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COMMISSION

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Environmentally Preferred Advanced Generation

Catalytic Stabilizer for Industrial
Gas Turbines

FEASIBILITY ANALYSIS

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PREFACE

The Public Interest Energy Research (PIER) Program supports public interest energy research and development that will help improve the quality of life in California by bringing environmentally safe, affordable and reliable energy services and products to the marketplace.

The PIER Program, managed by the California Energy Commission (Commission), annually awards up to \$62 million of which \$2 million/year is allocated to the Energy Innovation Small Grant (EISG) Program for grants. The EISG Program is administered by the San Diego State University Foundation under contract to the California State University, which is under contract to the Commission.

The EISG Program conducts four solicitations a year and awards grants up to \$75,000 for promising proof-of-concept energy research.

PIER funding efforts are focused on the following six RD&D program areas:

- Residential and Commercial Building End-Use Energy Efficiency
- Industrial/Agricultural/Water End-Use Energy Efficiency
- Renewable Energy Technologies
- Environmentally-Preferred Advanced Generation
- Energy-Related Environmental Research
- Strategic Energy Research

The EISG Program Administrator is required by contract to generate and deliver to the Commission a Feasibility Analysis Report (FAR) on all completed grant projects. The purpose of the FAR is to provide a concise summary and independent assessment of the grant project using the Stages and Gates methodology in order to provide the Commission and the general public with information that would assist in making follow-on funding decisions (as presented in the Independent Assessment section).

The FAR is organized into the following sections:

- Executive Summary
- Stages and Gates Methodology
- Independent Assessment
- Appendices
 - Appendix A: Final Report (under separate cover)
 - Appendix B: Awardee Rebuttal to Independent Assessment (Awardee option)

For more information on the EISG Program or to download a copy of the FAR, please visit the EISG program page on the Commission's Web site at:

<http://www.energy.ca.gov/research/innovations>

or contact the EISG Program Administrator at (619) 594-1049 or email

eisgp@energy.state.ca.us.

For more information on the overall PIER Program, please visit the Commission's Web site at <http://www.energy.ca.gov/research/index.html>.

Catalytic Stabilizer for Industrial Gas Turbines

EISG Grant # 99-26

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Introduction

Air emissions from combustion turbines used in mechanical and power generating applications are a major issue when seeking approval for installation. Oxides of nitrogen, NO_x, are major constituents of those emissions. Gas turbine manufacturers have developed dry, low NO_x (DLN) technology to reduce NO_x emissions from over 200 parts per million to a range of 9 to 25 parts per million (ppm). These levels of emissions are achieved without the use of water or steam injection, or the use of selective catalytic reduction (SCR) devices in the exhaust. When SCR technology is combined with DLN technology the NO_x emissions are reduced to the range of 2.5 to 5 ppm. This is the most common technology suite for large (>50MW) combustion turbines. Unfortunately SCR technology is very expensive making its use on the smaller combustion turbines uncommon. Smaller combustion turbines serve an important purpose in California's overall energy strategy when they are used in combined heat and power applications. In these installations over 70% of the energy of the fuel is put to productive use.

Researchers have determined the major reasons that DLN technology is limited to 9 ppm NO_x. The primary reason is the use of a pilot burner to stabilize combustion over all operating conditions (i.e. startup, part load, full-load, and transients.) Without the pilot burner the engine could cease operation during various engine exercises. The pilot burner also reduces combustor "rumble", a vibration that can destroy an engine in a relatively short period of time. Although DLN pilots commonly burn only 2-5% of the fuel at full load, they are still the source of about 50% of the NO_x emissions in a DLN burner. If the pilot burner emissions could be eliminated or reduced, a DLN burner could achieve NO_x levels of less than 5 ppm.

This project tested the feasibility of using a catalytic stabilizer to replace the pilot burner in a regular DLN burner. The concept is to install the catalytic stabilizer in the fuel injectors (there may be 8 to 18 injectors in one DLN burner assembly). While catalytic combustion techniques have been under test for decades, those concepts replaced the entire DLN system with a catalytic system. The novelty of this concept is the use of catalytic technology only for the pilot burner, a small part of the overall combustion assembly. Full catalytic systems are large, often requiring extensive redesign of the engine casings. The catalytic stabilizer used in this project was built into an existing fuel injector without having to redesign major engine components. If this technology proves to be acceptable to the turbine manufacturers it could be readily retrofitted into combustion turbines already in the field. The use of the catalytic stabilizer could reduce DLN emissions to less than 5ppm NO_x.

The catalytic reactor used in this study can begin and sustain operation at the relatively low outlet temperatures typical of today's combustion turbine compressors. That is the temperature of the air that after being compressed enters the combustion assembly. Operation of catalytic

devices at such low temperatures (as low as 671° F) is unusual and a key feature that makes this concept work.

Objectives

The goal of this project was to determine the feasibility of building a catalytic stabilizer in place of the pilot burner in a standard engine fuel injector. The following project objectives were established:

1. Design the catalytic stabilizer to fit into an existing fuel injector for a Taurus 70 engine (Solar Turbines Inc.).
2. Determine if the catalytic stabilizer can begin and sustain fuel injector operations at the relatively low temperatures of the engine compressor outlet air. (Is a pre-burner required for the catalytic system?)
3. Achieve NO_x emissions of less than 5 ppm for the Taurus fuel injector with the catalytic stabilizer replacing the standard pilot burner.
4. Determine if the catalytic stabilizer will allow leaner operation of the fuel injector.
5. Evaluate the operation of the catalytic stabilizer at a number of standard engine operating conditions.

Outcomes

1. The catalytic stabilizer fits into the existing Taurus 70 engine without major modification to the injector.
2. No pre-burner is required for the operation of the catalytic stabilizer. The catalytic stabilizer lit off at temperature around 355°C (671° F) during high pressure testing of the catalytic stabilizer – which is lower than the 435°C combustor inlet temperature.
3. The integrated catalytic stabilizer and the Taurus 70-injector assembly delivered NO_x and CO emissions below 5 ppm.
4. The catalytic stabilizer allowed leaner operation of the injector.
5. The catalytic stabilizer demonstrated variable-load operability. In addition, low emissions were obtained at both 100% and 50% load conditions.

Conclusions

The catalytic stabilizer was built into two Taurus 70 production fuel injectors. The modified injectors were operated at both ambient conditions and simulated engine pressures. Data supported the key objectives of the program. The catalytic stabilizer could be designed to fit into the space envelope allowed by the Taurus 70 fuel injector. It did begin and sustain operation without the use of a pre-burner. And low emissions were achieved.

1. There are potential cost advantages to this technology since major modifications to the injector were not necessary.
2. The modified fuel injector could begin and sustain operation without a pre-burner. The tests showed that no pre-burner is required for the operation of the catalytic stabilizer from half load to base load conditions for the Taurus 70 fuel injector. It also operated free from auto-ignition and flashback over a wide range of stabilizer fuel-air ratios and airflows. Auto-ignition and flashback can be major operational problems with fuel injectors resulting in severe engine damage.
3. The project successfully demonstrated NO_x and CO emissions of less than 5 ppm at Taurus 70 baseload (high pressure) conditions for a single injector.

4. The project demonstrated that leaner operation in the upstream end of the combustor can be achieved by the catalytic stabilizer. Additionally, the results show that the catalytic stabilized fuel injector can achieve low emissions at lower inlet temperatures than those required for a "conventional" catalytic combustor.

The project demonstrated that sufficient catalytic activity can be achieved by both baseload and half load conditions to achieve stable combustion.

After this project was completed the California Air Resources Board (CARB) lowered the limits on regulated emissions, including NO_x. This project achieved the targets that were based on regulations existing at the time of the proposal, as well as satisfied the new regulations with the effective date of 2003. However, the PA is concerned that the approach of this project will not provide an adequate operational safety margin in the emissions levels to satisfy the newly imposed regulations with the effective date of 2007. While this approach may find a broad world market with huge reductions in emissions world wide, it does not appear to be applicable in California in its current configuration.

Benefits to California

This project has contributed to the Public Interest Energy Research (PIER) program objectives for "Environmentally Preferred Advanced Generation" by advancing technology that will reduce emissions from combustion turbines typically deployed in mechanical and distributed power generation applications. Specific benefits are:

1. Improved air quality with cost savings. The catalytic stabilized fuel injector provides relatively low NO_x levels at a low cost. Customers will ask the manufacturer of the gas turbine to guarantee air emissions. At this time the manufacturers have not indicated where they will guarantee an engine with catalytic stabilizers. If the guarantee level is below the level set by the California Air Resources Board for distributed generation, the catalytic stabilizer could be used throughout California to meet those regulations at reasonable costs.
2. Elimination of the use of ammonia to achieve low emissions. Ammonia is not used with the catalytic stabilizer. If gas turbine operators must install an SCR to meet low emission requirements, a measurable amount of ammonia would "slip" into the atmosphere.
3. Enhanced distributed generation. Californians will select gas turbine distributed generation more readily if the manufacturer can guarantee emission levels meeting the 2007 regulations. This will enhance the deployment of distributed generation and cogeneration within the state.
4. Improved air quality from retrofit. Manufacturers can apply the catalytic stabilizer technology to selected existing engines during an engine overhaul and upgrade without major modifications to the engine. These retrofits will further enhance the air quality of California.

Recommendations

This grant proved the feasibility of replacing a pilot burner in a DLN combustor with a catalytic stabilizer. All tests were done with single injectors in test rigs. In subsequent research the development team should reconfigure the technology to satisfy the 2007 CARB emission regulations, install it into an actual engine and develop the control algorithms for engine operation. Engineers should measure emissions levels and compare them with the 2007 CARB regulations for distributed generation. Engineers should also determine reliability and lifetime of the catalytic stabilized device. The provider of the catalytic stabilized device and turbine

manufacturer must determine the costs to manufacture and install these devices and compare those costs to the costs of competing technologies.

The PA determined that the data generated during the initial grant was sufficiently complete and successful to recommend taking this technology to the next step of development. To meet the 2007 CARB regulations the catalytic stabilizer would have to be reconfigured. Though significant, reconfiguration should not be a show stopper. Continued cooperation with a major gas turbine manufacturer will accelerate the transfer of the technology into the marketplace. This technology will be of the greatest benefit to engines of less than 50 MW.

Stages and Gates Methodology

The California Energy Commission utilizes a stages and gates methodology for assessing a project’s level of development and for making project management decisions. For research and development projects to be successful they need to address several key activities in a coordinated fashion as they progress through the various stages of development. The activities of the stages and gates process are typically tailored to fit a specific industry and in the case of PIER the activities were tailored to be appropriate for a publicly funded energy research and development program. In total there are seven types of activities that are tracked across eight stages of development as represented in the matrix below.

Development Stage/Activity Matrix

	Stage 1	Stage 2	Stage 3	Stage 4	Stage 5	Stage 6	Stage 7	Stage 8
Activity 1								
Activity 2								
Activity 3								
Activity 4								
Activity 5								
Activity 6								
Activity 7								

A description the PIER Stages and Gates approach may be found under "Active Award Document Resources" at: <http://www.energy.ca.gov/research/innovations> and are summarized here.

As the matrix implies, as a project progresses through the stages of development, the work activities associated with each stage needs to be advanced in a coordinated fashion. The EISG program primarily targets projects that seek to complete Stage 3 activities with the highest priority given to establishing technical feasibility. Shaded cells in the matrix above require no activity, assuming prior stage activity has been completed. The development stages and development activities are identified below.

Development Stages:	Development Activities:
Stage 1: Idea Generation & Work Statement Development	Activity 1: Marketing / Connection to Market
Stage 2: Technical and Market Analysis	Activity 2: Engineering / Technical
Stage 3: Research & Bench Scale Testing	Activity 3: Legal / Contractual
Stage 4: Technology Development and Field Experiments	Activity 4: Environmental, Safety, and Other Risk Assessments / Quality Plans
Stage 5: Product Development and Field Testing	Activity 5: Strategic Planning / PIER Fit - Critical Path Analysis
Stage 6: Demonstration and Full-Scale Testing	Activity 6: Production Readiness / Commercialization
Stage 7: Market Transformation	Activity 7: Public Benefits / Cost
Stage 8: Commercialization	

Independent Assessment

For the research under evaluation, the Program Administrator assessed the level of development for each activity tracked by the Stages and Gates methodology. This assessment is summarized in the Development Assessment Matrix below. Shaded bars are used to represent the assessed level of development for each activity as related to the development stages. Our assessment is based entirely on the information provided in the course of this project, and the final report. Hence it is only accurate to the extent that all current and past work related to the development activities are reported.

Development Assessment Matrix

Stages	1 Idea Generation	2 Technical & Market Analysis	3 Research	4 Technology Develop- ment	5 Product Develop- ment	6 Demon- stration	7 Market Transfor- mation	8 Commer- cialization
Marketing								
Engineering / Technical								
Legal/ Contractual								
Risk Assess/ Quality Plans								
Strategic								
Production. Readiness/ Cost								

The Program Administrator’s assessment was based on the following supporting details:

Marketing/Connection to the Market. The project has submitted a Preliminary Business Plan detailing the product development to market.

Engineering/Technical. This project successfully demonstrated NOx and CO emissions of less than 5 ppm at 50 and 100% power level conditions for a Taurus 70 gas turbine. The researcher used a simulator when testing the single injector. The tests proved the technical feasibility of the innovation.

Legal/Contractual. Intellectual property related to the core technology is protected by patent.

Environmental, Safety, Risk Assessments/ Quality Plans. Initial drafts of the following Quality Plans are needed prior to initiation of Stage 4 development activity; Reliability Analysis, Failure Mode Analysis, Manufacturability, Cost and Maintainability Analyses, Hazard Analysis, Coordinated Test Plan, and Product Safety.

Strategic. This product has no known critical dependencies on other projects under development by PIER or elsewhere.

Production Readiness/Commercialization. Prior to commercialization of this technology, actual full-up engine testing must be preformed. Full engine testing is required to determine emission level compliance and to prove reliability of the complete engine with the catalytic stabilizers. The researcher has indicated that this type of testing is planned at a Solar Turbine test

facility in the year 2002. Engineers must develop control algorithms and determine engine emissions levels at that time.

Public Benefits. PIER research public benefits are defined as follows:

- Reduced environmental impacts of the California electricity supply or transmission or distribution system.
- Increased public safety of the California electricity system
- Increased reliability of the California electricity system
- Increased affordability of electricity in California

The primary public benefit offered by the proposed technology is more affordable electrical energy in California. This will be accomplished by reducing the cost of emission regulation compliance of power generated by more economically attractive distributed generation technologies.

Program Administrator Assessment:

After taking into consideration: (a) research findings in the grant project, (b) overall development status as determined by stages and gates and (c) relevance of the technology to California and the PIER program, the Program Administrator has determined that the proposed technology should be considered for follow on funding within the PIER program.

Receiving follow-on funding ultimately depends upon: (a) availability of funds, (b) submission of a proposal in response to an invitation or solicitation and (c) successful evaluation of the proposal.

Appendix A: Final Report (under separate cover)

Appendix B: Awardee Rebuttal to Independent Assessment (none submitted)

**ENERGY INNOVATIONS SMALL GRANT
(EISG) PROGRAM**

FINAL REPORT

CATALYTIC STABILIZER FOR INDUSTRIAL GAS TURBINES

EISG AWARDEE

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Inquires related to this final report should be directed to the Awardee (see contact information on cover page) or the EISG Program Administrator at (619) 594-1049 or email eisgp@energy.state.ca.us.

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Abstract

The purpose of this project was to test the feasibility of an ultra-low NO_x (less than 5 ppm) catalytic stabilizer for use in sustaining lean combustion of natural gas in both current and advanced industrial Dry Low NO_x (DLN) gas turbines. More specifically, this catalytic stabilizer will replace existing pilot burners that create excessive NO_x emissions.

This project involved the cooperation of Solar Turbines who is interested in exploring the use of this technology for its advanced industrial engine. PCI developed the catalytic stabilizer technology while Solar provided test support as well as prototype Taurus 70 injectors at no cost to the program.

After the design and analysis of several different stabilizer candidates, prototype configurations were fabricated to fit into the existing geometry of the Taurus 70 injector without major modification to the engine. First, the catalytic reactors for the stabilizer were separately tested for robustness and performance at atmospheric pressure at PCI. Once these tests were completed, the integrated assembly of the catalytic stabilizer and the injector was tested at atmospheric pressure at PCI for robustness, flame stability, and emissions. After satisfactory completion of these tests the integrated assembly was tested over several days at Solar Turbines' high pressure facility. During this high pressure testing, the integrated assembly displayed excellent robustness with no occurrences of either flashback or auto ignition. At the Taurus 70 baseload and half load conditions, the catalytic stabilizer operated without a preburner for natural gas, while producing low emissions. Most significantly, at baseload conditions, NO_x and CO emissions were less than 5 ppm while showing no signs of combustion-induced pressure oscillations, thereby demonstrating the proof of concept for such catalytic stabilizer technology. The next development steps, outside of the CEC Pier Program, will be to test the catalytic stabilizer technology in a full-scale atmospheric-pressure engine test rig followed by actual engine testing in 2002.

Key Words:

Pilot, catalytic stabilizer, catalytic pilot, industrial gas turbines

Executive Summary

Introduction

Currently, Dry Low NO_x (DLN) machines use pilot burners to stabilize combustion at all operating conditions (i.e. startup, part loads, baseload and transients). Although DLN pilots commonly burn only 2-5% of the fuel at baseload, they are still the source of significant NO_x emissions (on the order of 50% or more of the total NO_x) preventing the achievement of low emissions (less than 5ppm) for such DLN engines. This fact is crucial because increasing environmental concerns are challenging the U.S. power generation gas turbine industry to reduce NO_x emissions below those achieved by advanced DLN technology.

This project tested the feasibility of a novel concept for an ultra-low NO_x (less than 5 ppm) catalytic stabilizer to replace existing high-NO_x pilot burners. The expectation is that this catalytic stabilizer will help reduce emissions from industrial gas turbines while performing the same combustor stabilizing functions at all operating conditions. The proposed stabilizer replaces the highest NO_x-producing component (i.e. the conventional pilot) of a DLN system with an ultra-low NO_x lean catalytic stabilizer. This all but eliminates NO_x emissions formerly arising from the DLN pilot while allowing the catalytic stabilizer to be used more aggressively (i.e. directing a larger percentage of the total fuel to it), in turn minimizing the equivalence ratio of the main combustion zone and thereby further reducing overall NO_x emissions.

The catalytic reactor – which is the core component of the catalytic stabilizer – is based on Precision Combustion Inc.'s proprietary reactor technology. This reactor technology can operate on natural gas at the relatively low exit temperatures of today's industrial gas turbine compressors.

Objectives

1. Determine whether PCI's catalytic stabilizer technology will fit into Solar's existing Taurus 70 engine envelope without major modification.
2. Determine whether a pre-burner is required for catalytic stabilizer operation with natural gas.
3. Determine whether the integrated assembly of catalytic stabilizer and injector can deliver NO_x and CO emissions < 5 ppm for operation on natural gas.
4. Determine whether the catalytic stabilizer will allow leaner operation of injector.
5. Assess the operation of the catalytic stabilizer at all the standard engine operating conditions.

Outcome

1. The catalytic stabilizer fits into the existing Taurus 70 engine without major modification to the injector.
2. No preburner is required for the operation of the catalytic stabilizer with natural gas. The catalytic stabilizer lit off at temperature around 355°C during high pressure testing of the catalytic stabilizer. The light off temperature is lower than the compressor discharge temperature of 435°C at baseload condition of T70 engine.

3. The integrated catalytic stabilizer and the Taurus 70 injector assembly delivered NO_x and CO emissions below 5 ppm for operation on natural gas.
4. The catalytic stabilizer allowed leaner operation of the injector.
5. The catalytic stabilizer demonstrated variable-load operability. In addition, low emissions were obtained at both 100% and 50% load conditions.

Conclusions

The test results support the continued development of ultra-low NO_x catalytic stabilizer technology for industrial gas turbines and validate potential operational benefits of this technology in a power generation gas turbine. Specifically:

1. We demonstrated that today's PCI's catalytic stabilizer technology will fit into an existing engine envelope without major modification to the engine (in fact, two different catalytic stabilizer configurations were fabricated and integrated with two Solar Taurus 70 injectors without major modifications).
2. This project demonstrated that the catalytic stabilizer technology is very robust. During several days of testing, the catalytic reactor was free from auto-ignition and flashback over a wide range of stabilizer fuel-air ratios and airflows.
3. The tests showed that no preburner is required for the operation of the catalytic stabilizer with natural gas from half load to base load operation of the Taurus 70 machine. The catalytic reactor maintained sufficient activity during testing at inlet air temperatures of 430°C (full load compressor discharge temperature) and 385°C (half load compressor discharge temperature).
4. The project demonstrated that sufficient catalytic activity may be achieved at both baseload and half load to maintain stable combustion.
5. The project demonstrated that leaner operation in the front end of the combustor may be achieved with the catalytic stabilizer. The results show that the catalytic stabilizer can achieve low emissions at a front end temperature of 3050°F at baseload. This front end temperature at baseload is lower than the current baseload front end temperature of the Taurus 70 engines. Lower front end temperature signifies leaner combustion.
6. The project successfully demonstrated NO_x and CO emissions of less than 5 ppm for operation with natural gas at Taurus 70 baseload conditions for a single injector, tested at high pressure.

Recommendations

The next step in developing this technology is performance testing of the catalytic stabilizer technology in a Taurus 70 engine. To accomplish this, twelve (12) Taurus 70 injectors must each be equipped with a PCI catalytic stabilizers. These twelve catalytically-stabilized injectors will be installed in a backside-cooled annular liner and engine tested as the final proof-of-concept for this technology. Proof-of-concept at engine level is required for commercial consideration and acceptance by the gas turbine manufacturers. The following is a list of the remaining necessary tasks leading to the commercialization of the catalytic stabilizer technology in an existing Taurus 70 engine:

1. Mechanical analysis of the catalytic stabilizer: An analysis determining the stress caused by temperature gradients will need to be performed on the relevant components of the stabilizer. This analysis will identify any components that are at risk of failing before a total operational life of 8000 hrs is reached (a minimum life of 8000 hrs is required for all components). If any such components are considered at risk, their design will be modified accordingly.
2. Design simplification of the catalytic stabilizer: The mechanical analysis will also identify any manufacturability issues of components. Costs that might be considered prohibitive to the fabrication of cost competitive devices will be addressed. In addition, this analysis is intended to enable easier manufacturing of larger quantities of components.
3. Establish operating procedure for startup and steady state operation of the catalytic stabilizer in the Taurus 70 engine: Based on the single injector tests of the current project, the assembly of the Solar's T70 injector and catalytic pilot functions well at base load and 50% load for the Taurus 70 engine. After testing steady-state conditions at other loads in the single injector rig, PCI will need to determine the optimum fuel splits (e.g. stabilizer equivalence ratio, injector equivalence ratio and % of total fuel to stabilizer) and overall operation of the stabilizer/injector assembly over the entire startup schedule.
4. Establish control procedures for the modified Taurus 70 combustor: Based on the results from (3) above, the method and scheme for controlling fuel flows may be modified and optimized (e.g. controls software, control valves & fuel delivery system).
5. Fabricate 12 injectors and 12 stabilizers: A new set of twelve (12) catalytic stabilizers and injectors need to be fabricated – along with a backside cooled annular liner.
6. Perform atmospheric pressure rig testing: Atmospheric pressure rig testing of the twelve-injector/stabilizer system.
7. Perform Engine testing: Conduct engine testing at Solar Turbines.
8. Perform Cost analysis: Cost analysis for the manufacturing of catalytic stabilizers will need to be performed.

Benefits to California

This project has contributed to the Public Interest Energy Research (PIER) program objective of introducing clean and efficient combustion technology into the California economy. Through close involvement with Solar Turbines, a California based industrial gas turbine manufacturer, PCI has demonstrated emission benefits, raising Solar's interest in an engine test in 2002. This supports our acceleration toward commercialization possibilities in Solar's Taurus 70 engine. In doing so, PCI's catalytic stabilizer technology will give California such benefits as

1. Air quality with cost savings: The concept allows significant NO_x emissions improvement with respect to the existing state-of-the-art industrial turbine combustors. The additional cost of this combustion system enhancement per engine is expected to be relatively low, and could help power suppliers avoid significant treatment costs – as well as increase the life of components associated with DLN

technology. The ease of retrofit within a DLN combustor geometry may permit wider acceptance and installation in existing high emission engines. The combination of lower emissions (competitive with current emissions standards for large utility installations) in smaller power generation engines provides more flexibility in citing of production capacity facilitating even more opportunities for improvements in California air quality through both emissions savings and economic incentive to displace/replace higher emission products.

2. *Energy efficiency*: The catalytic stabilizer offers a significant increase in energy efficiency compared with aftertreatment and encourages replacement of older, less-efficient sources with modern, higher efficiency turbines.
3. *Global warming*: Natural gas combustion produces less CO₂ than alternative fossil fuel combustion. Furthermore, this technology may eliminate the need for SCR aftertreatment – treatment that can produce problematic ammonia slip thereby contributing to greenhouse gases. So, by promoting an increased gas turbine share of the power generation market, catalytic stabilizer technology helps advance California efforts to limit greenhouse gas emissions.
4. *Benefit to California gas turbine industry*: Currently, California industrial gas turbine manufacturers are losing world market share in the face of increasing European and Japanese competitive pressures (price and government subsidy). In addition tightening emissions regulations in both Japan and the U.S. virtually mandate SCR use. The industrial sized gas turbines (Solar Taurus 70) are not generally large enough to support the large additional capital costs associated with an after treatment technology such as SCR. Thus as the regulations tighten, only the very large combined cycle gas turbines get built because they can spread the SCR investment over more installed production capacity. Unless industrial sized gas turbines develop single digit NO_x technology, they face a long-term threat of being displaced by larger, more efficient 3 and 9 ppm NO_x-capable combined cycle gas turbines. Catalytic stabilizer technology with DLN offers a chance to reverse this trend for California based and other US industrial gas turbine manufacturers.
5. *Retrofit Potential*: In addition to equipping new gas turbine engines with reliable, ultra-Low NO_x catalytic technology, already-existing engines may also be readily retrofitted with this technology without major modification to the engine. This ability to retrofit current engines provides California with significant opportunities to economically meet ever-increasing environmental legislation.

Introduction

The purpose of the project was to demonstrate a proof of concept of a catalytic stabilizer for Solar Turbines' industrial engines. The objective was to replace the partially-premixed, pilots used in Solar's advanced and current industrial Dry Low NO_x (DLN) engines with a catalytic stabilizer from Precision Combustion Inc. to achieve low emissions. This project primarily supports the Environmentally Preferred Advanced Generation PIER subject area.

To achieve minimized NO_x emissions with adequate combustion stability, advanced DLN systems typically use a high fuel/air ratio combustion zone to stabilize the overall lean flame and achieve engine turndown of a combustor. In this approach, a lean reaction zone (which is very close to the lean limit) is stabilized – or "piloted" – by a relatively stable reaction zone (e.g. with a higher global fuel/air ratio or increased unmixedness in the stabilizing zone). In addition to providing stability at normal baseload operation, the pilot also provides similar stability for engine start-up, load ramping and fuel transfer operations. In such a piloted system, the high stability pilot zone burns only a small fraction of the fuel (e.g. 5-10%) but contributes a high fraction of NO_x (e.g. 50% or more of the total NO_x emissions). Though this type of fuel staging requires significant design skill – the payoff is large: the pilot burner or primary stage allows advanced DLN combustors to generally operate close to the overall lean limit, resulting in relatively low overall NO_x, e.g. 15 - 25 ppm. Nevertheless, dependence on a high stability, high NO_x pilot zone is proving to be a barrier to further NO_x reductions.

The problem arises from the challenge faced by the U.S. power generation gas turbine industry to achieve lower NO_x emissions than even advanced DLN technology can achieve – a challenge motivated by increasingly strict environmental regulations. This is leading to a rapidly increasing requirement for BACT aftertreatment systems such as SCR and SCONO_xTM for new – and even existing – power generation machines. Such requirements raise capital and operating costs while impairing efficiency. In the case of utility-sized machines, the result is experienced in higher energy costs being passed on the consumer. In the case of distributed power machines (industrial gas turbines) in the less-than-25 MW range (especially less than 10 MW), the result usually makes such projects economically unfeasible, thereby preventing industrial use of a highly efficient power source. The economic cost is likely to climb much more as aftertreatment becomes required for older machines upon upgrade, adding substantially to the cost of upgrade and potentially freezing in place inefficient older models.

The ultra-low NO_x catalytic stabilizer demonstrated during this project supports the commercial potential to support replacement of existing high-NO_x pilot burners now used for start-up, turndown and stabilization of combustion in Dry Low NO_x (DLN) industrial engines. PCI's catalytic stabilizer replaces this highest NO_x emissions component of a DLN system with an ultra-low NO_x lean catalytic burner also capable of minimizing the lean limit of the main combustion zone. This all but eliminates NO_x emissions from the pilot while allowing the stabilizer to be used more aggressively (i.e. directing more of the total fuel to the stabilizer) in minimizing main combustion zone emissions (i.e. by allowing leaner main zone operation). The enhanced stability of the catalytic stabilizer itself provides an operational capacity for reducing overall combustion zone acoustics at leaner conditions and improving turndown.

The catalytic reactor – which is the core component of the catalytic stabilizer – is based upon Precision Combustion Inc.’s patented reactor technology. This reactor technology can operate at the relatively low inlet temperatures existing in gas turbines.

Shown in Figure 1 is a schematic of the premixed catalytic stabilizer and the main injector used in Solar’s engines. The main fuel/air injector has its own swirler, which interacts with the catalytic stabilizer flow. The exit of the stabilizer may be specially tailored to produce favorable aerodynamics for this main/stabilizer interaction. The catalytic reactor shown in the center for the stabilizer replaces diffusion flame tube and fits into the existing combustor configuration without modification to the surrounding combustor geometry. A Taurus 70 engine consists of 12 such injector/stabilizer assemblies arranged in an annular fashion around an annular central liner.

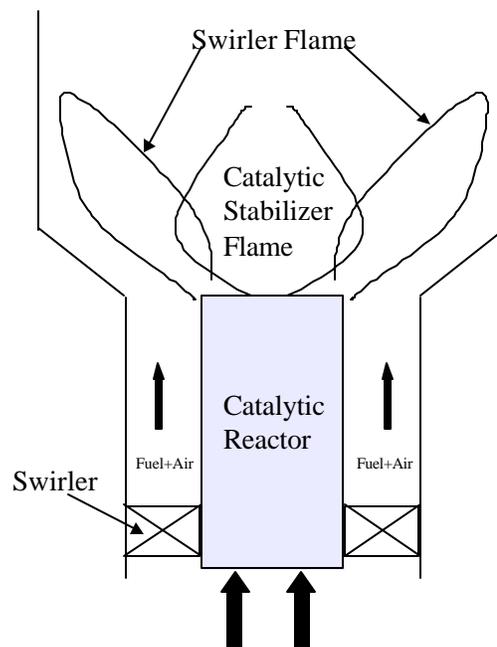


Figure 1:- Schematic showing the interaction between the premixed catalytic stabilizer and main injector

Project Objectives

The project objectives were similar to what had been specified in the proposal. Some of the objectives were either further tightened from the proposal or a quantitative value for a parameter was finalized which may have not been present in the initial proposal.

- Determine whether PCI’s catalytic stabilizer technology will fit into existing Solar’s Taurus 70 engine envelope without major modification.
- Determine whether a pre-burner is required for catalytic stabilizer operation on natural gas. In other words, assess whether PCI’s catalytic reactor technology used for catalytic stabilizer can be operated on natural gas at baseload temperature of 430°C for Taurus 70 engine. The temperature limit of 430°C is the compressor discharge temperature of the Taurus 70 engine

at baseload. The catalytic stabilizer must be active at that temperature if it is not to require a preburner.

- Determine whether the integrated assembly of the stabilizer/injector can deliver NO_x and CO emissions <5 ppm during operation on natural gas. The emissions criterion of NO_x emission <5 ppm set forth for the project is more restrictive than the NO_x criterion of <10 ppm proposed in our application. The reason for tightening the NO_x criteria was to provide the engine manufacturer with enough confidence to guarantee 9 ppm NO_x to its customer.
- Determine whether the catalytic stabilizer will allow leaner operation of the injector. The objective was to lower the current head-end temperature of the Taurus 70 combustor (note that a lower head-end temperature signifies leaner combustion).
- Assess the ability of the catalytic stabilizer to start-up the engine and operate at all loads. Emissions, however, are normally guaranteed from baseload down to 50% load in most engine applications.

Project Approach

The catalytic pilot/catalytic stabilizer development effort at PCI has been conducted under funding from CEC and DOE. To accomplish the project objectives, the following tasks were performed, with the second configuration of the catalytic stabilizer (mentioned below) being developed, fabricated, and tested under CEC funding.

Task 1. Establish engine and stabilizer test conditions as well as the allowable physical envelope

The primary goal of this task was to jointly (PCI and Solar Turbines) identify which Solar engine frame will benefit the most from PCI's catalytic stabilizer technology and then establish the physical dimensions required of the stabilizer in order to fit into the current injector. Both PCI and Solar mutually agreed to focus the catalytic stabilizer development on Solar's Taurus 70 engine. After identification of the engine, PCI received the load table for a typical Taurus70 engine (including a schedule for inlet temperature, pressure, air flow and fuel flow rates at different loads) as well as detailed drawings of a Taurus 70 engine. Table 1 shows the compressor discharge temperature and pressure (inlet conditions to the combustor), and pressure drop for the Taurus 70 machine (Hoshizaki, 1997)

Table 1- NOMINAL TAURUS 70 COMBUSTOR OPERATING CONDITIONS

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%

This information allowed PCI to calculate flow functions for the engine and atmospheric pressure testing at PCI (this flow function must be maintained in order to maintain the proper Mach number within the combustor). During testing at atmospheric pressure under Task 5, all

the conditions shown in Table 1 was maintained except the inlet pressure. As part of Task 1, PCI also estimated the amount of fuel and air flow rates required for the catalytic stabilizer and how these might be achieved without major modification to the injector. A larger fraction of both fuel and air would be used for the catalytic stabilizer than what were used by the standard pilot. Table 2 shows the percentage air-splits in the different section of the combustor for both the modified T70 injector with catalytic pilot and the Standard T70 injector. We observe that for the catalytic stabilizer configuration 12.2% of the air enters the stabilizer versus 3.3 percent for the pilot in the standard configuration.

Table 2- AIR SPLITS IN THE COMBUSTOR

Catalytic Stabilizer Configuration		Standard Pilot Configuration	
Catalytic Stabilizer	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%

Task 2. Design the several catalytic stabilizer candidates

In this task designs of several embodiments of the catalytic stabilizer were developed and analyzed to determine the feasibility of success, the fabrication difficulty, and potential fatal flaws. Of course, all design embodiments had to meet the constraint of fitting into the existing Taurus 70 injector envelope without major modifications. Based on the analysis – and to reduce the time involved in the development of catalytic stabilizer – two candidate designs were chosen. From hereon these two configurations will be referred to as Configuration 1 (developed, fabricated and tested under DOE funding) and Configuration 2. The catalytic reactor for Configuration 1 had a shorter reactor than that of Configuration 2. The detailed drawings for the fabrications of the two configurations were made only after they had been selected.

Task 3. Perform CFD studies of the catalytic stabilizer

In conjunction with Task 2, a Computational Fluid Dynamics (CFD) analysis was performed to reduce iterations in prototype manufacturing. FLUENT, a commercially available CFD code, was used. FLUENT was used to evaluate the mixing of fuel and air for the reactor in the stabilizer. Several designs for the premixer were investigated and the design that gave best mixing was chosen. The mixing goal was to achieve an unmixedness of less than 5% for the fuel and air mixture entering the catalytic reactor of the stabilizer. Although the reactor can handle higher levels of unmixedness, a tighter tolerance was used for this parameter to avoid any NOx penalty. This optimized premixer design identified through FLUENT was used for both versions

of the catalytic stabilizer. Experimental testing during Task 5 supported the qualitative prediction of good mixing at the inlet of the reactor by FLUENT.

Task 4. Fabrication and of the catalytic stabilizer

In this task the two configurations of the catalytic stabilizer were fabricated. All the components of the stabilizers were fabricated at Precision Combustion. However, a few of the components were sent to vendors for laser drilling and wire EDM (electrical discharge machining). Catalytic elements for the catalytic reactor were coated with catalytic materials and then integrated with the reactor housing. Both configurations were then integrated into the Taurus 70 injectors. The Taurus 70 injectors were supplied at no cost to the program by Solar Turbines.

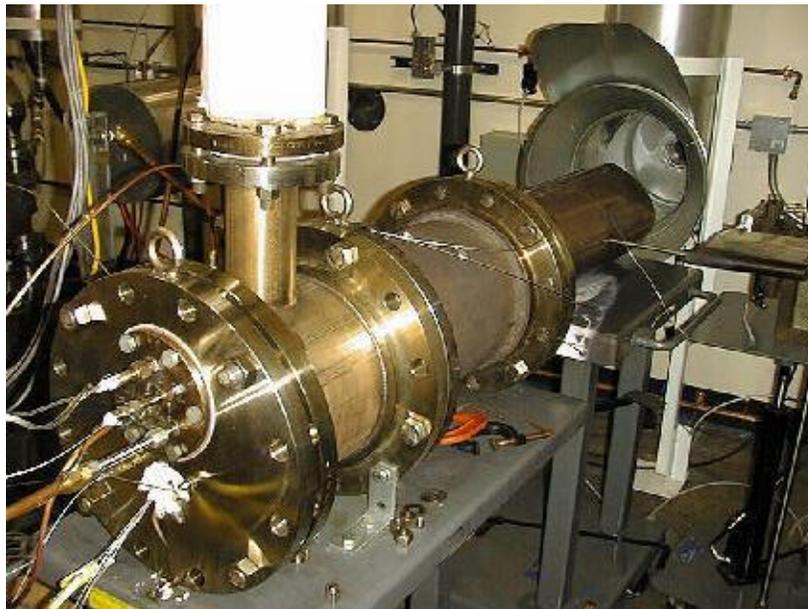


Figure 2:- Picture of the Pilot Testing Rig at PCI

In addition to fabrication of the catalytic stabilizers, a testway, which is shown in Figure 2, was modified to permit testing of the fully-integrated stabilizer/injector assembly at atmospheric conditions. For this purpose several flanges were fabricated to hold the assembly in the rig. Fuel and air supplies were plumbed to deliver the necessary fuel and air so that the aforementioned engine flow function can be matched and maintained.

Task 5. Full-scale, atmospheric pressure testing of the stabilizer at PCI & Task 6. Analysis of results

In this task both configurations were tested at PCI – with the catalytic reactor alone as well as integrated with the injector. First, fuel/air mixing in the premixer of the stabilizer was measured to validate CFD prediction. At the inlet of the reactor, samples were drawn for gas analysis at the same axial and radial position but different circumferential positions. Gas analysis by gas

chromatography showed that deviation from the average was less than 5%. This measurement of small deviation is in excellent agreement with the CFD prediction for deviation. After completing the mixing tests, both catalytic reactors were tested for reaction performance. The catalytic reactors lit off at nearly the same temperature for a given inlet air and fuel mixture. For both configurations, the temperatures of the catalytic elements were sufficiently below those limits set for durability.

After completing the testing for the catalytic reactors, the two different configurations were then integrated with Taurus 70 injectors and tested. Since the testing was conducted at atmospheric pressure, flow function, inlet air temperature, and the pressure drop similar to baseload conditions were maintained. During this portion of testing we discovered that the reactor T/C's as well as the gas analysis probes were affecting the stabilizer's performance. Due to this interference we had to re-instrument the catalytic stabilizer assembly.

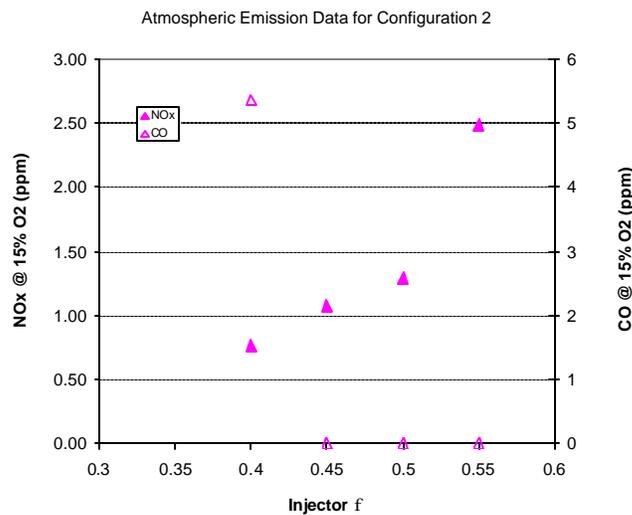


Figure 3:- NOx and CO results from atmospheric pressure testing of the modified T70 injector

After correcting this, emission measurements were obtained for different stabilizer and injector equivalence ratios. For both stabilizer configurations lean combustion could be sustained in the main injector. Figure 3 shows emission data obtained for Configuration 2 at atmospheric pressure condition as a function of natural gas equivalence ratios in the injector for a constant stabilizer equivalence ratio of 0.5. From this Figure we observe that injector operation could be sustained to an equivalence ratio of 0.4 and for the range of equivalence ratios shown in Figure 3, the NOx emission was below 5 ppm

To summarize, atmospheric testing of the catalytic stabilizer with the main-injector showed that the catalytic reactor was active and operating within durability guidelines. In addition, NO_x and CO emissions were very low for both 50% and 100% load conditions. Thus we felt confident in performing the next Task: testing the catalytic stabilizer at Solar's full pressure injector rig.

Task 7. Full scale, high pressure testing with Taurus 70 Injector

The objectives of this testing were to determine the operating temperature required for the catalytic reactors, to determine the durability and robustness of the catalytic reactor, to determine the performance of the catalytic reactors at high pressure and, finally, to determine the emissions and acoustics at baseload conditions for the integrated catalytic stabilizer and injector assembly.

Both stabilizer configurations were tested at Taurus 70 baseload conditions for operation with natural gas. The tests were conducted in Solar’s Single Injector High-pressure Facility. The objectives of this testing were to determine the operating temperature required for operation on natural gas, to determine the durability and robustness of the catalytic reactor, to determine the performance of the catalytic reactors at high pressure and, finally, to determine the emissions and acoustics at baseload conditions for the integrated catalytic stabilizer and injector assembly.

All emission results will be discussed 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.

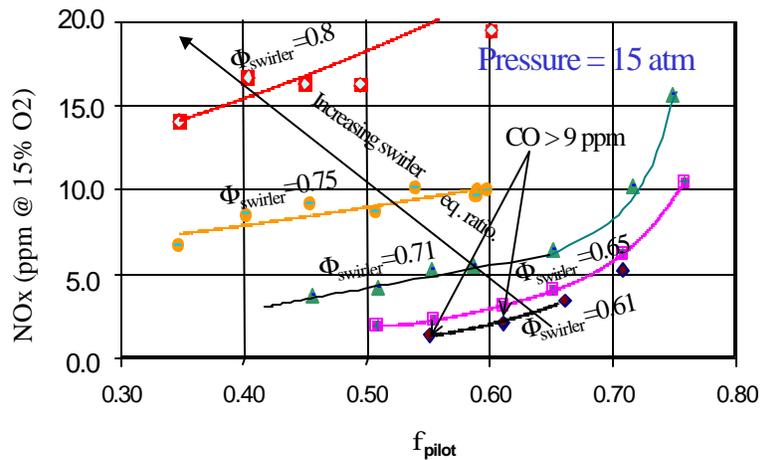


Figure 4:- NOx emission dependence on catalytic pilot equivalence ratio

Figure 4 shows the sensitivity of NOx emission data obtained to catalytic pilot equivalence ratios at a pressure of 15 atmosphere during operation on natural gas for configuration 2. The symbols show the experimental data obtained after correction to 15% O2 in a dry sample, and the lines represent trend lines drawn through the data points with constant swirler equivalence ratio. These group of data will be referred as “Data from Day 1 testing”. For a constant swirler equivalence ratio ($\phi_{swirler}$), emission data were first collected with the highest pilot equivalence ratio ($NO_x < 20$). 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 4. CO was lower than 10 ppm at all other data points shown in Figure 4.

We observe from this figure that for higher swirler equivalence ratios less piloting is necessary and blowoff occurred at lower pilot equivalence ratios. This is expected and the increased stability is achieved at the expense of higher NOx emission. Below ϕ of 0.65, NOx dependence on the pilot equivalence ratio was linear.

Figure 4 also shows that the best NOx emission (NOx < 5 ppm) can be obtained for this configuration of modified Taurus 70 injector, when the swirler equivalence ratio is in the range of 0.5 to 0.65 and the pilot equivalence ratio is in the range of 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 (0.6-0.65), blow-off would occur. This indicated that the catalytic pilot provided stability to the main flame.

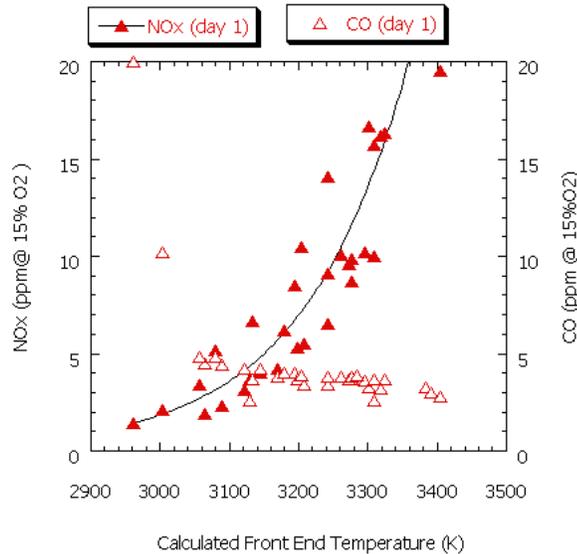


Figure 5:- Measured NOx and CO emission for the modified Taurus 70 injector at close to 100% load condition

Figure 5 shows the same emission data (CO and NOx) of Figure 4 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.

The symbols represent measured emission data (closed symbols represent NOx 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 5 also shows the emission at the modified operating temperature of approximately 3050 °F (1677 °C/ 1950 K) for this modified configuration at 100% load to be around).

We observe 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 3000- 3150 °F (1627-1732 °C/1900 – 2005 K). In T70 injector test with standard pilot with a similar (same effective area) swirler, NO_x emission of 15 ppm resulted for an operating front end temperature of approximately 3400 °F (1868 °C/2140 K). Clearly, the use of larger air split for the catalytic pilot, - can be observed from flow-splits shown in Table 2, - has permitted operating at lower front end operating temperature and thereby decreased NO_x.

Figure 5 also shows that at front end temperature of approximately 3070 °F (1687 °C/1960 K), measured NO_x values of 1.9 ppm and 5.2 ppm were observed. This scattering 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 compared to the data of Figure 4, it can be observed that a NO_x level of 1.9 ppm was observed for swirler and pilot equivalence ratios of 0.61 and 0.66 respectively, whereas for the higher NO_x case swirler and pilot equivalence ratios were 0.61 and 0.71 respectively. The use of a higher pilot equivalence ratio was responsible for the increase in NO_x. These data shows that there is an optimum percent of pilot fuel flow above which increasing the percentage has detrimental effect on NO_x emission.

Thus NO_x and CO emissions are not a single valued function of the calculated front end temperature. Depending on the pilot and swirler equivalence ratios, these emissions can be different at the same calculated front end temperature. Figure 5 thus in combination with Figure 4 help to identify the optimum operational space in terms of swirler and pilot equivalence ratios for lowest emissions.

Figure 6 shows the measured combustion driven pressure oscillation during testing of configuration 2 at baseload condition. We observe the pressure oscillation were low in the temperature range of 3025 °F- 3200 °F (1662 °C-1760 °C/1935- 2033 K)

Task 8 Final Report

The results of Task 1 to Task 7 are presented in this report along with conclusions and suggestions for future work. The results obtained during high pressure testing at Solar are also given in this report.

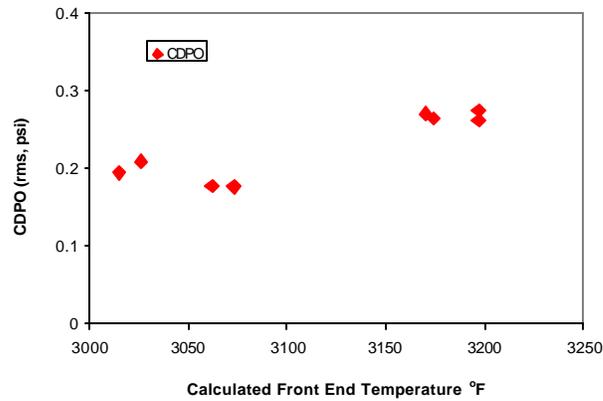


Figure 6:- Measured CDPO at baseload conditions

Project Outcomes

- *Catalytic stabilizer developed for the Taurus70 injector fits into the existing geometry*

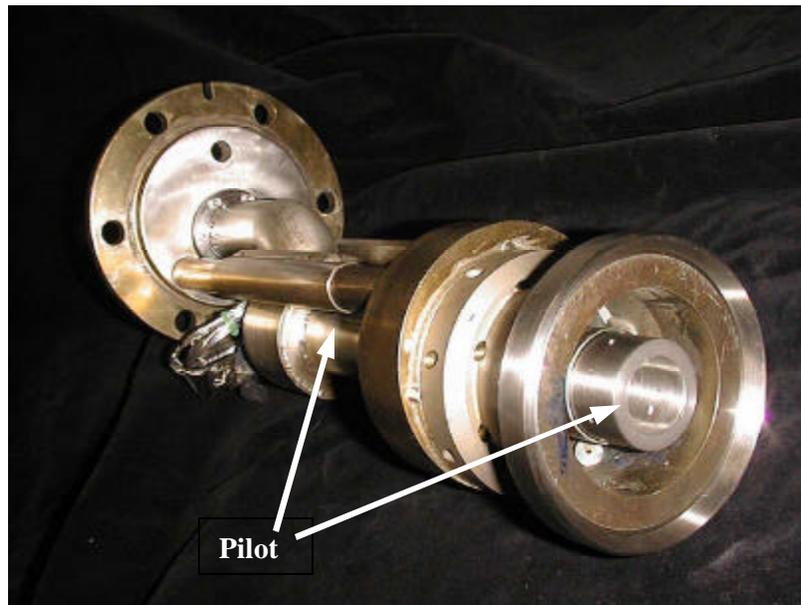


Figure 7:- Photograph of modified Solar Taurus 70 premixed fuel/air injector hardware, with PCI's catalytic stabilizer installed on the injector centerline (within the swirler hub). Orientation of the injector in the photograph shows the mounting flange at upper left, and the swirler and catalytic reactor exits at lower right

The catalytic stabilizers fabricated during this project fit within the swirler hub of the standard injector without any major modification. Figure 7 shows a picture of the stabilizer hardware integrated with the injector hardware

- *No preburner is required for the catalytic stabilizer operation on natural gas. Reactor lit off at temperatures lower than the temperature of the compressor discharged air at baseload for Taurus 70 engine.*

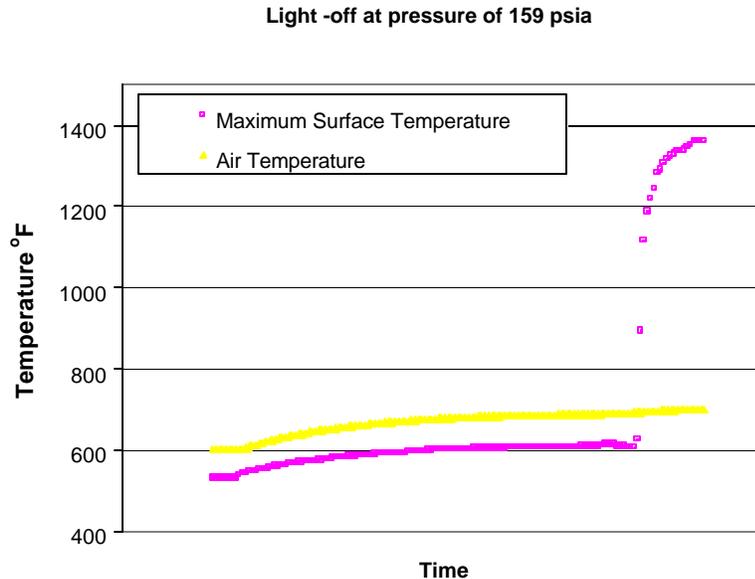


Figure 8:- Light-off data for the catalytic stabilizer at a pressure of 159 psia

Figure 8 shows a typical lightoff curve for Configuration 1 (the lightoff characteristics of Configuration 2 are similar) during operation on natural gas (CH₄: 95.82%, C₂H₆: 1.8%, C₃H₈: 0.32%, C₄H₁₀: 0.13%, CO₂: 0.89%, N₂: 1.0) at Solar Turbines’ facility. This plot shows the temperature of combustor inlet air, the surface temperature at a distance of 0.125” from the start of the catalyst section, and the maximum surface temperature – all as functions of time. The combustor inlet air temperature was approximately 670°F (355°C) and the initial surface temperature about 580°F (305°C) when catalyst light off occurred. This air temperature of 670°F is lower than the compressor discharged air temperature of 725°F (385°C) at 50% load. From this data we can conclude that the catalytic reactor of the stabilizer will be active without a preburner even during half load operation of the machine.

- *Achieved robust and durable operation of the catalytic stabilizer. No flashback or autoignition.*

During the several days of operation no autoignition or flashback in the stabilizer was observed. Once the reactor was lit off, the maximum temperature that was reached on the catalyst surface was similar to that observed during atmospheric pressure testing at PCI. This temperature was well below material specifications to meet a minimum of 8000 hours durability.

- *The integrated catalytic stabilizer and injector achieved NOx and CO emission < 5 ppm during single injector testing at a high pressure facility of Solar*

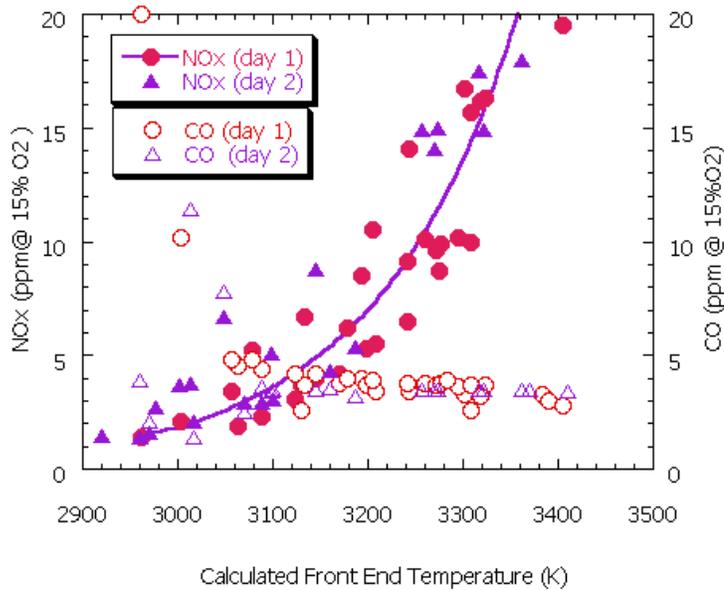


Figure 9:- Oxygen-corrected NOx and CO emissions vs. calculated front-end temperature

Figure 9 shows the base load emissions data obtained during the testing of a single injector integrated with a catalytic stabilizer at Solar’s high-pressure facility on two different days. The x-axis shows the calculated front-end (head-end) temperature with the y-axes showing corrected emissions (left axis for NOx and the right for CO). Note that the calculated front end temperature does not take into account any reverse-flow dilution air or dome cooling that may participate in the combustion process. As a result, the calculated adiabatic front end temperature is higher than the actual head-end temperature. The solid symbols (circles represent the 1st day data; triangles the 2nd day) denote NOx data whereas the open symbols denote CO data. The solid line is an exponential fit for 1st-day NOx data. The scattering in the NOx and CO data is discussed in the section that describes Task 7. Both CO and NOx emissions of less than 5 ppm can be achieved over the head-end temperature range of 3000- 3150 °F (1627-1732 °C/1900 – 2005 K) and emissions of less than 10 ppm can be achieved in the range of 3000°F to 3250°F (1627-1787 °C/1900-2060 K).

If we take an operating front end temperature at baseload of 3050°F, we can see that the emissions at this temperature are below 5 ppm (though the actual engine baseload front end flame temperature must be kept significantly higher – through the strategic use of combustion system air distribution – due to stability issues, the catalytic stabilizer allows a much lower flame temperature while maintaining both the overall firing temperature and stable combustion). The integrated assembly also has a wide operability range over which low emissions are achieved. This operability is crucial for field implementation of the technology.

- *Catalytic stabilizer is targeted toward leaner operation of the injector*

The targeted front end temperature at baseload for this configuration was 3050 °F, which – as stated earlier – is considerably lower than the baseload temperature of the current Taurus 70 engines in the field. A lower baseload head-end temperature signifies leaner stabilization of the injector with lower NOx.

- *Catalytic stabilizer delivered low emissions at 50% load conditions*

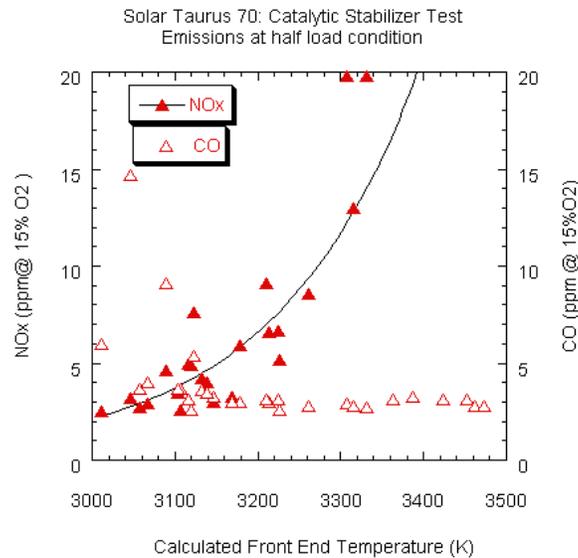


Figure 10:- NOx emissions at 50% load conditions from the single injector/catalytic stabilizer assembly testing

Figure 10 shows NOx data obtained during integrated single injector/catalytic reactor test at 50% load condition of the Taurus 70 engine. In the head-end temperature range of 3000°F – 3150°F, NOx emissions below 5 ppm and CO emission below 10 ppm were achieved. Once again, due to air cooling flows (dilution, dome, etc.) the actual temperature in the primary zone is lower than that presented in the figure. The fact that the stabilizer can operate at 50% and base loads provides enough confidence to conclude that this level of emission can be achieved between 50%-100% load for T-70 engine. At 50% load the compressor discharge

temperature will be high enough to sustain catalytic activity allowing the stabilizer to be used to stabilize combustion from 50% to base load.

Conclusions and Recommendations

- The test results support the continued development and efforts to commercialize catalytic stabilizer technology as ultra-low NO_x technology for industrial gas turbines.
- We demonstrated that PCI's catalytic stabilizer technology will fit into existing T-70 engine envelope without major modification to the engine. Two different catalytic stabilizer configurations were fabricated and integrated with the Taurus 70 injector without major modifications.
- The project demonstrated that the catalytic stabilizer technology is significantly robust: during several days of testing the catalytic reactor was free from auto-ignition and flashback even with wide variation of fuel-air ratio and airflow to the stabilizer
- The tests show that no preburner is required for the operation of catalytic stabilizer technology from half load to base load operation of Taurus 70 machine. The catalytic reactor maintained sufficient activity during testing at inlet air temperatures of 430°C (full load compressor discharge temperature) and 385°C (half load compressor discharge temperature).
- The project demonstrated that sufficient catalytic activity can be achieved both at baseload and half load to achieve stable combustion.
- The project demonstrated that leaner operation in the head-end of the combustor can be achieved with the catalytic stabilizer. In addition, the catalytic stabilizer can achieve low emissions at a head-end temperature of 3050°F. This calculated front end temperature is lower than the front end temperature currently achievable in the Taurus 70 engine at baseload. The current field limitations are due to combustion instability of the current Solar's combustor. However, the catalytic stabilizer will allow combustor inlet air to be diverted from cooling and dilution air to the head-end. Lower front-end temperature signifies leaner combustion.
- The project successfully demonstrated NO_x and CO emissions less 5 ppm at baseload conditions of Taurus 70 injector for a single injector at high pressure.

The next step in developing this technology is a performance test of the catalytic stabilizer in a Taurus 70 engine. To accomplish this, twelve (12) Taurus 70 injectors must each be integrated with a PCI catalytic stabilizer. These twelve catalytically-stabilized injectors will be installed in a backside-cooled annular liner. This engine test will be the final proof-of-concept for this technology and is a required step in the Solar's path to technology commercialization in their industrial engines. Additional funding will be required to conduct the following:

1. Mechanical analysis of the catalytic stabilizer: An analysis determining the stress caused by temperature gradients will need to be performed on the relevant components of the stabilizer. This analysis will identify any components, which are at risk of failing before a total operational life of 8000 hrs is reached (a minimum life of 8000 hrs is required for all components). If any such components are considered at risk, their design will be modified accordingly.
2. Design simplification of the catalytic stabilizer: The mechanical analysis will also identify any manufacturability issues of components. Costs that might be considered

prohibitive to the fabrication of cost competitive devices will be addressed. In addition, this analysis is intended to enable easier manufacturing of larger quantities of components.

3. Establish operating procedure for startup and steady state operation of the catalytic stabilizer in the Taurus 70 engine: Based on the single injector tests of the current project, the assembly functions well at base load and 50% load for the Taurus 70 engine. After testing steady-state conditions at other loads in the single injector rig, PCI will need to determine the optimum fuel splits (e.g. stabilizer equivalence ratio, injector equivalence ratio and % of total fuel to stabilizer) and overall operation of the stabilizer/injector assembly over the entire startup schedule.
4. Establish control procedures for the modified Taurus 70 combustor: Based on the results from (3) above, the method and scheme for controlling fuel flows may be modified and optimized (e.g. controls software, control valves & fuel delivery system).
5. Fabricate 12 injectors and 12 stabilizers: A new set of twelve (12) catalytic stabilizers and injectors need to be fabricated – along with a backside cooled annular liner.
6. Perform atmospheric pressure rig testing: Atmospheric pressure rig testing of the twelve-injector/stabilizer system.
7. Perform Engine testing: Conduct engine testing at Solar Turbines.
8. Perform Cost analysis: Cost analysis for the manufacturing of catalytic stabilizers will need to be performed.

Public Benefit to California

This project has contributed to the Public Interest Energy Research (PIER) program objective of introducing clean and efficient combustion technology into the California economy. Through close involvement with Solar Turbines, a California based industrial gas turbine manufacturer, PCI has demonstrated emission benefits, raised Solar's interest in an engine test in 2002, which supports catalytic pilot's acceleration toward commercialization possibilities in Solar's Taurus 70 engine. In doing so, PCI's catalytic stabilizer technology will give California such benefits as

1. Air quality with cost savings: The concept allows significant NO_x emissions improvement with respect to the existing state-of-the-art industrial turbine combustors. The additional cost of this combustion system enhancement per engine is expected to be relatively low, and could help power suppliers avoid significant aftertreatment costs – as well as increase the life of components associated with DLN technology. The ease of retrofit within a DLN combustor geometry may permit wider acceptance and installation in existing high emission engines. The combination of lower emissions (competitive with current emissions standards for large utility installations) in smaller power generation engines provides more flexibility in citing of production capacity facilitating even more opportunities for improvements in California air quality through both emissions savings and economic incentive to displace/replace higher emission products.
2. Energy efficiency: The catalytic stabilizer offers a significant increase in energy efficiency compared with aftertreatment and encourages replacement of older, less-efficient sources with modern, higher efficiency turbines.
3. Global warming: Natural gas combustion produces less CO₂ than alternative fossil fuel combustion. Furthermore, this technology may eliminate the need for SCR

aftertreatment – treatment that can produce problematic ammonia slip thereby contributing to greenhouse gases. So, by promoting an increased gas turbine share of the power generation market, catalytic stabilizer technology helps advance California efforts to limit greenhouse gas emissions.

4. **Benefit to California gas turbine industry:** Currently, California industrial gas turbine manufacturers are losing world market share in the face of increasing European and Japanese competitive pressures (price and government subsidy). In addition tightening emissions regulations in both Japan and the U.S. virtually mandate SCR use. The industrial sized gas turbines (Solar Taurus 70) are not generally large enough to support the large additional capital costs associated with an after treatment technology such as SCR. Thus as the regulations tighten, only the very large combined cycle gas turbines get built because they can spread the SCR investment over more installed production capacity. Unless industrial sized gas turbines develop single digit NO_x technology, they face a long-term threat of being displaced by larger, more efficient 3 and 9 ppm NO_x-capable combined cycle gas turbines. Catalytic stabilizer technology with DLN offers a chance to reverse this trend for California based and other US industrial gas turbine manufacturers.
5. **Retrofit Potential:** In addition to equipping new gas turbine engines with reliable, ultra-Low NO_x catalytic technology, already-existing engines may also be readily retrofitted with this technology without major modification to the engine. This ability to retrofit current engines provides California with significant opportunities to economically meet ever-increasing environmental legislation.

Development Stage Assessment

The Development Assessment Matrix below indicates that PCI has progressed through Stage 6 with Marketing and Engineering /Technical activities as they relate to the PCI catalytic stabilizer technology embodied in an actual device that fits within a commercial Solar Taurus 70 industrial gas turbine. Much of the Marketing and Business Assessment activities have been covered by PCI in the development of a Business Plan for Clean Turbine Systems, a manufacturing business venture proposed by PCI to a DOE CAP audience in May 2000 to develop the PCI catalytic combustor manufacturing capacity. A copy of that Plan is included in the Appendix to this report.

We address the Contractual as well as Strategic (includes licensing and manufacturing) in the Clean Turbines Business Plan as well. An assessment of those categories listed below does indicate that PCI is through Stage 3 in all areas.