Catalytic Combustor for Fuel-Flexible Turbine

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ABSTRACT

Under the sponsorship of the U. S. Department of Energy's National Energy Technology Laboratory, Siemens is conducting a three-year program to develop an ultra low NOx, fuel flexible catalytic combustor for gas turbine application in IGCC. The program is defined in three phases: Phase 1- Implementation Plan, Phase 2- Validation Testing and Phase 3 – Field Testing. The Phase 1 program has been completed. Phase II was initiated in October 2004.

In IGCC power plants, the gas turbine must be capable of operating on syngas as a primary fuel and an available back-up fuel such as natural gas. In this program the Rich Catalytic Lean (RCL™) technology is being developed as an ultra low NOx combustor. In this concept, ultra low NOx is achieved by stabilizing a lean premix combustion process by using a catalytic reactor to react part of the fuel, increasing the fuel/air mixture temperature.

In Phase 1, the feasibility of the catalytic concept for syngas application has been evaluated and the key technology issues identified. In Phase II the catalytic concept will be demonstrated through subscale testing. Phase III will consist of full scale combustor basket testing on natural gas and syngas.

Table of Contents

EXECUTIVE SUMMARY 1

TASK II.2 – FUEL FLEXIBLE CATALYST DEVELOPMENT 3

LIGHTOFF TEMPERATURE STUDIES 4

NATURAL GAS LIGHTOFF STUDIES 6

SYNGAS LIGHTOFF STUDIES 8

HYDROGEN LIGHTOFF STUDIES 10

TASK II.4 – DEVELOPMENT OF CATALYTIC MODULE 11

MILESTONES 16

CONCLUSIONS 16

List of Figures

Figure 1– SWPC Catalytic Stabilized Combustor 1
Figure 2 – Traditional Ceramic Coating 4
Figure 3– Siemens Metal Ceramic Coating 4
Figure 4 – Schematic of the Single Tube Reactor 5
Figure 5 – Instrumented Reaction Section for the Single Tube Rig 5
Figure 6 – Lightoff Data for Catalyst Materials 7
Figure 7 – O2 Conversion Data from Catalytic Surfaces 8
Figure 8 – Lightoff Data on Syngas 9
Figure 9 – Red Coating from Operation on Syngas 10
Figure 10 – Module 8 with Dual Fuel Injection (Natural Gas and Syngas) 11
Figure 11 – Module 8 Assembeled to the Cover Plate 12
Figure 12 – Comparison of Module Test Data at Solar and PGI 13
Figure 13 – Module Test Data Corrected for Spring Clip Leakage 13
Figure 14 – Module 8 Test results as a Function of Firing Temperature 14
Figure 15 – Temperatures in the Catalyst Section 15

List of Tables

Table 1 – Summary of Catalytic Combustor Design Options for IGCC 2
Table 2 – Syngas Composition by Volume 9
Table 3 – Hydrogen Lightoff Studies 10

EXECUTIVE SUMMARY

The Rich Catalytic Lean (RCL ™) technology, Figure 1, is being developed as an ultra low NOx gas turbine combustor for Integrated Gasification Combined Cycle (IGCC). In this concept, ultra low NOx is achieved by stabilizing a lean premix combustion process by using a catalytic reactor that produces a nominal gas temperature increase in the fuel/air mixture (by converting part of the fuel).

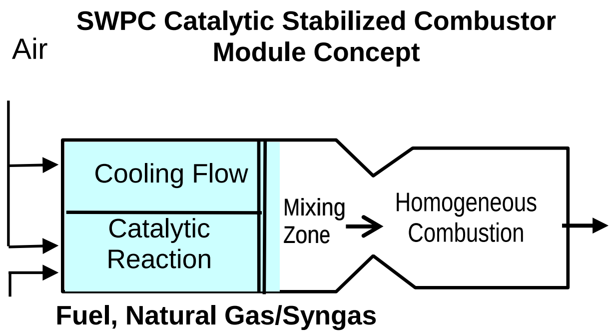

Figure 1 – SWPC Catalytic Stabilized Combustor

A key challenge in developing a fuel flexible catalytic combustor is the ability to provide one base design that will accommodate the different process flow conditions that are indicative of different IGCC plant designs. Cold Vs hot gas cleaning, degree that the gas turbine is integrated with the IGCC plant and how the plant might be optimized for efficiency Vs power output all impact the process flows that must be managed within the combustor. In Phase 1, the feasibility of the concept for syngas applications was evaluated, benchmarked and a validation test program (Phase 2) is defined. Specifically,

Catalytic module and combustor design concepts are defined for fuel flexible operation that minimize changes to the current catalytic reactor design, thus retaining the product of prior engineering and development. The proposed module design options are summarized in Table 1. In Phase 2 these design options will be developed, tested and evaluated.

Table 1 – Summary of Catalytic Combustor Design Options for IGCC

Concept Approach	Syngas Operation	Natural Gas Operation
No change to the current catalytic module design.	Options include staging or bypassing syngas and nitrogen to increase fuel conversion on the reactant side.	No impact
No change to the current catalytic	Syngas air split can be optimized but will require	No impact

module design. Utilize an eductor to control air split.	higher syngas pressure to drive the eductor.	
Modify current catalytic module for syngas.	Can be optimized for syngas conversion.	Requires device to control air split during natural gas operation.

During Phase II these concepts will be developed and tested. The catalytic combustor and module product definition will be further developed for the IGCC W501FD engine application. The focus will be on improvements required for syngas and the higher firing temperature of the W501FD engine. Highlights of this phase of the project were testing of SWPC catalytic coatings on natural gas and syngas, redesign of the baseline catalytic module with dual fuel capabilities for natural gas and syngas and redesign and testing of the catalytic basket for the STG-5000F configuration.

TASK II.2 – FUEL FLEXIBLE CATALYST DEVELOPMENT:

Because the RCL combustion design does not have a preburner, lightoff temperature is critical to successful operation. Lightoff is defined as the temperature at which the catalyst surface initially becomes active. Once the catalyst is lit it will remain active even if the temperature is reduced below the initial lightoff temperature. Testing in the combustor basket rig has shown that combustor dynamics are high at loads in excess of 80% when the catalyst was not active. To insure sufficient margin, the target lightoff temperature was set to be 50% load on the SGT-6-5000F engine, this corresponds to roughly 350 C. All catalyst coatings are initially screened for lightoff. Those with acceptable lightoff are then tested for durability. All coating are compared to the baseline coating developed by Precision Combustion Inc. (PCI). The PCI coating lightoff is consistently between 300 and 330 C.

The main development focus for this program has been traditional coatings, ceramic washcoat with precious metal catalyst. The PCI coating is an example of a traditional catalytic coating. The catalyst is applied to a Haynes 230 tube. Haynes 230 was chosen because of it's resistance to oxidation. Oxidation is a concern because the tube is only 0.010 in thick. The active metal catalyst can be platinum, palladium, rhodium or a mixture. Preliminary testing has shown that pure platinum catalysts have a lightoff temperature of greater than 450 C and therefore do not satisfy the lightoff requirements for this program. Development on this program has focused on palladium and palladium based mixtures for the catalyst. Figure 2 shows the catalyst system for the traditional ceramic catalyst. In addition to the traditional ceramic coatings an internal Siemens ceramic metal coating has been developed as shown in Figure 3.

The catalytic coating development on this program is pursued with the following industrial partners:

•ACS Advance Catalyst Systems	Dr. Larry E. Campbell
•Engelhard	Dr. Tom Giroux, Dr. Bob Farrauto
•Guild Associates Inc.	Dr. Joseph Rossin
•Miratech	Don Newburry
•CFI/CTI Coatings for Industry/Coating Technologies Inc	Dr. Basil Mucha

The first 4 companies are involved in the production of traditional ceramic catalyst materials. CFI/CTI is involved in the design of the Siemens metal ceramic coating.

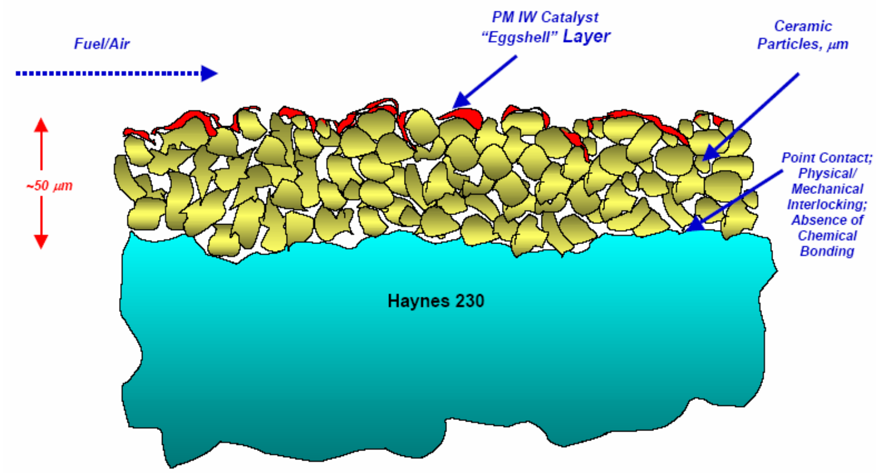

Figure 2 Traditional Ceramic Coating

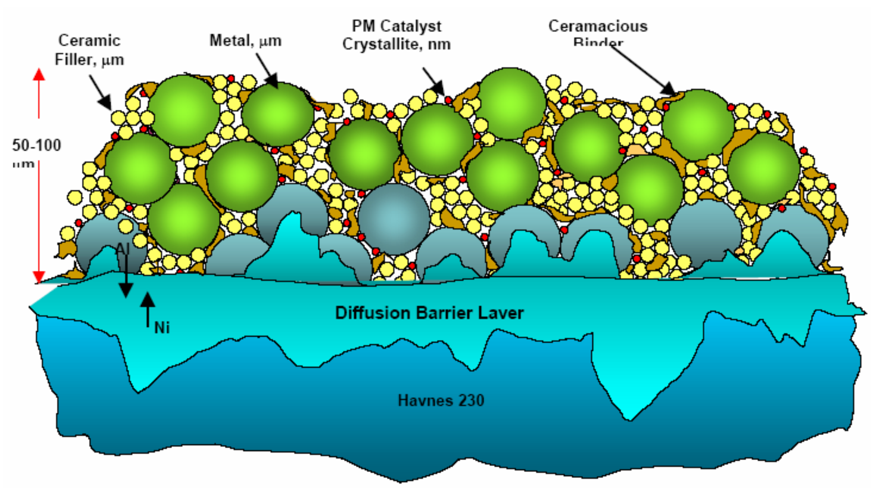

Figure 3 Siemens Metal Ceramic Coating

LIGHTOFF TEMPERATURE STUDIES

Lightoff temperature measurements are performed in the Siemens single tube facility located at Casselberry labs. This facility has the capability of testing of a single catalytically coated tube at the same conditions as would be encountered in an engine. A schematic of the single tube rig is shown in Figure 4. Mass flow controllers are used to independently control the rich combustion air, the cooling air and the fuel. With this test facility it is possible to study the effect of variation in flow split on lightoff and conversion. The temperature of the two air streams is controlled by two tube furnaces. The catalytic tube is placed in a cylindrical reactor vessel which is designed to simulate the same velocity of the gas on the outside of the tube as would be encountered in the engine. Figure 5 shows the cylindrical reactor vessel.

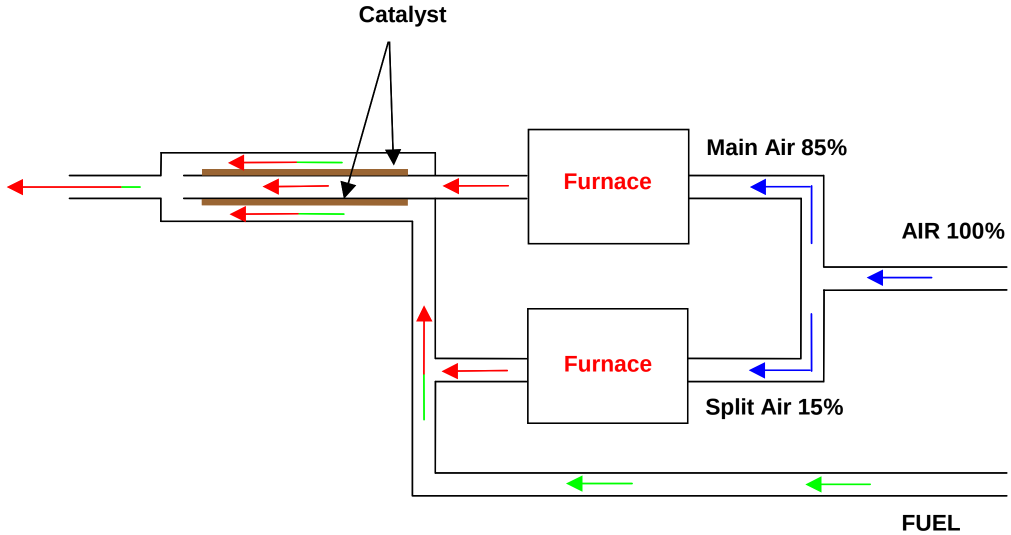

Figure 4 Schematic of the Single Tube Reactor

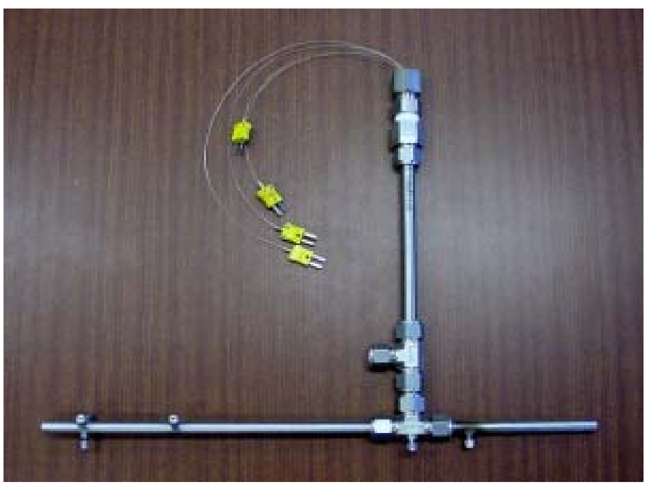

Figure 5 Instrumented Reaction Section for the Single Tube Rig

The catalytic tube is instrumented with three TCs attached to the surface of the catalyst. Two TCs are placed downstream of the reactor to measure the mixture gas temperature exiting the catalyst section. Additional TCs are used to measure the temperatures of the two inlet air streams and the fuel. After leaving the reactor the gas stream is cooled in a water jacketed section and then diluted to below the flammability limits with air and exhausted through a stack. The reactor vessel is instrumented with 3 gas chromatograph ports. One port is located upstream of the catalyst section in the reacting mixture and is used to determine the air split to the catalytic section. A second port is located near the end of the catalytic section and is used to determine the amount of fuel and oxygen conversion in the reaction zone. The last GC port is located down stream of the reactor and measures the composition of the mixed gas streams. In addition to the GC ports an oxygen meter is used to measure the oxygen concentration in the reactor.

Lightoff testing is performed using the following procedure.

- The air flows are set to the desired values. For all lightoff testing the split air is set to 15%. The O2 concentrations from GC port one are used as a check on the accuracy of the flow meters.
- The tube furnaces are set to produce a gas temperatuere below the expected lightoff.
- The fuel flow is set to the desired value.
- The temperature of the tube furnaces are gradually increased until lightoff is achieved.
- Light off is measured by a rapid increase of the temperature at the catalyst surface.
- If lightoff is not achieved by 440 C the coating is not considered viable.
- If lightoff is achieved below 440C the inlet temperature is brought to 376C and a full set of GC data is recorded to determine conversion. In addition to the GC the O2 meter is used from GC port two as a check on the conversion.
- If lightoff is successful achieved, the coating is tested 5 additional times. This is necessary to determine the effect of repeated lightoffs on coating performance. With the PCI coating lightoffs tend to decrease with additional testing. On other coatings the lightoff tends to increase as additional lightoffs are performed. Five lightoffs were chosen because based on experience the lightoff temperature tends to reach a constant value after this time.

Lightoff data was obtained for natural gas, syngas and hydrogen. Because lightoff temperatures are significantly lower on syngas and hydrogen than on natural gas, initial screening of coatings was performed primarily on natural gas. If a coating has an acceptable lightoff on natural gas, it will lightoff on syngas and hydrogen. Even platinum coatings which had natural gas lightoff above 440 C met the target lightoff temperature when tested on syngas.

NATURAL GAS LIGHTOFF STUDIES

The majority of the work on precious metal catalyst has been with palladium. Platinum catalysts have light off temperatures above 440 C and are not applicable to this design. Future work will include bi metallic combinations of platinum and palladium and tri metallic combinations of platinum, palladium and rhodium. Initial work has focused on the loading of the precious metal catalyst, the method of application and the interaction of the catalyst material with the washcoat.

The majority of the tests were performed with an Alumina washcoat. Preparation of the washcoat is critical to the available surface area and lightoff performance. Some work was done with presintering the washcoat at 800 C and 1000 C. The washcoats examined include commercial stabilized Alumina washcoats including EcoCat (KLN3) from Miratech and COM and ATO washcoats from Engelhard. Modified alumina washcoats have been examined including X% La_2O_3–Al_2O_3, X %ZrO_2–Al_2O_3, SiO_2-Al_2O_3.

Figure 6 shows natural gas lightoff data obtained to date. Currently the PCI catalyst is the only catalyst which meets the lightoff criteria of 350 C. It is interesting to note that for most of the catalyst materials tested the lightoff is initially low and then increases after a number of lightoffs. Several of the candidate materials had an acceptable lightoff on the initial test but subsequent testing resulted in an increase in lightoff temperature. After 5 lightoffs these materials tend to reach a stable repeatable lightoff temperature. The PCI catalyst is an exception in that the initial lightoff is high but the lightoff temperature tends to decrease as the tube is run. Work is ongoing to determine the cause of the lightoff increase and develop a solution. A design of experiments is planed in to evaluate the catalyst material and washcoat formulation.

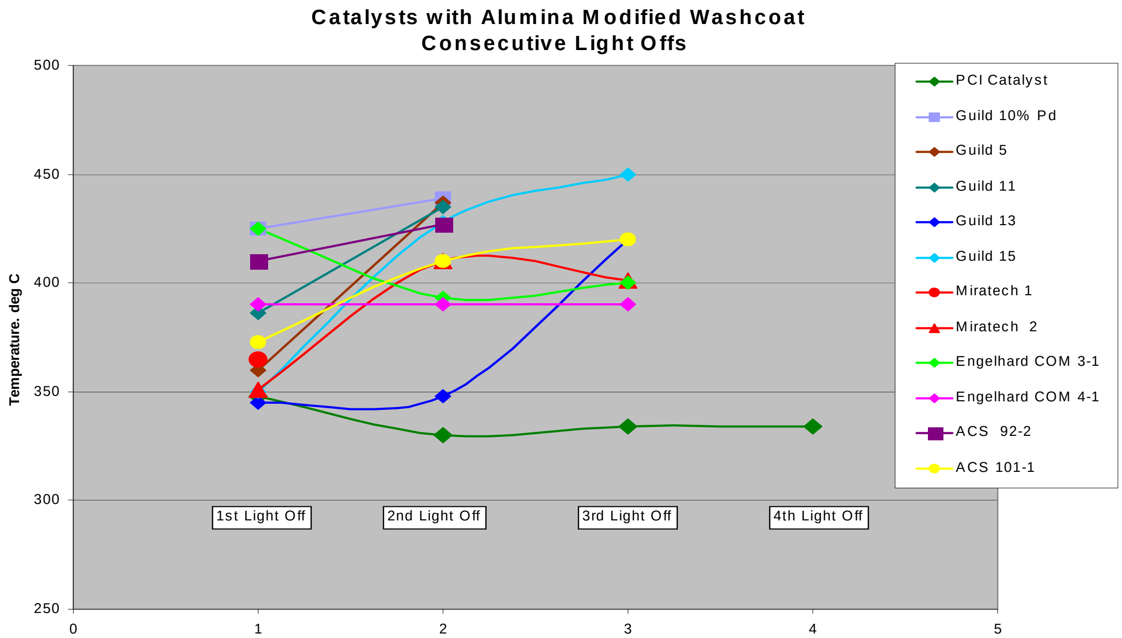

Figure 6 Lightoff Data for Catalyst Materials

Figure 7 shows the measured oxygen conversion from the catalyst on consecutive lightoffs. It is interesting to note that the conversion is not correlated to the lightoff temperature. On tubes where the light off temperature increased the oxygen conversion was unaffected. All catalysts tested had acceptable conversion. It would be expected that the coating with the lowest lightoff temperature would have the highest reactivity and therefore the highest conversion. This is not the case as Figure 7 shows the PCI coating which had the best lightoff performance had lower conversion than most of the coatings tested.

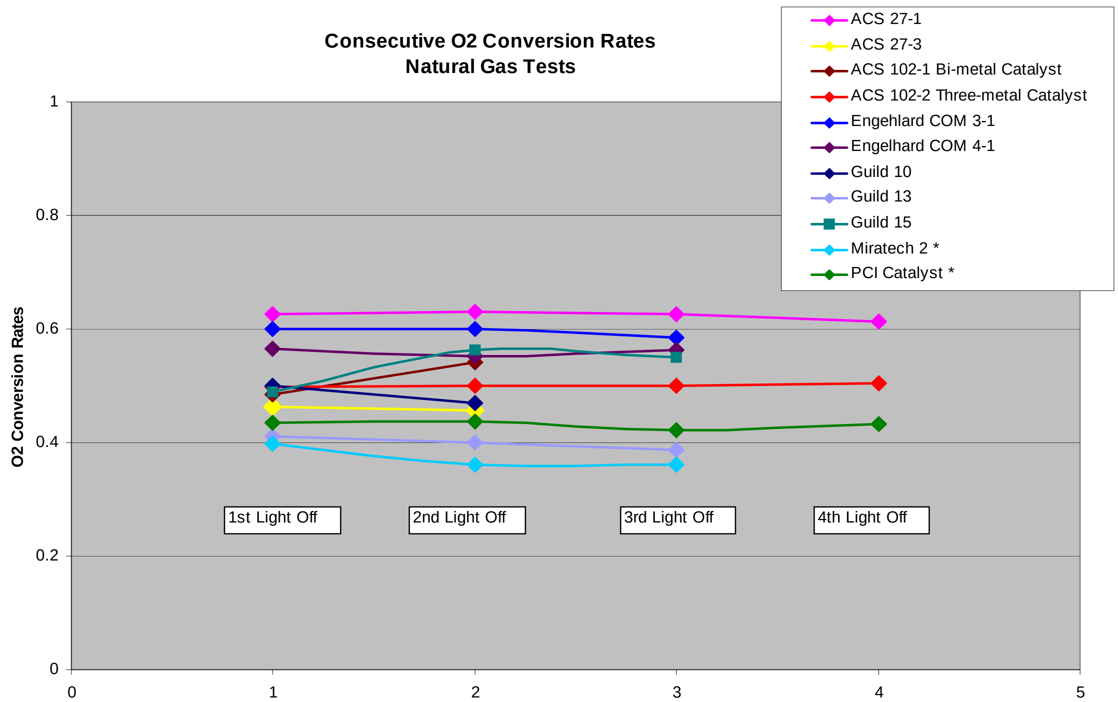

Figure 7 O2 Conversion Data from Catalytic Surfaces

SYNGAS LIGHTOFF STUDIES

Syngas lightoff tests were performed on PCI, ACS and Engelhard coatings. The syngas was simulated using bottled gases with the composition shown in Table 2. This composition was chosen as representative of the output of a typical of IGCC application. Unlike natural gas, the syngas tests were all performed at a flow split of 10%. The initial tests performed on the ACS tube at 15% split resulted in a catalyst surface temperature of 975 C. This exceeds the maximum allowable temperature for the catalyst. When the split was reduced to 10% the catalyst surface temperature was reduced to 732 C which within the design limit and is similar to the performance on natural gas. Figure 8 shows the lightoff temperatures for all of the coatings tested on synags. All of the coatings tested had lightoff temperatures below 300 C, easily meeting the target of 350 C. The Engelhard coating was a platinum rhodium catalyst which could not achieve lightoff on natural gas below the 440 C limitation of the rig.

Syngas experiments also highlighted the importance of using stainless steel tubing when operating on a fuel with a high CO content. Some of the early test results were stopped because of the formation of a red coating on the surface of the tube. The coating did not affect the lightoff temperature but did cause a reduction in the fuel conversion. If the tube with the red coating was operated on natural gas the red coating could be removed. This red coating was analyzed as iron oxide. Figure 9 shows the catalytic tube before and after operation on syngas. The source of the iron was a mystery because the rig is assemble with only stainless steel piping. The red coating was traced to the formation of iron carbonyl in the gas cylinders. At the high pressures in the gas cylinders and at the temperatures found in the summer in Florida it was possible to form the iron carbonyl in the gas cylinders. The iron carbonyl is unstable and deposits out as iron oxide at the high temperatures of the catalyst tube during lightoff. The iron carbonyl problem disappeared when the iron cylinders were replaced with aluminum.

CH4	7.42%
CO	59.83%
CO2	7.89%
H2	23.97%
N2	0.89%

Table 2 Syngas Composition by Volume

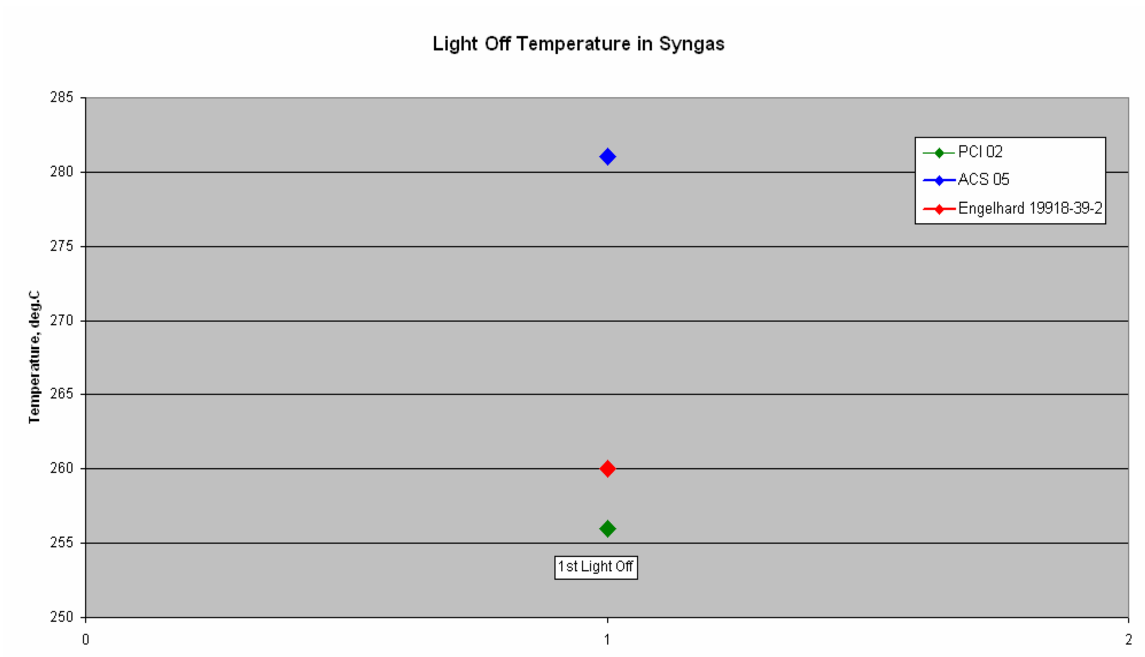

Figure 8 Lightoff Data on Syngas

Figure 9 Red Coating from Operation on Syngas

HYDROGEN LIGHTOFF STUDIES

Hydrogen lightoff tests were performed on the PCI coated tube. The purpose of this study was to confirm catalyst activity and verify the applicability of the catalytic design to hydrogen fuel. In order to be conservative, hydrogen testing was performed at an air split of 5%. As Table 2 shows the lightoff of the catalyst on hydrogen was not an issue. Lightoff was obtained at temperatures as low as 42 C. After lightoff the air temperature increased to approximately 230 C. Under these conditions the split was increased to 7%. As expected the higher split resulted in an increase in both catalyst and gas exit temperatures. It was not possible to obtain temperatures above 230 C because of excessive temperatures in the down stream pipe after the catalyst exit section. With the current design the velocities in the down stream pipe were not large enough to prevent a flame during hydrogen operation. The rig was been redesigned to reduce the pipe diameter in the down stream section. Further testing will be performed on the single tube rig to optimize the design for hydrogen. Higher splits will be tested.

Inlet Temp	Cat Temp	Exit Temp	Air Split
72 C	214 C	132 C	5%
42 C	175 C	103 C	5%
235 C	350 C	290 C	5%
234 C	454 C	314 C	7%

Table 3 Hydrogen Lightoff Data

Task II.4 – Development of Catalytic Module

Module Test Results

For phase II of the program the module testing was moved to the Siemens small industrial turbine facility in Lincoln, England. This facility has the capabilities to test a catalytic module at full SGT-6-5000F conditions on both natural gas and syngas fuels. Previous testing at Solar Turbines was limited to scaled FD conditions and natural gas. As part of this program a new module design, module 8 was created. Module 8 uses the basic flared tube design with the fuel injection manifold redesigned to include the capability for syngas operation. By using the flared tube design in these tests it is possible to obtain a good baseline comparison with the results obtained at the new facility to the previous testing at Solar Turbines.

The module design with the two fuel manifolds in shown in Figure 10. Two separate fuel feeds are required for natural gas and syngas. This is due to the fact that the flow rate of syngas to the module is significantly higher because of its lower heating value. The injection hole pattern for each manifold was optimised using CFD analysis. It is not possible to obtain a single injection hole pattern that would work acceptably for both fuels. Figure 11 shows the final assembled module 8.

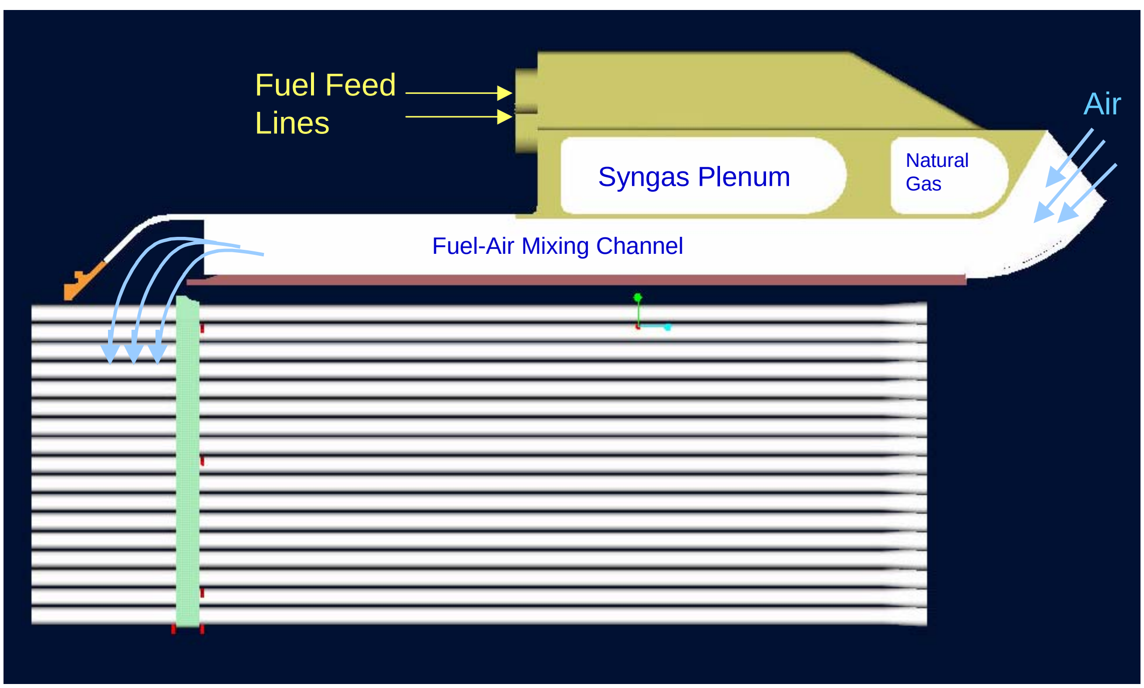

Figure 10 Module 8 with Dual Fuel Injection (Syngas and Natural Gas)

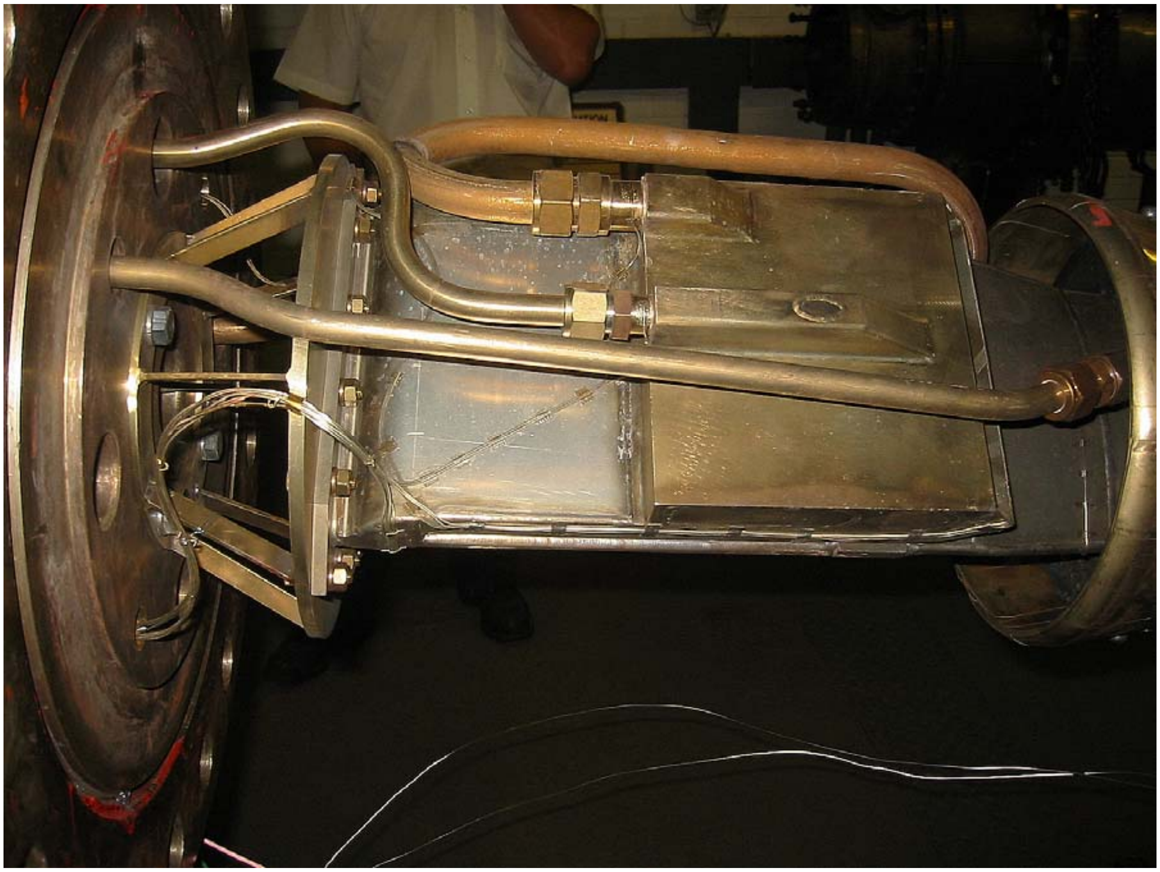

Figure 11 Module 8 Assembled to the Cover Plate

Because of limitations of the compressor at Solar Turbines it was not possible to test the module at full pressure FD conditions. For these tests the flow function was matched and the module pressure was reduced from 17 bar to 12 bar. The PGI facility has a higher capacity compressor, it is now possible to perform module tests at full FD conditions. For the baseline comparison several reduced pressure points from the previous test program at Solar were reproduced in addition to the full pressure points. An AFR sweep was performed at full FD conditions to determine the performance of the module as a function of firing temperature. Figure 12 shows the results from this round of tests compared to the previous tests at Solar. The reduced pressure tests at PGI match well with the July 2002 Solar tests but are slightly higher than those obtained in January 2002. In the January 2002 Solar test program the module exit was sealed tightly with a low leakage seal which did not allow properly for thermal expansion. This seal was replace with a spring clip on subsequent testing. The spring clip allows for thermal expansion but results in roughly 5% of the air bypassing the catalytic module. When the data was corrected for the differences in leakage caused by the spring clip, the data from all three test campaigns are essentially the same as can be seen from Figure 13. The data obtained at full pressure shows a slight increase in NOx emissions as would be expected.

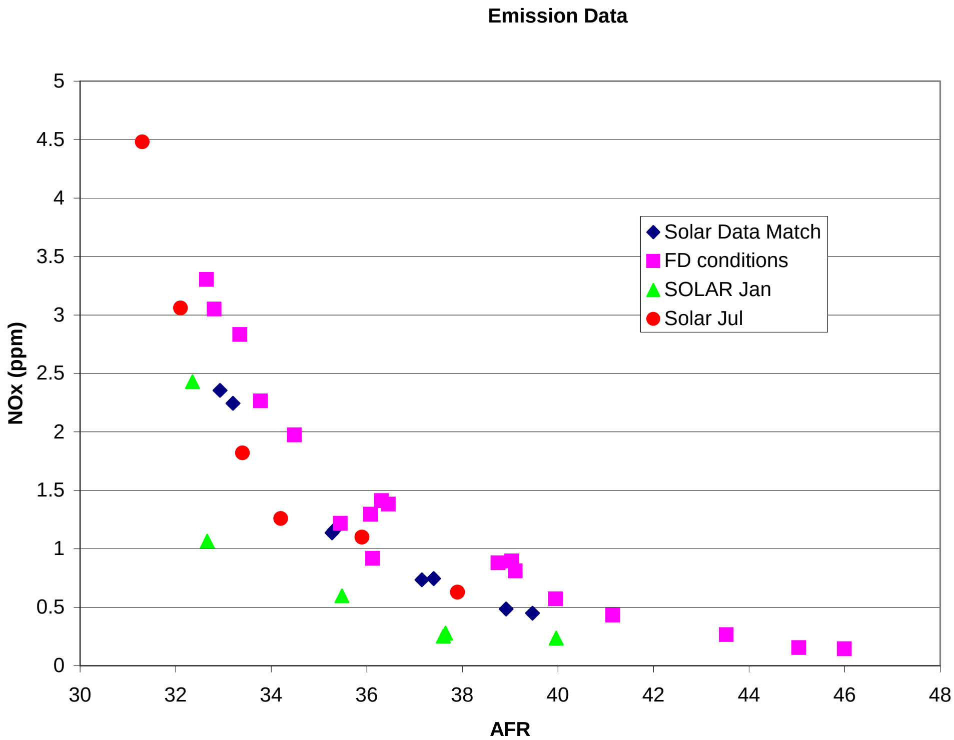

Figure 12 Comparison of Module Test Data at Solar and PGI

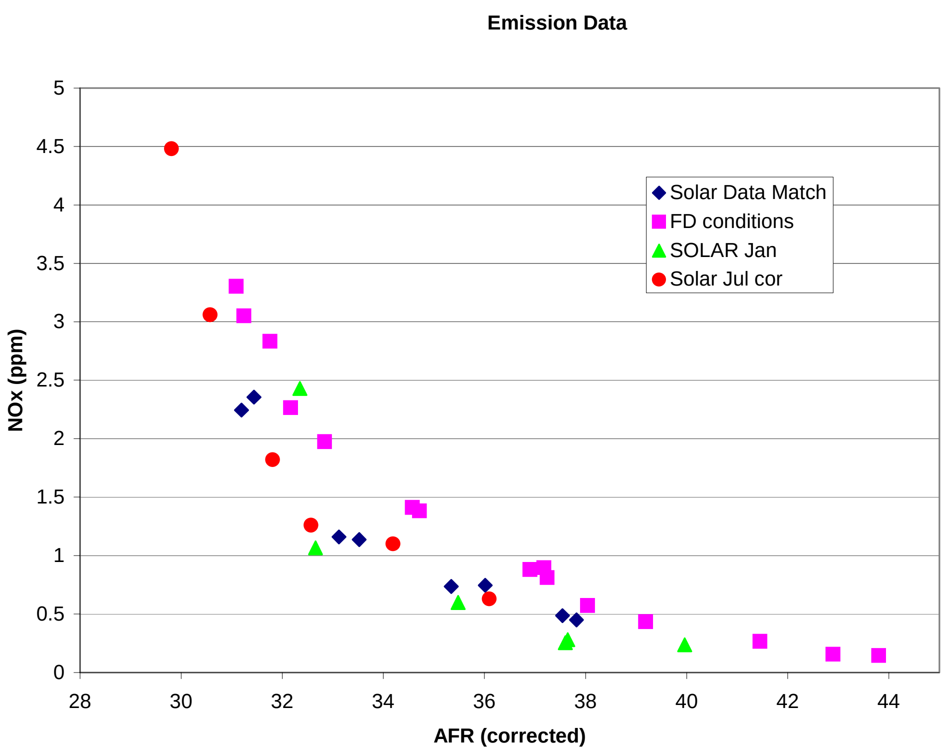

Figure 13 Module Test Data Corrected for Spring Clip Leakage

Figure 14 shows the data obtained on module 8 as a function of temperature. The CO emissions were negligible until just before the flame blew out at 1300 C. The NOx emission targets of the program (2 ppm) were met with the module testing up to a temperature of 1560 C.. The next step in the module test program is to evaluate the module 8 performance on syngas and evaluate the performance of alternative module technologies.

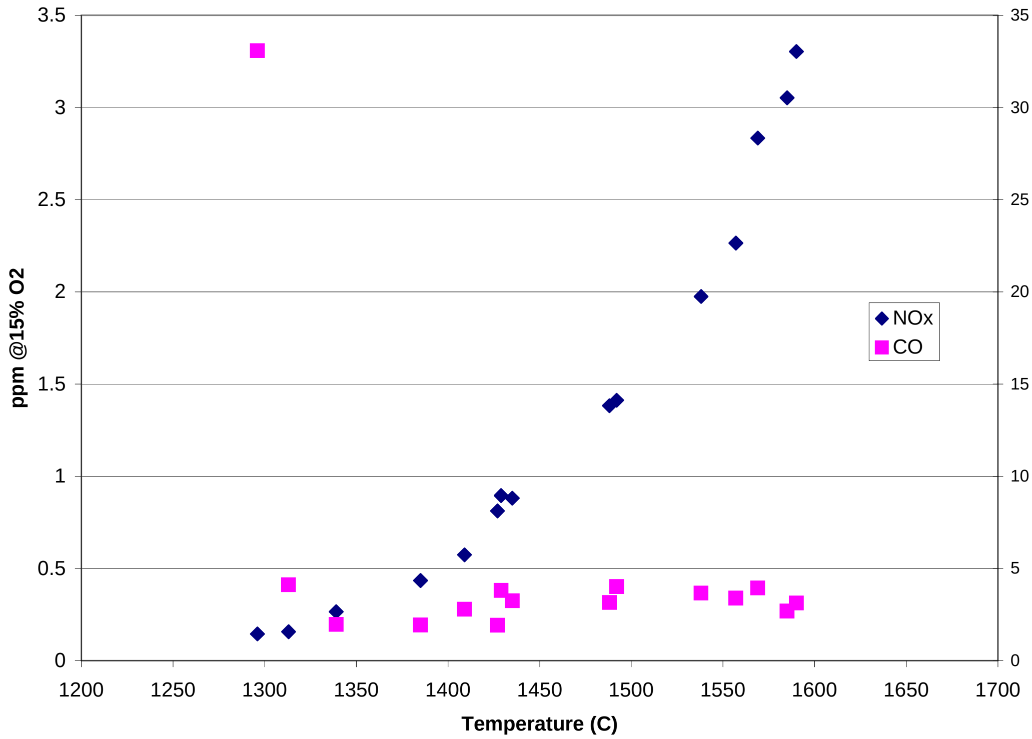

Figure 14 Module 8 Test Results as a Function of Firing Temperature

Gas samples of the reacting mixture were obtained from the inlet to the catalytic section and a a point near the exit of the catalyst. These samples were analysed using an online gas chromatograph. From the gas chromatograph results it was determined that the flow split was 13%. This split is slightly lower than the design value of 15% but is consistent with previous data on the flared tube design. The fuel conversion rates measured were 19-22% and the oxygen conversion rates were roughly 60%. The measured catalyst temperatures and module gas exit temperature are compared to modelling results in Figure 15. Measured temperatures were slightly lower than those from the model. The measured catalyst temperature is roughly 700 C and the measured gas exit temperature is 550 C. The is well below the design limits. Future work will look at increasing the air split and fuel conversion.

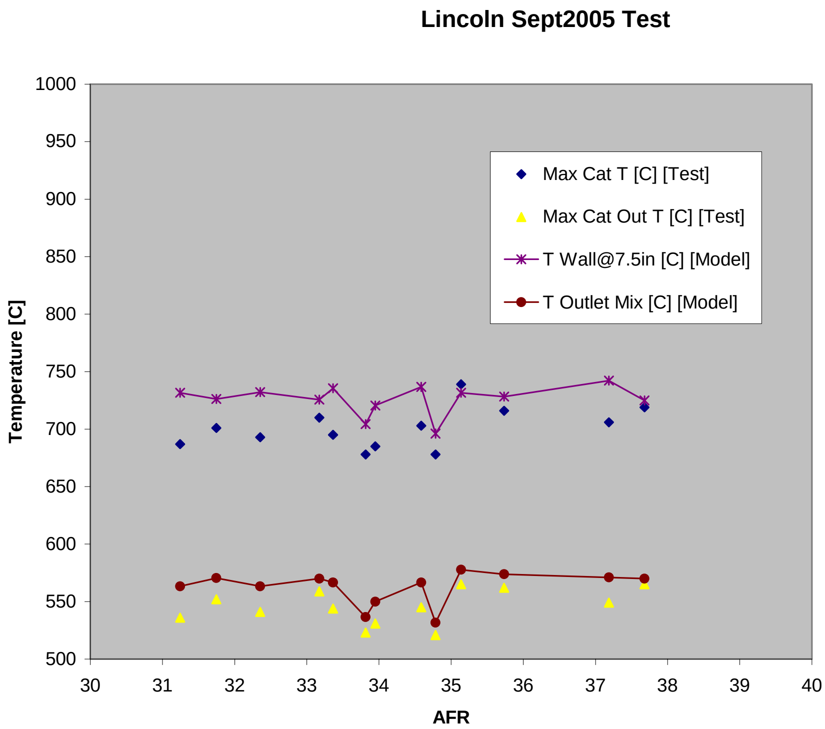

Figure 15 Temperatures in the Catalyst Section

STATUS OF MILESTONES

First Quarter

10/1/04-12/31/04

Obtain Light off data on SWPC coating on both natural gas and syngas.

Status: complete

Second Quarter

1/1/05-3/31/05

Modify basket design to 501F configuration required for syngas tests.

Status: complete

Third Quarter

4/1/05-6/30/05

Flashback testing in the 60 tube rig

Status: complete

7/1/05-9/30/05

Subscale Testing on hydrogen

Status: complete

CONCLUSIONS

The major accomplishments during this phase of the project are:

- 60 tube rig was operational and flashback studies were performed on the redesigned capture plate.
- Screening tests were performed on natural gas for several coatings. Still need to optimise the precious metal concentrations and substrate composition. Work continues with five outside coating suppliers.
- Initial durability tests were performed at elevated temperatures.
- Module test facility at the Siemens PGI location in Lincoln, England is operational.
- The baseline module with the syngas/natural gas manifold was tested on natural gas at the PGI facility. The results compared well with previous testing at Solar Turbines. The new facility was able to provide data at higher pressure and temperature than the previous tests.