Virtually everyone directly involved in the design, operation, and maintenance of gas-turbine-based powerplants is well aware of the adverse effects high ambient temperatures and dirty rotating blades and stationary vanes have on compressor performance and power production capability.

**Cooling inlet air.** The most efficient way to maximize output and revenue during the warm months, when power prices typically are highest, is by cooling ambient air before it enters the compressor. Recall that gas-turbine (GT) output is directly proportional to the air mass flow rate. But, since the volumetric flow rate is relatively fixed, the mass flow of the turbine decreases as ambient temperature increases—warmer air being less dense.

Evaporative coolers, historically the most popular of the technology alternatives for GT inlet cooling, reduce temperature by evaporation of water that cascades over a wetted honeycomb media as air passes through the media. Wetted media can cool the inlet air to within a few degrees of the ambient wet-bulb temperature.

Fogging has become a popular evaporative technology over the last decade and now there are well over 1000 systems installed on GTs worldwide. They saturate GT inlet air by spraying very fine droplets of water into the air stream. Fogging systems are capable of cooling the inlet air to the wet-bulb temperature, so they’re more effective than wetted media.

Chillers can cool the inlet air to temperatures much lower than those possible with evaporative systems. Mechanical (electric) and absorption (steam) chillers can maintain any desired inlet air temperature down to about 42°F, independent of ambient wet-bulb temperature. But they have significantly higher capital and operating costs than evaporative technologies.

**Negative impacts of compressor fouling** include reduced compressor air flow, pressure ratio, and efficiency, which cause a “rematching” of the turbine and compressor and a drop in power output and thermal efficiency.

At least one expert estimates that fouling is responsible for 70% to 85% of the total performance loss experienced by GTs during operation. Output losses of between 2% (favorable conditions) and 15% to 20% (adverse conditions) have been attributed to fouling. To learn more, access www.combinedcyclejournal.com/archives.html, click Fall 2004, click “Gain a competitive edge with a better understanding of GT compressor fouling, washing” on the cover.

The two primary methods for maintaining GT compressors at high efficiency are offline and online washing. Goals of the former are to clean a dirty compressor and restore power and efficiency to virtually “new and clean” values. Objectives of online washing are to keep the compressor clean, thereby extending the period between shutdowns required for offline cleaning and retaining desired power output and efficiency.

**Important to glean** from the foregoing is that injection of water into the inlet air stream and/or directly into the compressor are industry best practices critical to achieving plant pro forma performance and power-production goals. While all OEMs are concerned with what goes into their GTs, compressors for the 7F series of engines manufactured by GE Energy, Atlanta, may be more sensitive than at least some others to impingement by water droplets associated with evaporative cooling and online washing.

This conclusion by the editors is drawn from user comments regarding operating restrictions imposed on customers by several of the OEM’s technical information letters (TILs), most recently TIL 1603. Owners have told the editors that this letter, released in mid 2008, strongly suggests that customers comply with its operating guidelines to mitigate erosion of blades in the first stage of the compressor—so-called R-zero (R0).

Owners with OEM service agreements presumably would jeopardize their contracts if they didn’t implement the 1603 directives. Those not bound by GE agreements might decide to do otherwise, but could run afoul of insurance carriers that believe OEM guidelines should be followed.

Several owner/operators told the editors that the OEM’s TIL recommends...
Users, consultants share fogging views, experiences

After listening to Thomas Mee at the CTOTF’s Fall Turbine Forum in Tucson, the editors contacted several users and consultants regarding their views and experiences with fogging—most specifically, its impact on compressor-blade erosion. The effort to provide more balanced coverage of the on-going industry debate did not achieve the level of success envisioned. Calls were initiated during the busy outage season and, understandably, many were not returned. Below are “sound bites” from conversations with the editors and e-mail replies to specific questions.

Economic justification for fogging. A cross section of the industry offered the following:

- Expect fogging to increase power output by 7% to 8% given 20 deg F of cooling. One user’s calculations was based on ambient conditions of 95F dry bulb, 75F wet bulb.
- Heat rate may improve by as much as a few percent; exact number depends on cycle arrangement and site conditions. The heat-rate improvement on a combined-cycle plant is negligible.
- Double-digit NOx emissions reductions are possible on some engines under certain conditions.
- Lower capital cost than other traditional inlet-air cooling options. One user put the total installed cost per “fogging kilowatt” at about $70 for 7EAs and $80 for earlier GTs—certainly inexpensive peak power. All systems were retrofitted.
- Another user’s calculations showed the annual owning/operating cost of a fogging system for a 7FA was $200,000 per annum less than that for a media-type evaporator. Reasons include efficiency and output losses associated with the pressure drop across the wetted media. This is true even when one considers the higher cost of the demineralized water required for fogging.

Comments specific to the 7FA fogging debate:

- We fog several 7FAs. Knowing there are serious consequences to wet R0s, we are cautious and diligent about monitoring. We expect some erosion and consequently follow the guidelines of TIL 1603 very closely. We also fog 7EAs but don’t have the same level of concern regarding erosion damage to them that we have for the 7FAs.
- The OEM should develop more specific and quantitative blade-deterioration criteria than the 8-mil erosion limit that it has specified. Once the 8-mil limit is reached, you have to operate dry. Our experience indicates you will erode 8 mils quickly when conducting regular online water washes. I believe washing has a far greater impact on erosion than fogging.
- Anything that damages the leading edge of a compressor blade reduces its fatigue resistance and that blade will crack sooner than one not so damaged. But the root cause of R0 cracking is blade harmonics-period. My experience indicates the OEM’s fogging system is a maintenance nightmare and it is linked to leading-edge erosion.
- We do offline water washes only, no online washing (multiple responses).
- Plant’s 7241 7FA with a flared compressor and enhanced P-cut blades operates in base-load combined-cycle service. It is fogged about 1500 hr/yr. The enhanced P-cuts, which replaced original non-P-cut blades, have a service history spanning more than 16,000 hours and have been inspected six times. Blades have noticeable erosion but the OEM does not require dental molds on airfoils of this design.
- The original fogging system was installed downstream of the inlet bleed-heat header and just upstream of the trash screen and inlet duct elbow, above the compressor inlet. It was replaced nearly four years ago with a more robust system having nearly twice the number of spray nozzles and relocated to just behind the inlet filters. The new array’s 0.006-in. orifice nozzles replaced 0.008-in. nozzles.

Online washing is done every other day when temperature is above 50F; offline washing is a semi-annual event. Goal when the fog system is in service: 90% relative humidity as determined by Vaisala Inc instrumentation at the compressor inlet. Fogging is initiated automatically when ambient temperature reaches 62F. A nozzle monitoring system warns when low pressure or high flow is indicated. Plant periodically experiences filter plugging and the affected filters are replaced when this occurs.
- Cracked R0 blades have been found on a significant percentage of units inspected in the last nine months of 2008. Industry scuttlebutt is that the OEM will be issuing (no date known) a technical information letter recommending initial-inspection and reinspection guidelines as well as a recommended inspection interval.
- Online wash five minutes daily. No other information provided.
- Dovetail cracks found on R0 blades of one GT in a 2 x 1 configuration after only 1600 hours of operation and 132 starts. No water ever was used in the machine at this plant, which is located well inland (no “ring of fire” effects).
- Cracking found on R0 blades of 7FAs located more than 25 miles from the coast. These units sit across the fence from another OEM’s GTs which are problem-free.
- Plant was commissioned with standard R0 blades. They were replaced a year later with P-cuts to mitigate the risk of blade liberation resulting from leading-edge erosion and/or FOD. In less than three years, the P-cuts were refitted with standard blades to mitigate risk from P-cut cracking. Plant then stopped fogging to prevent the possibility of blade erosion; units never had been washed online. Despite the precautions, a crack was found in one of the pristine blades two years later.
- We have done only one offline wash on this unit, never an online wash. No other information provided.
- Our 7FA Model 7221 (unflared compressor) in base-load combined-cycle service was fogged approximately 1500 hr/yr for about nine years. Foggging stopped when P-cut blades were removed and replaced with non-P-cut airfoils. The original R0 blades had more than 12 mils of erosion after about six years of fogging service when replaced with P-cuts. Approximately three years later the P-cuts were removed. The OEM UT-inspected the blades and errantly condemned them for cracking that could not be confirmed off the engine.

Online washing is done every other day when temperature is above 50F; offline washing is a semi-annual event. Foggging array with nearly 900 nozzles is located just behind the inlet filters; silencer,
time limits for online washing that depend on the design of R0 blades installed. Recall that the OEM has changed the design of its blades several times since the first F-class unit went into operation.

TIL 1603 also is said to present intervals for so-called “dental-mold” impressions of the leading edges of R0 blades to determine if erosion is within what the OEM considers safe limits. If it is not, repairs may be required to mitigate cracking risk.

A concern of several users who spoke with the editors was that the recommended intervals between inspections for erosion were of relatively short duration (in some cases, 100 hours of “wet” operation or less). Wet operating hours are defined as hours of operation with fogging, water wash, or with an evaporative cooler that has water droplets stripped off because of improper design/operation. As for the expenses associated with inspection (staff and outage time, lab costs, etc), who pays? A rhetorical question: the owner, of course. Is the expense budgeted? Doubtful.

A few plant personnel also expressed concerns about a level playing field. They said the inspection intervals associated with a non

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Fog inlet cooling – starting from only $25/kW
Erosion concerns in GE F frames may just disappear with the planned introduction of the OEM’s new compressor rotor in spring 2009. However, cost undoubtedly will be an issue.

A third-party alternative, also expected in the spring, is said to offer redesigned airfoils to accommodate as much online washing and inlet-air evaporative cooling as users might want to use. This would be a far-less-costly alternative, but it undoubtedly would violate the terms of the OEM’s service agreements. Plus, this solution would require your insurer’s approval.

CTOTF looks for answers

The rolling controversy over whether evaporative inlet cooling systems and/or online washing systems can be held accountable for R0 blade erosion—and if one or both can, to what degree—was the motivation for inviting Thomas Mee III, chairman and CEO, Mee Industries Inc, Monrovia, Calif, to address delegates to the CTOTF 2008 Fall Turbine Forum on fogging technology.

Mee participated in the group’s GE Roundtable in mid September, focusing on optimizing fog evaporation and minimizing compressor water ingress. Dominion Energy’s Larry Rose, vice chairman of the roundtable, moderated the session. Previously, members of the Combustion Turbine Operations Task Force had heard from a representative of Gas Turbine Efficiency, Orlando, Fla, on the technology of online washing (access www.combinedcyclejournal.com/archives.html, click 2Q/2006, click “CTOTF” on issue cover and scroll to p 56).

By way of background, Mee Industries has supplied nearly 750 fogging systems for GTs worldwide (81 for GE F frames) and it claims global market leadership in this sector. Many Mee systems have more than 10 years of experience; also, a significant percentage were designed for wet compression—so-called high fogging (access www.combinedcyclejournal.com/archives.html, click spring 2004, click “Recent experience indicates wet compression meets expectations when done correctly” on issue cover).

The challenge for any moderator of an electric-power industry meeting is to keep supplier presenters focused on the technology and to resist the temptation to discuss features and benefits. Judging from a few user comments, Mee met expectations. He can talk endlessly, or so it seems, about the physics of water droplet behavior in GT systems. One reason is the company’s history of research on the subject. A “summary” of this work is presented in three comprehensive papers published as part of the "Proceedings of ASME Turbo Expo 2003.”

Mee’s message was that fog droplets don’t directly cause erosion. While compressor suctioning of unatomized, flowing, and pooling water is potentially conducive to problematic wear and tear of R0 blades, proper design of fog and drain systems can prevent damage from these sources.

He began with a brief discussion of factors critical to the design of an effective fogging system. Droplet size is of primary importance because small droplets evaporate quickly. Those too large to evaporate in less than two seconds—the approximate time it takes air passing through the inlet filters to reach the compressor—will either fall out on the duct floor or enter the compressor.

The majority of existing fogging systems use either impaction-pin (Fig 1) or swirl-jet nozzles. “Both nozzles create an expanding conical spray plume,” Mee told the group, “which gets progressively thinner as it moves away from the orifice.” Eventually, turbulence created by the interaction of the high-velocity water jet with the surrounding air causes the plume to break apart. Surface tension causes
the water particles to adopt a spherical shape.

Impaction-pin nozzles form a conical plume by impacting the high-velocity water jet from an open orifice against the small pin shown in the illustration. Research by Mee Industries indicated that impaction-pin nozzles produce smaller droplets than swirl-jet nozzles when compared on a level playing field—that is, the same flow rate, pressure, etc. Specifically, Mee Industries’ impaction-pin nozzles are designed to produce a fog in which 90% of the droplets are 20 microns or smaller. To put this in perspective, consider that the average human hair is 100 microns in diameter (Fig 2). Size really does matter. Mee took a few minutes to discuss the physical nature of water droplets. “Droplets are spheres,” he said, “and thinking of them only in terms of diameter can be very misleading.” When someone speaks of a 30-micron droplet that seems very small, he continued, but it has nearly three-and-a-half times the mass of a 20-micron droplet and falls out of the air stream twice as fast (Fig 3). Laboratory tests conducted by Mee Industries determined that 20-micron droplets were “table stakes” in the design of a fog system for the sensitive 7F frame (Figs 4 and 5). Mee said this was confirmed in the field.

2. Impaction-pin nozzles produce a fog with 90% of the droplets 20 microns or smaller, Thomas Mee told CTOTF attendees in explaining the capabilities of his company’s product.

3. Droplets are spheres and thinking of them only in terms of diameter can be very misleading.

4. Smaller droplets produced by impaction-pin nozzles create a smoke-like white plume.
In Fig 4, note that the small droplets produced by impaction-pin nozzles create a smoke-like white plume that spreads to a diameter of about 12 inches only about a foot from the spray nozzle.

A comparison photo shown to attendees revealed that the larger droplets from swirl-jet nozzles produced a plume with a defined edge and a spray that is less opaque.

Another important fact: Measurements taken during the lab tests show that droplets cease to coalesce inside the spray plume less than a foot from the nozzle—in fully humidified air. This means that it’s important to measure droplet size far enough from the nozzle orifice to get the true size of droplets produced by that nozzle.

**Location, location, location.** Fundamentals reviewed, Mee explained why he believes the 7F series of machines is seeing more water at the compressor inlet than necessary. Fig 6 shows that the OEM’s recommended location for fog nozzles in its F frames generally does not allow sufficient time for droplet evaporation and can lead to flowing water at the compressor inlet.

Referring back to Fig 5, note that droplet diameter after one second of evaporation time is about five times larger than after two seconds. It follows, Mee continued, the more time you allow for evaporation the less likely it is for an R0 blade to experience erosion on the leading edge.

He suggested locating the nozzle array immediately downstream of the air filters (Fig 7). This would allow about two seconds for evaporation—twice the time available than when following the OEM’s guidelines for fog-nozzle location. Mee mentioned that his company’s first fog system for an F-series machine was designed to remove flowing water in the high-velocity area of the inlet duct.

**Improper design** of the fogging system results in flowing water at the compressor inlet and a greater likelihood of erosion damage to first-stage blades.

**10. A proper system** for removing flowing water minimizes the probability of erosion damage.

**11. Small gutter** installed around the compressor inlet prevents suctioning of water over the bellmouth. Details provided here are patent-protected.
After fogging well over 1000 hours annually for nearly 10 years, the operator reported relatively little blade erosion attributable to fogging.

Mee paused to discuss the importance of proper nozzle manifold design in preventing water accumulation at the compressor inlet. He showed a CFD (computational fluid dynamics) plot at the filter wall of a typical 7FA to illustrate the large variation in velocity across the ductwork (Fig 8). The message: Air velocity must be considered by designers in the placement of nozzles to avoid localized over-saturation. Translation: More nozzles are required in high velocity areas than in low-velocity regions of the ductwork.

However, no matter how tight the design, the inlet-air system is dynamic and sensitive to changes in air temperature, humidity, wind direction and velocity, GT load, etc. This makes it impossible to “tune” the system to maintain the ideal 100% saturation condition at the compressor inlet throughout a given production run.

Windows at the bellmouth for visual inspection of pooling or running water are a good idea. Flowing water at the inlet can be avoided by setting the fog system control parameter so the system always slightly “under-fogs.” This can dramatically reduce the amount of water at the compressor inlet.

Mee then showed attendees where to look for flowing water during operation (Fig 9):
- On ductwork walls; be sure it is not being sucked over the inlet scroll.
- On the rear wall; be sure it is not accumulating on the inlet cone and being sucked into the compressor.
- On the floor; be sure pooled water is not being sucked into the compressor.

Locating spray nozzles as close to the air filters as practical and designing the nozzle array to accommodate the velocity profile across the ductwork are critical to success, for sure. But proper design and arrangement of gutters and drains also are necessary to provide the contingency to accommodate varying operating conditions.

Fig 10 shows where Mee recommended gutters and drains to minimize the probability of free water gaining access to the compressor. Also note the recommendation for moving the trash screen further upstream than the OEM’s traditional placement—this to prevent condensation of fog and the formation of large droplets close to the compressor inlet.

Fig 11 shows details of the small gutter Mee Industries installs around the compressor inlet to prevent suctioning of water over the bellmouth: Fig 12 the details of wall gutters and drains. Mee mentioned the company has a patent that covers methods for removing flowing and pooling water from the inlet ducts so it cannot be suctioned into the compressor as unatomized water.