Catalysis Today 83 (2003) 279–288

CATALYSIS TODAY

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Achieving ultra low emissions in a commercial 1.4 MW gas turbine utilizing catalytic combustion

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Received 1 May 2002; accepted 18 March 2003

Abstract

The drive to achieve low emissions from gas turbines has been an ongoing challenge for over 30 years with the reduction of NO_x levels representing the most difficult issue. Catalytic combustion represents the technological approach that can achieve the lowest level of NO_x, in the range of 3 ppm and lower depending on the combustion system design. The program to develop a catalytic combustion technology that can achieve ultra low levels of NO_x, CO and unburned hydrocarbons (UHCs), applicable to a wide range of gas turbine systems and with long term durability is described. The technological approach is to combust only a portion of the fuel within the catalyst with the remaining fuel combusted downstream of the catalyst allowing the catalyst to operate at a low temperature and thus obtaining good long term catalyst durability. This catalytic combustion approach is then applied to a 1.4 MW gas turbine to demonstrate feasibility and to obtain real field experience and to identify issues and areas needing further work. The success of this demonstration lead to a commercial combustor design. This combustor and the final commercial package is described and the performance specifications discussed.

Keywords: Gas turbine; Catalytic combustion; Ultra low emissions

1. Introduction

Catalytic combustion has been studied since the early 1970s as an improved means for combusting hydrocarbon fuels with the objective of lower emissions, more compact combustors or extended operating ranges. A number of reviews have been published covering the basic development work and its application to gas turbines [1,7,10,16]. Several groups have developed and demonstrated catalytic combustor hardware for specific gas turbine engine designs but have not run actual gas turbine tests. Pillsbury and co-workers reported the development and testing of a single full-scale catalytic combustor for the Westinghouse 92 MW 501D engine [11,14]. These tests were done with No. 2 fuel oil and evaluated strategies for startup and loading. The catalyst inlet fuel–air mixture was very non-uniform limiting the operation to approximately 50% load and giving high CO emissions. Beebe and co-workers developed a full-scale combustor for the General Electric 9E gas turbine and demonstrated this combustor over the entire operating load range [2,3,15]. This work demonstrated NO_x levels of 3 ppmv (at 15% O_2) and CO and UHC levels below 2 ppmv (at 15% O_2) at full load and turndown from full load to 75% load with emissions of NO_x, CO and UHC below 10 ppmv (at 15% O_2). Dutta [4] described a full-scale catalytic

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0920-5861/$ – see front matter © 2003 Published by Elsevier Science B.V.
doi:10.1016/S0920-5861(03)00248-7

combustion system for a 5 MW Solar recuperated gas turbine that include an innovative viable geometry design to cover a wide load range with low emissions. Reported emissions at full load were 1.5 ppmv NO_x, 8 ppmv CO and 4 ppmv UHC (at 15% O_2).

Several groups have developed and tested catalytic combustion systems on gas turbine engines. Kajita and co-workers reported the development and engine demonstration of a catalytic combustor for a 170 kW Kawasaki S1A-02 gas turbine [5,6,8]. Initial performance showed a NO_x level of 6 ppmv (at 15% O_2) and CO at 400 ppmv. After 200 h of operation, the CO had increased above 1500 ppmv due to catalyst deactivation due to the high operating temperature of the catalyst, 1100 °C (2010 °F). Subsequent work by Sadamori et al. [12] evaluated a new catalyst material, a thermally stable manganese substituted hexaaluminate honeycomb catalyst material and catalyst module design applied to the same Kawasaki combustor and gas turbine system. After 220 h at full load, NO_x emissions were in the range 11–17 ppmv (at 15% O_2) and CO emissions were 265 ppmv [13]. O'Brian [9] described a catalytic combustion system on a 50 kW gas turbine that was operated for 8 h with emissions of 6 ppmv NO_x, 97 ppmv CO and 0 ppmv UHC, all at 15% O_2. The design approach was for essentially full fuel combustion within the catalyst, and because the gas turbine operated with a low turbine inlet temperature, the catalyst outlet temperature was limited to approximately 1000 °C (1830 °F). No data was reported at lower loads or at longer operating times.

All the gas turbine combustor and engine tests utilized catalytic combustion system designs with full combustion of the fuel within the catalyst and outlet gas temperatures ranged from approximately 1000 °C (1830 °F) to 1200 °C (2200 °F). These catalyst operating temperatures put tremendous demands on the catalyst. The major issues are thermal sintering stability, vaporization of the catalytically active components, thermal shock failure of ceramic substrates and oxidation of metallic substrates. While these problems may be overcome at 1000 °C and below, most modern gas turbines require combustor outlet temperatures ranging from 1200 °C (2200 °F) to 1500 °C (2730 °F). At these higher temperatures, thermal sintering, vaporization and oxidation become intractable problems. For example, a 1 wt.% platinum catalyst operating at gas turbine conditions and at 1000 °C would lose 80% of this platinum in 18 h [17]. The approach taken in this development program was to lower the catalyst operating temperature in the range 800–950 °C while still achieving combustor outlet temperatures in the range 1000–1500 °C and above.

2. Basic technology development

The basic technological approach used in this program was to inject all of the fuel upstream of the catalyst but to combust only a portion of the fuel in the catalyst and the remainder downstream of the catalyst. The catalyst materials and system design were then developed to maintain a low catalyst temperature, below 950 °C at fuel–air ratios that would ultimately give combustor outlet temperatures as high as required but certainly up to 1600 °C. This approach is shown in Fig. 1. The fraction of fuel combusted in the catalyst is determined by the turbine operating parameters such as pressure, final combustor outlet temperature, gas flow velocity, etc. Typically, 40–60% of the fuel is combusted in the catalyst and the remainder in the region just downstream of the catalyst.

The reactions downstream of the catalyst consist of a homogeneous radical reaction with the radical build up and subsequent reaction process as shown in Fig. 2 for the conditions of the KHI M1A-13A machine. As the hot gas stream exits the catalyst, the OH and H radical concentrations grow until a critical concentration is achieved at which point a rapid chain reaction takes over and the methane and other fuels are rapidly consumed. The first product is CO which grows to a relatively high concentration, approximately 1 vol.%.

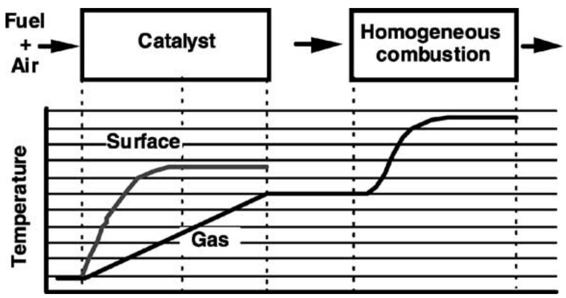

Fig. 1. Schematic of catalytic combustion section showing partial combustion in the catalyst.

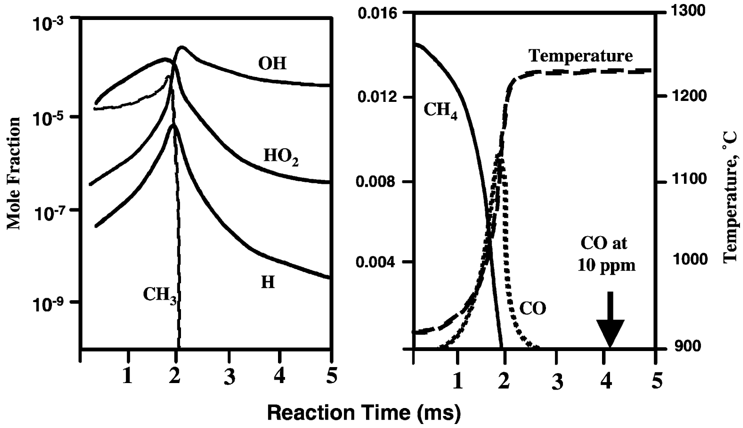

Fig. 2. Results from kinetic model calculation of homogeneous reaction downstream of the catalyst.

This CO then burns away, but more slowly then the hydrocarbon fuel components. To obtain a very low CO level such as 10 ppm as required by some current emissions regulations, it requires over 4 ms. The post-homogeneous reaction time is controlled by the required CO emissions level. The slow rate of CO combustion in this homogeneous radical reaction process leads to the requirement for a minimum combustor exit temperature. This is shown in Fig. 3 where the reaction time to obtain 1×10^{-5} mole fraction of CO is shown to be strongly dependent on the combustion temperature. To obtain a reasonable short reaction time, the combustion temperature must be above 1100 °C. Below 1100 °C the CO reaction becomes too slow to effectively remove the CO in a reasonable combustor design.

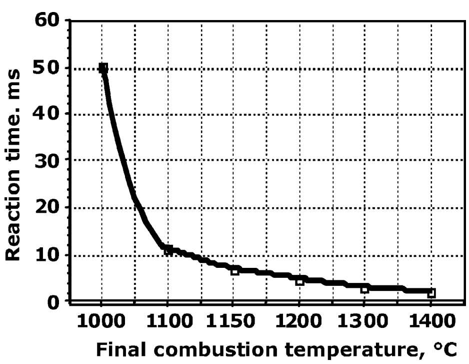

Fig. 3. Calculated reaction time to achieve a CO concentration of 1×10^{-5} fraction (10 ppm in the turbine exhaust).

A major part of the development program was the creation of a set of computer models that would allow the simulation of the performance of the catalyst. One tool that is used to simulate the performance of a particular catalyst design is shown schematically in Fig. 4. This tool takes as input, the details of the catalyst such as length, corrugation structure, washcoat porosity and thickness, kinetics of the catalyst for combustion of the fuel, surface area of the catalyst active components etc. In addition, the model also uses as input the process conditions including gas velocity, fuel–air ratio, temperature and pressure etc. The model then predicts the temperature profile through the catalyst, the fuel conversion and the outlet gas temperature and composition. This simulation model has been validated by comparison with data from a variety of subscale and full-scale tests on both rigs and gas turbine engines and over a variety of conditions and catalyst types covering the range of interest for current gas turbine products. A second simulation tool is a catalyst sintering model that incorporates sintering of the active catalyst phase. This model is based on physically realistic kinetic networks of the sintering process and can predict the catalyst performance or activity at any time and at any position throughout the catalyst. The combination of this catalyst sintering model and the single channel performance model provides a simulation tool that can predict performance of the catalyst over the 8000 or 16,000 h life of the catalyst. These tools have been converted into engineering design tools and are routinely

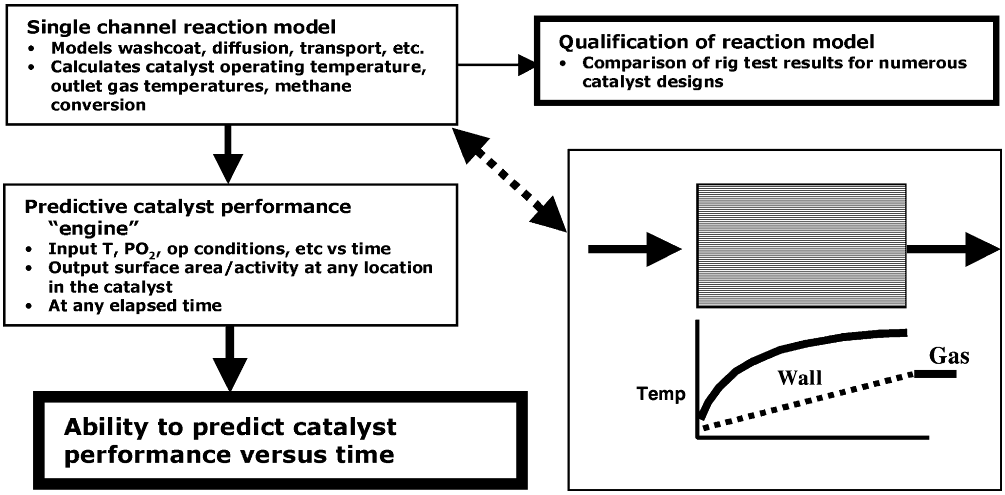

Fig. 4. Single channel simulation model of catalytic combustion catalyst system.

used in the catalyst design and application engineering process.

3. Demonstrator combustor system

To demonstrate the Xonon® catalytic combustion system on a gas turbine, a demonstrator combustor was designed and built [18]. A gas turbine with an off-engine silo type combustor was selected to all the combustor to be exchanged without modification to the engine. The KHI M1A-13A machine was selected since it was an industrial machine with a single combustor and of reasonable size. In addition, this demonstration combustor was targeted to operate only with natural gas fuel and to achieve the target low emissions performance over an operating load range 90–100% load. The combustor system operating conditions and the strategy for integration with the catalyst is shown in Fig. 5. The ISO compressor discharge temperature for this gas turbine is 330 °C while the design requirement for the catalyst inlet temperature is 450 °C. In addition, a flame type burner will be required to start the gas turbine. A preburner will be used upstream of the catalyst to accomplish both of these functions. Just downstream of the preburner is a fuel injector and fuel–air mixing system to prepare the fuel–air mixture entering the catalyst. Down stream of the catalyst is a reaction volume to allow for the post-catalyst homogeneous reaction where the remaining fuel is combusted.

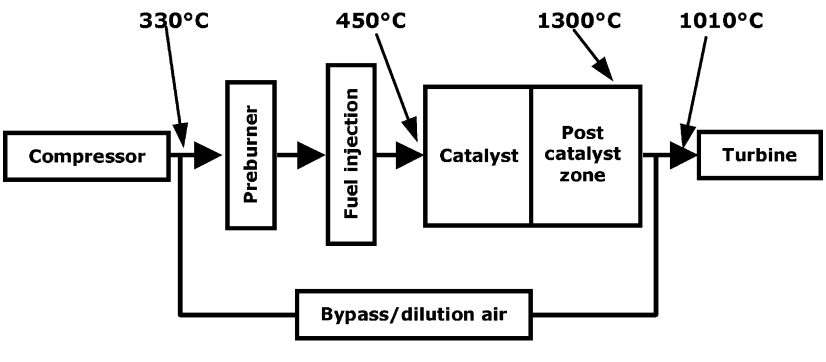

Fig. 5. Design strategy for the demonstrator combustor to match the engine conditions with the catalyst operating requirements.

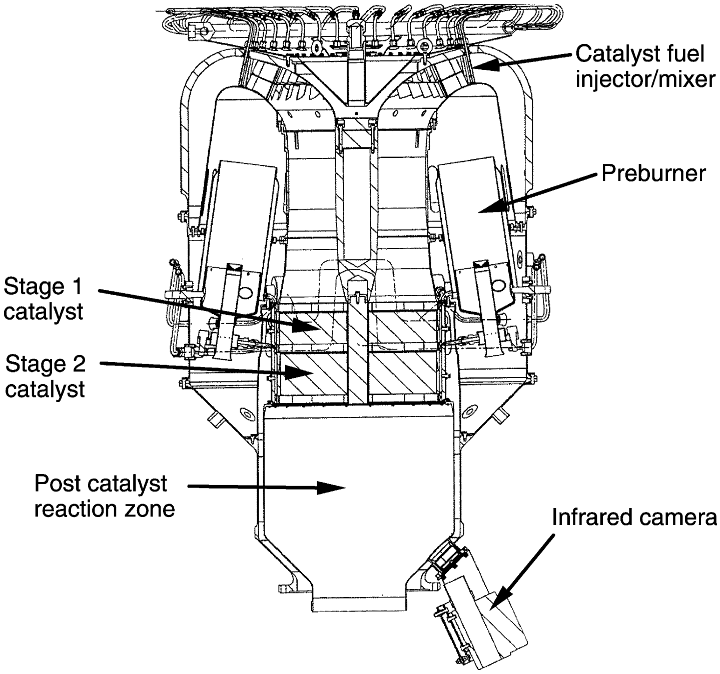

Fig. 6. Cross-section diagram of demonstrator catalytic combustor.

Some compressor discharge air bypasses the preburner and catalyst and reenters the flow stream upstream of the turbine. Much of this are is used for scroll cooling. This bypass air raises the fuel–air ratio within the catalyst to the design range of approximately 1300 °C. The combustor cross-section is shown in Fig. 6. The compressor discharge air flows along the post-catalyst reaction zone and into the annular space containing the preburners. The preburners are of a lean premix design to minimize the level of NO_x production and have sufficient operating range to provide the large temperature rise necessary to start the gas turbine and to provide stable operation at the low temperature rise required at full load operation. The hot gas exiting the preburner flows to the catalyst fuel injection mixing system. This is a radial inflow swirler system that uses multipoint injection and aerodynamic mixing to fully mix the fuel–air mixture prior to entering the catalyst. The target specification for fuel–air uniformity was ±3% and the measured performance was less than ±1.5%. The catalyst was a two-stage system with an inlet stage designed with high activity to operate at a low inlet temperature and a second stage designed to have high thermal stability and durability at the higher catalyst outlet temperatures. The burnout zone was sized to allow sufficient reaction time to combust the remaining fuel and CO to the target levels of <10 ppm CO and unburned hydrocarbons (UHCs). Performance data from this demonstrator system is shown in Table 1. The system performance showed <5 ppm CO and UHC and <3 ppm NO_x over the 90–100% load range. Total system pressure drop was

Table 1
Performance results from the demonstrator catalytic combustion system

Operation overview	
Total operating hours	1057 h
Fired starts to FSNL	206
Total fuel consumed	769,950 lb
System pressure drops at base load	
Catalyst	1.53% (1.96 psid)
Preburner	1.58% (2.02 psid)
Fuel–air mixer	0.38% (0.48 psid)
Combustor total	4.43% (5.67 psid)
Emission performance maintained over 1000 h run	
CO and UHC	<5 ppm at full load
CO and UHC	<10 ppm over 70–100% load range
NO_x	<3 ppm over 90–100% load range

reasonable with the catalyst contributing only 1.5%. The mixer system contributed only a small amount to the total system pressure drop. Additional contributors to pressure drop were dump losses and friction losses in the various parts of the combustor system. The system was operated over 1000 h and during the testing was started and shut down numerous times including a number of full load trips. A fired start to full-speed-no-load (FSNL) causes the preburner and the catalyst to cycle through their maximum temperature range thus demonstrating the durability of the catalyst system and the combustor to real transients and thermal cycles.

4. Development of the commercial product

Reduction of NO_x emissions has been a very important issue for gas turbine manufacturers for many years. Within KHI, work directed at NO_x reduction for the M1A-13 machine has been ongoing for past 14 years. Fig. 7 shows the improving trend in emissions performance of the KHI M1A-13 machines. The first production machine was introduced to the market in 1989. This machine had a NO_x level of 120 ppm corrected to 15% oxygen and would guarantee 42 ppm of NO_x using water or steam injection. In 1994 the M1A-13D machine with the first dry low emissions (DLEs) system was introduced with a guaranteed 42 ppm NO_x. Since then, the DLE system has been improved with a guaranteed 21 ppm NO_x offered 1995 and 11 ppm NO_x in 1996.

However, still lower NO_x levels are required to access the power generation market in many parts of the United States. For this reason, KHI and Catalytica Energy Systems have embarked on a program to apply the Xonon® catalytic combustion technology to the M1A-13 machine. The emissions performance target will be <3 ppm NO_x over a 70–100% load range.

After the successful operation of the demonstrator combustor, the lessons learned were used to develop a new combustor design targeted at a commercial product. This second generation combustor was initially designed, fabricated and tested by Catalytica. Subsequently, in a joint development program with KHI, this combustor was further developed to a commercial engine and package. The major modifications included:

- *Operability*
    - The low emissions load range of the demonstrator combustor was only 90–100%. To increase the load range to the target of 70–100% for the commercial product including ambient temperature range and operating margins, a bypass system was designed. This system would allow a variable amount of compressor discharge air to bypass the catalyst and then reenter the flow path just

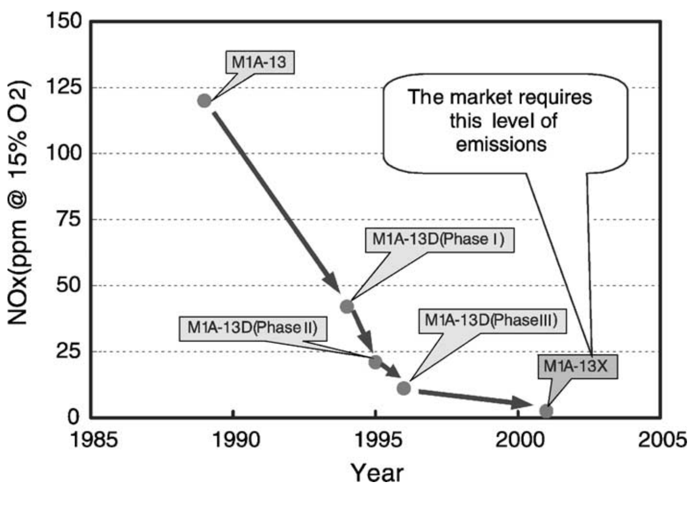

Fig. 7. Improving trend in NO_x emissions of KHI M1A-13 machines.

downstream of the post-catalyst reaction zone. As the load is decreased and fuel flow to the catalyst decreases, then increasing the amount of bypass air will allow the fuel–air ratio through the catalyst to remain high and within the catalyst operating window.

- ◦ The catalyst operating window is dependent on the fuel composition and any changes in the performance of the catalytic combustion system. To compensate for such changes, a real time adaptive control system was developed to monitor the performance of the catalyst and the information used to adjust the operation of the preburner and bypass to maintain the catalyst within its operating window.

- *Maintainability*
  - ◦ The catalyst module, in particular the container, was redesigned for easier servicing. The initial catalyst is designed for 8000 h life and at the service interval, the new design would allow a fast turn around for catalyst replacement.
  - ◦ An improved seal between the catalyst core and the container was developed to eliminate this leakage path. This modification would give improved module durability and improved long term operation over the load range.

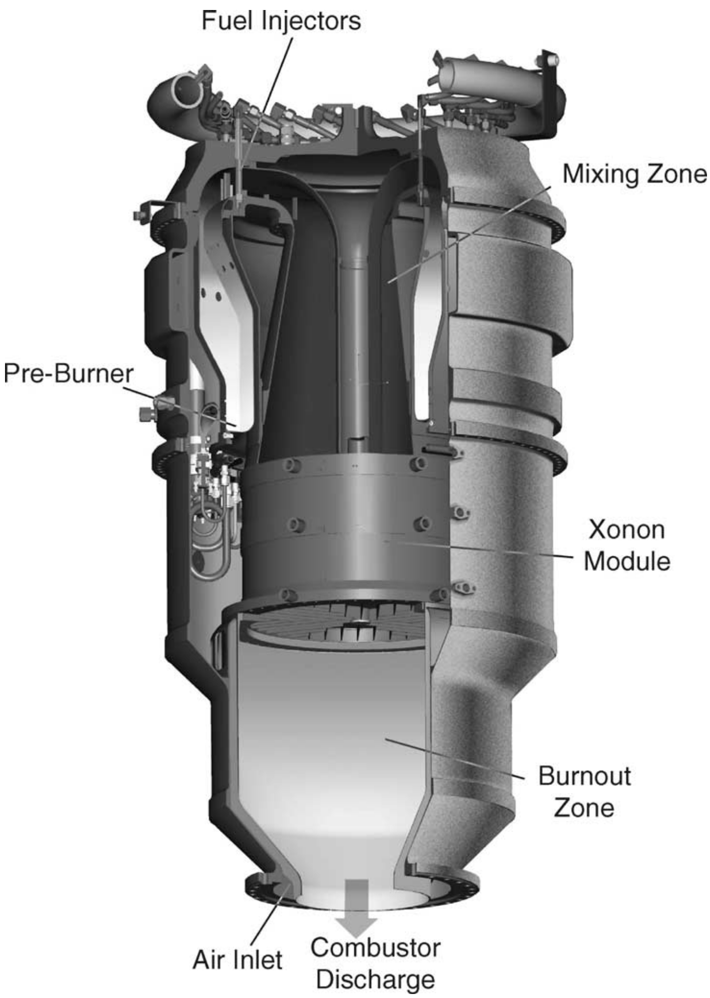

Fig. 8. Cross-section diagram of the commercial KHI M1A-13X combustor.

  - The catalyst composition was modified with to incorporate improved materials that would provide improved activity and greater durability.
  - While the demonstrator combustor had numerous pieces of instrumentation including over 100 thermocouples, numerous pressure taps and sampling tubes, the instrumentation was reduced to the minimum required. Instrumentation that was determined to be required in the commercial unit was upgraded to components that would have the required durability and to allow easy servicing including replacement in the event of instrument failure.
- *Production cost*
  - The preburner was redesigned from a 4-can can annular system to an annular system which significantly reduced parts count and simplified assembly.
  - The flow path was simplified to reduce the complexity of the combustor design and the fuel–air mixer was redesigned to reduce the potential for flame holding that could reduce reliability and availability.
  - All components of the combustor system and catalyst module (except the catalyst core) were subjected to structural analysis and life assessment to achieve an estimated 40,000 h operating life. This can reduce life cycle cost.
  - Some materials of construction were changed to lower cost alternative based on the measured operating temperatures and the design was modified to reduce manufacturing cost. This included moving several of the bolted joints to reduce fabrication complexity and to simplify assembly and servicing.

This combustor was designed and fabricated and installed in a test facility at a utility generating station owned by Silicon Valley Power on an M1A-13A machine with a scroll from the M1A-13D machine. The scroll from the M1A-13D machine required less air for cooling better matching the combustor air flow requirements. This configuration, with the M1A-13D scroll, is similar to the final configuration in the test of the demonstrator combustor. A cross-section of the combustor is shown in Fig. 8 with the major components labeled.

Table 2
Field test results from KHI M1A-13X combustor operated at Silicon Valley Power test sites

Performance criteria	Results (as of 12/31/1999)
Run hours	>8600
NO_x emissions	<2.5 ppm (at 15% O_2)
CO emissions	<6 ppm
UHC emissions	<1 ppm
Availability (total uptime/total time)	90.5%
Reliability (1-forced outage rate)	98%
Dynamic pressure oscillations (noise)	<0.46 psi (rms) over entire load range
Ambient temperature range during test	7–44 °C
Low emissions operating load range	70–100%

5. Commercial system performance

The performance of the commercial combustor is shown in Table 2. The field test facility was fully instrumented with a continuous emissions monitor that tracked NO_x, CO, UHC, O_2 and CO_2. High speed Kistler pressure transducers were installed in the preburner area, in the mixing zone and in the post-catalyst reaction zone to monitor dynamic pressure fluctuations. A special fuel–air sampling system was installed upstream of the catalyst inlet to allow the fuel–air mixture uniformity to be periodically measured. Data, including load, engine parameters, combustor parameters, emissions, fuel flows, temperatures, etc. were

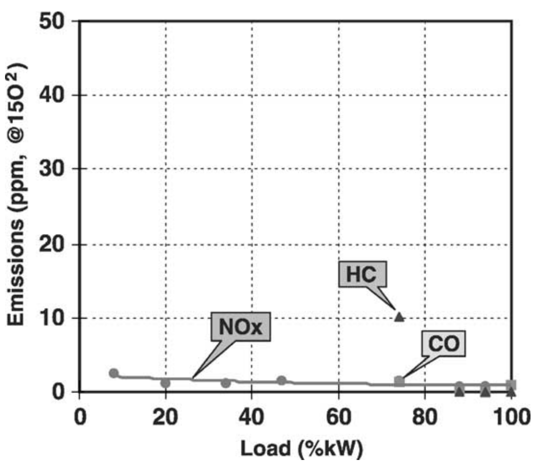

Fig. 9. Performance of the KHI M1A-13X machine over the load range.

Fig. 10. KHI M1A-13X gas turbine package.

all recorded by the engine control system every 2 s and the data archived for subsequent analysis.

Table 2 shows the results for the field test RAMD (Reliability, Availability, Maintainability and Durability) run of 8600 h. During this period, the availability of the machine was 90.5%. That is, the machine operated 90.5% of the total time, including scheduled inspections, scheduled performance tests and any schedule hardware or control system modifications or upgrades. The reliability, which counted only the unscheduled or forced outages, was 98%. The major cause of forced outages were control system and package problems. Since the durability run extended over a full yearly cycle, ambient temperature in Northern California varied from 7 to 44 °C. The dynamic pressure of <0.46 psi (rms) was the highest recorded value over the load range.

The commercial product targets were met. Over an operating load range of 70–100%, emissions of CO and UHC <10 ppm and NO_x <3 ppm were obtained. The turndown performance is shown in Fig. 9. As the load goes below 70%, the emissions of CO and UHC rise due to the low combusted gas temperature in the post-catalyst reaction zone. The temperature is insufficient to fully combust the remaining fuel and CO. The commercial engine generator package is shown in Fig. 10.

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