Low Emission Gas Turbine Combustor Field Demonstration

Final Report

FOR

California Air Resources Board

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DISCLAIMER

The following report presents work completed on ARB Contract Number 96-337 entitled "Low Emission Gas Turbine Combustor Field Demonstration." This project was performed by Catalytica Combustion Systems, Inc. (CCSI) for the California Air Resources Board. This final report covers all tasks up to February 26, 1999.

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ABSTRACT

A catalytic combustion system design and development program has been successfully completed with the first gas turbine field demonstration with an ultra low emission catalytic combustion system. The program was initially intended to provide a retrofit catalytic combustion system for a Pratt & Whitney FT4 gas turbine. A parallel development program for the Kawasaki M1A-13A gas turbine used the same combustor with little modification. Reevaluation of the two programs led to the conclusion that a field demonstration with a single combustor on the M1A-13A gas turbine had a greater probability of success. The FT4 program was put on hold until the field demonstration with the M1A-13A gas turbine was complete. The testing demonstrated that the combustion system was capable of operating over a range of power levels with NOx emissions less than 3 ppm and CO emissions at less than 10 ppm. It also showed that a catalytic combustion system could operate under the conditions imposed by the utility grid. The next step in system development beyond CARB participation is completion of an 8000 hour RAMD (Reliability, Availability, Maintainability, Durability) test to demonstrate catalyst durability. Commercialization will follow RAMD testing.

EXECUTIVE SUMMARY

The concept of catalytic combustion has been recognized as the ultimate solution for NOx control in gas turbines for over 20 years. Many research companies have tried to solve the problems associated with its application. None have succeeded until the technological breakthrough by Catalytica Combustion Systems, Inc. (CCSI) with XONON™ Flameless Combustion.

CCSI has worked on this technology since 1988 and to date has invested over $20 million in development programs and in research and testing facilities. As part of the development programs, CCSI has installed at its Mountain View facility two sophisticated high-pressure sub scale combustor test rigs which simulate the conditions present in a gas turbine combustor. With these test rigs, catalytic combustion reactors can be operated at the actual conditions of a gas turbine combustor, including simulation of start-up and shut down. Atmospheric test capability has also been added to the Mountain View facility for XONON combustion system component testing. A XONON Technology overview is found in Appendix A.

CCSI has developed the basic technology, the specialized materials and the fabrication procedures that are part of this XONON technology. The technology has been demonstrated in CCSI's high pressure test facilities at conditions typical of modern gas turbine engines. Test results show that XONON technology can achieve emission levels of <3 ppm NOx with CO and UHC levels <10 ppm. In addition, CCSI has developed technology needed to interface the XONON catalyst module with the gas turbine including the structural support and container for the catalyst and required fuel injection technology.

CCSI has programs with the major turbine manufacturers including GE, Solar Turbines, and Rolls Royce Allison to apply catalytic combustion technology to new gas turbines. In CCSI's joint program with General Electric, full scale tests have been performed at turbine operating conditions in the laboratory in a single catalytic combustor. The single can is one of 10 cans of the GE MS9001EA series gas turbine, a 105 MW gas turbine used for electric power generation with a combustor discharge temperature of 1250°C (2280°F). The tests demonstrated for this particular catalytic reactor design ultra low emissions and the potential for turbine grade durability. Emissions of less than 3 ppmv NOx were achieved at baseload conditions. The basic design approach was the starting point for the XONON 2 program addressed in this report. The XONON 2 program picks up where the earlier programs left off and takes the technology to commercial field demonstration and availability to the power generation and mechanical drive markets.

The XONON 2 combustion system includes the combustor with catalyst module, control system, and fuel delivery system. The combustor design and development was accomplished by CCSI. The first catalytic combustion system (XONON 1) design was done by the Agilis Group in West Palm Beach, Florida under CCSI's direction. The

XONON 1 work was not a part of the ICAT program. Initial design for the XONON 2 system was also done by the Agilis Group, but the finalization of the preburner and mixing systems was done by CCSI engineers based on testing and Computational Fluid Dynamics (CFD) analysis. The Woodward Governor Company designed and developed the controls and fuel delivery system with assistance from CCSI. Both companies performed component development testing on system hardware in preparation for the engine demonstration.

The first gas turbine testing with a catalytic combustion system (XONON 1) was done on a Kawasaki M1A-13A gas turbine. The gas turbine was installed in a production test cell at AGC in Tulsa, Oklahoma and operated with a water brake dynamometer. Several modifications were made to the initial design based on information gathered during testing at typical industrial operating conditions. Various control strategies were tested to provide the required fuel scheduling for acceleration to full speed at no load (FSNL) while limiting catalyst and metal temperature rise rates and temperature distribution. Fuel strategies were also tested to accelerate the system from FSNL to full power in response to demand. This work was successfully completed with the measurement of full load NOx levels of less than 3 ppm. Before completion of testing at AGC, a 1000 hour endurance test was run to gain experience with catalyst durability and gas turbine operation over extended periods.

XONON 1 testing at Tulsa showed that a gas turbine could operate successfully with catalytic combustion. It also showed that the NOx emission targets of less than 3 ppm could be reached. One feature of commercial operation that was not measurable was the reaction to the demands of the electrical grid. The plan was to move testing to another site at which operation against the grid was possible.

A Kawasaki M1A-13A gas turbine generator set was purchased by CCSI for continued combustion system testing. The generator set was for demonstration at the CCSI test facility in Santa Clara, California, where the generator could be connected to the utility grid. Prior to testing, the system was shaken down with the XONON 1 catalytic combustor used in testing at Tulsa and subjected to source testing for the air quality permit. Permitting was accomplished and testing began on the XONON 2 combustor.

Testing at the Santa Clara test facility was planned to demonstrate the combustor's ability to automatically connect to the utility grid, operate continuously on the grid, to react to sudden load sheds and to operate at the target emission levels. During this time, the controls were also tuned to provide the stability necessary to handle the demands of the grid. The conclusions drawn from demonstration are that the system (1) is capable of operating continuously while connected to the utility grid, (2) can be reliably and repeatedly started and auto synchronized with the grid, (3) and can be operated and controlled in a manner to meet the emission requirements.

The ICAT program funding covered the design of the XONON 2 combustion system components and assemblies for rig test as well as the engine-ready hardware demonstrated on the gas turbine. It also covered the design and construction of the test facilities at Mountain View and Santa Clara and the installation of the Kawasaki generator set, system shakedown, as well as the field demonstration of the XONON 2 combustion system operating against the utility grid. The results discussed in this report are for the entire combustion system program through field demonstration at the Santa Clara Test Facility.

It is intended that a commercialization plan be implemented to introduce the tested system into commercial operation on Kawasaki M1A-13A gas turbines. It is also expected that this commercialization program will provide valuable data and information directly useable in the application of XONON combustion systems on a variety of other gas turbines.

INTRODUCTION

For many years, companies have been looking for a way to apply catalytic combustion to gas turbines. The reason for this application is to cost effectively reduce emissions from the gas turbine exhaust below currently achievable levels. CCSI has been working on the application of catalytic combustion since 1988 and has patented a process unlike those used by others. The purpose of this field demonstration program is to continue combustion system development and to demonstrate the commercial viability of the system on a gas turbine.

The XONON 1 combustion system development program began in 1995 which led to the first gas turbine operation with catalytic combustion in 1996 at the AGC engine test facility in Tulsa, Oklahoma. The XONON 1 system design and development was accomplished through the combined efforts of CCSI, The Agilis Group in West Palm Beach Florida, and Woodward Governor Company in Loveland, Colorado. The testing on a Kawasaki M1A-13A gas turbine was successfully completed at the AGC test facility after eighteen months of intense activity. The system reached NOx emission levels of less than 3 ppm at engine operating conditions. A 1000 hour endurance test completed the XONON 1 program. Examination of test data and inspection of the catalyst module following the 1000 hour test indicated a need for design changes for structural as well as performance reasons.

The structural issue that became apparent dealt with the catalyst module component that contains the second stage catalyst and is exposed to the catalyst outlet temperature. This component is a honeycomb structure intended to provide maximum support with minimum interference to the gas flow. Based on the information collected from Tulsa, the design was changed for XONON 2. A separate program, funded by the California Energy Commission, was initiated to deal with the materials, design, and manufacturing process aspects. Finite Element Analysis of the resultant design indicates that the component will achieve its design life.

The performance issues requiring attention were related to preburner turndown, recirculation in the gas flowpath upstream of the catalyst face, and uniformity of the fuel/air mixture and temperature at the catalyst face. Since the majority of NOx comes from the preburner, it is essential that the preburner temperature be kept as low as practical during all steady state modes of operation. For expected catalyst life, flameholders are unacceptable upstream of the catalyst face. For optimized combustor performance, it is essential that the gas temperature coming from the catalyst is as uniform as possible. This is a function of the uniformity of the fuel mixture and of the temperature of the mixture entering the catalyst.

The XONON 2 combustor development program began before the XONON 1 program was completed. As with the XONON 1 program, CCSI, the Agilis Group, and Woodward Governor provided the majority of the engineering support. Extensive amounts of Computational Fluid Dynamics (CFD) and Finite Element Analysis (FEA) for both stress and thermal evaluation were used. The providers of CFD were ADAPCO and Combustion Science and Engineering, Inc., both of which are industry leaders. The FEA was provided by experienced CCSI engineers.

Prior to the beginning of the XONON 2 program, a XONON 4 program was started to develop a combustion system for the Pratt & Whitney FT4 gas turbine with the City of Glendale as a participating customer. This was the program that was initially intended to provide the ICAT field demonstration. It was determined that the operating conditions for the single combustor on the Kawasaki M1A-13A gas turbine were very close to the operating conditions for a single combustor for the Pratt & Whitney FT4 gas turbine. This allowed for parallel development with shared technology. With the commonality in mind, the XONON 2 program began as a companion program with the FT4 to provide the next version of the M1A-13A with the initial emphasis being placed on the FT4.

Well into the XONON 4 program, a decision was made to change emphasis from the FT4 XONON 4 program to the M1A-13A XONON 2 program. This was done with engine demonstration in mind. Initially the FT4 field demonstration was planned to occur at a Florida Power and Light facility. FP&L subsequently declined to participate and the field demonstration site was replanned for Glendale. After further analysis of the demonstration test complexity, it was decided to change emphasis to the M1A-13A program since only one combustor rather than eight was required for testing. This would greatly reduce the controls development and take away the effect of multiple combustors for the initial field demonstration. At this same time, California Air Resources Board was notified and a change was made to the ICAT contract allowing the field testing to occur at Santa Clara on the M1A-13A gas turbine.

The XONON 2 design is based on XONON 1 experience as well as CCSI core technology development. The combustor mounts directly on the gas turbine interface flange (Figure 1). Figure 2 shows a XONON 2 combustor in the horizontal position. The air from the engine air compressor flows through the annular region between the combustor case and the inner hot gas flowpath. The preburner is located in the upper region of that annulus before the air turns radially through the mixer (swirler) and reverses direction to pass through the catalyst. The preburner function is to preheat and maintain the compressor air at catalyst activation temperature. The purpose of the mixer is to premix the catalyst fuel with the preburner exit gas and to present it at the catalyst face at the required fuel-air ratio uniformity. Downstream of the catalyst is the burnout zone in which the unburned hydrocarbons and CO are burned out to the design levels. The burnout zone liner is the interface with the engine hot gas path to the turbine inlet.

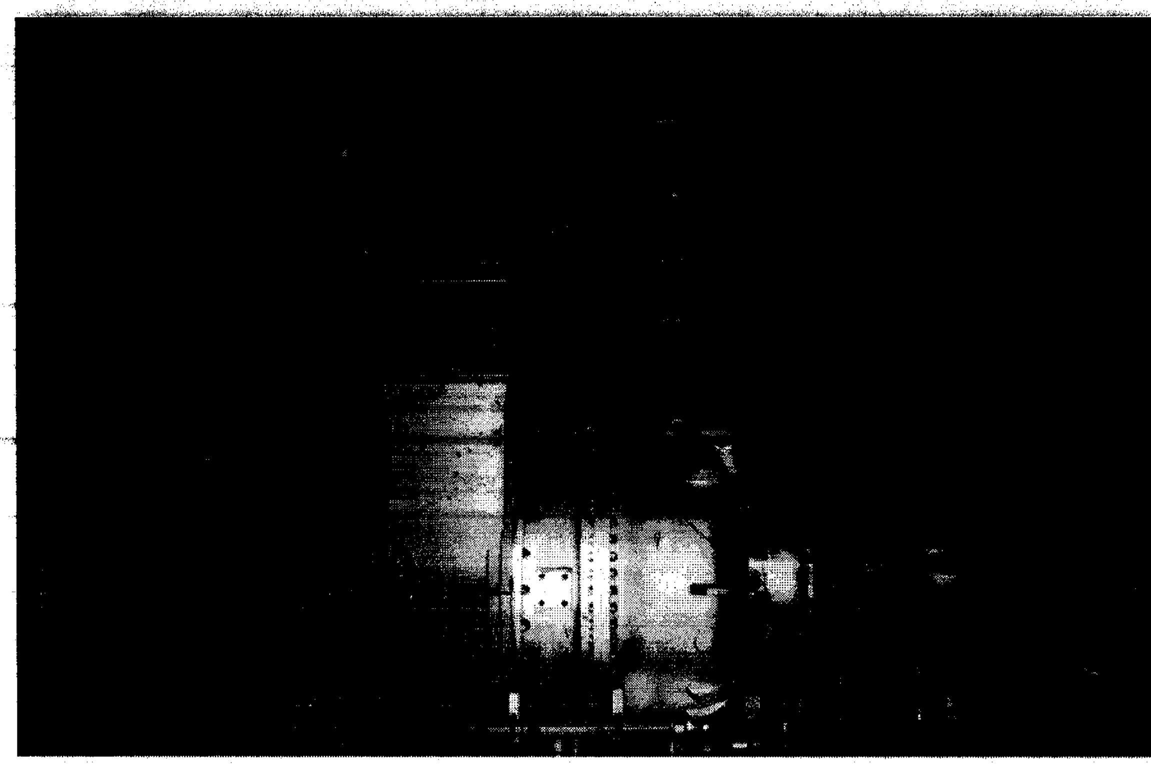

Figure 1
Kawasaki M1A-13A Gas Turbine on Test in Tulsa, Oklahoma

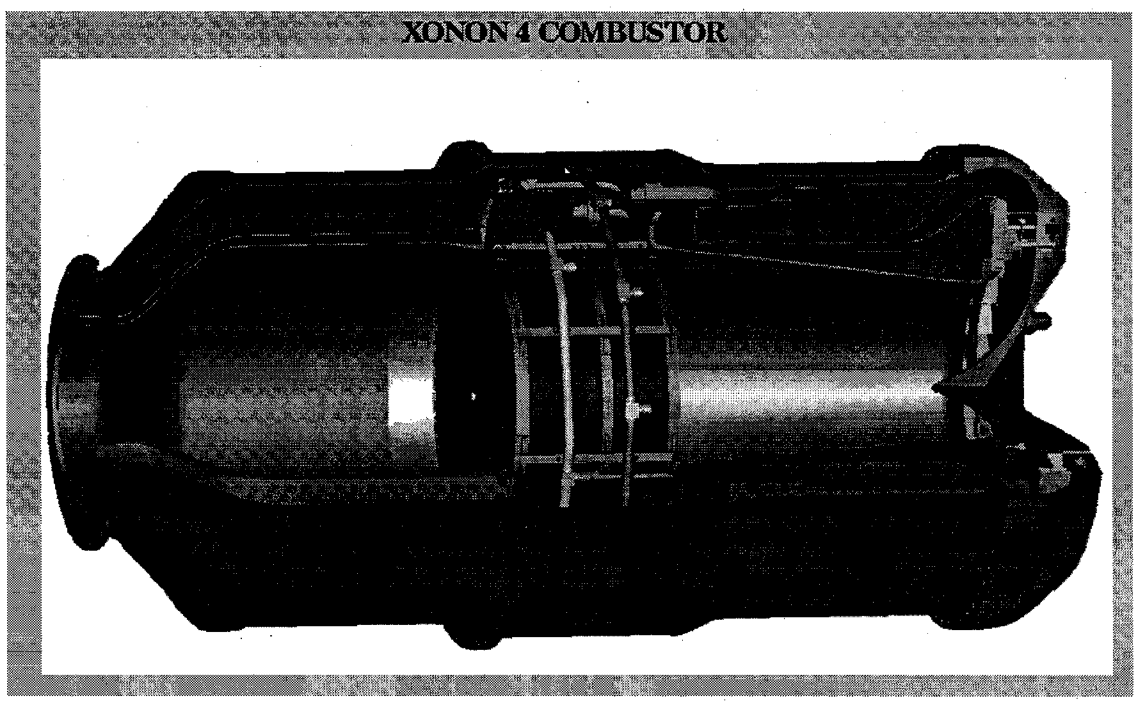

Figure 2
XONON 2 Combustor for Kawasaki M1A-13A Gas Turbine

DESIGN AND DEVELOPMENT

The same XONON 1 catalyst design was maintained for the XONON 2 catalyst. Testing at Tulsa provided no new information that would cause a change in the catalyst composition. The catalyst demonstrated the ability to reach the expected emission levels and further refinement of the design will be dependent on revelations from XONON 2 testing and/or core technology development. The operating window (see Appendix A) appeared to be sufficient for additional testing with the XONON 2 combustor configuration.

For assembly and containment in the combustor, the catalyst must be installed in a container. The container must provide rigid axial support but must not restrain growth of the catalyst in the axial or radial directions. The container must interface with the combustor in such a manner so as not to constrain its growth in either direction. During transient startup and shutdown as well as steady state, the catalyst and container hardware are subjected not only to high temperatures but also high differential temperatures. During startup, the components with thin materials in the container heat up and expand thermally much faster than some of the heavier components. During shutdown, the thin components cool faster than the heavier components. Features present in the design allow components to expand at different rates without damage. Materials and clearances are of great importance. The design worked well in XONON 1 and was maintained for XONON 2. There were some minor modifications caused by interface changes in the XONON 2 combustor design.

The XONON 1 radial fuel/air mixer concept was retained for XONON 2. Fuel/air uniformity measurements showed excellent results. Analysis of the XONON 1 flowpath between the mixer and the catalyst face indicated that a rather large amount of recirculation was present. This was verified by atmospheric rig testing, CFD analysis, and by periodic ignition events seen through observation windows in the combustor during engine testing. These ignition events were believed to occur in the recirculation zones as a result of burning solid objects discharging from the preburner. At this time, the source of those objects has not been determined. One possible source was from the inlet air. The Tulsa test facility did not include an inlet air filter. Dust or other particles in the air could have ignited in the preburner and passed into a recirculation zone causing ignition. It was apparent that these ignition events were not allowable from a safety or availability perspective because of the resultant catalyst inlet high temperature shutdown..

Extensive analysis went into the XONON 2 redesign of the radial fuel/air mixer to maintain the fuel/air uniformity as well as to eliminate the large recirculation zones. A combination of CFD analysis and atmospheric rig test validation of the CFD was used to identify the recirculation problem and correct it. Rig test hardware was instrumented with (1) static and total pressure taps for wall flow characteristics, (2) pressure rakes to measure profiles across the flow path, and (3) yarn tufts to provide visual comparison with the pressure measurements. This was done with a variety of radial mixing vane configurations to influence the flow dynamics within the flowpath. The result of this work was a swirler design which not only provided the required mixing and fuel/air uniformity at the catalyst face, but also a flow path free of recirculation. Engine testing has proven this to be true. There have not been any shutdowns in the 53 hours of XONON 2 testing as a result of ignition upstream of the catalyst.

The XONON 1 preburner configuration was four individual can combustors evenly spaced in the annular preburner flow path. For XONON 2 an annular preburner was believed to be capable of better preburner outlet temperature uniformity as well as lower preburner temperature turndown. Extensive analysis and testing was accomplished with the new preburner design. Several atmospheric tests were done at the CCSI Mountain View facility. These tests were designed to provide visual analysis of the burner operation and temperature uniformity analysis. They resulted in a preburner design that showed good potential for the engine configuration

With a promising preburner design resulting from the atmospheric rig tests, testing was shifted to the high pressure test rig at the Caterpillar Research Facility in Mossville, Illinois. The high pressure testing was planned to provide correlation between high pressure test data and atmospheric test data. A camera was installed in the test rig to allow observation of the flame to evaluate its location and characteristics. During testing the camera position was changed so that the attachment point of the flame could be identified. Initial testing showed that the flame was inconsistently stabilizing in two locations. This was thought to be so because of a lack of a distinct flame holding feature. Flame stabilizing devices were added which subsequently provided the required stabilization. After further performance tuning based on analysis of the test data, a traditional bluff body design configuration was selected to provide the flame holder. Based on the results from rig testing, this configuration was included in the combustor design for testing with the Kawasaki M1A-13A at the CCSI Santa Clara test facility.

The remainder of the components in the combustor did not require the rigorous testing given to the mixer and the preburner. With the exception of the burnout zone liner downstream of the catalyst, the remaining major components were the external pressure containment parts. These parts were subjected to the design analyses required by code for operation in an industrial environment. FEA was used on the dome section because of the combination of high pressure and temperature. Less rigorous analyses were used for the other pressure containment parts. FEA was used for the liner downstream of the catalyst to evaluate its buckling resistance.

The fuel control system and the fuel delivery system design and development was done by the Woodward Governor Company. The fuel system consists of fuel supply for the primary and secondary burners in the preburner and main fuel supply for the catalyst. The engine conditions require that the preburner operate during all modes of operation to assure sufficient mixture temperature entering into the catalyst. Because of these three separate supplies, the control and fuel delivery systems are more complex for a catalytic combustor than for a common diffusion flame combustor. Precise scheduling and timing to control the startup, maintain constant load, and react to transients including load shedding is essential. The control system needs to monitor all critical functions for protection and control. It must also provide for autosynchronization of the main breaker with the grid prior to closing.

The design of the fuel control system included the construction of a simulator to allow logic testing prior to engine testing. With the simulator, Woodward was able to evaluate system performance at steady state and transient conditions. The result was a system ready for engine testing and the associated tuning.

Initial testing of the control logic used with the XONON 2 system was done in Tulsa on the XONON 1 system. Since this was the first time for catalytic combustion to operate on a gas turbine engine, extensive attention was given to the control logic for all modes of engine operation. The same basic successful control system was taken from Tulsa and installed at Santa Clara for the XONON 2 testing.

FIELD DEMONSTRATION

The initial gas turbine testing for the XONON combustion system was done at the AGC test facility in Tulsa, Oklahoma. This testing was done with a water dynamometer and provided the opportunity to integrate the controls and fuel system with the gas turbine, to measure the performance of the catalyst, and to test the concepts for the other components in the combustor which support the catalyst operation. A great deal of good information was gathered, but one bit of very important data was the reaction of the system to step loading and load shedding common with the utility grid.

The construction of CCSI's Santa Clara test facility (Figure 3) was accomplished to provide a test facility to demonstrate the operation of catalytic combustion in a commercial application connected to the utility grid. The Santa Clara test facility site is on the grounds of the Silicon Valley Power Gianera Power Station in Santa Clara, California. The site preparation included grading, laying of foundations, electrical conduit trenching, and the installation of equipment. An existing Kawasaki M1A-13A generator set was modified for the installation of the XONON combustor. The modified generator set was installed and anchored to a newly constructed foundation (Figure 4). A trailer was located adjacent to the generator set to provide the control room and installation of the control system including the controls for the XONON combustion system. A utility circuit breaker was installed to interconnect with the generator switchgear. The engine fuel system was connected to the fuel supply for the existing Silicon Valley Power GE Frame 5 peaking generator sets.

Figure 3
Santa Clara Test Facility

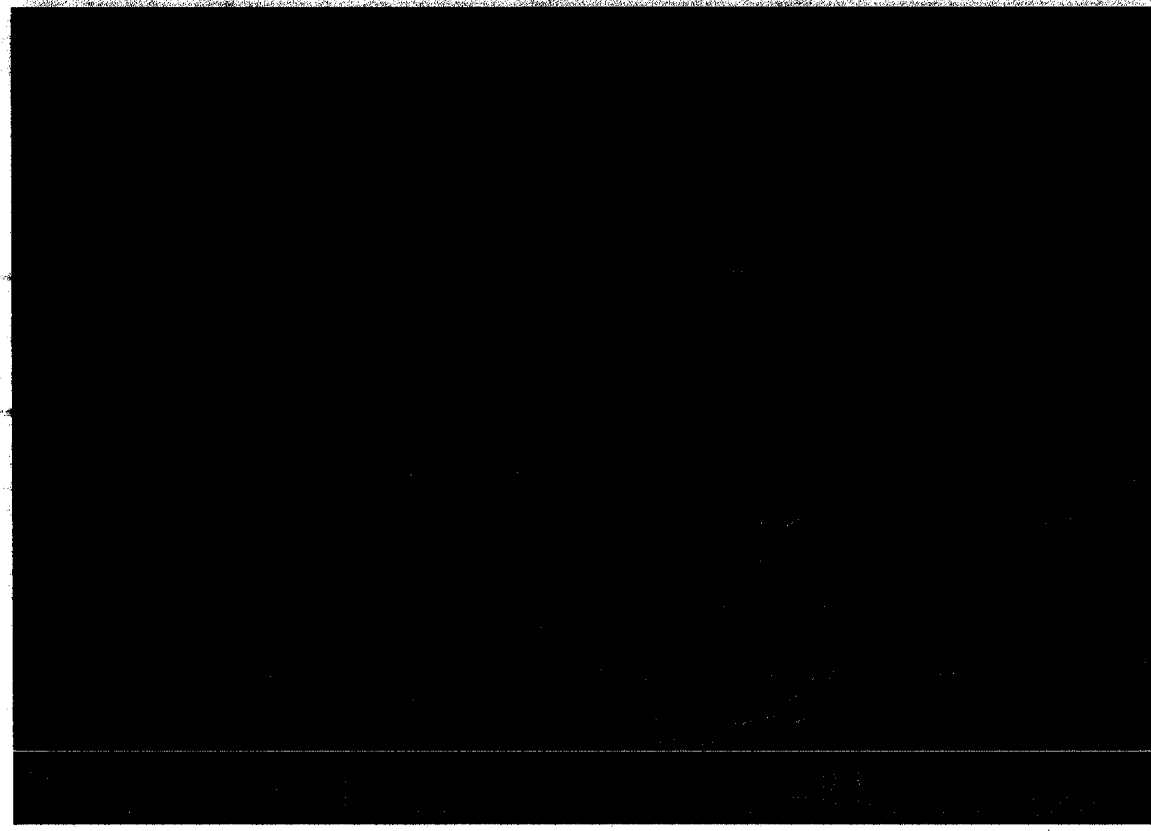

Figure 4
Modified Kawasaki M1A-13A Generator Set

The objective of the testing at the Santa Clara test facility was to demonstrate a commercially acceptable catalytic combustion system on a gas turbine driven generator set engine connected to the utility grid. The goals were (1) to operate the system over an entire range of conditions while connected to the utility electrical grid, (2) to make adjustments to the control system to assure safe operation, and (3) to demonstrate operation at NOx emission levels no greater than 3 ppm. In addition to the testing to achieve the objective, this task included the design work for and the construction of the CCSI Santa Clara Test Facility.

The testing began in mid October, 1998 with shakedown of all equipment and systems. Initial shakedown was with the XONON 1 system since this system had been previously run successfully. In mid November, the unit was connected to the utility grid. This was an historic event in that it was the first time that a gas turbine with a catalytic combustor had operated against the grid. This was also the first system to operate at less than 3ppm NOx on the utility grid without exhaust gas cleanup. The system then was successfully source tested for completion of the air quality permit process. The local Continuous Emissions Monitoring System was calibrated to provide validation for all future system emission measurements. The XONON 1 combustor was then removed and replaced with the XONON 2 combustor for field demonstration.

Initial testing of the XONON 2 was planned to tune the fuel scheduling to provide for reliable and repetitive startup and steady state operation. Within a short period of time, the engine was taken to full power and the emissions measured. Without further tuning, the engine achieved its NOx target of less than 3 ppm and its CO target of less than 10 ppm. Figure 5 shows typical near full-load emissions results for a subsequent test.

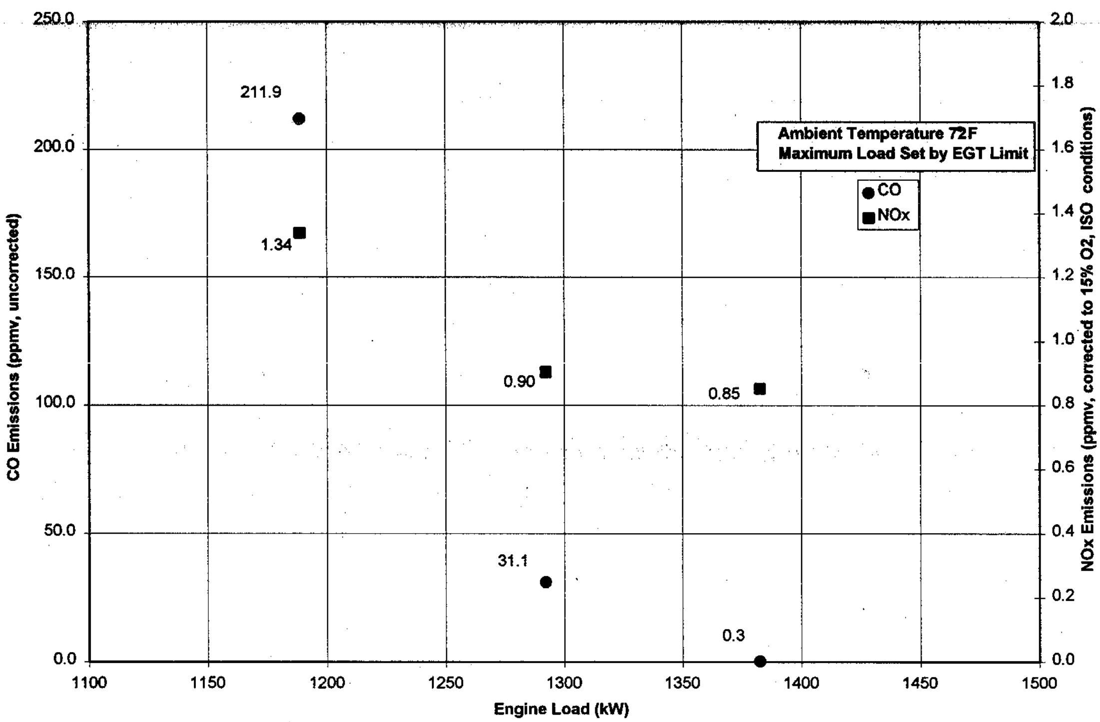

Figure 5
CO and NOx Emissions Verses Load for XONON 2

Additional tuning was done to the controls to adjust fuel schedules and start time. Combustor performance mapping was also accomplished. A total of 53 hours and 26 starts were accomplished before the demonstration was completed and the combustor disassembled for inspection. The inspection revealed some material distortion in the swirler section. Subsequent analysis revealed rapid transient temperature changes early in the controls tuning are likely to have caused this condition. As a preventative measure, the swirler was redesigned to remove some of the growth restraints that existed in the original design. These components are in the design phase and are not yet ready for production. Details of their construction are considered proprietary, however, design prints are available for viewing by the California Air Resources personnel at the CCSI Mountain View facility.

TEST RESULTS

Preburner turndown

This testing showed that the preburner is operating as expected, in terms of primary zone lean blowout equivalence ratio (LBO phi) and minimum temperature rise. NOx emissions of less than 3 ppm were measured at high load. NOx emissions are higher at low load due to the shift in preburner primary zone airflow.

A primary zone turndown was conducted at 1000kW to determine the lowest temperature rise that the primary could support. The target was to turn down enough to allow stable operation at a catalyst inlet temperature of 435C. To achieve this, the primary zone air was reduced.

Figure 6 shows the NOx emissions as a function of preburner outlet temperature. As can be seen, the preburner can operate down to 847F (452C) which corresponds to a catalyst inlet temperature of 799F (426C); the target was achieved.

Figure 6 also shows the shift in NOx emissions with reduction in primary airflow. At a fixed preburner outlet temperature (corresponding to a given preburner fuel flow), the NOx increased as expected. This increase is due to the increase in primary zone fuel to air ratio which results in a locally higher flame temperature in the primary zone.

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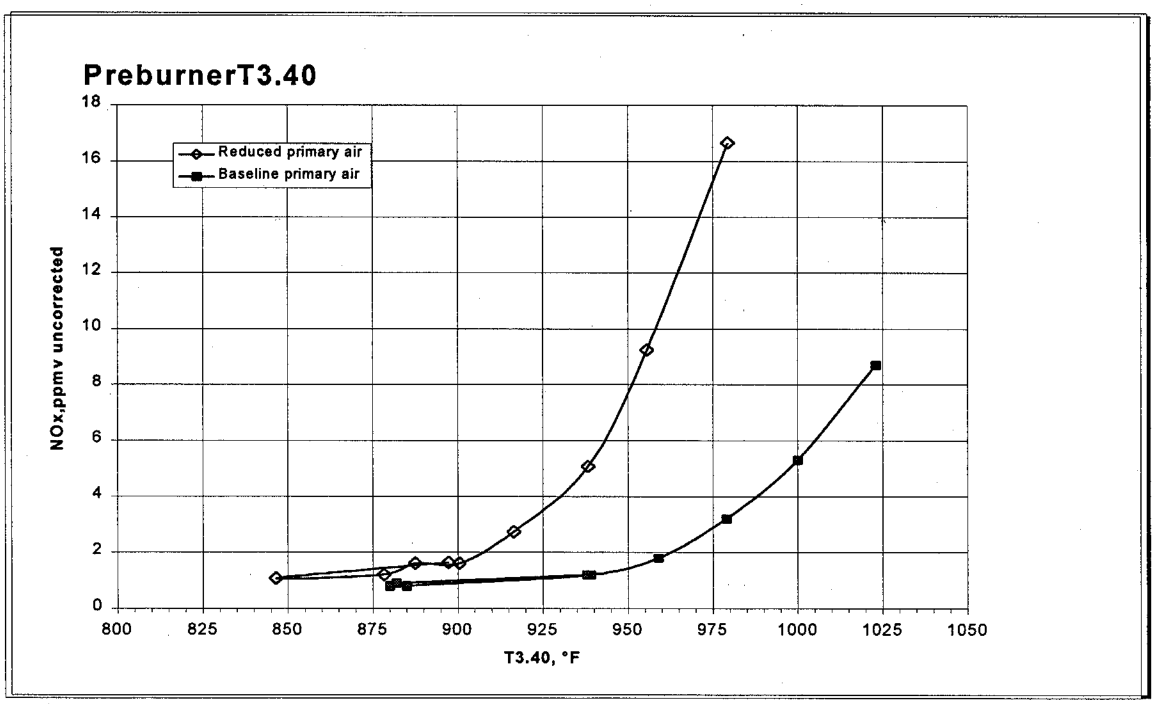


Figure 6
NOx vs. Preburner Outlet Temperature at 1000kW

Catalyst Fuel/Air Uniformity

A Fuel/Air (F/A) scan was conducted at full load with the result shown in Figure 7. The premixer is functioning within specification and providing a F/A uniformity of +/- 0.72% at the catalyst face.

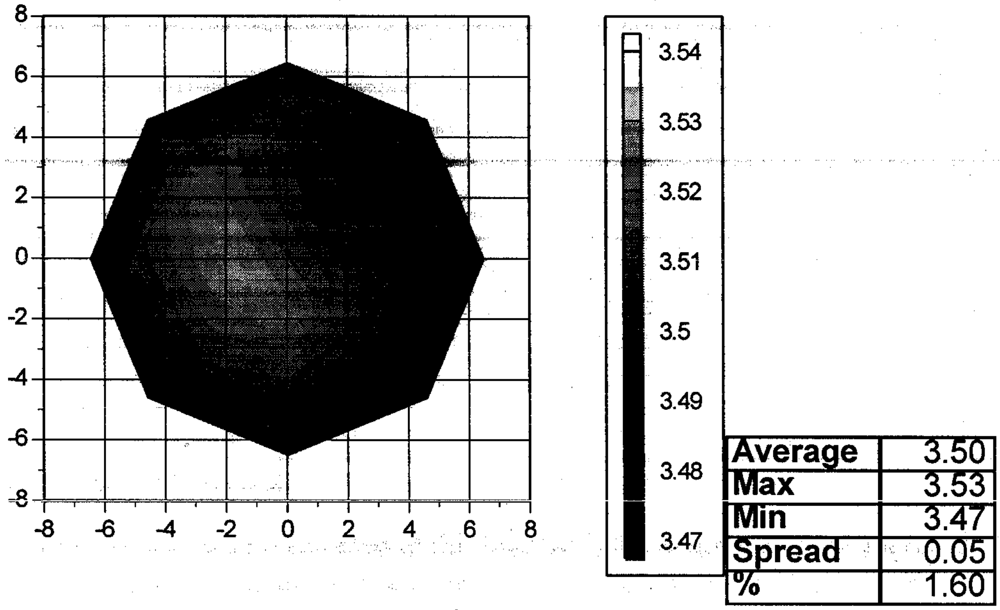


Figure 7
F/A Scan at Full Power

Emissions performance

At full load, the preburner fuel is reduced such that NOx falls between 0.9 to 1 ppm (Figure 8). Preburner fuel increases as the turbine unloads, resulting in higher preburner primary zone reaction temperatures and therefore increased NOx production. With the catalyst installed for this test, the % load range in which emissions are kept to target is not as great as expected for the commercial configuration. The catalyst design will be optimized to increase the range of low emission operation for the next phase of testing which is the RAMD endurance test. It should be noted that the ultra low NOx reading during this test is with control settings which are not necessarily consistent with production designs. A more robust control algorithm will result in higher NOx output, but well within the 3 ppm target.

NOx and CO emissions are both higher at engine operation below peak load. This is due to simplifying design decisions made during the development of the XONON 2 system, which was optimized for operation at full load. Exact values of part-load CO emissions are considered proprietary at this time, however, they could be made available to California Air Resources personnel at the CCSI Mountain View facility.

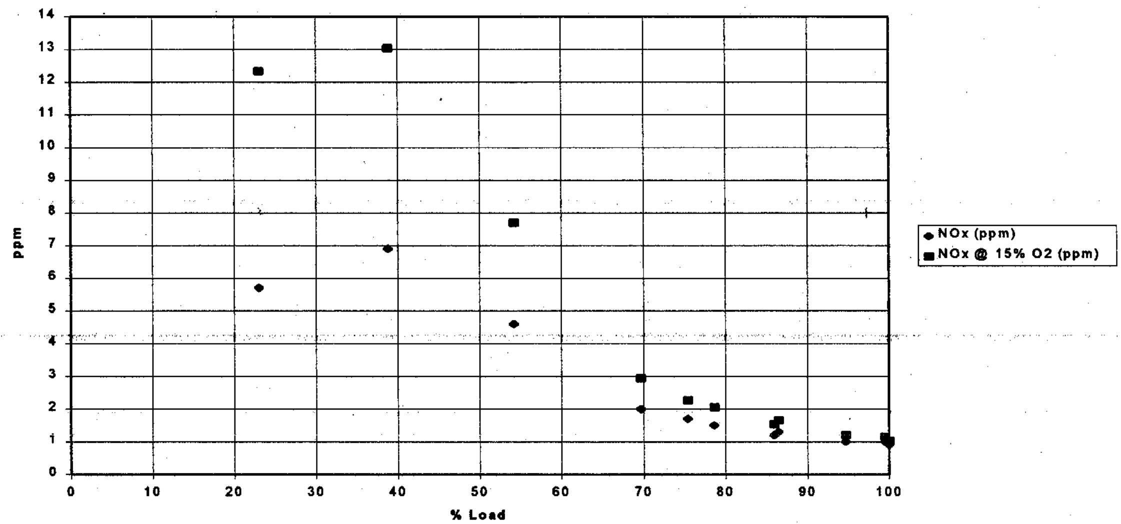


Figure 8
NOx vs. % Load

Overall Combustor System Performance

This test series demonstrated the suitability of the XONON 2 combustion system performance for commercial operation. Continuous operation for periods up to seven hours without unscheduled shutdown showed that the random shutdowns experienced with XONON 1 did not exist. NOx levels of less than 3 ppm were measured from full power to 60% power. The NOx emissions at idle speed were near 10 ppm uncorrected and decreased to 6-7 ppm in the 20-40% load range. These readings were taken with a fixed control algorithm to examine flexibility without system change. More extensive testing conducted subsequent to the work described here established that further development work with controls and preburner design will lead to lower emission levels at the lower power levels. Various specific tests were run from no load to full load with NOx emission levels in the 3 ppm range. The optimum combination of control setting and hardware configuration has not yet been selected for commercial robustness. In general, as system robustness is increased, the overall operating range at less than 3 ppm decreases. Additional development work will be done to determine the optimum mechanical configuration and amount of control. It is expected that acceptable NOx levels will be attained at operating levels less than 70% load and that corrected NOx levels at full speed/no load will also be significantly reduced.

The commercial operation deficiencies exhibited by XONON 1 have been corrected. As expected, the periodic ignition events of XONON 1 have not appeared in XONON 2 testing. Preburner outlet temperature uniformity has been improved. Preburner temperature turndown has improved providing for even lower production of NOx at full

load. The design of the XONON 2 combustor allows it to be smaller, easier to produce and assemble, and more maintainable than the XONON 1 combustor.
Post test inspection revealed some damage caused by improperly designed internal components. Subsequent analysis has led to modifications which finite element analysis shows to correct the structural problem. The modification consisted of changes that allowed for thermal expansion of a previously over constrained component. The unit is currently in shakedown testing with the new hardware, and will soon begin RAMD endurance testing. This testing is referred to as ICAT program task 3 and is not an ICAT funded activity.

The completion of this successful demonstration established a milestone in low emission combustion technology. It not only provided data to authenticate the claims that catalytic combustion can substantially reduce emissions without exhaust gas cleanup, but also that a combustion system can be designed, manufactured, and operated successfully on a gas turbine in commercial service connected to the utility grid.

Work will now continue to optimize the system for cost, reliability, availability, maintainability, durability, and performance.

The XONON 2 combustion system is not ready for introduction as a commercial product. Introduction will occur following additional testing to verify endurance capabilities. The designs and all test information not included in this report are currently considered proprietary and are not available for distribution to the public. All information is, however, available at the CCSI Mountain View facility for California Air Resources Board review upon request.

COMMERCIALIZATION PLAN

The CCSI plan for commercialization of the XONON combustion system began with the prototype system operated in the test cell in Tulsa, Oklahoma. The next step was the test program sponsored by the California Air Resources Board ICAT program that successfully field demonstrated the system's commercial capability against the utility grid. The hardware configuration tested in the ICAT program is being upgraded based on data and information gathered during the demonstration. The commercialization program now moves to the RAMD (Reliability, Availability, Maintainability, Durability) testing which will include an 8000 hour endurance test. Data and inspection results from this test will be evaluated for possible changes to the hardware to add commercial quality robustness where necessary. The first commercial sale of the system will then be made to provide actual field application experience. This sale is expected to take place at the end of RAMD testing in approximately 12 months

CCSI's commercialization plan is designed to be responsive to the needs of the various OEM's and to provide technology and/or hardware as required. The next phase of commercialization will include application of the XONON technology to a wide variety of gas turbine engines. In some cases, the technology will be sold for inclusion in the OEM's combustion system design and manufacture. In other cases, the entire combustor design will be sold to the OEM for manufacture. Combustor hardware may also be sold directly to the OEM for installation on his engine. In all cases, CCSI will provide the catalyst module (catalyst and container) hardware as proprietary equipment.

CCSI currently is working with several OEMs on catalytic combustion programs. The results from the ICAT field demonstration will be incorporated into the designs of the hardware for these OEM applications as the programs move toward commercial application for these engines.

A copy of the XONON™ COMMERCIALIZATION STATUS document distributed by Catalytica Combustion Systems, Inc. is attached as Appendix B.

PROJECT SUMMARY

A field demonstration of an ultra low emissions gas turbine combustor was completed. This was the first demonstration of catalytic combustion in an industrial type operation connected to the utility grid. The conclusions drawn from the demonstration are that the system (1) is capable of operating continuously while connected to the utility grid, (2) can be reliably and repeatedly started and auto synchronized with the grid, (3) and can be operated and controlled in a manner to meet the emission requirements.

The concept of catalytic combustion has been recognized as the ultimate solution for NOx control in gas turbines for over 25 years. CCSI has worked on this technology referred to as XONON™ Flameless Combustion since 1988 and to date has invested over $20 million in development programs and in research and testing facilities. During this time, CCSI has developed the basic technology, the specialized materials, and the fabrication techniques for an operating XONON combustion system. The XONON technology has been demonstrated in CCSI's high-pressure rig test facilities at conditions typical of modern gas turbine engines. These results show that this technology can achieve emission levels of <3 ppm NOx with CO and UHC levels <10 ppm. In addition, CCSI has developed technology needed to interface the catalytic combustion system with the gas turbine including the structural support and container for the catalyst and the required fuel injection and control technology.

CCSI has programs with the major gas turbine manufacturers to apply XONON catalytic combustion technology to new gas turbines. Full-scale laboratory testing at turbine operating conditions has been performed by these manufacturers. The tests demonstrated ultra low emissions and the potential for gas turbine grade durability. Emissions of less than 3 ppmv NOx were achieved at baseload conditions. This basic design approach was the starting point for the XONON program addressed in this report. The ICAT program picks up where the earlier programs left off and takes the technology to commercial field demonstration and application to the power generation and mechanical drive markets.

The XONON combustion system includes a combustor with catalyst module, control system, and fuel delivery system. The combustor design and development was accomplished by CCSI. For the initial XONON 1 combustion system (not part of this ICAT program), the combustor design was done by the Agilis Group in West Palm Beach, Florida under the direction of CCSI. Initial design for the XONON 2 system, as demonstrated in this program, was also done by the Agilis Group. The finalization of the XONON 2 preburner and mixing systems was done by CCSI engineers based on testing and CFD analysis. The Woodward Governor Company designed the controls and fuel delivery system with assistance from CCSI. Both Woodward and CCSI did component development testing on system hardware in preparation for the engine demonstration.

The first gas turbine testing of a catalytic combustion system was done with a XONON 1 combustion system installed on a Kawasaki M1A-13A gas turbine. The gas turbine was installed in a production test cell at the AGC facility in Tulsa, Oklahoma and tested with a water brake dynamometer. Several modifications were made to the initial design based on information gathered under engine operating conditions. Various control strategies were tested to provide the required fuel scheduling for acceleration to full speed at no load (FSNL) while controlling catalyst and metal temperature rise rates and temperature distribution. Fuel strategies were also tested to accelerate from FSNL to full power in response to demand. This work was successfully completed with full load NOx levels of less than 3 ppm. Before completion of testing at AGC, a 1000 hour endurance test was run to gain experience with catalyst durability and engine operation over extended periods.

The testing at Tulsa showed that a gas turbine could operate successfully with catalytic combustion. It also showed that the emission targets could be reached. One feature of industrial operation that was not measurable was the reaction to the demands of the electrical grid. The plan was to move testing to another site at which operation against the grid was possible.

A Kawasaki M1A-13A gas turbine generator set was purchased by CCSI for continued combustion system testing. The generator set was intended for field demonstration at the CCSI test facility in Santa Clara, California, where it could be connected to the utility grid. Prior to testing, the system was shaken down with the XONON 1 catalytic combustor from the Tulsa testing and subjected to source testing for the air quality permit. Permitting was accomplished and testing began.

Testing at the Santa Clara test facility was planned to demonstrate the next version of XONON designated XONON 2. The test series was to demonstration the XONON 2 combustor system's ability to automatically connect to the utility grid, operate continuously on the grid, to react to sudden load changes, and to operate at the target emission levels. During this time, the controls were also tuned to provide the stability necessary to handle the demands of the grid.

The test series demonstrated the suitability of the XONON 2 combustion system performance for commercial operation. Continuous operation for periods up to seven hours without unscheduled shutdown showed that XONON 2 operability had improved over XONON 1. NOx levels of less than 3 ppm were measured from full power to 40% power. The NOx emissions at idle speed were less than 10 ppm.

The completion of this successful demonstration established a milestone in low emission combustion technology. It not only provides data to authenticate the claims that catalytic combustion can substantially reduce emissions without exhaust gas cleanup, but also that a combustion system can be designed, manufactured, and operated successfully on a gas turbine in industrial service connected to the utility grid. Work will now continue to optimize the system for cost, reliability, availability, maintainability, and durability, and performance.

Funding for this Low Emissions Gas Turbine Combustor Demonstration Progam was provided by the California Air Resources Board (CARB) Innovative Clean Air

Technology (ICAT) Program. For further information about the ICAT program, please refer to the CARB website at www.arb.ca.gov/research/icat/icat.htm.

APPENDIX A

XONON TECHNOLOGY OVERVIEW

This appendix provides a brief description of the key elements of the XONON flameless combustion technology. Development of the technology began eleven years ago with a recognition of the fundamental characteristics of NOx production in high temperature environments and an analysis of approaches to catalytic combustion that were tried unsuccessfully in other laboratories. Starting from these early assessments, CCSI devised and developed a new approach that has resulted in a breakthrough for catalytic combustion for gas turbine applications. The essential features of that technology and recent experiences in its application are included in this Appendix.

FUNDAMENTALS

NOx formation

NOx is formed when the nitrogen and oxygen molecules in air are exposed to temperatures high enough to break some of the interatomic bonds. The active nitrogen- and oxygen-containing species thus formed can recombine with one another to generate NO and/or NO_2, the mixed products being referred to generically as NOx. The amount of NOx produced depends upon the amount of time the gas mixture is exposed to high temperature and especially upon the temperature itself. This dependence is shown in Figure A-1 for conditions typical of a gas turbine combustor — 10 atm pressure and 20 milliseconds residence time.

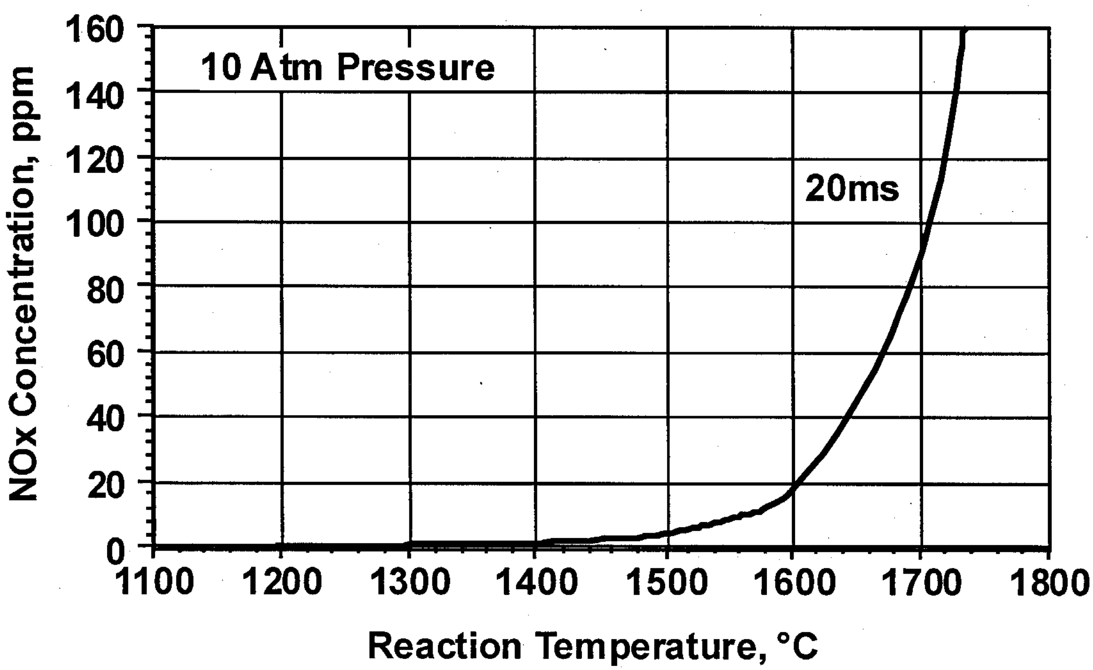


Figure A-1. NOx production versus temperature at a specific pressure and residence time (milliseconds) in the reaction zone.

It is evident from the curve in Figure A-1 that NOx production increases dramatically with increasing temperature when the temperature exceeds about 1600°C (2900°F). Temperatures in the hottest regions of a diffusion flame can exceed 2200°C (4000°F) for brief periods; so there is little possibility of achieving single digit NOx levels when a turbine is fired with a diffusion flame combustor. If, on the other hand, the peak combustion temperature can be limited below 1500°C (2700°F), NOx levels can be less than 2 parts per million (ppm). Unfortunately, at the fuel-air ratios low enough to achieve such low NOx concentrations, flames are highly unstable leading to flame-out or fluctuations which cause severe combustor vibrations; so even a lean premixed combustor cannot operate in this most desirable low temperature range to achieve ultra-low NOx emissions.

In contrast, catalytic combustion does not involve a diffusion flame at all. When the catalyst is at its operating temperature, fuel and oxygen react on the catalyst surface and release the heat of combustion regardless of the fuel-air ratio in the gas mixture. The fuel-air ratio entering the catalyst simply needs to be high enough to generate the desired turbine inlet temperature at full conversion of the fuel. In current turbines the required maximum temperature at the catalyst exit is generally 1300°C (2400°F) or lower; so Figure A-1 shows that extremely low concentrations of NOx are possible using catalytic combustion.

Earlier approaches to catalytic combustion

The potential for achieving ultra-low NOx emissions via catalytic combustion has been recognized for more than 25 years. The most common approach has been to mix the fuel and air upstream from the catalyst and allow complete combustion of the fuel within the catalyst itself, as depicted in Figure A-2. The challenge for this approach can be seen in

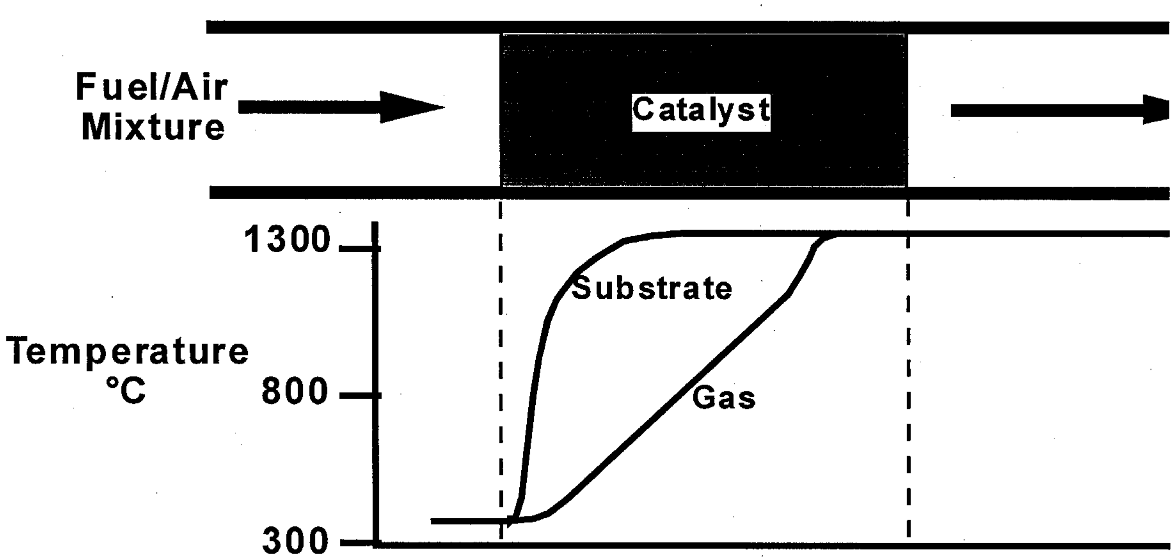


Figure A-2. Temperature profiles in traditional approach to catalytic combustion.

the catalyst substrate temperature profile in Figure A-2. Because the reaction at the catalyst surface is diffusion limited, i.e., the fuel molecules react as fast as they can diffuse to the surface, the surface temperature rises rapidly to the value ultimately obtained in the bulk gas stream after complete combustion of the fuel. This temperature is well above the level that most catalytic materials can tolerate. Consequently, the catalysts used in this approach have suffered from the following:

- Sintering and vaporization of active components
- Fracture of ceramic supports due to thermal shock
- Poor durability

Several laboratories have continued efforts to develop catalytic materials that can be used at such extreme temperatures, but to date the progress toward a commercially viable system has been limited.

XONON TECHNOLOGY

Approach

CCSI's approach was to specifically avoid full combustion of the fuel within the catalyst itself. CCSI developed a staged system in which a portion of the fuel is consumed within the catalyst, but the final combustion that generates the highest temperatures takes place in a volume downstream from the catalyst. The scheme is diagrammed in Figure A-3. Initial fuel combustion is accomplished stepwise in two or more catalyst stages, each designed for its own particular purpose and set of reaction conditions. By isolating the highest temperatures downstream from the catalyst, this approach circumvents many of the issues of high temperature catalyst stability that plagued the traditional approach to catalytic combustion. The XONON approach achieves the desired high combustor outlet temperature, but with the operating temperatures of the catalyst stages themselves

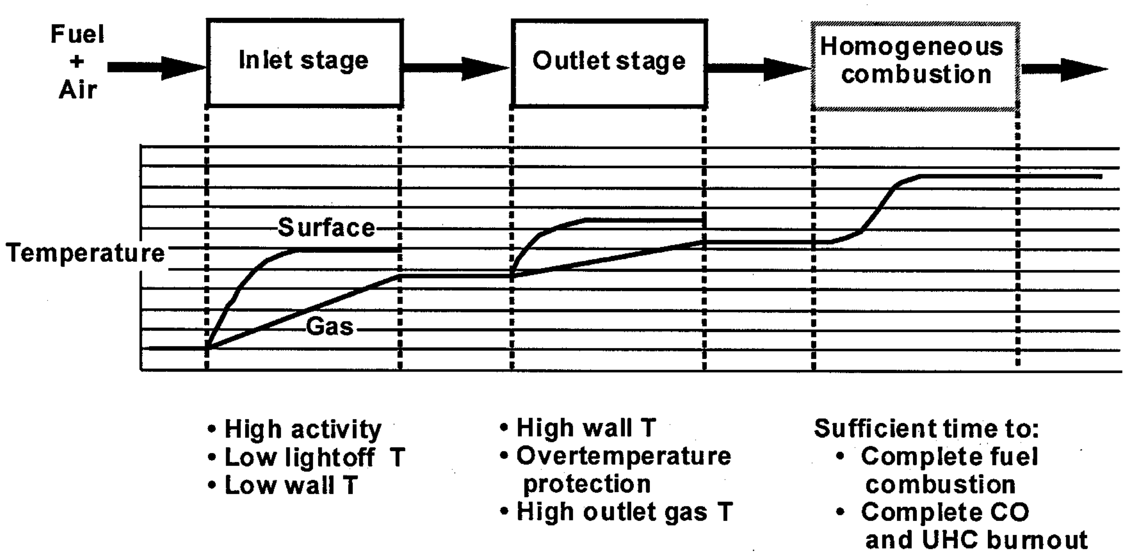


Figure A-3. Staged catalyst system of XONON technology maintained at levels low enough to allow the catalysts to sustain their performance for extended periods. The characteristics of the reactor stages and the associated temperature profiles are shown in Figure A-3.

Strategy

Developing the staged approach to catalytic combustion required a strategy more sophisticated than simply limiting the fuel combustion by decreasing the catalyst length. The temperature profiles in Figure A-2 show why such a simple strategy would be ineffective. For the catalyst depicted in Figure A-2, cutting the catalyst length in half would indeed limit the outlet gas temperature to roughly 800°C. However, the substrate temperature would not be similarly limited, and the substrate would still reach the full adiabatic combustion temperature (1300°C in Figure A-2) even in the shorter catalyst.

CCSI has developed and patented two strategies for controlling the catalyst substrate temperature at levels well below the full combustion temperature. One exploits the unique chemistry of palladium and its oxide to function as a chemical thermostat; the other involves special designs to integrate heat transfer surfaces among the catalytically active surfaces within the channel structure of the catalyst. These temperature limiting features maintain the catalyst at the desired operating temperature, thus preserving catalytic activity and allowing use of metal rather than ceramic substrates. Metal substrates offer advantages for mechanical design and thermal shock resistance.

Chemical thermostat

At typical operating conditions within the catalyst, palladium can exist either as the metal itself (Pd) or as its oxide (PdO). The distribution between the two forms is governed by the thermodynamics of the oxide decomposition reaction:

$$\mathrm{PdO} \underset{\text{Low Temp}}{\overset{\text{High Temp}}{\rightleftharpoons}} \mathrm{Pd} + \frac{1}{2}\mathrm{O_2}$$

At any fixed partial pressure of oxygen (O_2), the temperature determines whether the stable form of palladium is the oxide or the metal, with high temperatures favoring decomposition to the metal. The relationship between the total pressure and the oxide-metal transition temperature is depicted in Figure A-4. Conveniently, the transition temperature is in a desirable range for combustion catalysts.

Palladium oxide has high catalytic activity for methane combustion, while the metallic form has much lower activity. The oxide is the stable form of palladium at the low temperatures where methane combustion is initiated; so low lightoff temperatures can be achieved with palladium oxide as the active component of the catalyst. As the reaction accelerates and the temperature rises, the catalyst temperature reaches the PdO-Pd

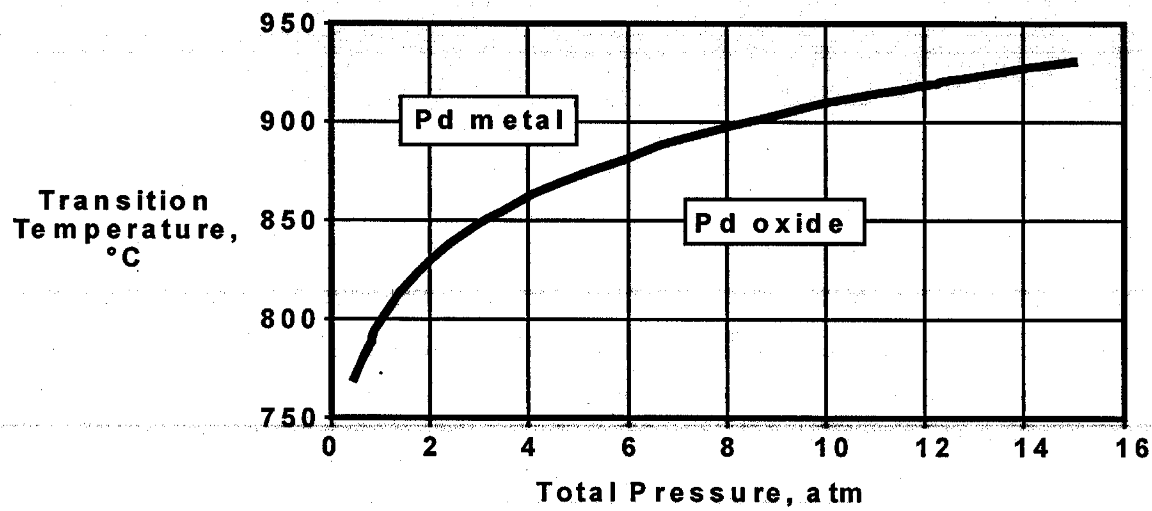


Figure A-4. Palladium metal/palladium oxide transition temperature versus total pressure.

transition temperature. The palladium oxide in the catalyst decomposes to palladium metal, and the catalytic activity decreases accordingly. In this way the oxide-metal transition acts to limit the catalyst surface temperature, and the reversibility of the transition allows the system to act as a thermostat in controlling the temperature at the level determined by the thermodynamics shown in Figure A-4. Changes in the catalyst formulation can shift the curve in Figure A-4; so the limiting temperature can be adjusted by varying the catalyst design.

A demonstration of the thermostatic behavior of a palladium catalyst is shown in Figure A-5. The behavior of a platinum catalyst, which does not form a stable oxide, is shown as well. In the tests, the catalyst substrate temperature was monitored while the fuel-air ratio entering the catalyst was progressively increased. Once the fuel-air ratio was sufficient to generate full catalyst activity (a ratio of about 0.01), both catalyst temperatures were close to the adiabatic combustion temperature, as expected from the discussion of diffusion limited catalyst behavior in Figure A-2. From that point the temperatures in the platinum catalyst tracked the adiabatic combustion temperature up to the limit of the test. In contrast, the temperature of the palladium catalyst was modulated by the transition from the active oxide to the less-active metal at about 780°C (1440°F). This transition effectively prevented the substrate temperature from exceeding 780°C (1440°F) despite the fact that the fuel concentration entering the catalyst had an adiabatic combustion temperature significantly higher than that level.

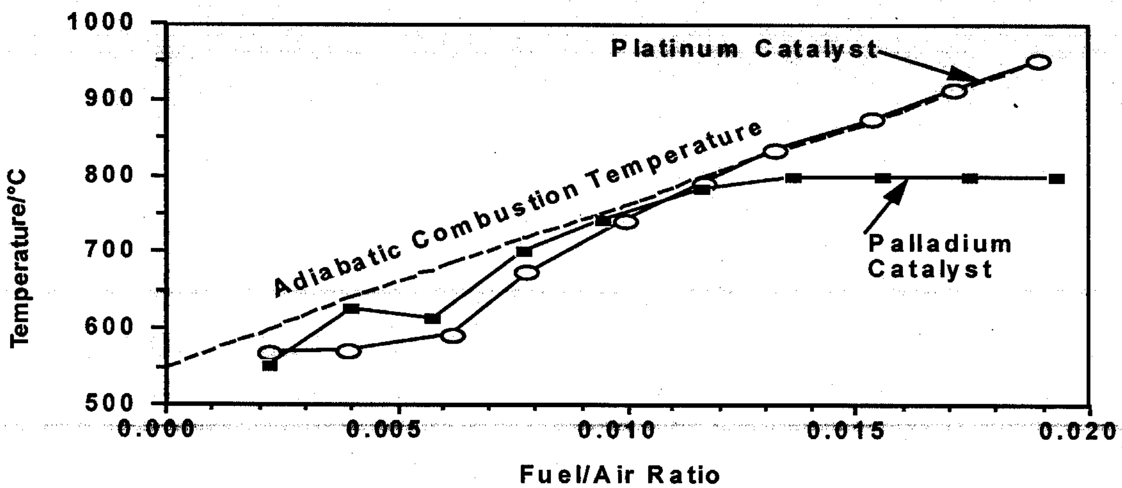


Figure A-5. Demonstration of palladium catalyst acting as a chemical thermostat at the oxide transition temperature

APPLICATIONS

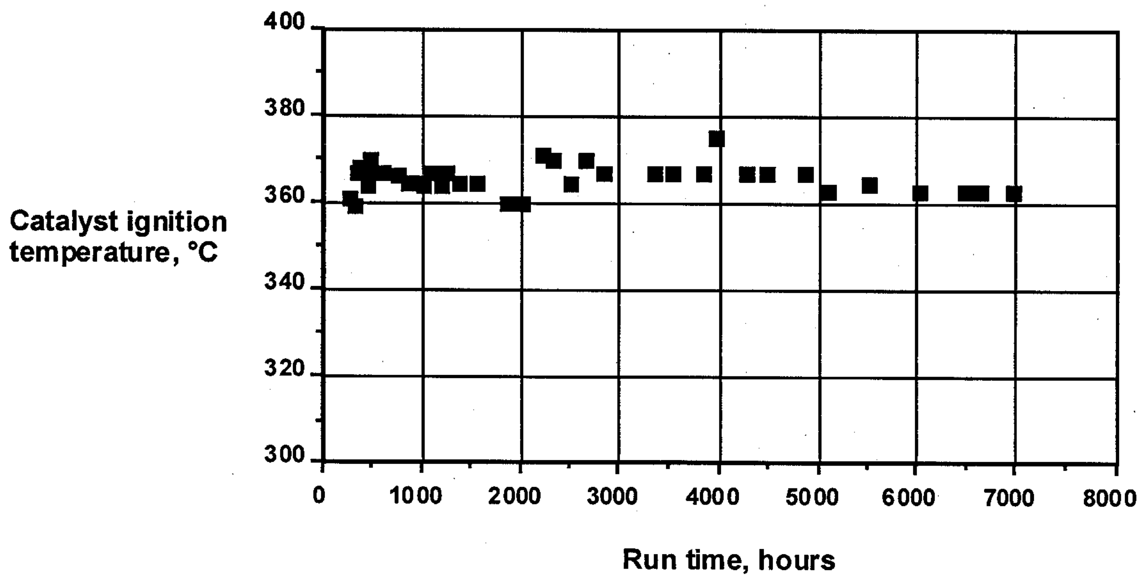
Durability experience

The initial target for durability of the catalytic combustor system is 8000 hours of operation. Relatively early in the development program, a catalyst system was operated at atmospheric pressure with stable performance over a period of 7000 hours. The ignition temperature, a measure of catalyst activity, of that system is plotted versus the time on stream in Figure A-6.

A durability test under conditions more representative of those in a gas turbine combustor was recently conducted for an accumulated run time totaling 1000 hours. The emissions measured during the course of that test are plotted in Figure A-7. The figure show that the levels of unburned hydrocarbons, carbon monoxide, and NOx were well below 5 ppm throughout the test.

In normal operation, the catalyst in a gas turbine combustor will be exposed to various contaminants that may be present in the air, fuel, and perhaps lubricating oils ingested into the hot gas path. The likely contaminants and their potential effects on catalyst performance are being evaluated in an ongoing experimental program at CCSI. Results to date are summarized below.

Figure A-6. Catalyst activity measured periodically during extended operation in a test at atmospheric pressure.



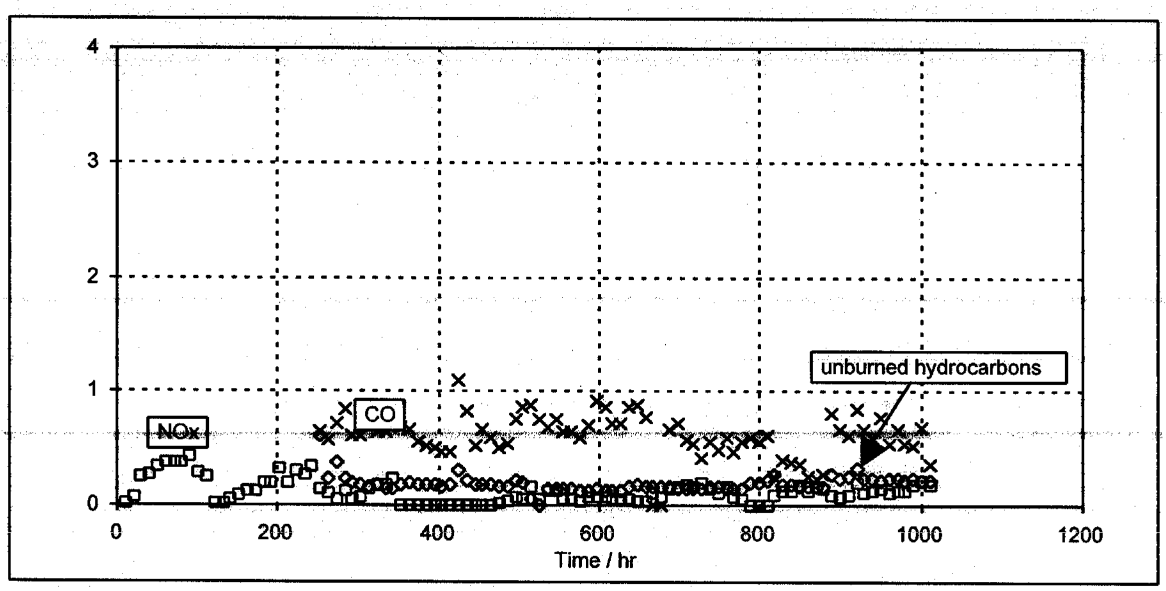


Figure A-7. Emissions during durability test at typical gas turbine operating conditions [P = 9.4 atm, outlet T = 1300°C (2370°F)].

Survey data of contaminant composition and concentrations in ambient air for several sites in California were used to define the conditions for catalyst durability testing. In order to accelerate the tests, the contaminant concentrations were chosen so that the amount of the contaminant passing through the catalyst during the 50-hour durability test would be equivalent to 8000 hours of operation at the actual contaminant levels. The reaction temperatures and pressure were adjusted to simulate the conditions anticipated for a gas turbine catalytic combustor.

Tests have been completed for effects of "dust" and "salt" on catalyst performance. The ambient air quality data suggest that the major components in airborne particulates are silica and alumina, compounds ubiquitous in the earth's crust. Fine particles of these two materials were injected into the fuel-air mixture upstream from a prototype catalyst at levels approximately 160 times the reported ambient concentrations in order to accelerate 8000 hours' exposure into a test of about 50 hours duration. The two-stage catalyst performance, as reflected in the gas temperatures entering and exiting each stage, is shown in Figure A-8. The stability of the temperatures during the contaminant injection suggests that exposure to "dust" does not have a detrimental effect on the catalyst.

"Salt" in ambient air presumably is due to droplets of sea water entrained in the air and carried inland. The fact that ambient levels are highest at sites near the ocean and lowest at remote sites supports this view. For laboratory testing, a synthetic solution containing the five most prevalent components of sea salt (mostly sodium chloride) was injected into the fuel-air stream upstream from the catalyst at a level representative of filtered turbine inlet air. Again, the catalyst performance was sustained for the duration of the 50-hour test, as shown in Figure A-9.

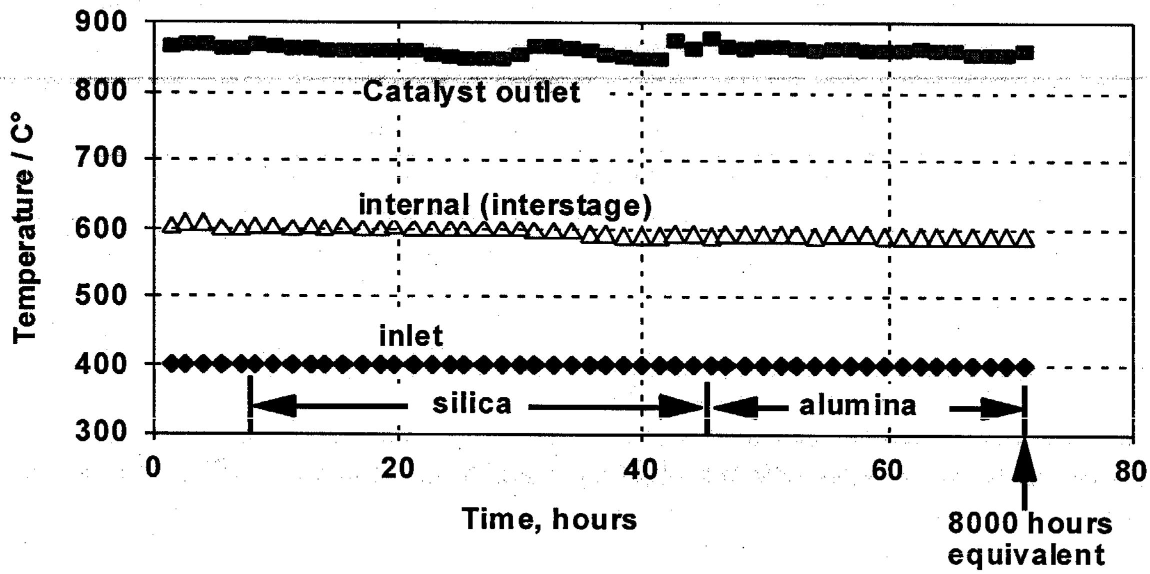


Figure A-8. Catalyst performance during accelerated exposure to primary components of ambient air particulates.

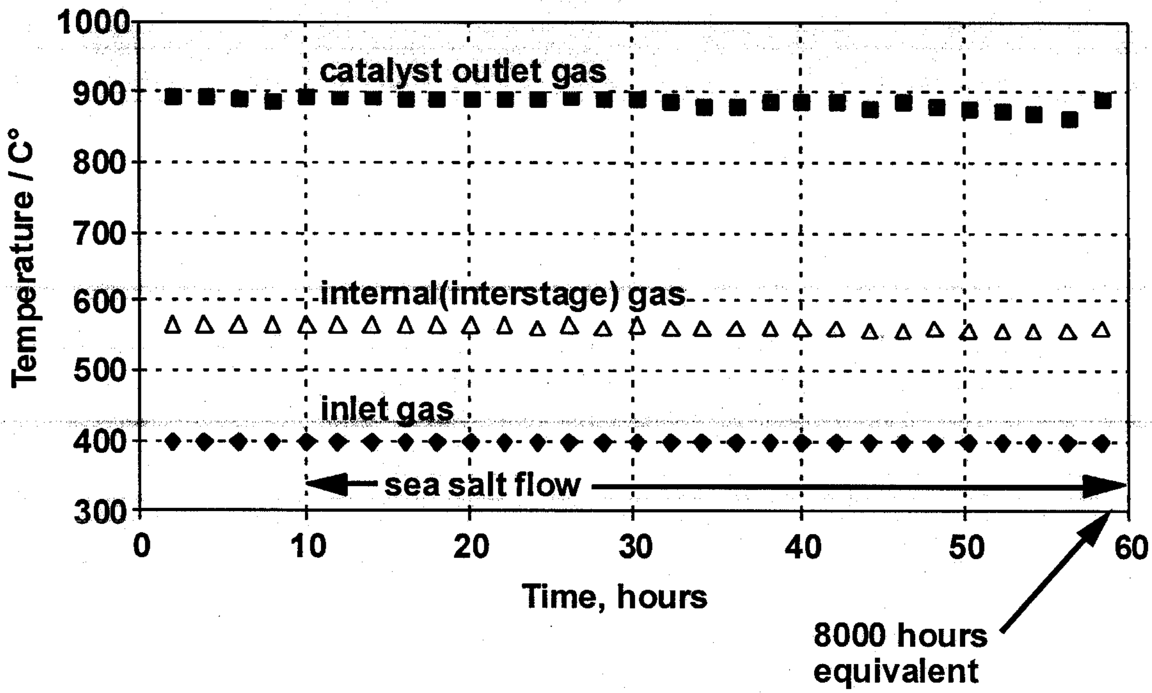


Figure A-9. Catalyst performance during accelerated exposure to components of sea salt.