Catalytic Combustion for Ultra-Low NOx Hydrogen Turbines

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ABSTRACT

Precision Combustion, Inc., (PCI) in close collaboration with Solar Turbines, Incorporated, has developed and demonstrated a combustion system for hydrogen fueled turbines that reduces NOx to low single digit level while maintaining or improving current levels of efficiency and eliminating emissions of carbon dioxide.

Full scale Rich Catalytic Hydrogen (RCH1) injector was developed and successfully tested at Solar Turbines, Incorporated high pressure test facility demonstrating low single digit NOx emissions for hydrogen fuel in the range of 2200F-2750F. This development work was based on initial subscale development for faster turnaround and reduced cost. Subscale testing provided promising results for 42% and 52% H_2 with NOx emissions of less than 2 ppm with improved flame stability.

In addition, catalytic reactor element testing for substrate oxidation, thermal cyclic injector testing to simulate start-stop operation in a gas turbine environment, and steady state 15 atm. operation testing were performed successfully. The testing demonstrated stable and robust catalytic element component life for gas turbine conditions.

The benefit of the catalytic hydrogen combustor technology includes capability of delivering near-zero NOx without costly post-combustion controls and without requirement for added sulfur control. In addition, reduced acoustics increase gas turbine component life. These advantages advances Department of Energy (DOE's) objectives for achievement of low single digit NOx emissions, improvement in efficiency vs. post-combustion controls, fuel flexibility, a significant net reduction in Integrated Gasification Combined Cycle (IGCC) system net capital and operating costs, and a route to commercialization across the power generation field from micro turbines to industrial and utility turbines.

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EXECUTIVE SUMMARY

Precision Combustion, Inc. (PCI), in close collaboration with Solar Turbines, Incorporated, has developed and demonstrated a combustion system for hydrogen fueled turbines capable of maintaining or improving current levels of efficiency, while simultaneously reducing NOx to the low single digit level and eliminating emissions of carbon dioxide. The subscale and full scale testing demonstrated that for hydrogen based fuels, the catalytic injector will produce, at a given dilution, significantly lower NOx emissions compared to conventional combustion systems with increasing benefit as hydrogen content increases.

The full scale rich catalytic hydrogen (RCH) injector for hydrogen combustion testing was designed and fabricated based on the successful results obtained in the subscale testing. The catalytic injector was designed by PCI, while the pilot was designed by Solar Turbines, Incorporated to be used during start-up. Atmospheric flow testing was conducted at PCI for full scale injector validation. Unmixedness, effective areas, reactor temperatures and start-up testing with natural gas was conducted. Pilot and injector stability and start-up was successfully demonstrated with natural gas.

Full scale single injector hydrogen combustion testing was successfully completed at Solar Turbines, Incorporated test facility. Test results demonstrated the catalytic combustor to achieve low single digit NOx emissions and low acoustics. Post testing visual inspection showed combustor integrity demonstrating the catalytic injector robustness for hydrogen combustion environment. The full scale combustion testing at Solar Turbines, Incorporated demonstrated the validity of the catalytic injector technology for low single digit hydrogen combustion emission application.

In support of the full scale-scale hydrogen injector, subscale 10 atm. hydrogen combustion testing at PCI's test facility for simulated engine operating conditions with hydrogen fuels was performed. Subscale injector configurations were designed, developed and tested to evaluate performance and achieve ultra low NOx emissions. Two generations of subscale injectors were tested. Gen I was tested for catalytic performance optimization and, based on Gen I testing, Gen II was designed and tested for engine integration. Computational Fluid Dynamics (CFD) studies were conducted to evaluate different reactor geometries and techniques were applied to improve the catalytic contribution, leading to reduced NOx emissions and acoustics. Fabrication and testing of subscale injectors showed the catalytic injectors were capable of achieving ultra low NOx (less than 2 ppm) for 42% and 52% H_2 combustion.

In addition to subscale and full scale testing, catalytic element testing for substrate oxidation, thermal cyclic testing and steady state 15 atm. operation was also conducted. This testing involved work done under this program and other programs supporting development of the Rich Catalytic technology for other programs. Multiple substrates were evaluated and tested. Two high temperature alloys were downselected for high pressure catalytic element long term testing and long term oxidation testing. Catalytic element testing in a simulated gas turbine environment demonstrated promising results for substrate and catalyst stability. The testing demonstrated stable and robust catalytic element component life for gas turbine conditions.

The benefit of this hydrogen combustor technology includes capability of delivering near-zero NOx without costly post-combustion controls and without requirement for added sulfur control. This advances DOE's objectives for achievement of low single digit NOx emissions, improvement in efficiency v/s post-combustion controls, fuel flexibility, a significant net reduction in IGCC system net capital and operating costs, and a route to commercialization across the power generation field from micro turbine to industrial and utility turbines.

INTRODUCTION

The Clean Coal Power Initiative (CCPI) by the Department of Energy (DOE) is directed towards resolving the environmental challenges resulting from use of coal for power generation. The objectives involve, but are not limited to, achieving near-zero carbon-dioxide emissions through carbon capture and storage (CCS), and advancing coal gasification technologies. These technologies can produce clean burning hydrogen fuel, which can be used to run hydrogen turbines for power generation. This has led to a significant interest in the combustion of hydrogen in gas-turbine engines for medium/large scale clean power generation.

For fossil fuels, hydrogen is produced by gasification processes, wherein the syngas produced is cleaned and the carbon monoxide (CO) is converted to carbon dioxide (CO_2) by water gas shift (WGS) to provide more hydrogen. The CO_2 in the product gases is then removed and sequestered or otherwise utilized. In addition, hydrogen can be produced through the disassociation of water using solar, nuclear power, or by other methods. The hydrogen fuel is then available as a clean fuel (carbon-free). These approaches are described in the literature [1-4].

Advanced combustion approaches are required to crossover from current natural gas and oil resources to hydrogen/syngas. Thus the DOE National Energy Technology Laboratory (NETL) has focused on a range of research and development (R&D) programs to utilize hydrogen as a fuel for distributed and centralized power generation. Hydrogen-fueled turbines would be used in Integrated Gasification Combined Cycle (IGCC) power plants with the goal of eliminating CO_2 emissions. These systems will also reduce emissions of NOx to low single digit ppm levels, reduce gas turbine capital costs, and increase cycle efficiency. Certain key challenges with the use of hydrogen, such as autoignition, flashback and flame stability issues, have to be resolved to achieve stable and sustained performance [5, 6]. In order to meet the above requirements, novel combustion techniques must be developed. Multiple analytical and experimental research activities are being pursued for using hydrogen as the fuel source while achieving low NOx emissions. Research is ongoing using premixed combustion [5, 7] and steam diluted diffusion flames [8].

PCI in collaboration with Solar Turbines, Incorporated, through DOE’s Fossil Energy Turbine Technology R&D program has developed rich catalytic combustion technology for low NOx gas turbine engines. This technology offers a potential breakthrough in accomplishing DOE’s Turbine Technology research program objectives. Potential technical benefits include stability, reduced combustion acoustics, and NOx emissions sufficiently low to avoid the need for costly post-combustion controls e.g. Selective Catalytic Reduction (SCR) [9-12]. For hydrogen and syngas specifically, there is the potential benefit that, with reduced diluent, NOx emissions will be substantially lower than current diffusion flame combustion systems allowing reduction in require diluent levels (increasing efficiency). The fully developed technology will also be beneficial for other DOE fuel flexible combustor programs [13, 14] with multi-fuel capability (natural gas to syngas to hydrogen) and the potential of retrofitability for existing engines further facilitating implementation of the technology. This advances DOE's objectives for achievement of NOx emissions of less than 2 ppm, improvement in cycle efficiency, fuel flexibility, and a net reduction in IGCC and hydrogen combustion system capital and operating costs.

BACKGROUND

For combustion of high-hydrogen fuels such as syngas, PCI has leveraged its Rich-Catalytic Lean Burn (RCL®) combustion technology to enable and demonstrate ultra-low NOx emissions and low acoustics.

For the combustion of natural gas, the RCL® combustion system has been developed and demonstrated in high pressure single injector and in engine testing capable of delivering NOx less than 3 ppm [9-12]. 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 portion of the air is mixed with all of the fuel and contacted with the catalyst, while the second portion of air is used to backside cool the catalyst. The reaction/heat release is constrained by the amount of oxygen on the catalyst bed, controlling flashback and substrate overheating. At the exit of the reactor, the catalyzed fuel/air stream and the cooling flow are rapidly mixed to produce a reactive mixture prior to final lean-burn combustion.

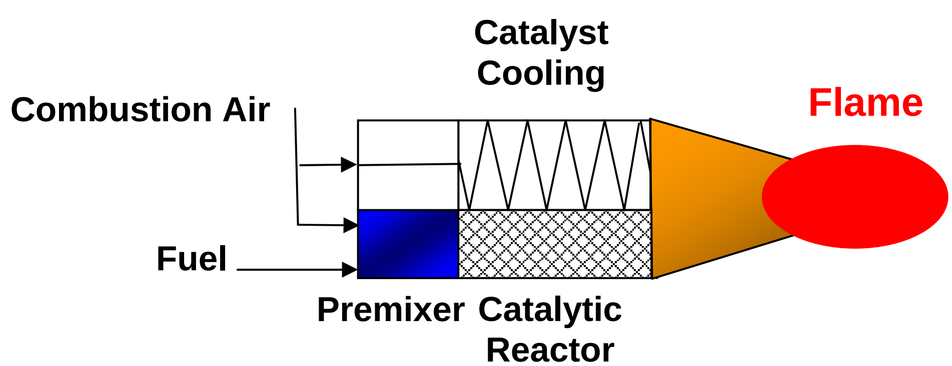


Figure 1. Schematic of a Rich Catalytic System

This RCL® 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.
- 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 puts the reactor in a non-

oxidizing (reducing) environment. As a result it reduces catalyst volatilization and substrate oxidation, enhancing catalyst life and allowing wider choice of catalyst type.

The Rich-Catalytic system has been successfully tested in both rig and engine tests for natural gas fuel. Combustion test results from work with Solar Turbines, Incorporated showed NOx emissions as low as 1 ppm achievable in single injector rig tests, while the engine tests showed NOx emissions around 3 ppm, both with CO below 10 ppm. The engine test also demonstrated excellent Rich-Catalytic operability and turndown through the entire range of engine operating conditions, including transient events such as start-up, shutdown, and load shifting [9-12].

In addition to testing with natural gas, the Rich-Catalytic combustion system has been tested at subscale with alternative fuels at pressure. Testing has demonstrated multi-fuel operation of the catalytic reactor, followed by ultra-low NOx combustion downstream of the catalyst for multiple fuels, including simulated low Btu fuel such as blast furnace gas (BFG), refinery fuel, syngas fuel, gasoline and vaporized diesel fuels [14]. For hydrogen fuel capable gas turbines, adaptation of this combustion system technology would offer substantial capital and operating cost savings.

For high reactivity fuels, such as syngas and high hydrogen, the RCL® combustor is modified to Rich Catalytic Hydrogen (RCH) combustion mode. In this mode, the reactor effluent and cooling air combine to form a partially pre-reacted flame. Prevention of auto-ignition in the downstream burnout zone is not necessary. Downstream of the flame, within the combustor, the air used for reactor cooling mixes with the combustion products to give the desired combustor outlet temperature. Low NOx emissions are obtained because of pre-reaction of fuel in the catalytic reactor and distribution of the pre-reaction heat. In the downstream flame zone, part of the cooling air bypasses the flame front, and as a result, part of the pre-reaction heat also bypasses. As a result the flame front temperature or peak flame temperature gets reduced (though reduction in flame front chemical and thermal energy through pre-reaction and thermal bypass) and thereby decreases NOx emissions.

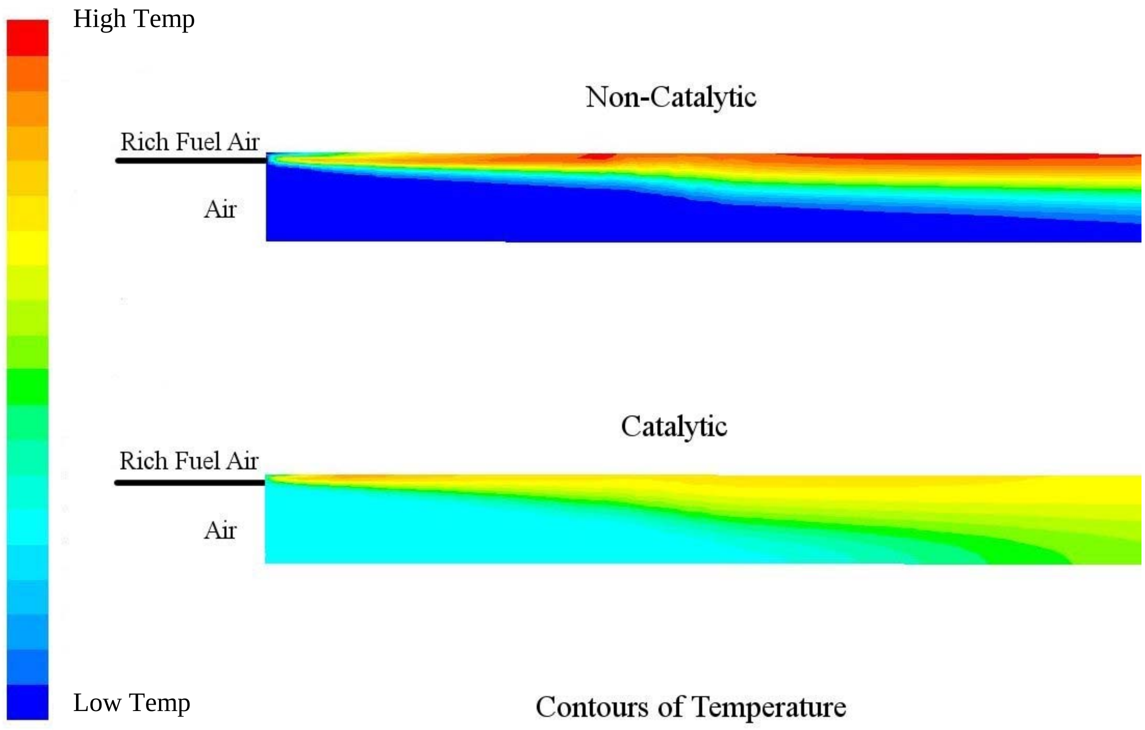


Figure 2. Temperature Profiles of RCH Combustor Zone Showing Low Peak Flame Temperatures with Catalytic Activity

This prediction of lowering of the peak flame temperature for the catalytic case was verified by using FLUENT, commercially available Computational Fluid Dynamic (CFD) software as shown in Figure 2. To save computational resources, only the combustor of the catalytic reactor was modeled. The catalytic and cooling channel outlet conditions were used for the inlet conditions to the combustor. The Eddy-dissipation model was applied to simulate the fast chemistry of hydrogen combustion. The assumption here was that turbulence slowly convects/mixes hydrogen and air into the reaction zone where they burn quickly. The CFD calculations showed a significant drop of the maximum temperature of the flame in the combustion subsequent to a catalytic reactor, thus strongly reducing NOx production.

The results of this testing and the inherent behavior of rich catalytic combustion make it an ideal candidate for further development and application to low emission hydrogen turbine applications. The following sections discuss the experimental setup and results of testing of the rich catalytic combustion system with hydrogen fuels.

EXPERIMENTAL SETUP

PCI Subscale Test Rig:

In order to evaluate the performance of the catalytic injectors for hydrogen operation, the subscale test rig at PCI was used. The rig consisted of the injector section followed by the high pressure combustor burnout section followed by the cooling section and the exhaust with the back pressure valve.

All tests were performed at a pressure of 10 atm. with inlet air and fuel temperatures heated to 400C/750F and 200C/390F respectively to simulate turbine inlet air temperature. Two subscale reactor concepts were considered during this testing. The first subscale reactor (Gen. I) had two air supply systems: one providing air to the cooling channels and the second supplying air to the catalyst portion of the reactor bed. This arrangement allowed the use of varying catalytic air splits (the ratio of the air flowing through the catalyst reactor path divided by the total reactor and cooling air) to determine the affect of increased catalytic reaction on combustor performance. For the second reactor (Gen. II), air was supplied using a single air supply. In this configuration the air split was fixed by the hardware. This configuration more accurately represented the full scale engine hardware.

A sub-scale catalytic injector for high-pressure testing with hydrogen fuel was fabricated and is shown in Figure 3. Direction of flow is from top-right to bottom-left in the figure. The reactor was instrumented with thermocouples to measure catalyst and housing temperatures, flush-static pressure ports to measure reactor pressures, and gas sample

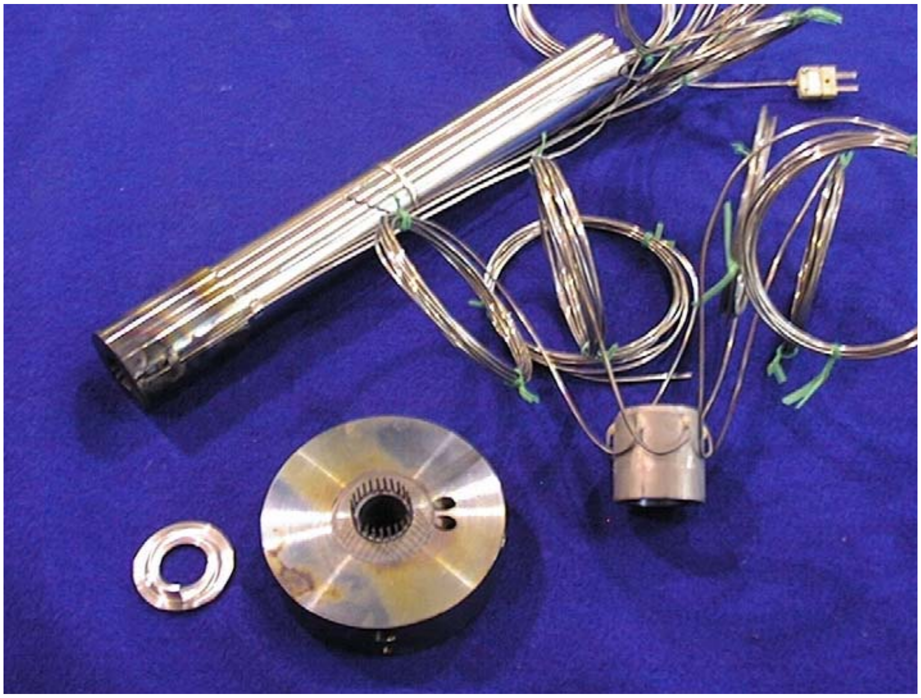


Figure 3. Photograph of Subscale Catalytic Reactor Components for Hydrogen Combustion

extraction ports to measure gas composition entering and exiting the reactor. These instrumentation lines were coiled and are visible in the photograph.

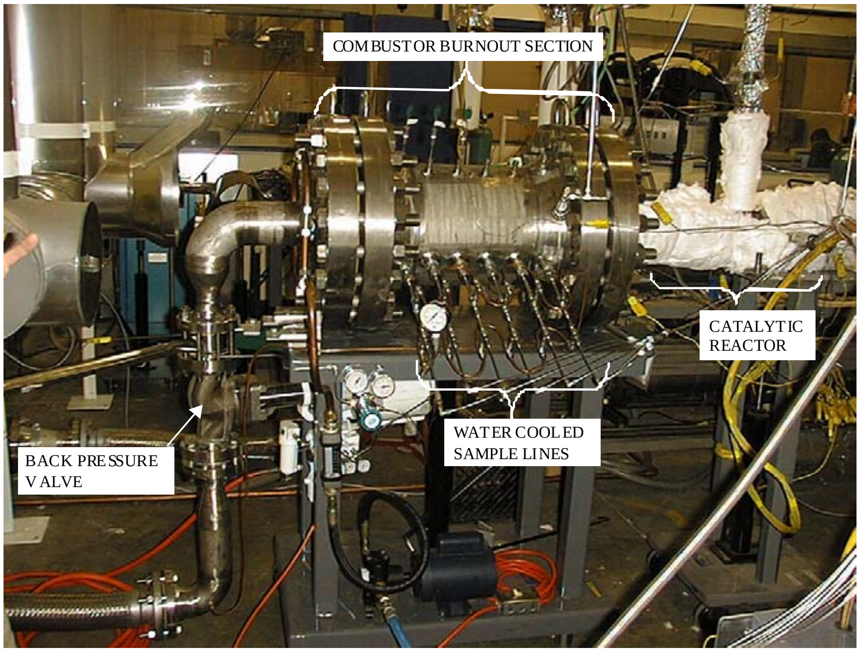


Figure 4. Photograph of PCI's 10 Atm. Subscale Combustor Rig for Hydrogen Combustion

For high-pressure testing, the catalytic reactor was inserted into the 10 atm. combustion test rig shown in Figure 4. Flow is from right to left, and the reactor is inserted at the right-hand-side. For testing and parametric studies, two independently controllable air supplies were available (both heated and at high pressure): the larger air supply (entering from the right) provided catalyst reactor backside cooling air, which became primary zone combustion air in the gas-phase combustor; and the smaller air supply (entering from the vertical pipe at the top-right of Figure 4) provided air to the fuel-rich fuel/air mixture. A heater was used to heat the nitrogen diluent and hydrogen fuel. Downstream of the reactor, the partially reacted gases and the catalyst cooling air mixed and burned in the high-pressure combustor burnout section labeled in Figure 3. Here, gas-phase combustion completed the burnout of fuel within a 5.08 cm/2-inch inside-diameter ceramic combustor liner. The combustor burnout section was instrumented with S-type thermocouples to measure flame temperatures axially along the combustor liner at 7.62cm/3-inch increments, and gas sample extraction ports (one at each axial thermocouple location). The cross-sectional area of the Gen I subscale reactor was 2.15 cm^2/0.3342 in^2, and cross-sectional area of the ceramic-lined combustor section was 20.25 cm^2/3.14 in^2 giving about a 10:1 dump ratio on an area basis. The Gen II subscale reactor had a cross-sectional area of 1.17 cm^2/0.1811 in^2 (thus a dump ratio of 20:1).

Combustion air for the test rig was provided by a compressor system that can deliver flows up to 0.07 kg/s/0.15 lb/s at 12 atm. and 400C/750F. A water-injected high-temperature back-pressure valve permitted complete combustion reactions (downstream of the catalytic test-piece) at full pressure, within the ceramic-lined pressure vessel. All flows (air, fuel, diluent) were metered with electronic mass flow controllers. Each fuel component was separately metered and then mixed with the other components. For the current tests, two fuel stream components were introduced: H_2 and N_2.

National Instruments PC-based data acquisition systems were used for automated data acquisition, control, and processing. Combustor exhaust gas streams were measured by an array of analyzers including a Thermo Environmental 42H chemiluminescent NOx analyzer and a paramagnetic oxygen analyzer with automated data-logger capabilities. A micro gas chromatograph (GC) was used for species measurement for calculating the air split.

Atmospheric Full Scale Single Injector Rig at PCI

In order to conduct full scale flow testing of the module and preliminary analysis of the hardware, the full scale module was installed in the atmospheric flow rig at PCI. Full scale injector, flow testing and evaluation of the injector performance at atmospheric conditions were performed in the atmospheric rig at PCI (Figure 5). This rig can deliver flows up to 0.75 pps at 2 atm. and 400C/750F. Leak and flow testing was conducted to ensure there were no leaks in the system after installing the full scale injector. Necessary instrumentation was hooked up for data recording. The full scale injector was installed in the high flow rig for conducting effective area, unmixedness and flow testing.

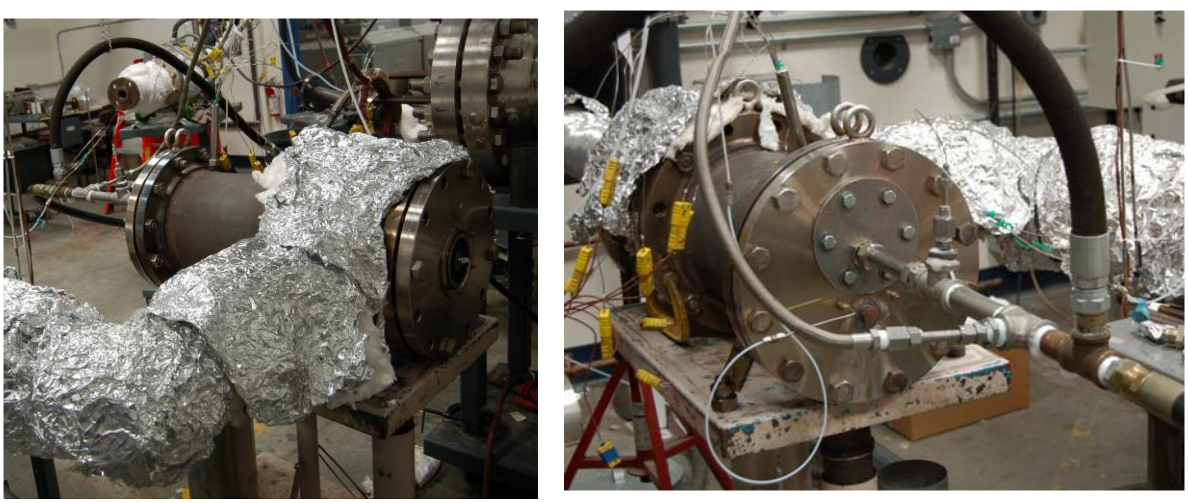


Figure 5. High Flow Rig for Atmospheric Testing at PCI

Solar Turbines, Incorporated Test Facility Setup:

The full scale single injector fabricated by PCI was tested in the single injector test rig. Full Scale single injector testing was conducted at Solar Turbines, Incorporated test facility. The facility was upgraded to handle hydrogen-nitrogen flows as shown in Figure 6. The nitrogen and hydrogen tanks with high volumetric flows were setup and the supply lines to the rig were installed and inspected as shown in Figure 6(a).

Figure 6(a). Solar Turbines, Incorporated Test Facility Setup Showing the N_2 Supply Tank and the Supply Lines

On-off valves were installed in the plumbing lines from the tank to the rig, to ensure proper shutdown of the system in case of an emergency as shown in Figure 6 (b). In addition to valves on the supply lines, electronic emergency stops were hardwired into the rig data system control. All the safety equipment necessary for hydrogen testing and high flow low pressure drop filters were installed as shown in Figure 6 (c). Shakedown and flow testing was conducted to ensure proper functioning of the various equipments. Testing at pressure was conducted with helium gas to ensure no leaks existed.

Figure 6 (b). Solar Turbines, Incorporated Test Facility Setup Showing the On-Off Valves for Start-Up and Shut Down for Safety

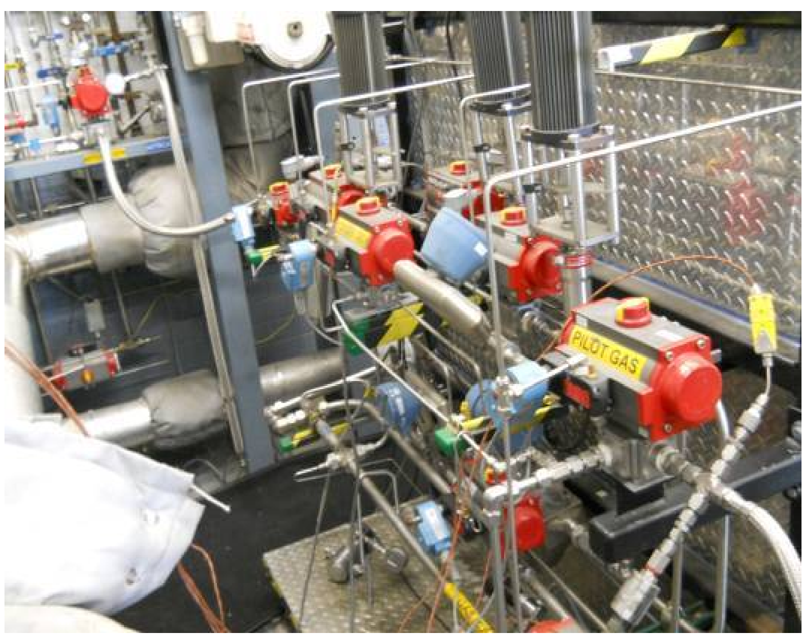


Figure 6(c). Solar Turbines, Incorporated Test Facility Showing the H2-N2-Pilot Fuel Skid with Filters and Emergency Stops

Figure 7 shows the high pressure single injector rig setup at the Solar Turbines, Incorporated test facility. The flow is from right to left in the figure shown. High pressure, high temperature air was supplied using compressors and heaters were installed to heat the air to the desired temperature. The rig pressure was controlled by a downstream pressure valve. Sample probes were used for emission measurement in the combustor region. The samples probes and the exhaust was water cooled. Data acquisition software was used for monitoring and recording all the test parameters. A flame in the combustion zone was detected by measuring an increase in the combustor exit temperature. Fifty percent hydrogen was the upper limit permitted for testing with hydrogen-nitrogen mixtures at this test facility. In addition, the maximum available nitrogen flow capacity limited testing to maximum of 8 atm. The inlet air temperature was 370C/700F and inlet fuel temperature was ambient. Full scale testing was limited to steady state operation at conditions as near to Solar Turbines, Incorporated Taurus 70, T70, full load engine as possible [9]. No transient (i.e. start-up, load shedding, and shutdown) conditions were examined at the time. The test plan matrix was finalized for the testing to be conducted. The results of the testing are discussed in the following section.

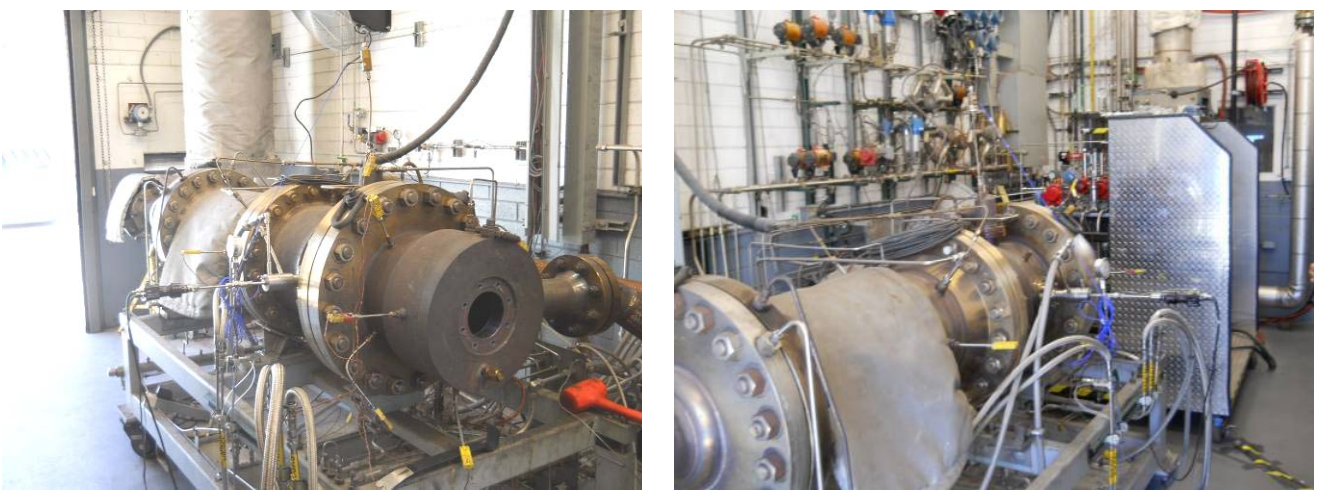


Figure 7. Solar Turbines, Incorporated Single Injector Full Scale Test Rig

TECHNICAL RESULTS

Subscale 10 Atm. Testing at PCI

To evaluate and demonstrate the performance of the catalytic injectors subscale testing was conducted in PCI's subscale high pressure (10 atm.) rig for catalytic injector screening and performance improvements. Two generations of the reactors were tested to demonstrate catalytic performance improvement and enhance catalytic contribution. The first generation reactor (Gen. I) used two separate flow paths for the combustion air that allowed more control of reactor operating parameters. This allowed tuning of the reactor to give optimal performance. The second generation (Gen II) used a single air flow design to simulate actual gas turbine operating conditions. For the Gen II design, two different catalytic geometry configurations were tested to improve the ability to retrofit the catalytic injectors based on engine integration and packaging. Gen I testing demonstrated that catalytic reaction was increased by increasing air split. Higher catalytic reaction resulted in reduction in NOx emissions. Gen II testing showed that the module could achieve low emissions and be integrated within the engine. The results of this testing showed that the rich catalytic reactor was capable of producing low single digit NOx emissions with hydrogen fuels; a level much below what is seen in conventional diffusion flame hydrogen burners[1]. These low emissions were achievable at reactor bed temperatures conducive to catalytic element stability.

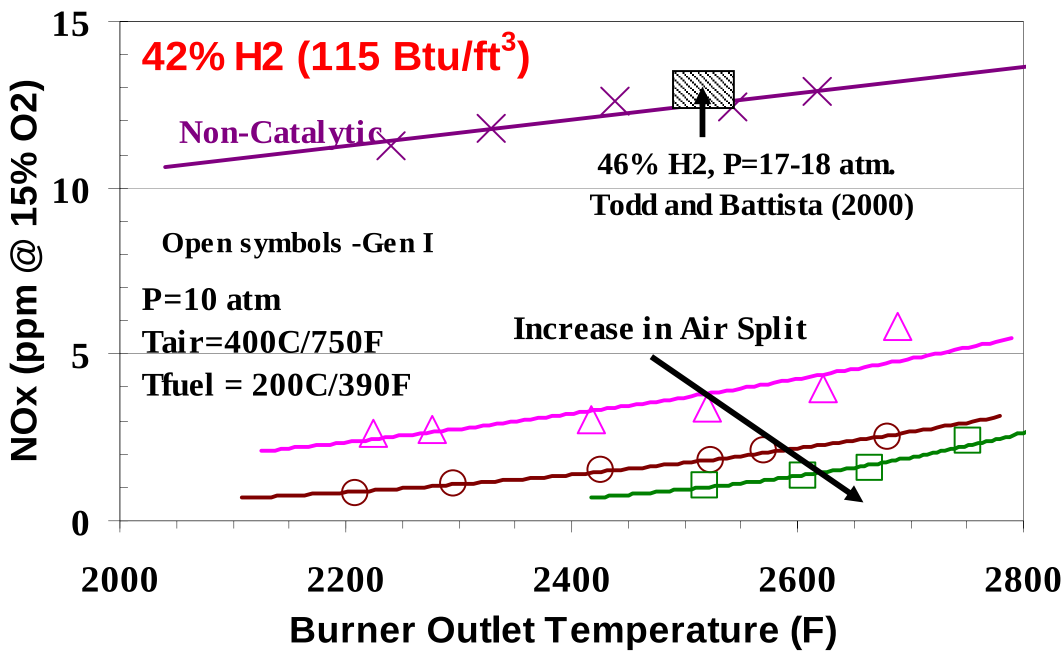


Figure 8. Effect of Catalytic Air Split (Catalytic Conversion) on NOx emissions for 42 % H_2

Gen I Subscale Performance Testing:
Figure 8 shows the effect of catalyst air split on the NOx emissions with varying burner outlet temperature (BOT) for 42% hydrogen (by volume) with remainder being nitrogen. BOT is the calculated adiabatic flame temperature in the primary zone. In this context, this is the calculated adiabatic flame temperature of the total hydrogen-nitrogen mixture and air entering the catalytic system (including both backside cooling and reactor air). Increasing the air split, increased the catalyst bed reaction, leading NOx emissions to reduce below 1 ppm levels. To further show the effect of the catalyst air split on NOx, "non-catalytic" data were taken where only fuel flowed through the catalytic channel and all air flowed through the cooling channel. Since no catalytic conversion of fuel occurred in the reactor, the NOx production was found to be a similar order of magnitude as was seen for standard diffusion flames engine data [1].

Testing was also conducted to rule out the effect of the differing momentum ratios. In this case, in addition to the fuel (H_2 and N_2), additional N_2 was added through the catalytic channel, such that the velocity exiting the catalytic channel would be the same as the catalytic case (which has split air). It was observed that NOx emissions were around 11 ppm for the matched velocity non-catalytic test for BOT 1385C/2525F, about 1 ppm less than non-matched but quite similar to the other non-catalytic case in which the jet momentum ratios were not maintained. In any case, non-catalytic testing produced NOx much greater than catalytic testing which produced levels as low as 1 ppm. Thus it can be concluded that the catalytic pre-reaction decreases NOx and momentum ratio does not play a significant role in the decrease in NOx. In addition, increasing catalytic air split increases the pre-reaction, hence lowering the NOx emissions to ultra-low levels. Based on this Gen I testing, a design that can produce high air split and be integrated with the engine (such as single air source design) was developed as discussed in the following section.

Experimental Testing and CFD for Improving Catalytic Air Split:
The Gen I injector as discussed, had two separate flows (one to the catalyst region and the other to the cooling section). In order to develop an injector capable of being integrated with the engine, a single air supply injector had to be designed. In addition, the design had to ensure the desired air split entering the catalyst could be maintained for low NOx performance. This design configuration was called Gen II. To improve the catalyst air split for increased catalytic contribution, design modifications were analyzed and implemented. Computational Fluid Dynamics (CFD) studies were performed and different geometry configurations were evaluated and analyzed as discussed below.

CFD studies were performed to improve the catalytic air split. A two dimensional axisymmetric model was created to simulate the catalytic fuel air mixer region of the Gen. II injector. The CFD FLUENT simulation software was used to solve for the flow field, with turbulence simulated Reynold's Stress Model and, due to the high velocities expected, a compressible fluid model was applied. For the purposes of this study, all flows were considered to have the properties of air. This simplified the setup, reduced convergence times, and sufficiently accurately simulated the field of interest. The CFD of the Gen II injector was then subjected through a series of runs to investigate and optimize for increased catalytic air split. This was achieved by changing the geometry of the air-fuel mixture entering the catalyst zone. Figure 9 shows four selected flowfields developed through the CFD analysis. In Figure 9, the axis of symmetry, catalytic air inlet, fuel inlet, and the outlet of the system are shown. The tube geometry and length was varied and this affected the flow though the catalyst as seen by the increased tube velocity. As shown in Table 1, the four design configurations were downselected, analyzed and evaluated. Design 4 provided the highest air split of 2.5 times compared to a baseline (Design 1) injector. Based on these analytical studies, Design 4 was chosen as the best case.

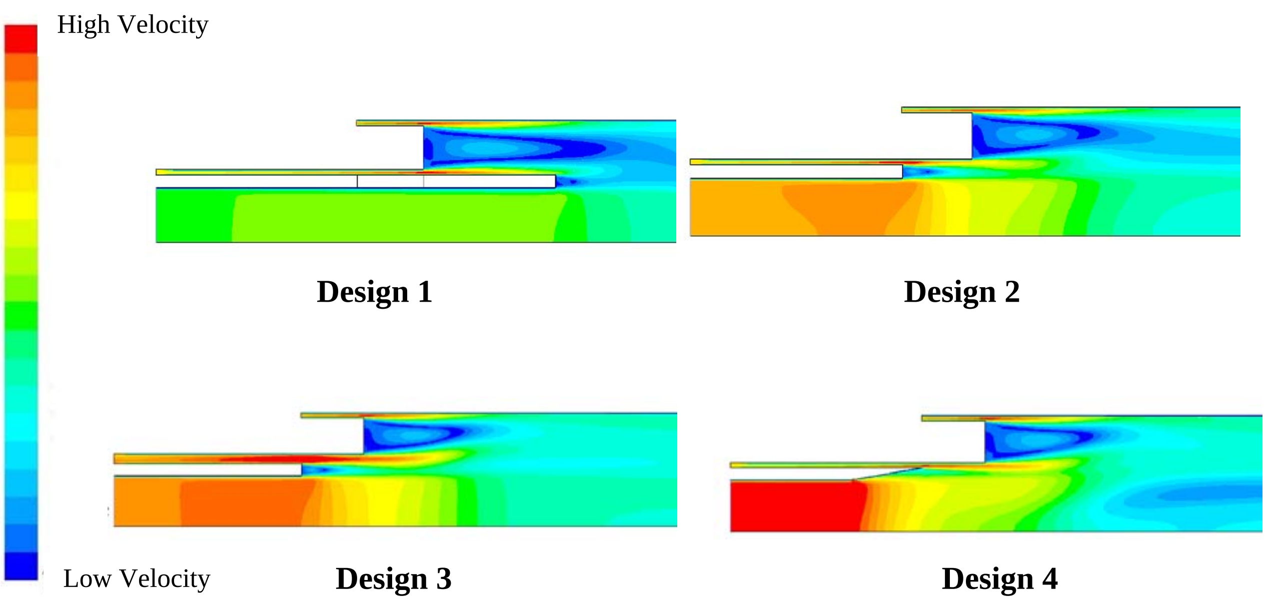


Figure 9. CFD Analytical Studies Showing Different Geometrical Designs for Increasing Air Split

Table 1. CFD Analysis Conducted to enhance Air split in the catalyst region

Design Configuration	Increase in Air Split
Design 1	25%
Design 2	91%
Design 3	96%
Design 4	151%
*Air Split = Catalyst Air/Total Air	

After conducting the CFD studies, the Gen II (single air source) subscale injector was designed and fabricated to simulate "in-engine" conditions. Testing was conducted to evaluate the air split of the system and compare to CFD predictions. Table 2 shows the experimental results conducted in the subscale rig at two flowrates to cover the entire diluent flow regime. Low flows representing lower diluent levels provided lower air split of 1.6 times that of a standard injector design. Meanwhile, increasing the diluent flow, increased the air split to three times demonstrating greater catalytic contribution. The results indicated that even with an increase in the diluent flowrates; a high air split could be achieved. This also directly relates to increase in the catalytic contribution and hence to reduced NOx emissions. The results reasonably matched the CFD simulations providing further confidence in the data. This design was then further used to conduct subscale and full scale hydrogen fuel emission testing.

Table 2. Experimental Testing showing increase in catalyst air split compared to standard injector for two different flow regimes

Flowrates	Increase in Air Split
Flow 1	60%
Flow 2	200%

Gen II Subscale Performance Testing:

The subscale design fabricated for air split evaluation was used to conduct subscale testing at pressure. Two design configurations were considered to allow flexibility for engine integration. The first design designated as Gen II – Injector A was reduced catalyst geometry. The shorter subscale catalyst injector was selected to see the effect of catalytic conversion on NOx emissions and turndown potentially allowing a reduction in injector length further improving engine retrofits capability. The second configuration was designated as Gen II – Injector B, which had standard catalyst length and was used as the optimized catalytic injector design.

The current state-of-the-art in NOx reduction for hydrogen fuel includes the use of a diluent such as nitrogen or steam. However, the use of diluents causes an increase in both capital and operating system costs with an added effect of reduced flame stability. For this testing, two levels of nitrogen dilution were evaluated to understand the effect of varying hydrogen percentages on catalytic performance and NOx emissions.

Figure 10 shows the NOx emissions data obtained for two injector configurations for two diluent levels for the Gen II design. Gen II Injector A had a reduced catalyst length than Gen II Injector B.

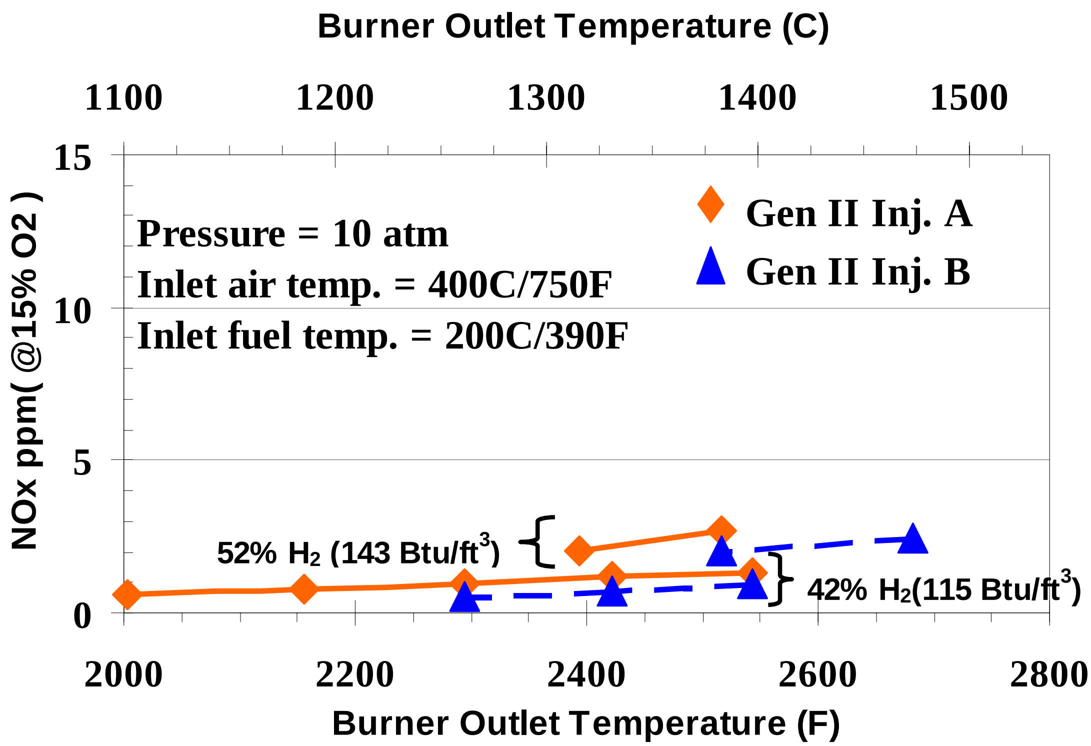


Figure 10. NOx Emissions Performance of Gen II Injectors

Both the Gen II Injectors (A & B) achieved less than 3 ppm NOx emissions for fuel mixtures of 42 and 52% hydrogen. Even with high diluent (58% N_2 by volume), a characteristic of many opportunity fuels; a stable downstream flame could be achieved due to increased reaction in the catalyst bed. Also, as the BOT was lowered the mixture moved from rich to near-stochiometry in the catalyst bed, thereby increasing the bed temperature which helps improve flame stabilization. As the hydrogen percentage was increased from 42% to 52% an increase in NOx was seen due to reduced diluents in the mixture and hence higher temperatures in the flame zone (discussed in detail later). This increase in NOx is small (1 to 2 ppm) and well below conventional diffusion combustion system levels. In addition, the NOx emissions were significantly less sensitive to dilution levels than results given in Todd and Battista [1] for hydrogen diffusion flame, implying reduction of dilution can be possible while maintaining reasonably low levels of NOx. Even though the increase in NOx was apparent, with an equivalent combustor and engine operability the rich catalytic hydrogen injector will produce significantly less NOx compared to diffusion combustion systems. This leads to the potential use of lower levels of dilutions in regions where NOx control is desired but at regulatory requirements less stringent than sub 3 ppm.

The Gen II Injector A (Figure 10) showed a slight increase in the NOx emissions due to reduced catalyst length for both 42% and 52% H_2. This was expected since lower fuel conversion in the catalyst region results in higher energy released in the post-catalyst zone, leading to higher NOx emissions. However, this increase was small, showing that reduced length injectors can give excellent (less than 2 ppm NOx) emissions performance easing the process of engine integration and packaging.

At lower BOT the catalyst surface temperature increased since the fuel rich stoichiometry was reduced. NOx control by lowering outlet temperature or increasing air split is limited by the catalyst surface temperatures. With increased catalytic reaction there is more energy released within the catalyst bed thus producing higher surface temperatures (since cooling air flow is essentially constant for the ranges of air splits of interest and given hardware configuration). The effect of decreasing adiabatic flame temperatures on reactor wall temperatures and the effect of increasing air split - higher catalytic conversion - is shown in Figure 11. As expected, the catalyst bed wall temperature increases with lowering BOT – a desirable feature to provide enhanced flame stability as the operating conditions approach Lean Blow Out (LBO) and also with increase in the air split. Gen II had a higher air split and hence higher catalyst surface temperature than Gen I. The burner outlet temperature was not lowered any further due to the catalyst reaching the maximum design temperature as discussed below.

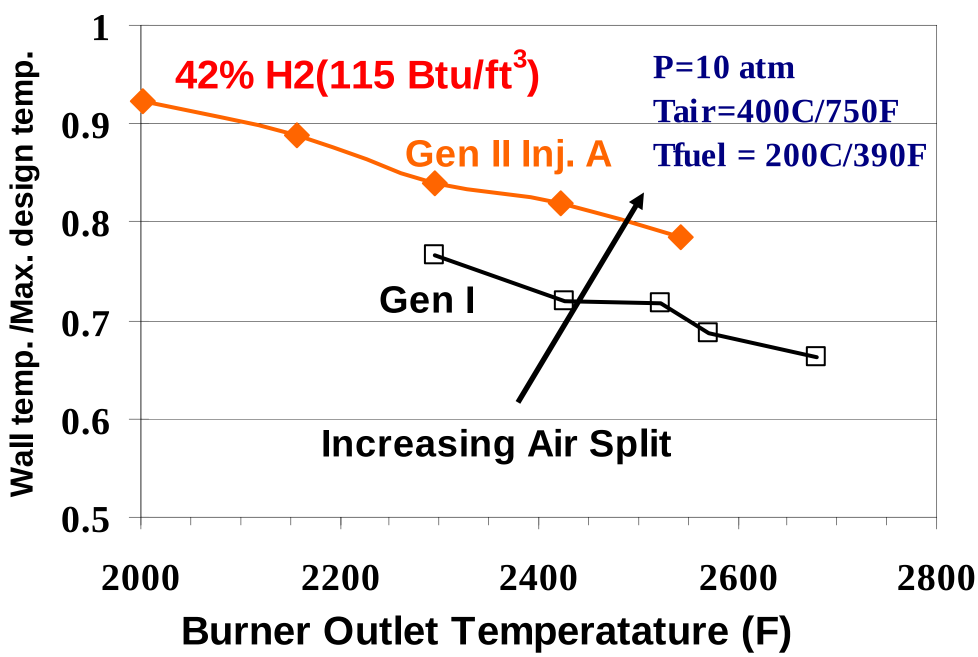


Figure 11. Catalytic Reactor Temperature for 42% H_2 with Increasing Air Split (Catalytic Conversion)

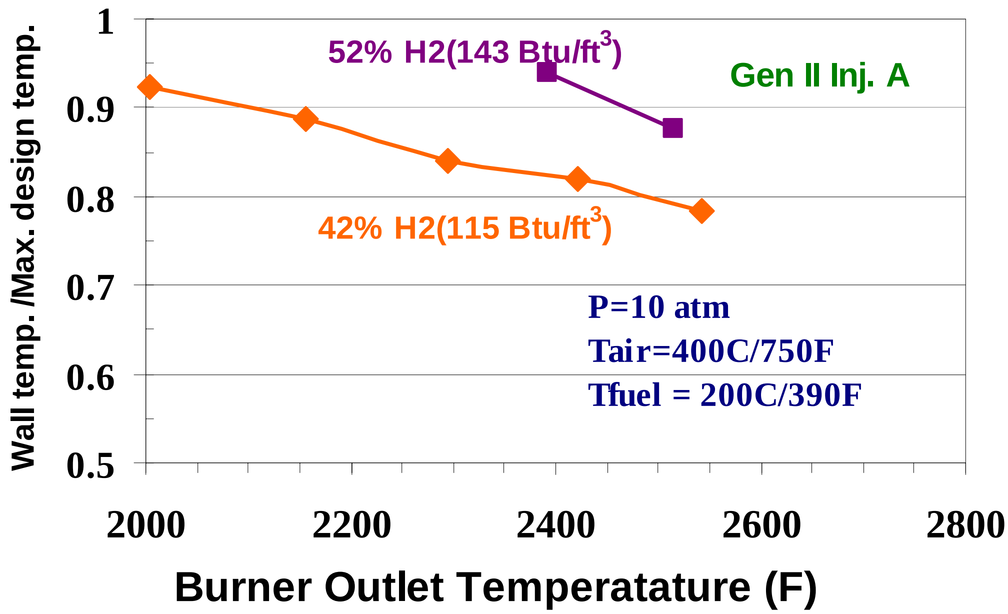


Figure 12. Catalytic Reactor Temperature for 42% and 52% H_2 with Increasing Burner Outlet Temperature

Figure 12 shows the change in the catalyst wall temperature with 42% and 52% H_2. Increasing the hydrogen component in the fuel (by reducing the diluents) raises the surface temperature; however, the temperature remains within material limits. This increase in surface temperature can be attributed to a decrease in the diluent (nitrogen) in the catalytic channels, hence a rise in the temperature. The catalytic reactor provides a low operating temperature due to its inherent characteristic of rich catalytic operation and being backside cooled by the air. Improving the backside cooling can further lower the catalyst temperature.

This reduced temperature operation together with a fuel rich environment (non-oxidizing) decreased catalyst volatilization and sintering, factors judged potentially life-limiting for catalytic combustors. In addition, the variation of catalytic surface temperature was small across wide variation in burner outlet temperature (500F). This indicated catalyst reactor robustness in that a large change in operating conditions (i.e. load shedding or acceleration) will have a minimal impact on catalytic bed lifetime, ideal for gas turbine applications. During transient operation (start up and shut down) there is period of time when the catalytic system passes through stoichiometric conditions which may lead to high reactor temperatures. However, during extensive testing of the catalytic reactor with natural gas and other fuels (e.g. syngas), including the hydrogen-nitrogen mixtures in this study, no damage to the catalyst or the substrate was observed during the transient operation within the designed operating regime. This lack of damage is attributed to the brief time that the catalytic system was exposed to these conditions (high flow velocities leading to low residence times at stoichiometric conditions) with the thermal mass of the catalytic system and to the catalyst being backside cooled moderating any temperature spike.

In order to keep the efficiency of the engine equal to or higher, the pressure drop through the catalytic injector needs to be kept low. The pressure drop through the injector increases due to the high volumetric flowrates. However, the RCH system was designed to maintain existing gas turbine pressure drop design constraints. The overall pressure drop of the subscale injector was 4.5% or less. This lies within typical engine specifications.

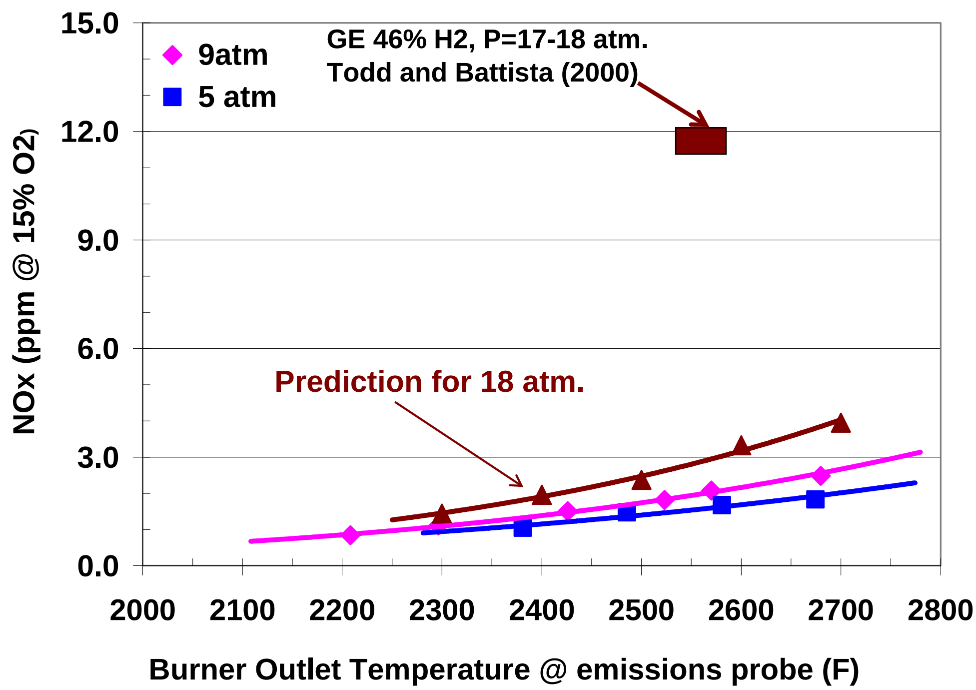


Figure 13. Effect of pressure on NOx emission for Hydrogen Combustion (42% H_2)

The subscale testing was conducted at a pressure of 9-10 atm. due to rig limitations, whereas Todd and Battista NOx emissions were obtained for a pressure of 17-18 atm. In order to study the impact of this increased pressure on NOx emissions, testing was conducted at two different pressures and the NOx emissions was predicted for 18 atm. as shown in Figure 13. Experiments were run at pressure of 5 atm and 9 atm. for 42% hydrogen fuel at a constant air split for the Gen I injector. The data reported by Todd and Battista were from a GE 6FA IGCC combustion system combustor were at a BOT of 1400C/2550F. At BOT of approximately 1470C/2570 F, the NOx emissions at pressure of 9 atm. increased by 18% to 2 ppm from 1.7 ppm at pressure of 5 atm. This 18% increase in NOx with near doubling of pressure showed small dependency on pressure. Using the scaling laws that can be obtained at each BOT from the 5 atm and 9 atm. predictions of NOx at 18 atm. was calculated. This is shown by the solid red line in Figure 13. The expected NOx from the rich catalytic combustor design was still much less than the results shown by Todd and Battista [1]. It was observed that the predicted

NOx at 18 atm. and BOT of 1400C/2550F was still lower by a factor of three from the data of Todd and Battista (2000).

In order to improve the efficiency of the engine, reduction in dilution is desired. However, reduced diluents leads to issues such as flashback, auto-ignition and higher flame speeds, all potentially damaging to the engine. In addition, reduced diluent leads to higher NOx emissions. The effect of N_2 dilution on NOx emissions for catalytic combustion of hydrogen fuel was studied and is shown in Figure 14. All the NOx emissions data shown were obtained at a constant catalytic air split. As can be seen from the figure, reduced diluents (going from 42% H_2 to 75% H_2) increases the energy released in the flame zone at the same adiabatic flame temperature leading to increased flame zone temperature, hence leading to increased NOx emissions. However, in comparison to Todd and Battista, the PCI injector NOx emissions were significantly lower. The PCI injector produced roughly a third of the emissions at a hydrogen level of 46%, a quarter at 60%, and as little as 10% of the emissions at 70% hydrogen. Alternately, the PCI injector can produce the same emissions at 75% hydrogen as the Todd and Battista system produces at 46% hydrogen. This does show that for high hydrogen content the catalytic injector will produce low NOx emissions compared to conventional combustion systems with increased benefit at higher hydrogen levels.

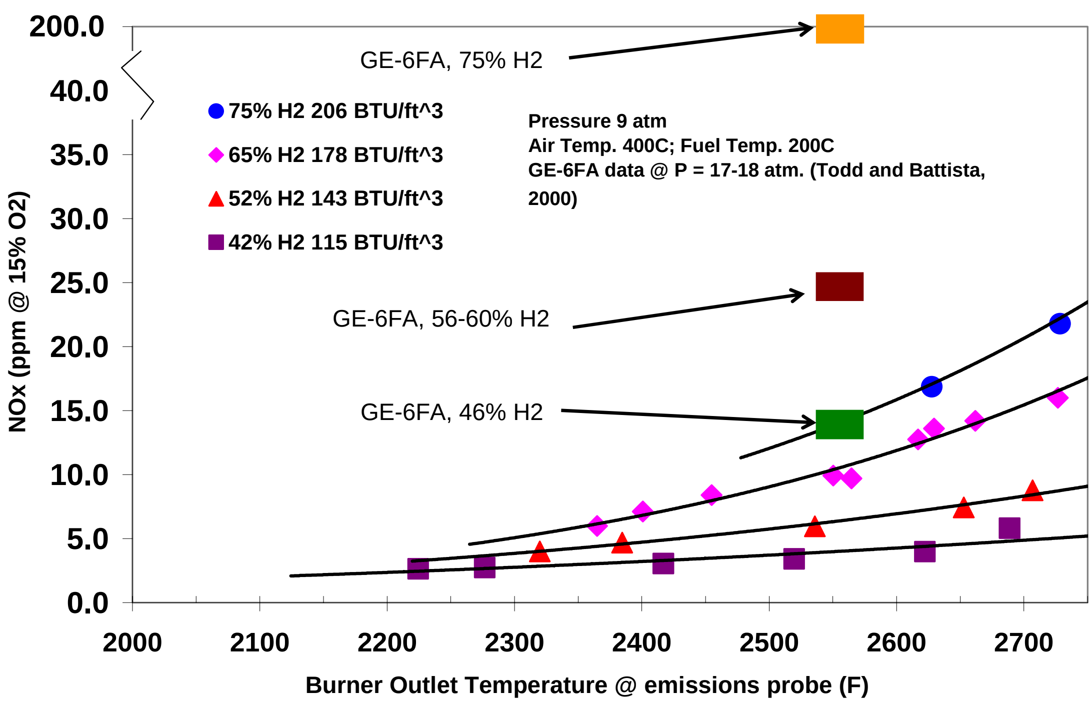


Figure 14. Effect of N_2 Dilution on NOx Emissions

Based on the successful subscale testing at PCI, a full scale single injector Rich Catalytic Hydrogen (RCH1) injector was fabricated for testing at the high pressure test facility at Solar Turbines, Incorporated.

Full Scale Single Injector Fabrication:

Upon successful completion of subscale testing, a full scale single injector module was fabricated by PCI designated as Rich Catalytic Hydrogen (RCH1). The full scale module included a pilot designed by Solar Turbines, Incorporated as shown in Figure 15. Thermocouples (TC's) and sampling ports were installed for temperature and species measurements respectively. The full scale single injector was developed as a modular piece for engine integration for utility and industrial application. Typical engine envelopes as well as engine operation such as start-up were considered part of the development. The full scale injector was fabricated with the flanges, for installation in the single injector test rig at the Solar Turbines test facility. Before shipping the injector to Solar Turbines, the injector was installed in PCI's atmospheric test rig for shakedown testing, measurement of effective areas, and unmixedness characterization as discussed in the next section.

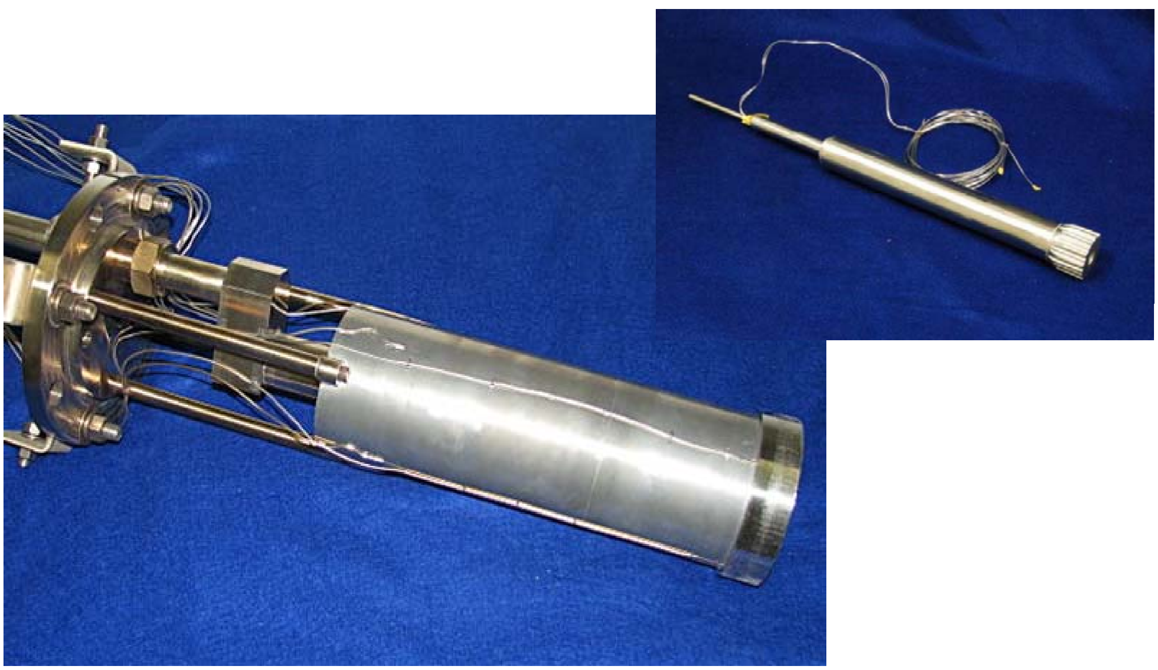


Figure 15. Fullscale RCH1 Injector Hardware for Hydrogen Combustion Fabricated by Solar Turbines, Incorporated (Pilot) and PCI (Injector)

Atmospheric Full-Scale Single Injector Testing at PCI

Validation and stability testing of the full scale single injector was performed. The full scale single injector hardware was assembled and installed in the high flow rig setup at PCI for conducting effective area, unmixedness and flow testing. Necessary instrumentation (TC's, pressure ports, and gas sample lines) was hooked up for data recording. For start-up, shakedown and stability testing, commercial pipeline natural gas was used as the fuel component.

Effective area testing was conducted to ensure that the RCH1 has a similar behavior as that of the subscale and pressure drop matches that desired for the engine integration. Table 3 shows the results of the effective area testing normalized to a per catalytic tube basis to account for the differing scales of the injectors. As shown, the full scale RCH1

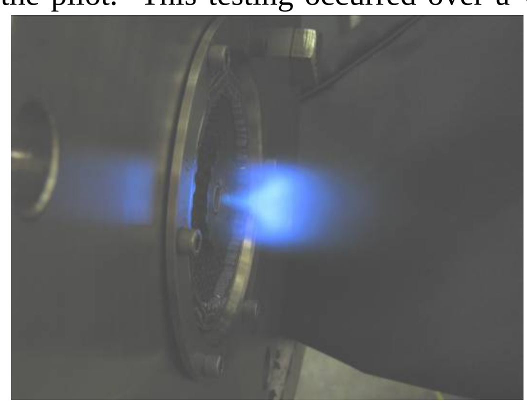
Table 3. Effective area comparison for Full scale and subscale injectors

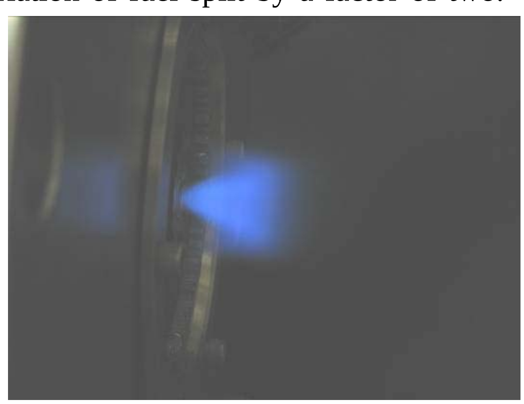
Aeff/tube	in^2
Subscale Gen II - Inj B	0.0043
Fullscale Gen II - RCH	0.0041

injector testing is in agreement with the subscale testing showing that the catalytic elements are sufficiently modular to provide repeatable scaling. Based on the effective area of the full scale RCH1 injector, the injector is expected to match the targeted 4.5% air side pressure drop in the full scale testing at Solar Turbines, Incorporated.

Pilot Flame Stability Testing:

For start-up it was necessary to demonstrate pilot stability. In addition, to ensure smooth operation during full scale testing at Solar Turbines, Incorporated test facility, the operating envelope had to be determined. Hence, the pilot stability and robustness were tested. Figure 16 shows flame pictures of the pilot at two different pilot operating fuel splits. Figure 16 (a) is operating rich and shows strong flame anchoring to the end of the pilot and a highly energetic combustion region is seen in the core of the flame. In comparison figure 16 (b), operating at leaner conditions, has a weaker flame at the end of the pilot. This testing occurred over a variation of fuel split by a factor of two. Since





(a) Stable flame and anchored to pilot end **(b) Flame, though stable, closer to LBO**

Figure 16. Natural Gas Catalytic Pilot Flame for Two Pilot Fuel Splits

flame was stable over this range, the pilot will provide sufficient flame stabilization to the mains, if required.

For shakedown testing at PCI before providing the injector to Solar Turbines, Incorporated for testing, the injector was operated with natural gas due to PCI facility limitations regarding high flows of hydrogen. This testing is appropriate because natural gas, with its reduced reactivity compared to hydrogen, is a “worst case” fuel for testing reactor operation. In addition, the readily visible natural gas flames make it easier to see irregularities in flame structure for visual inspection of fuel distribution issues.

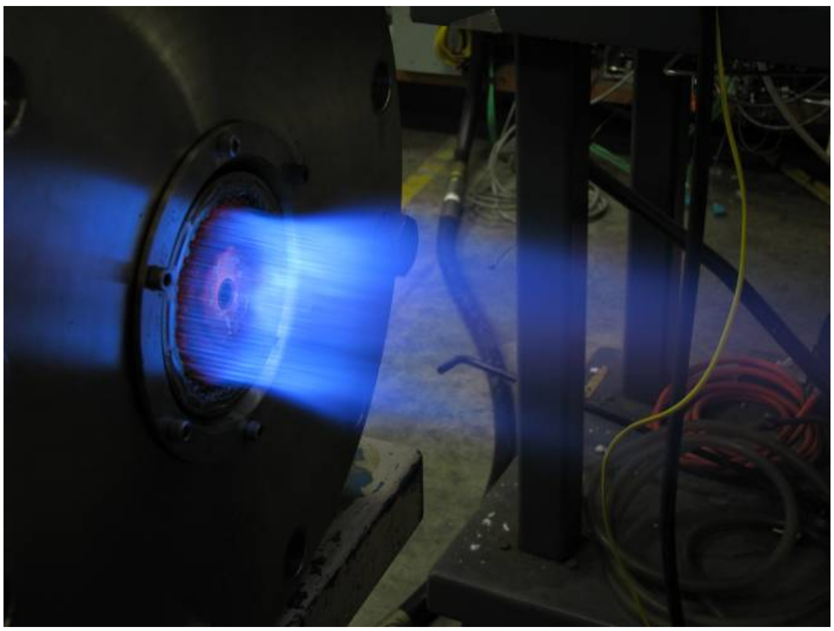


Figure 17 (a). Atmospheric Full Scale RCH1 Operation with Pilot P =1 atm, Tairin=300C/580F, Tfuel=25C/75F

With natural gas, the reactor lit off at a low inlet temperature and the operation showed stability across a range of conditions. This indicates that the catalyst is active and stable. The structure of the flame was an array of microflames establishing on the exit of the catalytic injector (Figs. 17 (a) through (c)). The microflames within a short distance from the end of the injector agglomerated into a main flame and quickly completed combustion. Flames were well established and stable over the range of testing conditions. In addition, the combustor exit appeared well cooled, with no obvious signs of over heating i.e. brightly glowing metal regions. However, based on observations of the flame, it was determined there was unmixedness as seen through variation in flame length (indicating high velocity or excess fuel) or in apparent intensity (indicating greater amount of air entrainment). Further analysis was made and it was determined that the unmixedness was above the preferred target level but not at levels harmful to the injector or the test rig. It was determined that testing would continue to determine performance levels with acknowledgement that modifications will need to be made to reduce unmixedness in the future. Post firing testing of effective area showed no change from previous results indicating structural integrity of the injector (i.e. no catalytic element damage).

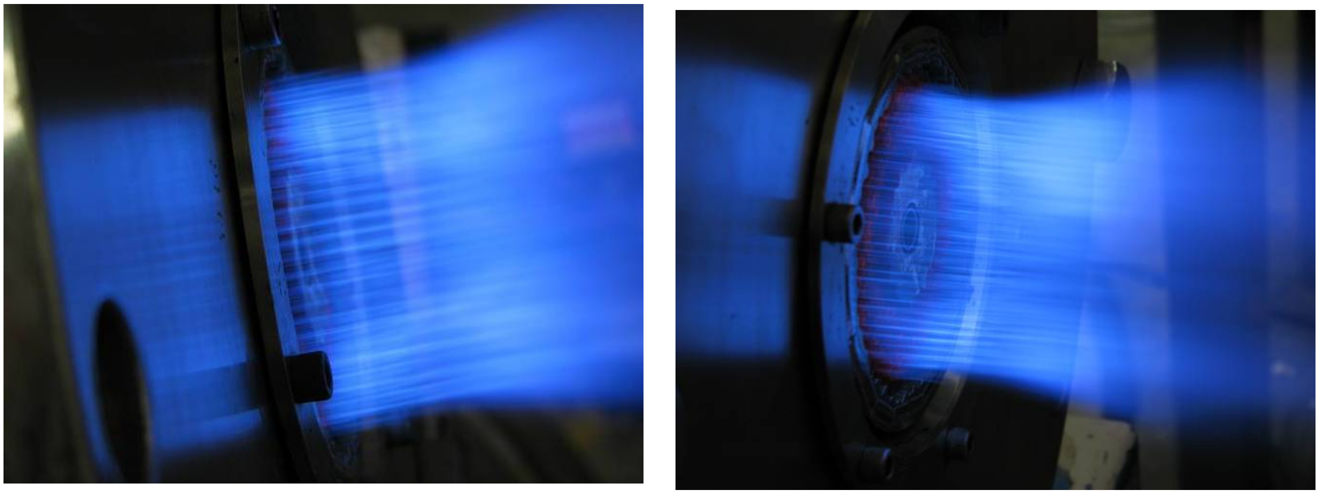


Figure 17(b). Atmospheric RCH1 Microflames with Natural Gas Operation
P =1 atm, Tairin=300C/580F, Tfuel=25C/75F.

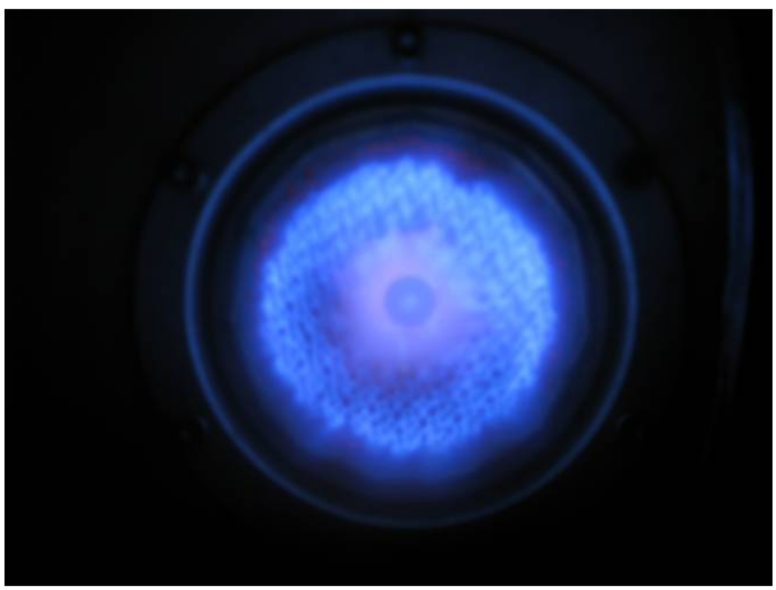


Figure 17 (c). RCH1 Microflames End-View Showing Unmixedness with Natural Gas Operation
P =1 atm, Tairin=300C/580F, Tfuel=25C/75F

Hydrogen Full-Scale Single Injector Testing at Solar Turbines, Incorporated Test Facility

The full scale single injector was shipped to Solar Turbines, Incorporated for effective area testing and installation. Results of effective area testing of the full scale injector at Solar Turbines, Incorporated test facility showed good agreement with PCI's effective area testing indicating good injector repeatability. The single injector high pressure rig was setup and low pressure drop air and fuel filters were installed. The combustion test plan was mutually developed amongst PCI and Solar Turbines, Incorporated engineering team. The test plan covered the upper level of the flow rates and a sweep of adiabatic flame temperatures.

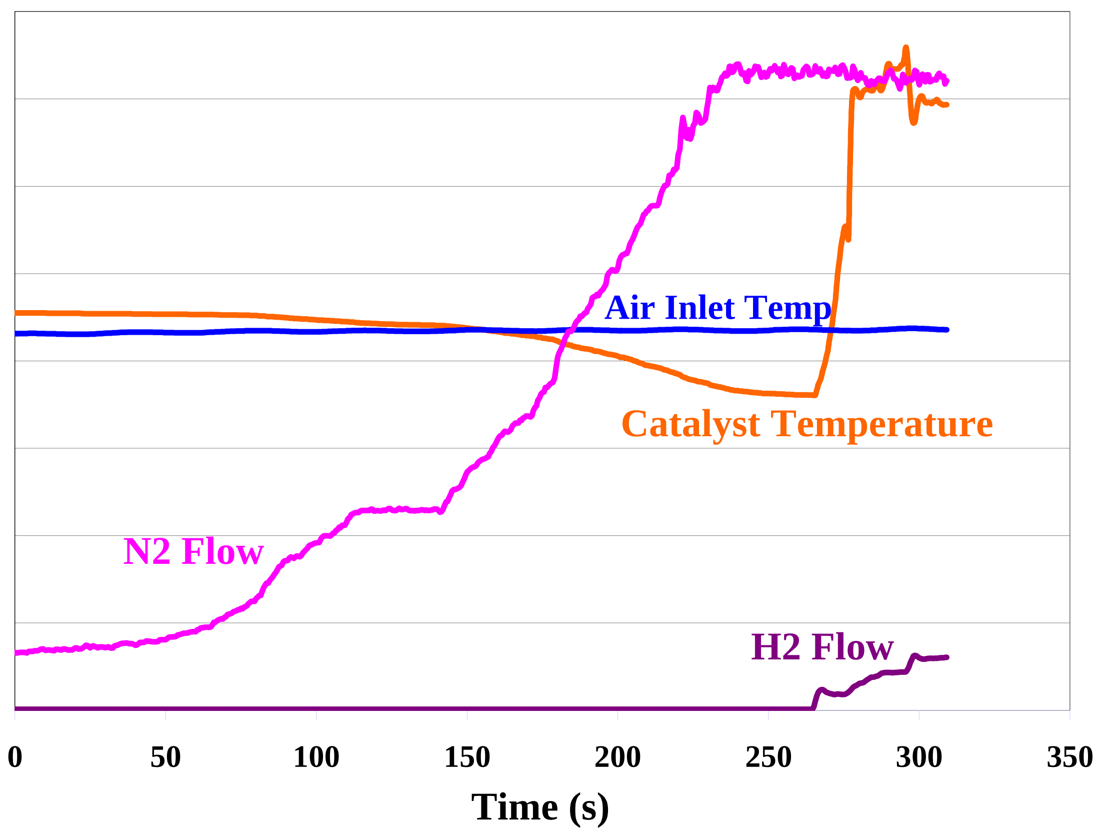


Figure 18. Full Scale Testing - Catalyst Lightoff Occurs Instantaneously with Introduction of Hydrogen Fuel in the Catalytic Injector

Initial testing focused on start-up, including both catalyst lightoff testing and ignition of the downstream combustor section. Initial full scale ignition occurred by fueling the central pilot with natural gas and the main injector with hydrogen fuel. Upon achieving flame stability, pilot fuel was turned off. The main hydrogen flame was unaffected. Thereafter the pressure was ramped up to 8 atm. and combustion testing was performed.

Additional lightoff testing without fuel to pilot was also conducted to study whether the system could be safely started on hydrogen only. As shown in Figure 18 the catalyst lights off instantaneously when hydrogen is introduced in the main injector section. This can be seen in the sudden increase in the catalyst temperature upon first introduction of hydrogen to the injector. Also, the exit temperature (measured well downstream of the combustor) increased showing that a flame was established and stabilized at the injector exit leading to complete combustion.

This achievement of rapid light off and stable downstream flame is important for operability (allowing simplification of startup procedures and acceleration of start-up) and safety reasons (significant reduction of unreacted fuel build-up in the system before ignition). In addition, the demonstration of injector lightoff without pilot fueling requirements indicates that the system has strong potential for application to a true zero carbon emissions system by eliminating the requirement for natural gas firing of the pilot. However, impact of elimination of natural gas firing on operability (i.e. load shedding) needs to be further considered.

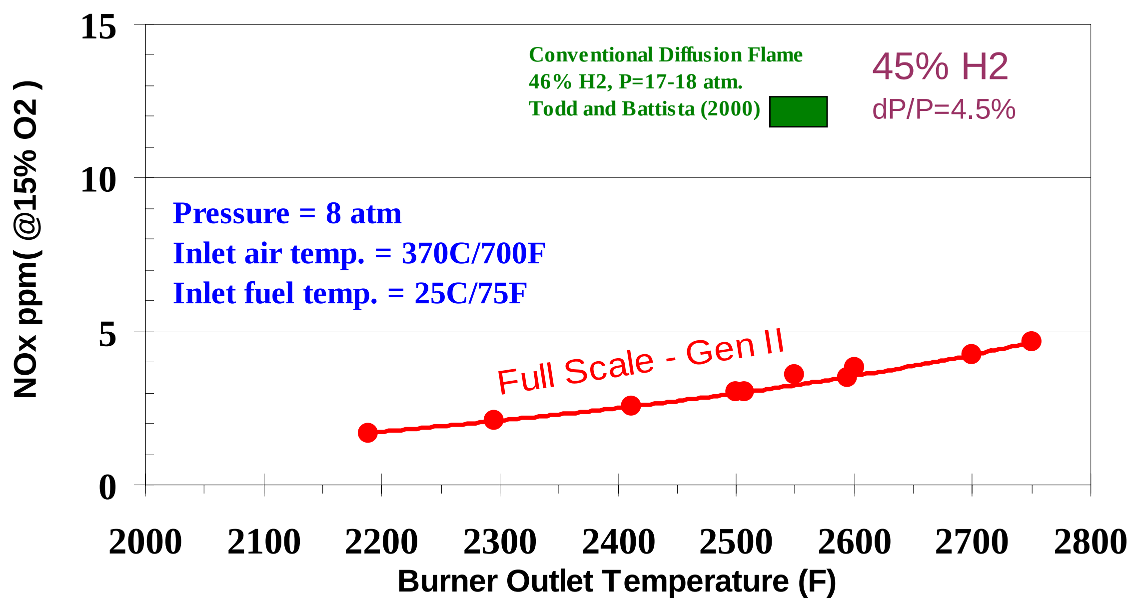


Figure 19. Single Digit Full Scale Single Injector NOx Emissions For 45% H_2 Testing at Solar Turbines, Incorporated

After startup, emissions, acoustic, and stability testing was conducted with 45% hydrogen. A sweep of the Burner Outlet Temperature (BOT) was performed to envelope all the operational conditions including current state-of-the art hydrogen turbines. The Burner Outlet Temperature is defined as the adiabatic flame temperature of the primary zone of the injector. Figure 19 shows full scale Rich Catalytic-Hydrogen (RCH1) injector NOx emissions in the low single digits (2-5 ppm corrected to 15% O_2) in the BOT range of 2200-2750F (1200C-1500C) at 8 atm. pressure with 45% hydrogen. These emissions were around one third of conventional diffusion flame ([1], adjusted for pressure).

These are promising results since a 66% reduction in NOx has already been achieved with the current injector with further reduction in NOx in the future injectors (with control of unmixedness and/or increase in split). This demonstrates at full scale the benefit of RCH in terms of (1) delivering lower NOx emission and/or (2) potential for use of reduced diluent (i.e. less operational cost) for a given NOx production level.

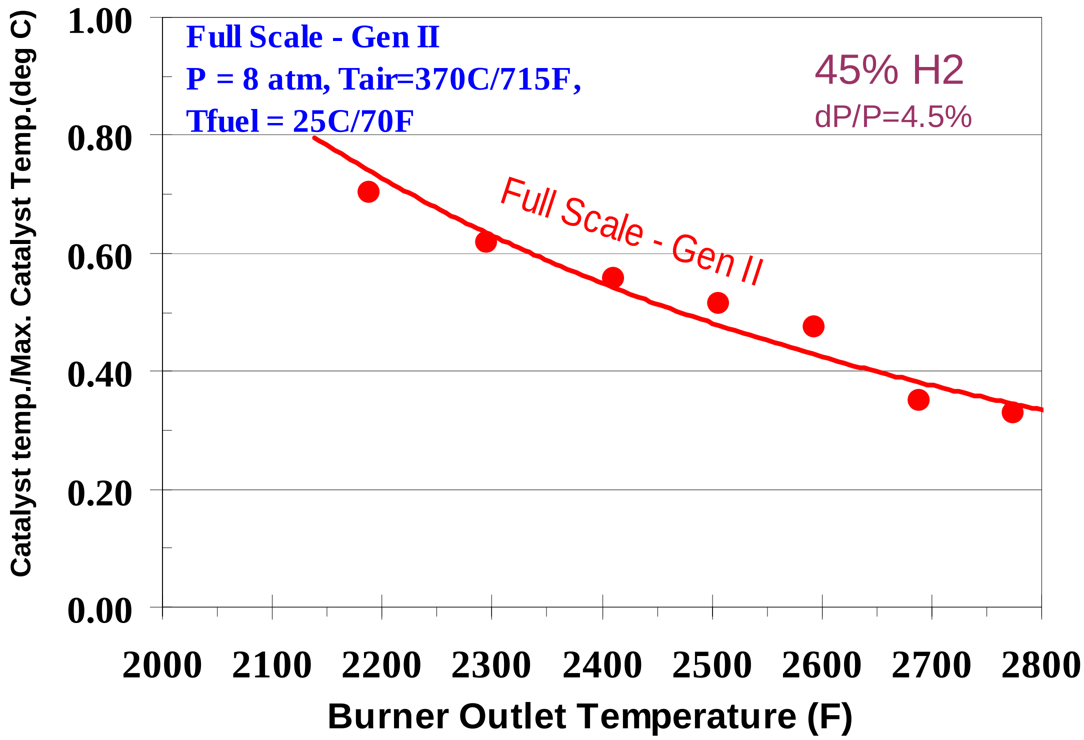


Figure 20. Catalyst Surface Temperature for Full Scale RCH1 Testing

In addition to NOx emissions, monitoring and recording of catalyst temperature for catalytic element component life was necessary. Figure 20 shows the catalyst temperature of the full scale injector normalized to the maximum design temperature. As shown, due to rich catalytic operation, the temperatures for the hydrogen testing were within the life limiting temperature of the substrate and the catalyst. Also, the substrate was backside cooled providing better control over the catalyst surface temperature. The other advantage of this design was improved flame stability at lower flame temperatures where combustor was stable due to increased catalytic contribution. While the reported data shows a minimum Burner Outlet Temperature of 1500C/2200F, this was not due to lean blow out of the burner. The design catalyst operating temperature, not stability, limited turndown. Wider turndown can be achieved by enhancing the injector cooling design and thus increasing the turndown. As shown by acoustic data, the potential for significant additional turndown existed.

Figure 21 shows the acoustics data recorded for the complete range of testing. The acoustics were very low (less than 0.1 psi) for the H_2 combustion testing in the adiabatic temperature range from 2200F to 2750F (1200C to 1500C). The low acoustics are explained by reduction of energy release in the flame zone (thus reduced drive energy for pressure oscillations) due to part of the total energy being release in the catalyst bed. In addition, the catalytic bed provides a buffer between the fuel injector and the downstream flame, effectively damping pressure feedback to the fuel inlet. While turndown was limited by maximum allowable bed temperature, acoustics indicates that the flame was still stable at low equivalence ratios. This can be seen from Figure 20. There was no observed increase in acoustics at low BOT, increased acoustics being a typical indicator of imminent blow out. The reduced acoustics improves component life of the gas turbine parts and hence reduced maintenance and operational costs.

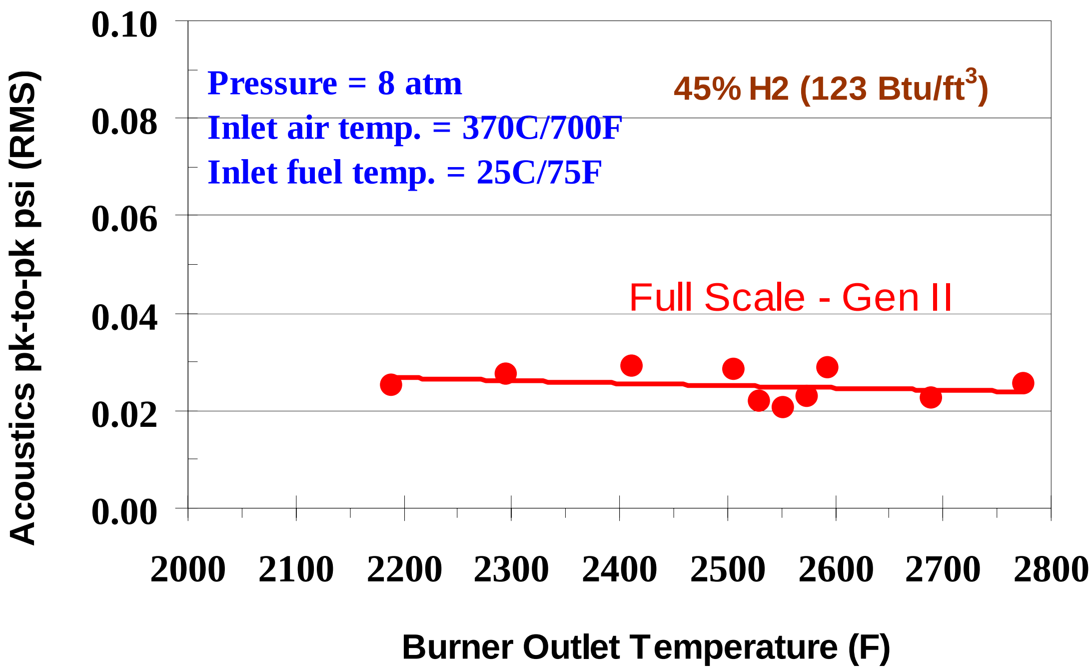


Figure 21. Low Acoustics for Full Scale Single Injector Testing

The Solar Turbine, Incorporated full scale injector test rig had optical access, however, hydrogen flames tend to have very low visibility. In order to view the flame location at high pressure, for one test the hydrogen fuel was doped with a small amount (5% by vol.) of natural gas to provide visibility. This testing was conducted at a pressure of 8 atm. with no fuel provided to the pilot. Figure 22 shows the hydrogen flame picture doped with natural gas. The flow is from right to left. Similar to the atmospheric testing at PCI (Figure 17), the flames were stabilized strongly at the end of the injector without pilot stabilization. This shows that the mechanism for flame stabilization is consistent, even at higher pressures. The levels of unmixedness seen in atmospheric testing could not be determined from the images due to reduced field of view and occlusions of the window.

However, it can be seen that much of the light emission occurs in near proximity to the exit of the catalytic reactor, implying that the majority of the combustion occurs quickly. This shows the production of a compact flame at pressure which will help in system integration and NOx reduction. The glowing seen on the bottom is an uncooled sampling probe that is heated due to close proximity of the microflames. This structure was for experimental instrumentation and would not be in a commercial product.

Figure 22. Hydrogen Flame Picture Doped with Natural Gas at Pressure of 8 atm.

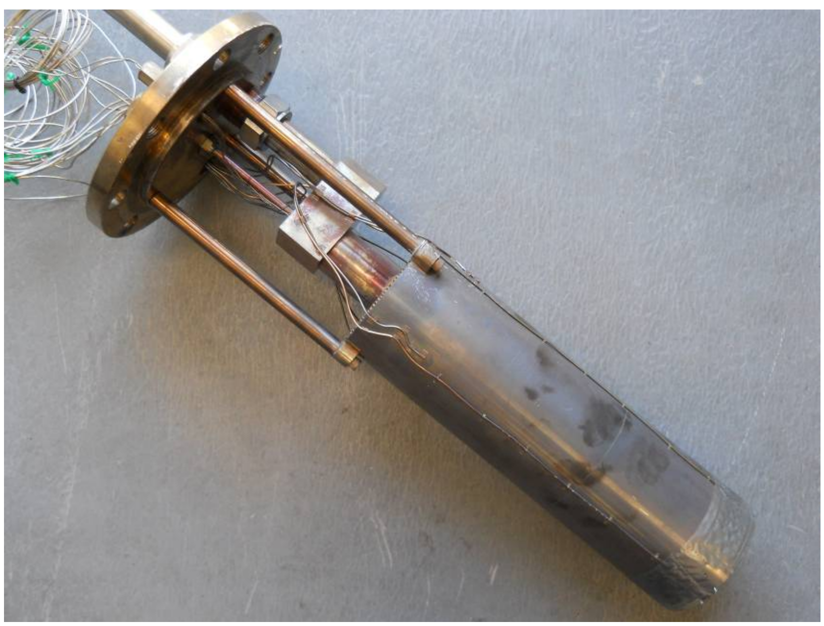


Figure 23. RCH1 Hardware after Testing Showing Good Integrity and Robustness

After conducting high pressure testing of the RCH1 injector the hardware was removed from the high pressure rig and inspected (Figure 23). Flow is from top left to bottom right. Visual and boroscope inspection showed structural integrity of the hardware. The injector was run for over 15 hours with hydrogen along with transients and steady state operation with additional hours of operation accumulated on this injector during atmospheric testing. This hardware was fully brazed and no further destructive type of inspection was conducted since the module can be used for further testing under this or other program. This gives preliminary indications of the structural and thermal integrity of the hardware, however, much more extensive testing will be needed to confirm.

Comparison of Full Scale Single Injector to Subscale Testing

Post testing data analysis of the full scale injector is shown in Figure 24. As shown, the results indicated that the full scale injector had 2 ppm higher NOx emissions compared to the subscale injector. This was primarily due to the previously identified poor fuel distribution within the injector causing localized regions of excessive flame temperature and residence time, both which tend to increase NOx emissions. This could be attributed to the method in which the fuel is introduced in the injector section. In addition, tighter manufacturing tolerances on the critical components would provide better fuel distribution. These modifications/improvements have been identified and can be implemented under a further program if lower NOx requirement is necessary.

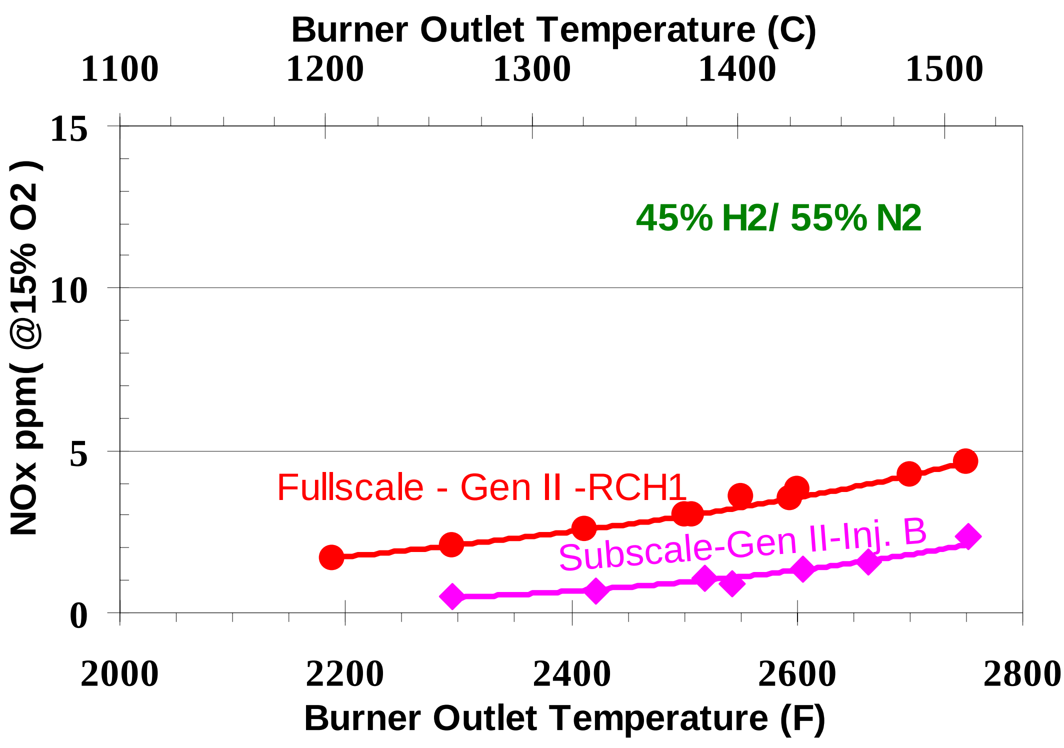


Figure 24. NOx Emissions Comparison of Full Scale vs. Subscale Injector

Catalytic Reactor Testing

The catalytic system has a service life target of 25,000 hours, however, for initial market entry the life is targeted to be 8,000 hours to gather service life data, address technical issues and build confidence. The intrinsic operating characteristics of the rich catalytic combustion operation, such as lower operating surface temperature and reducing catalyst environment (fuel rich), promote longer life. Testing focus has been on substrate and coating configurations with either testing in quiescent air at 900C/1650F conditions or combustion test at 9 and 15 atm. The 900C/1650F condition is an aggressive testing environment for initial downselection and hence was chosen. Testing was also conducted for engine transient operation. The catalytic element was introduced in a thermal stress rig and was subjected to multiple thermal cycles. Some of the test results are described in support of application of rich catalytic reactors to gas turbine engines and were supported by other DOE programs. The testing demonstrated stable and robust catalytic element component life for gas turbine conditions. Ultimately, testing in an actual engine will provide final data.

Oxidation Testing

Oxidation testing was performed with candidate substrate materials. Samples were subjected to furnace testing in a quiescent air environment of 900C/1650F and atmospheric pressure. This is higher than the reactor design temperature but was chosen as an accelerated aging scenario. The weight gain of the samples were monitored as an indication of oxidation/spalling/material changes (Figure 25) with increases in weight indicating oxidation (oxygen binding with the substrate metals forming oxides) and weight loss from oxide spalling. From this study, a substrate was selected that appears to

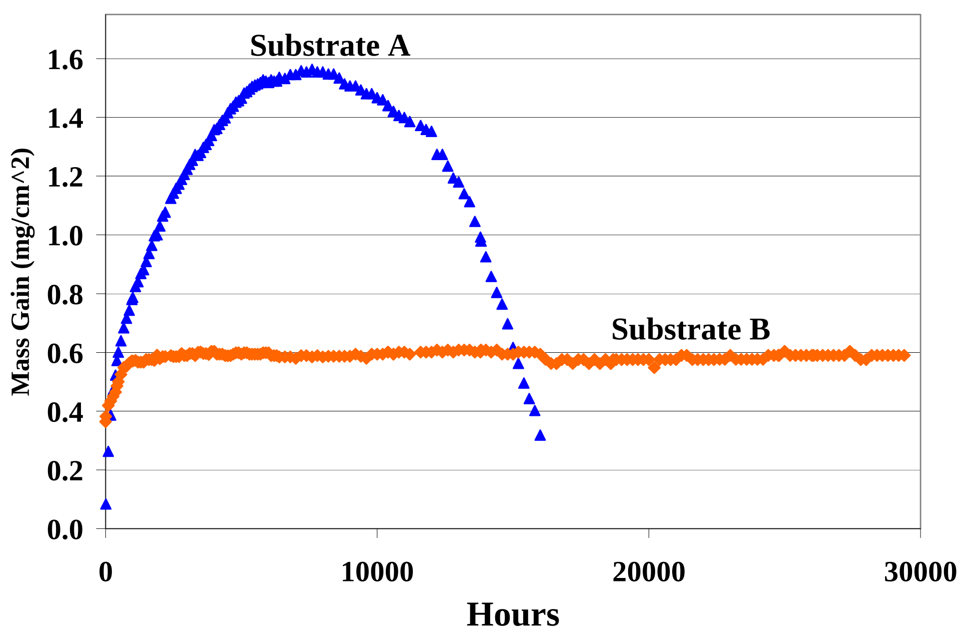


Figure 25. Mass Gain of Candidate Substrate Materials A and B in Quiescent Conditions of 900C/1650F at Atmospheric Pressure for Oxidation Testing

provide excellent performance; after an initial increase in mass as a surface oxide barrier was established, mass change was near undetectable for in excess of 25,000 hr. The testing is being conducted under other funding to identify the extent of the performance.

Single Catalytic Element Testing

Some of the initial testing was performed at 9 atm. During the later stage of testing, the test facility was upgraded to be able to test at 15 atm. corresponding to actual gas turbine engine. Testing was conducted in a high pressure, 15 atm. (1.5 MPa) environment similar to gas turbine conditions, at 400C/750F inlet temperature using a single element test rig. The test rig was instrumented with non-intrusive high temperature radiation pyrometers for surface temperature measurements, as standard thermocouples would not last testing or become intrusive to performance. In addition, the temperature of the mixed reactor exit gas, consisting of the reactor effluent mixed with the cooling oxidant flow, was monitored using a thermocouple. Outlet gas compositions were measured using a gas chromatograph, available during a portion of the test. Light-off testing was conducted at various time intervals during the durability testing period to ensure catalyst integrity. To ensure light-off repeatability this procedure was done with chemically pure grade methane each time with the same light-off conditions. The combustion tests were conducted using the local utility-supplied natural gas with the measured fuel composition as shown in Table 4.

Various catalyst formulations were also developed that would provide stability and performance over longer periods of time. The catalyst coating process was developed in a manner to provide stable and robust activity for a projected 25,000 hour lifetime. Each of these catalytic formulations was screened for shorter lengths of time, approximately ~140 hours. After the initial screening and performance evaluation the best candidate coatings and tubes were tested for extended period of time. The catalytic elements were subjected to testing including substrate screening and demonstration, oxidation resistance and single catalytic element testing at typical engine inlet conditions: 15 atm, 400C/750F, overall stoichiometric=0.5.

Table 4. Inlet Natural Gas Composition Fed to the Rig for Long Term Testing

Methane	95.50 %
Ethane	2.36 %
propane	0.40 %
nitrogen	0.61 %
CO_2	1.13 %

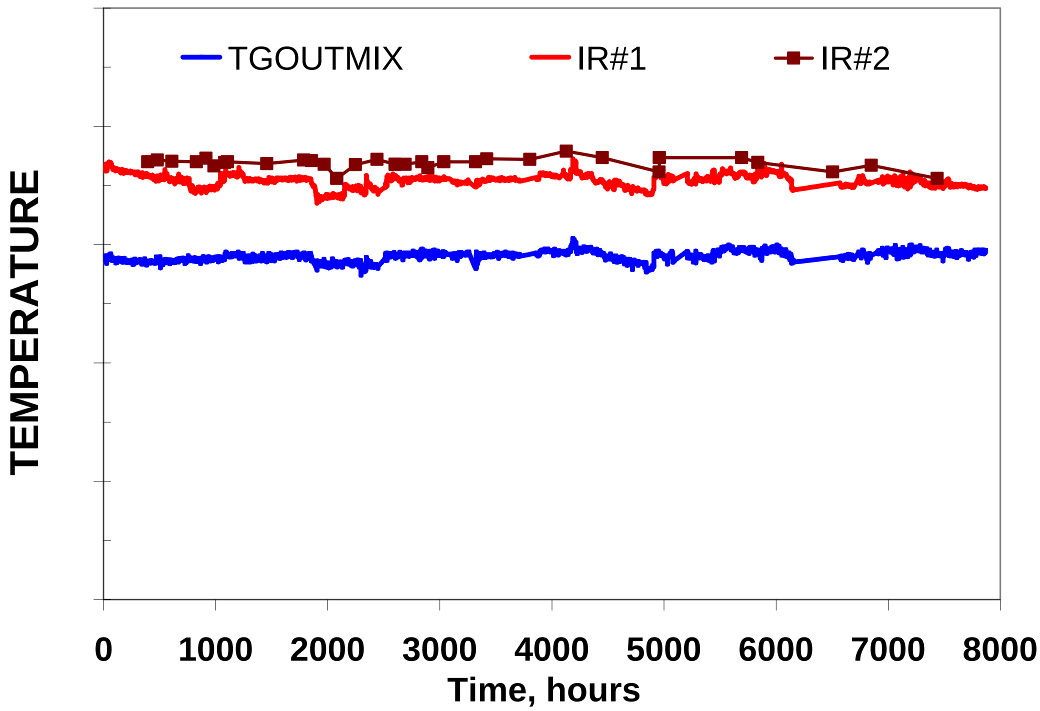


Figure 26. Steady State Operation of Single Catalyst Element. IR#1 and IR#2 are Catalyst Surface Temperatures measured by Infrared Probes, while TGoutmix is the Down-stream Gas Mixtures Temperature using a Thermocouple.

Figure 26 shows steady catalytic performance of a catalytic element for 8000 hours at 15 atm. with inlet air temperatures of 400C/750F. The figure shows a stable exit temperature (TGoutmix) and catalyst temperatures (IR#1, IR#2) over the duration of testing. This testing showed that there was no significant degradation of catalyst performance based on operating temperatures. Light-off temperatures, not plotted, varied only minimally during the test, suggesting only small levels of catalytic changes. Oxygen conversion (not shown) indicates the amount of oxygen reacted with the fuel and is a measure of catalytic performance. The O_2 conversion was measured intermittently during the testing and was stable along the period of testing.

Thermal Cycle Testing

The purpose of thermal cycle testing was to validate the catalyst under severe transient operation such as those in engine "trip cycle". A thermal cycling test rig (Figure 27) was set up by inserting the catalytic element into a high temperature furnace followed by

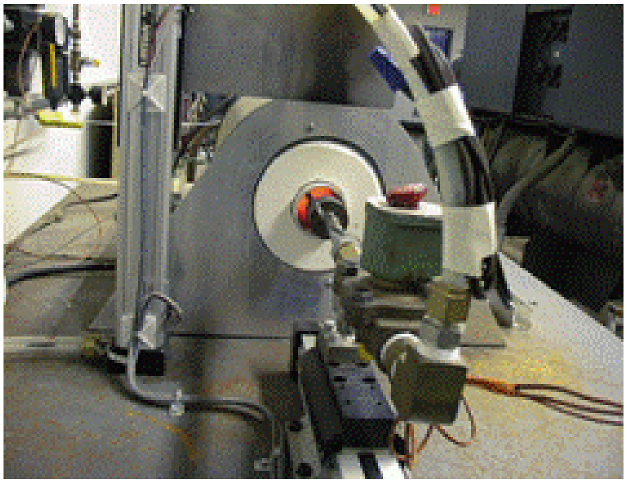


Figure 27. Thermal Cycling Test Rig

removal and sudden quenching using room temperature air. These cycles were comprised of heating samples to peak temperatures of 900C/1650F followed by rapid cooling (200 to 300C/sec (360 to 540^{o}F/sec)) to ambient temperature. These conditions were generated to create an accelerated test (since these peak temperatures are higher than those specified for the catalytic injector in the combustor) and allow the determination of the available margin for operation. It is assumed that 200 engine trips are equivalent to one-year life. Samples were examined after cycling for signs of degradation. The catalyst was found to be maintained for greater than 600 cycles of rapid heat up and cool down, supporting greater than 3 years life performance.

COMMERCIALIZATION OF RICH CATALYTIC TECHNOLOGY FOR MW SCALE ENGINES

In order to further develop the rich catalytic reactor technology for hydrogen based fuels in MW scale engines, Solar and PCI assessed the preferred product for initial development of a catalytically-fired, H_2-fueled industrial gas turbine (Table 5). A range of both technical and commercial considerations are assessed (in shades of grey) with regard to conversion to low NO_x hydrogen operation [15].

First, autoignition and flashback (Row 2, Table 5) will be concerns in the development of any gas turbine fueled with H_2. Choosing a turbine with lower operating pressure and lower combustor inlet temperature has reduced risk, although it may not be the highest efficiency engine design.

Availability of additional space (Row 3, Table 5) will be beneficial in the implementation of alternative burner designs for hydrogen to make development easier. The Taurus 70, Titan 130 and the Mercury 50 were introduced with low emission combustion systems. Thus the existing combustor housings provide more physical space to accommodate the rich catalytic reactors. Similarly, modest increases in combustor volume can be made more easily with these engines. Solar's other low emissions engines have undergone retrofits to integrate the larger low emission combustion systems. Thus these older engines would have tighter space constraints for a catalytically-based H_2 combustion system which would make development more difficult.

Components for smaller engines are less expensive to manufacture (Row 4, Table 5). In addition, these engines are less expensive to operate and require less time and manpower for engine build, installation, and removal. Previous experience in achieving low emissions from an engine will have benefits in reducing emissions from the rich catalytic combustion concept through two mechanisms (Row 5, Table 5). First, the knowledge of how emissions vary with inlet parameters for a particular combustor/liner/turbine configuration will help in predicting the best way of achieving lower emissions with testing. Secondly, as a baseline, the engines are already low emissions, therefore, all effort can focus on the reduction of emissions due to the hydrogen combustion. Ultra-low NO_x technology studies have been conducted at Solar for natural gas fuel. Generally, prior studies have been aligned with specific Solar products. The majority of the ultra-low NO_x work, including catalytic combustion, has been focused on the Taurus 70. Both the Taurus 60 and the Saturn have been the subject of low emissions studies in the past. The Saturn work was a proof-of-concept, using a non-standard engine configuration that is not commercially viable due to cost. With the exception of the Saturn engine, Solar's SoLoNO$_x$ low emissions technology has been integrated into the entire product line. Thus all of the development issues associated with lean-premixed combustion have been addressed and adequately resolved for natural gas fuel over the size range and operating conditions of the candidate engines. The issues associated with ultra-low NO_x rich catalytic combustion and H_2 fueling are similar to those already addressed, although the magnitude of the challenges may be greater. Thus the breadth of the H_2 fuel development effort is well defined.

Table 5: Relative Assessment of Solar Turbines Incorporated Products for Initial Development of a H_2-Fueled, Ultra-Low NOx Gas Turbine (Baird et. al, 2006)

Qualitative Assessment Scale:	Most Favorable		Least Favorable

Selection Criteria	Saturn	Mercury 50	Centaur 40/50	Taurus 60	Taurus 70	Mars 90/100	Titan
Nominal Power (Mw)	1.2	4.2	3.5/4.6	5.5	7.5	9.4/10.7	15
Risk of autoignition/flashback (comb. pressure ratio)	6.6	9.5	10.5	12	17	17	17
Ease of Integration (combustion system space availability)							
Relative Cost of Development Hardware.	$$	$	$	$	$$	$$$	$$$
Prior ultra-low NOx development work							
H2 fuel availability for field test							
Scalable/adaptable to other engines		recup'd engine					
Relative cost impact on current product	$$$	$	$$	$$	$	$	$
Relative market size							
Qualitative Summary Ranking							

There are a limited number of sites that have an adequate supply of a H_2-based fuel for a field test (Row 6, Table 5). Smaller engines, requiring less fuel, will increase the number of candidate sites. There is a high degree of commonality among Solar's simple cycle $SoLoNO_x$ engines (Centaur, Taurus, Mars and Titan) in terms of combustion system design and engine configuration. The catalytic combustion technology is expected to be the most adaptable within this group of engines (Row 7, Table 5). Not having an existing $SoLoNO_x$ variant makes the Saturn an unattractive engine for initial development. The Mercury 50 has a unique configuration due to its recuperated cycle. The high combustor inlet temperature of the Mercury 50 cycle represents a major hurdle in adapting H_2-based combustion technology for that engine. The high inlet temperatures may require unique designs to avoid autoignition and subsequent combustor damage. The relative cost ($/kW) of integrating H_2 combustion capabilities into Solar 's products (Row 8, Table 5) is expected to be lower as the engine size increases. This simply reflects the traditional "economy of scale" effect seen in most engineering projects.

From this analysis (Row 10, Table 5), both Solar and PCI believe that the Taurus 70 (T70) engine stands out as the preferred turbine to use for initial technology development and commercialization. The Taurus 70 represents a good balance of high performance, lower development cost and excellent market acceptance.

FUTURE WORK

Current results show promise for application of the Rich Catalytic Hydrogen catalytic injector technology to hydrogen fueled gas turbine engines, based on single high pressure injector testing indicating low single digit NOx and low acoustics. This offers encouragement as a potential for advancing the DOE's goal of low emission, zero carbon emission gas turbine power plants. The next steps in development will be designing and testing a reduced unmixedness full scale single injector followed by characterization of engine performance under steady and transient load variation (e.g. startup and load shedding). The system will further be scaled for full engine testing and evaluation of catalytic element stability (including effects of contaminants on catalyst) will be performed. Product commercialization including design for production and manufacturing margins will be considered for engine integration.

PAPERS AND PRESENTATIONS

Papers -

Baird, B., Karim, H., Etemad, S., Alavandi, S., Pfefferle, W. C., Smith, K., and Nazeer, W., (2006), "Catalytic Combustion for Ultra-low NOx Hydrogen Turbines," 23rd Annual International Pittsburgh Coal Conference, September 25-28, 2006.

Alavandi, S., Baird, B., Etemad, S., Karim, H., and Pfefferle, W. C., (2009), "Ultra Low NOx MW-Scale Catalytic Hydrogen Combustor For Advanced Coal Power Systems," Proceedings of ICEPAG, February 10-12, 2009.

Baird, B., Etemad, S., Alavandi, S., and Pfefferle, W. C., (2011), "Catalytic Combustion for Ultra-Low NOx Hydrogen Turbines," Proceedings of ICEPAG, February 2011.

Presentations –

Baird, B., Karim, H., Etemad, S., Alavandi, S., Pfefferle, W. C., Smith, K., and Nazeer, W., (2006), "Catalytic Combustion for Ultra-low NOx Hydrogen Turbines," 23rd Annual International Pittsburgh Coal Conference, September 25-28, 2006.

Alavandi, S., Baird, B., Etemad, S., Karim, H., and Pfefferle, W. C., (2009), "Ultra Low NOx MW-Scale Catalytic Hydrogen Combustor For Advanced Coal Power Systems," Proceedings of ICEPAG, February 10-12, 2009.

Etemad, S., Baird, B., Alavandi, S., and Pfefferle, W. C., (2010), "Catalytic Combustion for Ultra-Low NOx Hydrogen Turbines," Proceedings of ICEPAG, February 2010.

Baird, B., Etemad, S., Alavandi, S., and Pfefferle, W. C., (2011), "Catalytic Combustion for Ultra-Low NOx Hydrogen Turbines," Proceedings of ICEPAG, February 2011.

Review Meetings –

Design reviews were held between DOE and PCI in July 2007 and January 2009. The status of the project and the technical results were reviewed.

Patents-

Patent application entitled "Direct Injection Method and Apparatus for Low NOx Combustion of High Hydrogen Fuels" submitted, Patent application #12/001,931.

CONCLUSIONS

Full scale Rich Catalytic Hydrogen (RCH1) injector was developed and successfully tested at Solar Turbines, Incorporated high pressure test facility demonstrating low single digit NOx emissions for hydrogen fuel in the range of 2200F-2750F. This development work was based on initial subscale development for faster turnaround and reduced cost. Subscale testing provided promising results for 42% and 52% H_2 with NOx emissions of less than 2 ppm with improved flame stability.

Catalytic element reactor testing for substrate oxidation, thermal cyclic reactor testing to simulate start-stop operation in a gas turbine environment and steady state 15 atm. operation testing were performed successfully. The testing demonstrated stable and robust catalytic element component life for gas turbine conditions.

Future work in the program will apply lessons learned (improvement of fuel distribution) to further reduce NOx. Additional full scale injectors will be fabricated to demonstrate this improved performance in single injector high pressure rig testing. In addition, engine integration with gas turbine manufacturers to test in high pressure engine environment will be conducted.

This technology further offers an alternative approach for achieving ultra-low NOx emissions and improved cycle efficiency for hydrogen turbines. The technology's capability to operate with high stability and avoid flashback/early autoignition issues provides operating flexibility and the potential for avoiding the need to derate firing temperatures for autoignition or NOx reasons. The ability to minimize diluent requirements for a given NOx also improves cycle efficiency, and may prove attractive in world markets that are not seeking low single digit NOx but would value moderately low NOx at significantly reduced diluent costs. The fuel flexibility by virtue of rich catalytic combustion allows the same combustion system to be used for a variety of applications, including hydrogen, syngas, refinery fuel gas, other process gases, biogas, blast furnace gas, associated gas, and natural gas, all of which have been tested successfully at least at the subscale level.

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LIST OF ACRONYMS AND ABBREVIATIONS

BOT	Burner Outlet Temperature
CCPI	Clean Coal Power Initiative
CCS	Carbon Capture and Sequestration
CFD	Computational Fluid Dynamics
CO2	Carbon Dioxide
CO	Carbon Monoxide
DOE	Department of Energy
DLN	Dry Low NO_x
GC	Gas Chromatograph
H2	Hydrogen
IR	Infra Red
IGCC	Integrated Gasification Combined Cycle
LBO	Lean Blow-Out
LP	Lean Premixed
MW	Megawatt
N2	Nitrogen
NETL	National Energy Technology Laboratory
NO_x	Oxides of Nitrogen
OEM	Original Equipment Manufacturer
PCI	Precision Combustion, Inc.
PPM	Parts Per Million
R&D	Research and Development
RCH	Rich Catalytic Hydrogen
RCL®	Rich Catalytic Lean-burn
RMS	Root Mean Square
SCR	Selective Catalytic Reduction
SEM	Scanning Electron Microscope
SoLoNOx	Solar Low NOx
T70	Taurus 70
TC	Thermocouple
WGS	Water Gas Shift

GRAPHICAL MATERIALS LIST(S)