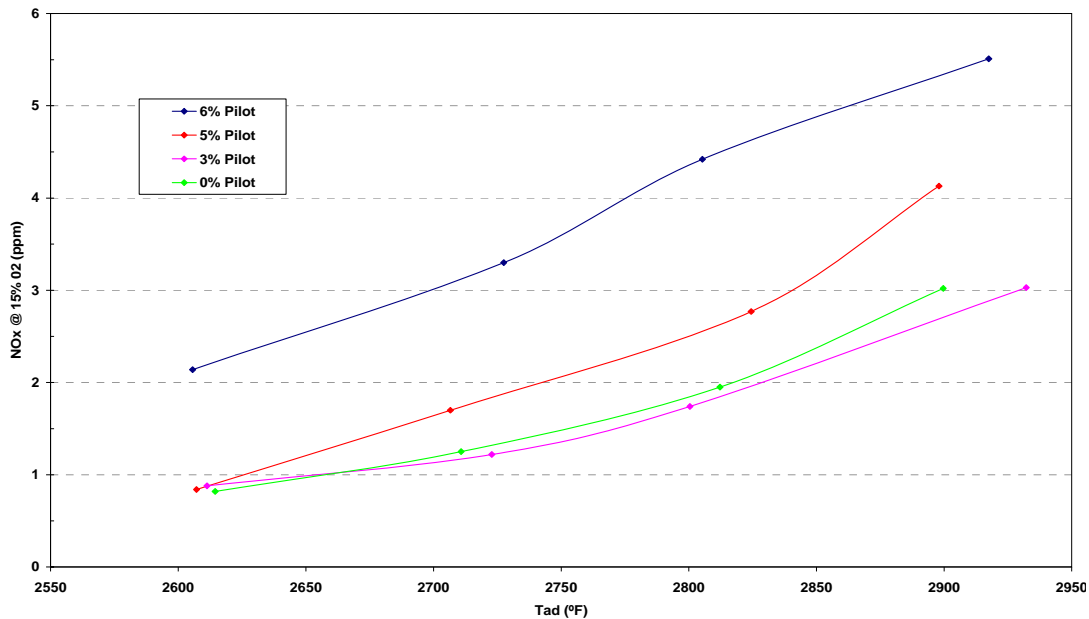


Figure 35. Medium Length Full RCL NO_x emissions at Atmospheric Conditions

High Pressure Single Injector Testing

Testing for the Full RCL[®] modules modified to retrofit in the T70 engine was conducted at Solar Turbines' high pressure facility. The test was conducted at inlet temperature and pressure of 800F/430C and 15 atm. (220 psia) respectively. The emissions performance of the injectors is shown in Table 6 at optimized pilot flows. The injectors gave less than 2 ppm NO_x emissions with a minimum NO_x of 0.54 ppm for the Full RCL[®] design of medium length. The lowest NO_x emissions are dependent on the catalytic volume available and the fuel conversion (shown in Table 5). The medium module had the optimum catalytic volume and hence showed the lowest NO_x emissions as compared to the other modules. The CO emissions for all the modules shown were less than 10 ppm.

Table 6. High Pressure Single Injector NO_x Emissions for Engine Retrofit Designs with Optimized Pilot Flows

	Medium	Short	Compact
Minimum NO _x (ppm @ 15% O ₂)	0.54	0.75	1.51
CO (ppm @ 15% O ₂)	3.32	3.5	0.46
Optimized % Pilot	6	4	4

NO_x emissions data suggests that low single digit emissions can be achieved with catalytic performance and pilot flow optimization. These designs also suggest the potential of retrofitting PCI's Full RCL[®] design technology in modular and highly compact space margins within the engine.

DURABILITY TESTING RESULTS

Reactor durability testing for engine applications in a high pressure/high temperature environment was conducted to demonstrate long term substrate, catalyst and washcoat performance. The durability testing process was designed to validate and extend the critical life-limiting factors for the reactor element. There are intrinsic operating advantages of the Rich Catalytic Lean (RCL[®]) urn combustion operation such as reducing catalyst environment (fuel rich) and lower operating surface temperature that promote longer catalytic life. However, this had to be proved in an actual gas turbine operating environment. Multiple catalytic formulations were screened with suitable downselected substrates for various lengths of time ranging from 100-6000 hours at actual gas turbine engine conditions. Based on the data from long term durability testing, potential solutions were evaluated and developed to address identified failure modes and extend life of the life-limiting factors. Post material analysis was conducted to validate structural integrity of the base metal, wash coat adherence and catalyst life. After extensive long term evaluation and validation testing of multiple catalytic elements, the reactor life is predicted to meet the 24,000 hours lifetime needed for engine integration and long term durability testing.

Long Term Oxidation Testing:

Long term (24000 hours) substrate oxidation testing was performed with candidate substrate materials. Multiple ferrous, nickel and cobalt based substrate alloys were selected for screening tests. Temperatures chosen ranged from 800°C to 1100°C/1470°F to 2000°F which were well above the catalyst operating temperature as an accelerated testing condition to identify life limiting factors for the substrate and for material screening. Testing was done with ambient air at atmospheric pressure. The oxidation performance of metals was tested in both coupons (for ease of experimentation) and tubes with both forms giving similar mass gain but with slightly differing oxide morphology. Some samples were tested after surface treatment in order to mimic various production processes. Samples were removed at regular intervals (100 to 200 hours) to measure mass gains. The weight gain of the samples were monitored as an indication of oxidation/spalling/material changes with increases in weight indicating oxidation (oxygen binding with the substrate metals forming oxides) and weight loss from oxide spalling. Samples were sectioned, mounted in epoxy, and polished prior to examination by SEM/EDS to determine oxide thickness and morphology.

Figure 36 shows the two substrates that performed well in the high temperature oxidation environment and were downselected for long term durability testing. Substrate A had excellent oxidation resistance properties at and below 800°C/1470°F and did not have any significant mass gain. It is expected that substrate A will perform similarly with minimum mass gain for the 24,000 hour lifetime. Substrate B also demonstrated good oxidation resistance properties with very little mass gain indicating no oxide buildup at 900°C/1650°F; however, this temperature was more than the desired catalyst operating target. From this study, it was concluded that for temperatures at or below 800°C/1470°F substrate A can be used for long term testing.

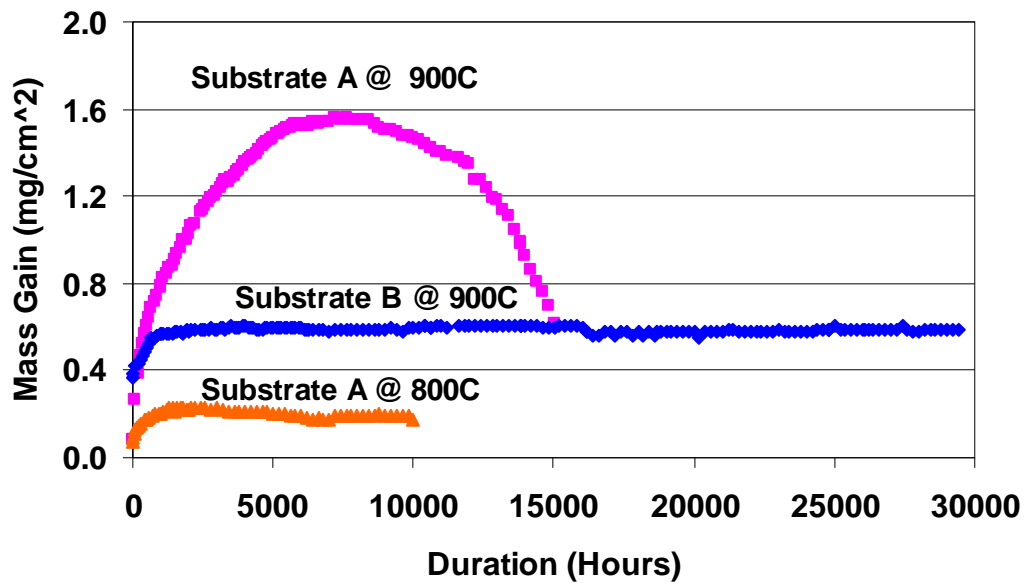


Figure 36: Static long term durability testing of substrate materials
Substrate A can tolerate < 800C for long durations and is less expensive
Substrate B has higher oxidation resistance at higher temperatures

Figure 37 shows the SEM cross-sections of the two downselected substrates that were tested in static environment. Figure 36a shows substrate A at 8000 hours tested at 800C/1470F. This substrate shows no grain boundary penetration indicating excellent oxidation resistance at these operating temperatures. Figure 36b shows substrate B tested at 900C/1650F, with no oxide penetration compared at 16000 hours. However, as discussed above, this temperature is

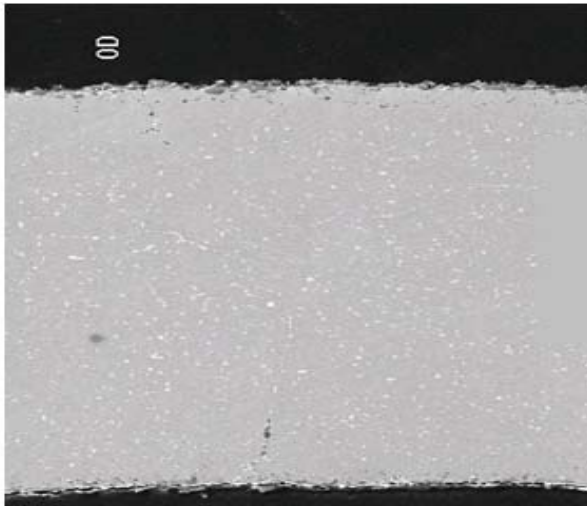


Figure 37a. Grain Boundary Penetration for Substrate A at 800C /1475F at 8000 hours

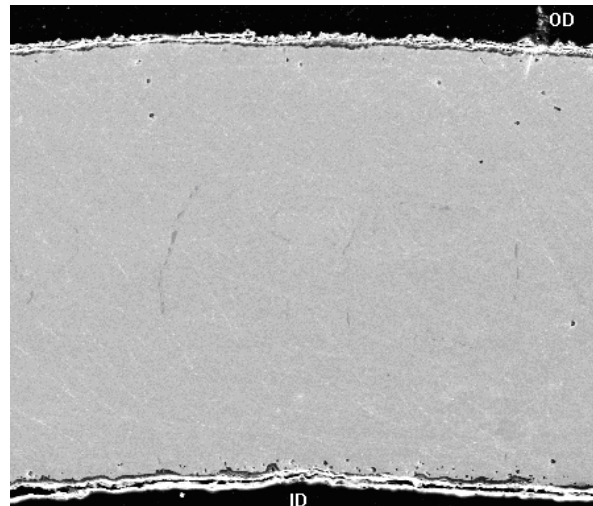


Figure 37b. Grain Boundary Penetration for Substrate B at 900C /1650F at 16000 hours

higher than the catalytic reactor operating system target for long term durability testing. Based on the results of the mass gain and oxide penetration both these substrates were considered viable candidates for long term high pressure durability testing.

Single Catalytic Element Testing:

In addition to long term substrate oxidation testing at static conditions, catalyst and washcoat performance testing was conducted in a high pressure (15 atm.)/high temperature (400C/750F) environment similar to gas turbine conditions. Initial long-term durability was performed on a subscale reactor test stand operating at 9 atm. The test stand was then upgraded by increasing the operating pressure to 15 atm., along with improvements in airflow, fuel flow, and heater capacities. Also, two additional durability rigs were added to allow simultaneous testing of different reactor materials and coating formulations. This allowed different test durations (for example, two identical samples being started at the same time, one of which could be removed at half life while the other remained for full life) to allow destructive evaluations to be performed at 2 different test periods. All the rigs were similar in design.

The rigs were instrumented with non-intrusive high temperature radiation pyrometers for surface temperature measurements since standard thermocouples would not last the complete duration of testing. The pyrometers were located along the axial length of the catalyst element that provided a better understanding of catalyst behavior and the temperature profile along the length of the tube. In addition, the mixed reactor exit gas (consisting of the reactor effluent mixed with the cooling air flow) was monitored using a thermocouple. Other thermocouples were installed to measure/monitor temperatures that were important for durability testing (i.e. fuel/air mixture inlet temperatures etc.). Measurement of the species leaving the reactor was monitored by gas chromatography at different intervals throughout the test to identify any reactor degradation. Lightoff testing was conducted at various intervals along the durability testing period to ensure catalyst integrity. To ensure lightoff repeatability testing was done with chemically pure grade methane each time with the same operating conditions. The durability tests were conducted using the local city gas with the measured fuel composition as shown in Table 7. The aging studies were conducted at the actual operating conditions that the catalyst would be subject to such as velocity, equivalence ratio etc.

Table 7. Natural Gas Fuel Composition Used for Long Term Durability Testing

Methane	95.50%
Ethane	2.36%
Propane	0.40%
Nitrogen	0.61%
CO2	1.13%
Total %	100.00%

Post analysis of the substrate and catalyst was conducted after the testing of the tubes. The analyses included surface area measurements via BET nitrogen adsorption, catalyst surface morphology and chemistry via SEM and EDS, catalyst crystallinity via XRD. Additionally, optical microscopy and SEM was used to examine mounted and polished cross-sections of the catalytic elements to determine the extent of materials degradation. The data was used to generate expected life times based on anticipated failure mechanisms.

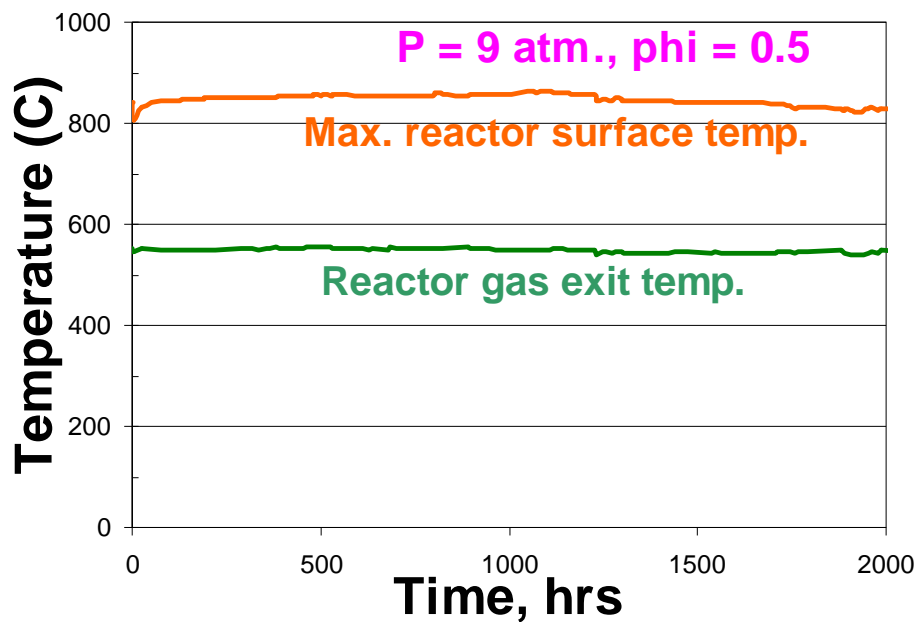
Washcoat/catalyst development:

Three major groups with washcoat/catalyst formulation variations with the two downselected substrates were tested as shown in Table 8. The set of groups were divided based on the variation in the washcoat formulation or catalyst formulation or both. It was important to ensure that the washcoat had the mechanical strength and adheres to the substrate and had the necessary properties to improve and maintain catalyst performance. Various washcoat formulations were developed that would provide greater stability and performance over longer periods of time. The catalyst process was developed in a manner to provide stable and robust activity for the 24,000 hour lifetime. Each of these catalytic formulations was screened for shorter lengths of time (~140 hours). After the initial screening and performance evaluation the tubes were tested for long term durability. Different washcoat formulations were tested in cyclic test rig for 600 cycles simulating harsh engine trip conditions (discussed in next section) to improve adhesion on the substrate and catalyst enhancements were done for long term durability.

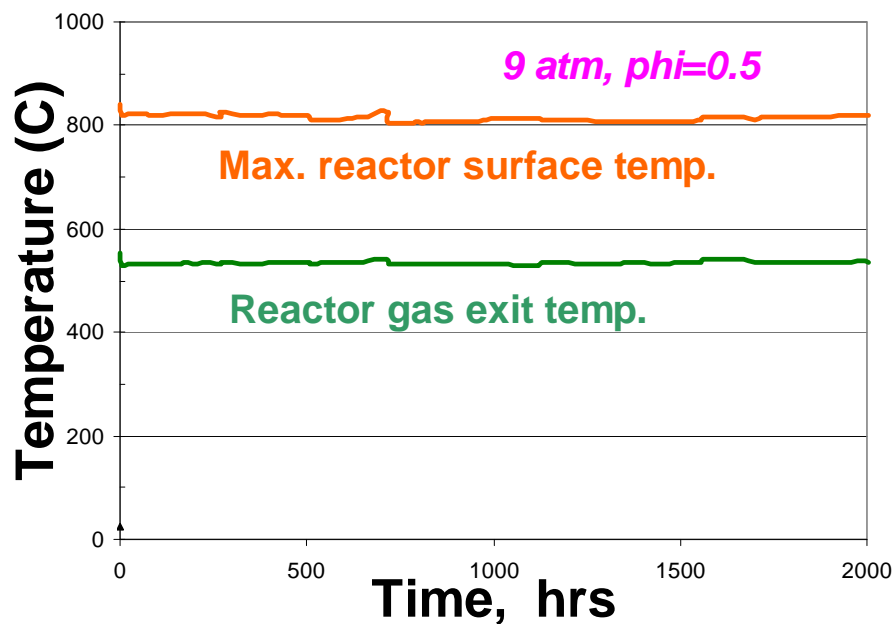
Table 8. Catalyst Formulation Testing

	Group 1	Group 2	Group 3
Substrates tested	A & B	A & B	A & B
Number of tubes tested	28	21	7
Total hours of testing	17000	7000	1000
Washcoat/cat/substrate variations	15	4	3

Durability testing was initially conducted at a pressure of 9 atm. with the available hardware and rig setup. This preliminary testing was done with the Group 1 formulation (Table 1) with the two different substrates. The testing was conducted at a surface temperature of 850C/1550F as an accelerated test and to understand its long term impact on reactor element characteristics. Both the tubes performed well for 2000 hours of testing and were considered as viable long term testing candidates (Figure 38). Post analysis showed good catalyst integrity and validated this formulation for long term testing. The test rig facility was upgraded to 15 atm. to match the actual engine condition. Also, two more rigs were fabricated at 15 atm. pressure to conduct the high pressure testing in parallel.



Substrate A (a)



Substrate B (b)

Figure 38: Two Single Catalytic Element Durability Testing done in series with different substrates (Pressure of 9 atm and Inlet Temperature of 400°C/750°F, Overall Equivalence Ratio of 0.5)

Figure 39 shows steady long term catalytic performance of a catalytic element for 5500 hours. The figure shows a stable exit temperature over the duration of testing. The maximum wall temperature (IR#2) for the durability testing was 750C/1380F based on RCL[®] performance testing at Solar Turbines, Incorporated as discussed in earlier sections. This testing showed that there was no significant degradation of catalyst/washcoat. Lightoff temperatures were steady showing no decay in catalyst life. This testing has successfully demonstrated a landmark catalyst performance at gas turbine conditions and is a candidate for future engine testing. Post analysis of this tube has not yet been conducted, since the testing has been continued through another program for an extended period of time past the 4000 hours.

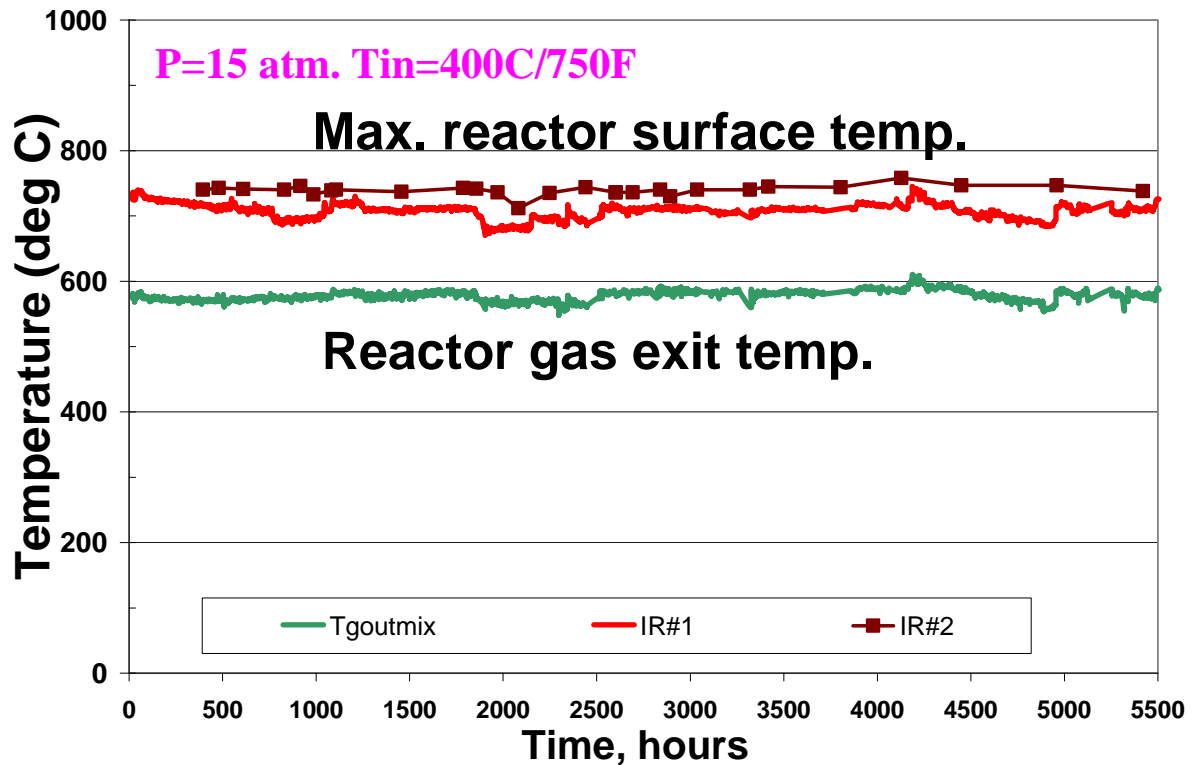


Figure 39. Steady state long term performance for 5500 hours of single catalyst element at P = 15 atm., Tin = 400C/750F

Thermal Cycle Testing:

This test was developed to simulate conditions during a standard trip cycle resulting from a sudden shut down of the engine (engine trip) which is the most severe condition in terms of thermal shock. The objective was to demonstrate the reactor robustness under transient engine trip condition.

In order to test the catalyst coated tubes, a thermal cycling test rig (Figure 40) was built. The testing was done in a single zone tube furnace set at a constant temperature for initially heating the reactor samples. Sample cooling was accomplished by rapidly removing the sample from the tube furnace and forcing high velocity air to flow. After the tube cooled to a predetermined low temperature it was reintroduced into the furnace for the next heating and cooling cycle. Cooling rate could be adjusted by changing the airflow velocity. These cycles were comprised of heating samples to peak temperatures of 900°C / 1650°F followed by rapid cooling (200 to

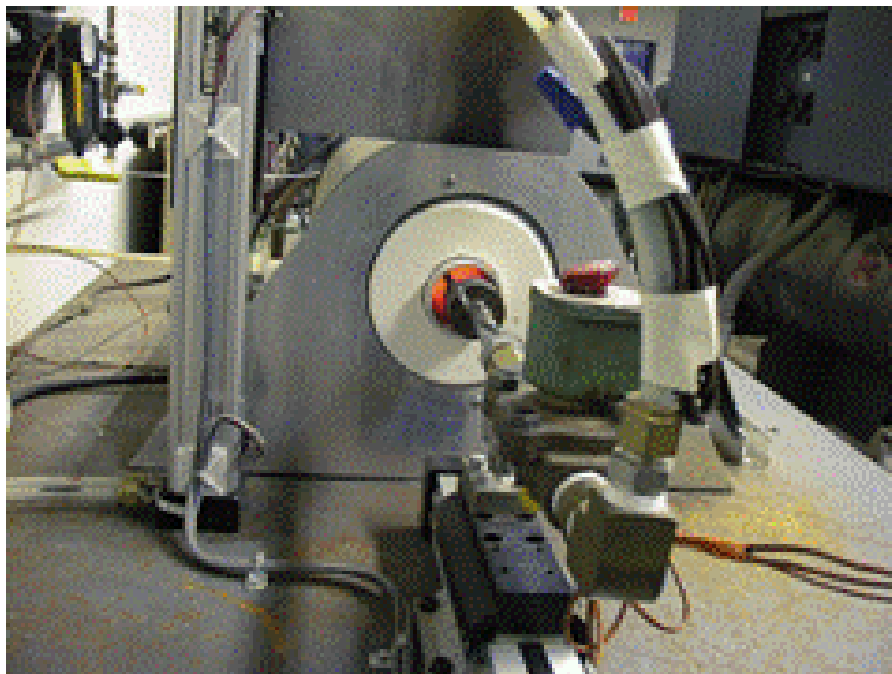


Figure 40: Thermal Cycling Test Rig

300°C/sec (360 to 540°F/sec) to ambient temperature. These transient conditions were generated to simulate the engine trip at an accelerated test (since these peak temperatures are higher than those specified for the catalytic module in the combustor) and allow the determination of the available margin for operation. It was assumed that 200 engine trips are equivalent to one-year life. Samples were examined after cycling for signs of catalyst delamination. The entire test apparatus was automated so that once the test conditions and number of test cycles were initially set; the test could run to completion unattended.

The downselected substrate test samples with formulations that would be used for the long term durability testing were tested in the thermal cycle rig. This testing helped eliminate preliminary catalytic losses that could arise due to thermal stresses. The downselected substrates were also tested in this rig to validate its performance. After successful completion of the thermal cycle testing, the catalytic element would be downselected for durability testing. The catalyst was found to be integral for most of the tubes and survived greater than 600 cycles of rapid heat up and cool down, supporting long term performance (> 3 years).

CONCLUSIONS

In an effort to produce low single digit emissions of NO_x and CO without the use of costly post-combustion controls, Rich Catalytic Lean-burn technology has been developed. Testing demonstrated the potential of this technology to reduce overall NO_x emissions to less than 3 ppm for a wide operating range. The catalytic pre-reaction provides enhanced reactivity to the gas mixture providing a stable downstream flame with ultra low emissions and large turndown.

RCL[®] Catalytic Pilot

A prototype catalytic pilot was fitted into an existing T70 injector without major modifications to the lean premixed portion of the injector. Testing of a single T70 modified injector (representative of the 12 injectors in an engine) has been completed. The catalytic pilot operated robustly without any flashback or auto-ignition even with wide variation of fuel/air ratio. No preburner was required for the operation of catalytic pilot from 50% load to 100% load condition. High pressure testing for catalytic pilot has demonstrated single digit (< 5 ppm) NO_x and CO emissions along with low acoustics at 50% and 100% load conditions for Solar Turbines T70 engine.

A T70 engine was chosen as a development platform for the proof-of-concept catalytic pilot concept. The production DLN injector allowed adequate space to integrate the catalytic pilot without significant modifications. As part of a DOE funded project, a set of injectors equipped with RCL[®] pilots with catalyst modules for natural gas applications was designed, developed, and tested in single and multiple injector test rigs for pressures ranging from atmospheric to high pressures typical of gas turbine operation. These results showed promise for the concept, so testing in a production engine was performed with a full set of 12 catalytically pilot equipped injectors. With optimization of fuel split between catalytic pilot and main swirler, NO_x emissions at baseload conditions of ~ 2.5 ppmv corrected to 15% O₂ were achieved. CO emissions were less than 10 ppm corrected to 15% O₂. Combustor acoustics were low (at or below 689 Pa or 0.1 psi) during testing. Reactor catalyst temperature was within the design limit and no-preburner was used. The initial emissions results are promising with this technology showing capability for providing an alternative to conventional DLN technology. Further development work is needed to establish engine integration and long term catalyst durability before advancing the pilot technology to production status.

Full RCL[®]

A new Rich-Catalytic Lean-burn (RCL[®]) combustion concept was tested at gas turbine conditions, first in a full-scale full-pressure single-injector rig, and second in a modified industrial gas turbine. Experimental testing confirmed ultra-low-NO_x capability of the RCL[®] combustion concept with NO_x emissions of < 2 ppm. Also, the ability to mix fuel-rich catalyst effluent with primary combustion air, without inducing autoignition, yet imparting significant stability to the downstream combustion process was demonstrated. The testing further demonstrated RCL[®] combustion feasibility for gas turbine engine operation. In particular, for engine start-up, acceleration, and operation at load by fuel injected only through RCL[®] injectors

(effectively a single fuel stage, with all fuel contacting the catalyst), and with simple engine controls that do not monitor catalyst temperature.

Engine integration of the Full RCL[®] modules was successfully demonstrated in a single injector simulated T70 engine rig. Testing showed NO_x emissions of < 2 ppm for the engine retrofittable designs with improved turndown. This testing demonstrated that the Full RCL[®] catalytic module can be retrofitted in tighter engine envelopes.

Durability testing of the substrate and catalyst material was successfully demonstrated at pressure and temperature showing long term stable performance of the catalytic reactor element. Stable performance of the reactor element was achieved when subjected to durability tests (>5000 hours) at simulated engine conditions (P=15 atm, T_{in}=400C/750F.). Cyclic tests simulating engine trips was also demonstrated for catalyst reliability. In addition to catalyst tests, substrate oxidation testing was also performed for downselected substrate candidates for over 25,000 hours.

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