User Experience—Operating a 300 MW Base Load Cogeneration Plant with High Water Injection Rates to Control NOx Emissions

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Abstract

This paper describes user experience with the operation and maintenance of a gas turbine based cogeneration plant operating at base load while injecting up to 80 gpm (303 l/min) of water to control NOx emissions to 42 ppmv (at 15% O2). The plant, located in the Kern River Oil Field, near Bakersfield, California, has produced an average of 294.6 MWe and 1.903 million lbs/hr (0.863 million kg/hr) of steam since achieving commercial operation in August, 1985. To date, the plant has achieved an operational reliability and availability of 98.9% and 95.4%, respectively. The effects of water injection on combustion hardware, as well as, overall gas turbine reliability and availability and equipment enhancements will be discussed.

Introduction

On August 18, 1985, Kern River Cogeneration company, a partnership of subsidiaries of Mission Energy Company and Texaco Producing Inc, brought into service its Omar Hill Cogeneration Facility, a 300 MWe gas turbine based cogeneration plant in the Kern River Oil Field near Bakersfield, California (Figure 1). The plant utilizes four (4) General Electric gas turbine/generators (GT-G), Model MS7001E, each exhausting into an unfired heat recovery steam generator (HRSG) producing 65% quality (wet) steam to the oil field for thermally enhanced oil recovery operations. The primary fuel for the plant is natural gas with a low sulfur distillate oil as a back-up. Support systems for the GT-G/HRSG units include: a water-deminerlization system, compressed-air systems, water-supply systems, and a distributed control system (DCS)(1).

During the equipment selection phase of the project, considerable concerns were raised regarding the effects of water and/or steam injection on the combustion system of the gas turbine, particularly the areas of system dynamics, combustion liner integrity, transition...
piece material creep, and reliability. Regulatory requirements imposed a limit for NOx emissions of 42 ppmv at 15% O2 or 140 lb/hr. At that point in time, there had been little operational experience with the Model MS7001E gas turbines operating at continuous base load output while controlling NOx emissions at 42 ppmv. Also, the operating experience, to date, primarily had been with steam as the NOx control medium rather than water. At Omar Hill, the steam produced for the thermally enhanced oil recovery operations, although softened, contains up to 1000 ppm total dissolved solids (TDS) and thus is not suitable for the production of saturated or superheated steam for injection into the turbine. A separate steam circuit could have been incorporated into the HRSG design, but it would have resulted in a much more complicated design with a lower reliability. Also by using water as the NOx control medium, demineralized water requirements would be reduced by nearly 60%. Because of this and the overall project goal of maximizing reliability and availability, it was decided to use water as the NOx control medium.

Following commercial operation, a conservative, graduated schedule of combustion system inspections was implemented to ensure that combustion system parts did not deteriorate prematurely and cause additional damage or a decrease in reliability. Also, as the plant was brought on line, a detailed parts tracking system was initiated to monitor operation, maintenance and repair activities.

As the experience level with these gas turbines increased, system enhancements were investigated and implemented. These enhancements were:

- On-line compressor cleaning
- In field gas swirl tip flow matching
- Installation of pre-filter media on gas turbine inlet
- On-line data acquisition
- Combustion parts maintenance packs

Production Statistics

Since commercial operation, the plant has generated 7,490 GWhrs of electrical energy, 42,411,258 million Btu’s (44.75 GJoule) of steam, and has consumed 86,587,746 million Btu’s Lhv (91.36 GJoule) of fuel gas and distillate oil through August 31, 1988. The overall simple cycle heat rate to date has averaged 11,560 Btu/kwhr (Lhv) with an overall thermal efficiency of 76.0%. The gross capacity of the plant has averaged 294.6 MWe and 1.903 million lbs/hr (0.863 million kg/hr) of steam.
During this time, the plant has been on-line 101,693.2 unit hours out of a possible 106,560.0 total unit hours for an on-time of 95.4% (Figure 2).

A summary of on-time history is shown in Figure 3.

A summary of forced, unforced, and balance of plant outages by year is presented in Figure 4.

The primary goal, once commercial operation had been achieved, while avoiding significant equipment damage, was the maximization of the combustion inspection intervals. As seen in Figure 7, the initial inspection interval selected was 2,000 fired hours. Following the GT-G manufacturer's recommendations, and based upon each successive combustion inspection, this interval was increased to the present interval of 6,500 fired hours. The primary reasons for the improvement in the inspection interval are:

- Combustion component modifications
- Optimization of water injection quantities
- Minimization of start/stop cycles
- Increased operating data base

Though initial inspection intervals were more frequent, plant availability was not been significantly because inspection related downtime has been minimized. As
maintenance crews became familiar with the turbine, outage time has been reduced from 72 hours to 40 hours (Figure 8).

To facilitate the inspection, a complete combustion change-out is made, with the inspection activities completed after the gas turbine is returned to service. To enable this type of inspection program and to avoid inspections during the summer peak periods, three (3) additional sets of combustion parts are maintained for the Omar Hill Facility. By having a spare set for three of the four units, considerable flexibility is achieved, which can mitigate any restrictions caused by delays in part repairs, unexpected outages, or scheduling conflicts. Because of the number of combustion parts, seven (7) sets total, and the need to monitor equipment reliability, a spare parts tracking system was developed. This computer-based system tracks the movement of major combustion parts (combustion liners and transition pieces) by serial number, fired hours, cumulative fired hours, chamber position, association with mating combustion parts, turbine identification number, service dates, and highlights, such as, whether or not the part has been scrapped or is active.

Small items such as bolts, lockplates, gaskets, clamp supports, crossfire tubes & retainers, and a matched set of fuel-gas swirl tips, are kept organized in a low profile plywood box which is filled, inventoried, and locked. This combustion pack has dowels, dividers, and bolt holes to organize the hardware. This ensures that all the normally consumable parts required to complete a combustion inspection are on hand and ready to be used. Two of these combustion packs are located in the on-site warehouse and are kept full at all times. An additional six sets of these parts are located elsewhere in the on-site warehouse or are on order at all times.

**Combustion System Description**

Figure 9 is a schematic of the gas turbine combustion system. The MS7001E machine has ten can combustion chambers each of which is made up of the components shown. The air from the compressor discharge reverse flows over the transition piece to provide some active cooling, and then flows to the combustion liner where it enters into the combustion process at the fuel-nozzle end. The compressor discharge air is also used for cooling the liner walls, and is used to shape the temperature profile of the hot gases in the dilution zone before these hot gases enter the transition piece and the first-stage turbine nozzle. In addition to the fuel and air mixture within the combustion area, water is injected at the fuel nozzle end of the combustor to control nitrous oxide emissions.

The Omar Hill units have been operating in continuous duty with the highest water injection rate of the present MS7001E fleet. Figure 10 is an example of the single fuel-nozzle system combustion activity of dynamic pressure oscillation that occurs as a function of water injection. As more water is injected, more combustion dynamic activity is generated which the combustion hardware must sustain since the dynamic activity

![MS7001E REVERSE-FLOW COMBUSTION SYSTEM](attachment:image.png)
aggravates the wear rates and fatigue life of the components. The units use a single fuel nozzle (one fuel nozzle per combustion chamber) whereas units currently being installed that will require even more water injection use multiple fuel nozzles per chamber. (Combustion development work has shown that a multiple fuel nozzle combustor is more tolerant to water injection than a single nozzle system). Because the combustor dynamics of these machines were expected to influence the life and planned inspection intervals, it was important that hardware performance be tracked carefully. A combustion components tracking program, by serial part number, was initiated to accomplish this. The results of this tracking is described below for each of the main combustion system components. Overall, the combustion system has performed extremely well. Hardware distress has been minimal and has been addressed in a methodical and consistent manner. By continuing to do so, the objective of a reliable combustion inspection interval of 8,000 hours or more will be achieved.

Combustion Liners

The slot-cooled combustion liner used in the Omar Hill machines is shown in Figure 11. The liner employs impingement and film cooling as shown in Figure 12. Other design features are:

- Thermal-barrier coating of the inside surface which reduces the metal temperature as much as 120 °F. This coating also smoothes out axial and circumferential thermal gradients to improve the thermal fatigue life.

- Hole reinforcing sleeves in high stress areas to improve thermal and high-cycle-fatigue capability in the combustion-hole to cooling-hole interface.

The combustion liners at Omar Hill have accumulated over 1,060,000 hours of service with an average service of over 14,400 hours per liner. This includes eleven liners that have been removed from service which themselves had averaged only about 7,700 hours before being retired. The areas of distress most frequently encountered have been:

- Wear of the spring seal at its interface to the transition piece.
- Wear at the interface to the fuel nozzle.
- Wear at the crossfire collar (interface to cross fire tubes).
- Cracking between cooling holes.
- Cracking at combustion holes.
- Cracking of liner cap on the inside hot gas surface.

The primary cause for retiring a combustion liner from service has been cracking between cooling holes. The introduction of the reinforcing sleeves in the liner mixing holes has made a major improvement in resisting this cracking mode but, with increased dynamic pressure activity caused by the high water injection rates, it is apparent that this cracking mode has not yet been eliminated. Design work is underway to further address this issue.
The heavy-wall (HTP784) transition piece used in the combustion system is shown in Figure 14 and is schematically shown in Figure 15. These transition pieces are made from Nimonic 263 material which has improved creep strength in comparison to earlier designs constructed of Hastelloy X material. The need for improved creep resistance was identified in early model MS7001E gas turbines employing Hastelloy X transition pieces when it was determined that the aft-end opening closed as a function of time. The firing temperature of the MS7001E has increased since the early machines, further aggravating the potential for creep closure. Now, however, after over 18,000 hours on many of these parts, the HTP784 performance indicates that the closure problem has been eliminated. Additional design features of this component are:

- Thermal-barrier coating of the inside surface.
- Patented cylinder mount aft-bracket attachment.
- Body rib stiffener.
- Improved floating seal design to minimize wear.
- Combination impingement cooling and film cooling at the aft-bracket mount.

Wear at the fuel-nozzle interface and the cross fire tube interface has been a nuisance but have been repairable. Design upgrades using hardface coatings are now available and are being considered for application to these machines.

Liner cap cracking on these machines has become much more frequent than observed on steam injected and non-abatement dry machines; thus, it appears that the water injection is responsible for the increased cap distress. It is hypothesized that the inner surface of the cap is thermally shocked when the water injection is initiated which leads to thermal fatigue and cracking of the part. Development work in this area has led to a redesign using thermal-barrier coating of the inner surface of the cap. A set of thermal-barrier coated caps will be installed in the fourth quarter of 1988 for field evaluation.

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The thermal barrier coating effectively reduces the metal temperature by about 100 °F and smooths out temperature gradients which improves the thermal cycling capability of the part. The impingement cooled and film cooled feature of the aft-bracket mount provides cooling in a location where strength is needed for the attachment loads as well as the vibratory operational loads.

The body rib stiffener was a part of the initial design to provide even additional margin for creep. Development work, involving the use of finite element analysis backed up by prototype parts operating in other MS7001 machines with no measurable creep closure, has resulted in the removal of the stiffener rib from the current design.

Early field experience of the HTP784 transition-piece assembly identified a design weakness with the aft-bracket casting. Cracking was found in the casting in the area of the hinge bolt, and a redesign was introduced to eliminate the problem. Figure 16 shows the old and new design bracket and the difference in design features. The new design helped transfer the mounting load from the base of the hinge joint to the outside diameter of the hinge joint. All HTP784 transition pieces are to have this change applied. To date, this design change has totally eliminated the cracking initially observed.

![Figure 16](image)

The aft frame wear from the floating seals and from the side seals has been minimal. The early design parts had side seals that had slotted passages machined into the seal in an attempt to provide additional cooling to the frame at the joint between transition pieces. Experience showed that this “serrated” configuration on the side seal surface caused wear in the slot of the transition-piece frame and, as a result, the seal design is now smooth and flat. The reduction in localized wear as a result of the change has been significant.

Of the high-time parts (16,000 to 18,000 fired hours), three transition pieces have experienced minor structural cracking in the body. This cracking, on all three, was found in the outer corner between the aft frame and the rib stiffener. The parts were readily weld repairable and returned for further service. Although the cause is not immediately known, these parts, as well as others, will be carefully tracked as they continue in service.

Overall, the transition piece performance for these highly water-injected machines has been excellent.

**Fuel Nozzle**

Each combustion chamber has a single fuel nozzle that can supply distillate oil or natural gas fuel to the combustion zone. In addition, the fuel nozzle provides the passages for atomizing air and water injection. Figure 17 is a schematic of the fuel nozzle. The primary mechanical interface between the fuel nozzle and the combustion liner occurs at the outside diameter of the fuel-nozzle gas swirl tip and the inside diameter of the combustion liner fuel-nozzle collar.

![Figure 17](image)

Experience has shown that the interface of the liner and fuel-nozzle has resulted in wear of the fuel-nozzle gas swirl tip outer diameter surface. Typical wear is shown in Figure 18. The wear is readily weld repairable and is not detrimental to the performance of the fuel nozzle in the degree that has been experienced to date. The gas swirl tip is normally replaced. However, if the cost of repair is substantially lower than the cost of a new gas swirl tip, then that part is shop repaired and returned to
service. Wear coatings have recently been made available for these contacting surfaces, and it is required that both the liner collar and the fuel nozzle tip surface be coated to achieve 8,000 hours between combustion inspections.

Early experience on the fuel nozzles also showed the development of face cracking of the gas swirl tip as shown in Figure 19. The thermal fatigue cracks emanate from the corners of the swirl tip slots and extend radially outward towards the outside diameter. This degree of face cracking, as shown, is not detrimental to the function of the part but it is not a desirable condition to have occur if it can be eliminated.

A design change was made that introduced brazing instead of electron beam (EB) welding in the tip construction and a material change was made from 304 SS to 430 SS. The use of a braze joint in lieu of only an EB weld at the joint between the outer surface of the vanes and the inner surface of the fuel-nozzle outer-tip ring provides uniform load distribution between the two parts and removes the thermal and stress concentrations in the vane corners. The material change, which reduced the thermal coefficient of expansion and increased the thermal conductivity, reduced the thermal stresses in the part. The redesigned fuel nozzle tip has nearly eliminated the face cracking of the fuel nozzle.

**Plant Operating Improvements**

High efficiency filters are used to remove particles that cause erosion of the compressor blading. The filters are self-cleaning, but the nature of the air being filtered makes the use of self-cleaning filters less than desirable. To extend the useful life of the filters, a graded density, 2 inch thick, polyester pre-filter is attached to a v-bank of eight filters at a time. It is held in place by the use of self-adhesive velcro. The pre-filter blanket is cut into sizes of 8 feet wide by 9 feet long and totally encloses the v-bank set of filters. This minimizes any seam that may allow un-prefiltered air to bypass the pre-filter. The total pressure drop of the pre-filter is less than 0.1 inch of water column. The life extension of the self-cleaning inlet air filters should at least be doubled from two to over four years. The pre-filter is replaced during each combustion inspection at 2.5% the cost of a new set of air filters. The pre-filter captures the larger particles and oil mist first before it gets to the final filter.

An on-line compressor cleaning system was installed within nine months after commercial startup. Even with high efficiency filtration, the loss in capacity would...
amount to six (6) megawatts per machine in less than 30 operating days. The only method of recovering this loss was to remove the unit from service, perform a compressor crank wash, and return the unit to service. This could be accomplished in six hours and resulted in restored performance. The on-line compressor cleaning system allows KRCC to wash the compressor at base load and greatly reduces the decline in capacity. This six (6) megawatt decline in capacity now takes over 120 days (Figure 20). No long term side effects have been observed in either the compressor or the hot-gas.

All four units have always experienced higher than normal exhaust temperature spreads. Even though all gas swirl tips must pass a statistical flow test before being released to the customer, KRCC took an extra step to help reduce this undesirable exhaust temperature spread. A test stand was built which contains a block-valve and a fine-tuning valve, an orifice plate with differential pressure taps, and a spare fuel-nozzle body into which fuel-gas swirl tips to be tested are mounted. At least twenty swirl tips are tested at a time, all in the same day. The supply pressure is held constant and the pressure drop through the orifice plate is recorded with the swirl tip mounted in the fuel-nozzle body. Swirl tips are grouped into sets of ten according to the pressure drop. Grouping this way has reduced the average exhaust temperature spread from 80°F to 40°F. Over time, this spread increases, but does not exceed the allowable exhaust temperature spread before the next scheduled combustion inspection.

Conclusion

The experience with very high water injection rates to meet 140 lb/hr (63.5 kg/hr) NOx emissions has shown that reliable machine operation can be achieved with an integrated approach between parts repair, parts replacement, and scheduled maintenance. A critical ingredient to continued reliable operation and the increase in combustion inspection intervals is the implementation of a disciplined hardware tracking program, a coordinated parts repair program, a disciplined spare parts procurement program, a coordinated maintenance schedule, and establishing and maintaining close working relationships with the design engineers of the gas turbine. By employing these techniques in a disciplined manner, premature failure or design distress can be identified and corrected in a timely manner, and a carefully coordinated maintenance program can provide assurance of high availability, reliability, and optimized economics for the installation.

References