Peak Capacity Enhancement at Northern States Power's Wheaton and French Island Stations Through Inlet Fogging

Mark Holmberg, David Herbig, Stanley Shilinski
Northern States Power Company

Russell Girtz, Russell McLandsborough
Black & Veatch Corporation

Thomas R. Mee, III
MEE Industries, Inc.

Introduction

In the summer of 1998, the increasing competition in the electric generation market and the industry's reluctance to build more plants had a significant impact on the pricing of a megawatt-hour. The need to add electric generation capacity to the Northern States Power Company (NSP) system for the summer peak of 1999 was further driven by the energy prices experienced in 1998 and the forecasted energy prices in the near future.

This paper describes the implementation of inlet fogging at two of NSP's combustion turbine plants to provide power augmentation. This paper includes descriptions of the fogging skids, the water treatment requirements, and the operational results.

Project Justification

The success of Tennessee Valley Authority's program of installing inlet fogging systems in their combustion turbine (CT) units initiated the NSP study of these systems as viable options for capacity enhancements.

A major concern was the potential risk of damage to the turbine compressor blades and other internals. Through further investigation, it was discovered that various turbine manufacturers were on the threshold of offering similar systems on their new CT frames. This significantly increased NSP's comfort with the technology and they proceeded in earnest to select and purchase inlet fogging systems for their CT plant sites.

The market for inlet fogging systems included one manufacturer with a majority of the CT applications and two or three others with considerably less experience in the utility industry. Two manufacturers of inlet fogging systems were selected and requested

About the authors

Northern States Power Company
Mark Holmberg, David Herbig, and Stanley Shilinski may be contacted at 01-612-330-5734.

Black & Veatch Corporation
Russell Girtz and Russell McLandsborough may be contacted at 01-913-458-2000 (e-mail: info@bv.com).

MEE Industries, Inc.
Thomas R. Mee, III, may be contacted at 800-732-5364.

to submit proposals to provide inlet fogging systems. The proposals included basic system operation and estimated the performance increase possible at each site. The responses confirmed the expectation that at least a 7 percent increase in capacity was achievable under the expected climatic conditions. At each site, the climatic conditions were taken directly from American Society of Heating, Refrigeration and Air-Conditioning Engineers, Inc. (ASHRAE) data for the nearest city.

In parallel with bidding and evaluating the inlet fogging systems, NSP evaluated sites based on the following criteria:

- Estimated cost per kW.
- Condition and capacity of the combustion turbines.
- Capacity limitations of the outlet transformers and transmission lines in warm temperatures of summer.
- Capacity limitations of the generator and generator cooling systems.
- Permitting process and schedule.
- Water source and scope of demineralized water treatment equipment.

The CT plant sites are located in Minnesota, South Dakota, and Wisconsin. A priority ranking was applied to the sites based on the above criteria.

Due to the short time frame (it was now February 1999) for an in-service date of June 15, 1999, the two CT plant sites in Wisconsin were selected. The schedule for the permitting process in Wisconsin could support the in-service date where the other state permitting processes would extend the in-service date beyond the summer peak season. The Wisconsin CT plant sites selected were Wheaton (Eau Claire) and French Island (La Crosse).

With the selection of the Wheaton and French Island sites complete, a contract was awarded to MEE Industries, Inc. (MEE) for eight inlet fogging systems.

The Wheaton Plant incorporates six combustion turbine units, four General Electric frames (three 7Bs and one 7B/E) and two Westinghouse frame 501AA.

The French Island Plant includes two Westinghouse frame 501B’s adjacent to a 30 MW steam plant.

The Wheaton and French Island CTs are used for peaking and ancillary services only. The capacity factors for them are under 10 percent.

Inlet Fogging

Because gas turbines are constant volume machines, air mass flow through the turbine is defined by inlet air density. As ambient temperature increases, air density drops. The turbine’s power generation capability also drops steeply, in the order of 1 percent for each 2° F increase in temperature. Thus, at a 100° F ambient condition, power output drops 20 percent below that available at International Standards Organization (ISO) conditions.

Inlet fogging is a controlled method of augmenting turbine power generation by recovering part of the power loss at higher temperatures by cooling the inlet air. The inlet air is cooled by a very fine water spray using a series of very small nozzles. The water absorbs heat as it evaporates, thus cooling the inlet air and increasing its density.

Advantages of an Inlet Fogging System

- It can achieve 100 percent of wet bulb temperature at any operating ambient condition. The fogging system output is staged to maintain 100 percent cooling as ambient temperature and humidity changes.
- Water droplet size produced by the nozzle is 14 microns, which evaporates to less than 5 microns in about 1 second. This size is so small that it does not cause any damage to compressor blade coatings or cause base material erosion.
- The pressure drop created in the inlet duct by the fogging nozzle manifolds is insignificant.
- Water quality used in fogging is high purity demineralized water that does not precipitate any potentially damaging minerals into the compressor, and may even assist in cleaning buildup from compressor blades.
- The power consumption is approximately 0.5 percent of the power increase, or roughly 0.05 percent of total power output of the turbine.
- The capital and operating costs are very low compared to alternative methods of power augmentation. No rework of existing inlet ducting to install the nozzle manifolds was required at NSP's plants.

- The pump skid is compact and of light design, making it easy to locate and install. NSP even considered moving the skids into storage for the winter months.
- A weather station is located on each pump skid which continuously computes the amount of cooling required.
- The high pressure pumps run at lower than design output speeds to enhance their service life and reduce maintenance.
- Overspray is available for further power augmentation. Further description of overspray is included below.
- Small amounts of the water may collect on the bottom of the duct and may be removed by the addition of a drain.
- There is some concern among operators that the inlet duct may rust due to the high humidity created by the fog system and the use of demineralized water. MEE's experience has shown that this is unfounded because none of the over 150 installations have reported this problem.
- All nozzle support members are welded to the duct and components of the manifolds are wire locked to these members to prevent damage to the turbine by loose parts. Since the axial thickness of a fog manifold system is small, it can be located in a number of places. In the case of air cooling only, as used at Wheaton and French Island, it can be placed upstream or downstream of the silencers. If the Wheaton and French Island systems had been designed for overspray, then there would have been two nozzle manifolds: one manifold to maximize evaporation and a second for overspray.

Possibility of Overspray for Power Augmentation

Overspray is the condition where more water is fed into the turbine inlet than is required to meet 100 percent humidity. The purpose of overspray is to further augment output power by interstage cooling of the compressor. Overspray is becoming accepted by the industry, and fog systems have been supplied with up to 0.6 percent of compressor mass flow overspray capability. The power increase from overspray is not as efficient as in the case of cooling, comparing the total quantity of water delivered. Typically, 0.5 percent overspray can achieve about 5 percent power augmentation, whereas 0.5 percent cooling can achieve an 8 to 10 percent power increase. Under optimum conditions, up to 15 percent power increase is achievable.

With overspray there is still a concern that compressor blade damage might ensue and that would be the case if large water droplets were used. A fog system can deliver overspray capability with droplet sizes that are below the size that may create any negative effects on compressor components. Droplets below 10 microns are so light that they generally follow the streamlines and flow around the compressor blades.

Overspray was not implemented at the Wheaton and French Island plants due to NSP's concerns of damage to the turbines. There was no time prior to procurement of the fogging systems to minimize the concern. NSP subsequently determined that the risk of minimal long term turbine damage is manageable and is considering overspray at other CT plants.

Alternatives to Inlet Fogging

The two primary alternatives to inlet fogging for power augmentation are mechanical chilling and evaporative cooling. Mechanical chillers are capable of achieving the largest drop in inlet air temperature of all the methods of inlet air cooling. There are compressor-type chillers driven by electric motors and absorption chillers which utilize steam or waste heat to drive the chilling process. The chillers are operated continuously or as part of the thermal storage systems which make ice during off-peak hours. The drawback, especially for peaking plants, is the large capital expense and operating and maintenance costs associated with the required equipment. It is difficult to prove financial justification for this method of cooling on peaking units.

Evaporative cooling uses the same thermodynamic principles to cool the inlet air to the CT as inlet fogging. A honeycomb-like pad of cellulose fiber material is installed across the inlet. This material is wetted and as the air is pulled through, the water evaporates to cool the inlet air. An advantage of the evaporative system is that they do not require the high purity demineralized water that is needed by inlet fogging. The standard evaporative cooling system requires substantial inlet duct modifications to install the wetting media that covers the entire inlet area. If not properly installed, the air flow velocity strips water droplets from the media which travels into the turbine and causes damage. As the humidity of the ambient inlet air increases, the performance of the evaporative cooler decreases. Under high humidity conditions, inlet fogging provides more cooling than standard evaporative coolers.

A major disadvantage of these two alternatives, beyond those mentioned above, is the time needed to design, procure, and install the systems.

Expected Performance

NSP expected a 7 percent increase in peak load capability from each of the CTs. The installed cost for the systems was expected to be between 40 and 60 $/kW.

Northern climate considerations

Since a fogging system takes advantage of the difference between dry bulb and wet bulb temperatures, or the number of cooling degrees, its performance depends on the availability of cooling degrees. In more northern climates, the number of cooling degrees is generally smaller. Compare a desert environment in Palm Springs, California, where there may be as much as 40° F cooling degrees available, while in Utica, New York, the cooling degrees available may be closer to 13° F. The design cooling degrees at the Wheaton and French Island sites is 24° F.

This factor impacts the economics of a fogging system and yet a fogging system can still offer significant economic benefits in most northern climates even if periods of useful operation are also shorter. A major factor in the viability of this project was the forecasted escalation of the value of peak generation.

The fog system technology has one very big advantage over other types of power augmentation; the basic design parameters offer a very high degree of flexibility suitable for adapting to northern climates.

Implementation

MEE fog systems technical description

The MEE Fog System is designed to deliver the right amount of water to generate the optimum amount of cooling at any ambient temperature condition. The maximum water usage at Wheaton is 23 gallons/minute for each CT and 26 gallons/minute for each CT at French Island. The system uses a series of high pressure plunger pumps operating at 2,000 psi and a specially designed impaction pin type small orifice nozzle, to create a fog of very small microdroplets. A picture of a typical pump skid is included in Figure 1. A fogging nozzle is shown in Figure 2.

The following is a description of the fogging system installed at Wheaton and French Island:

Pump skid controller and weather station

The fog pump skid has an on-board Programmable Logic Controller (PLC) and a weather station. The PLC, with input from the weather station, controls the safety devices and interlocks on the pump skids, maintains the measurement and calculation of weather data, manages the stages of fog cooling, and transmits data to the plant controls.

The weather station consists of a relative humidity sensor and a temperature sensor. The station is mounted on the fog pump skid but it could be remotely located.

Pump skid devices

The fog pump skid consists of a water flow meter, an inlet pressure switch, a discharge pressure switch, and a magnetic motor starter for the pumps.

Skid lock-out and enable feature

A remote switch must be closed by the plant computer signifying that all turbine related permissives are met and that the pump skid has been enabled for operation.

Pump skid faults and alarms

The following are the alarms used to monitor the status of the fogging skid:

A. Low water flow.
B. Low inlet pressure.
C. Low discharge pressure. Low discharge pressure would result in larger droplets being produced which may cause damage to the turbine compressor.
D. Auxiliary contact on motor contactors.

PLC fog staging function

The fog pump skids at Wheaton each have four pumps and at French Island they each have five pumps. The pumps are operated in a sequence that provides seven stages of fogging for the Wheaton CTs and nine stages of fogging for the French Island CTs. Staging typically allows 1° F to 3° F cooling per stage.

The operator can input the desired amount of overcooling (if overspray is implemented) or undercooling as compared to saturation. Set points over 100 percent will result in fog system overspray (i.e., will inject more water into the air stream than can actually be evaporated at the current ambient conditions. Excess water droplets will be carried by the air stream into the compressor section, where the heat of compression will cause them to evaporate).

Using ambient conditions information, the PLC computes how many stages of fog can be turned on without exceeding the set point and turns on that number of stages. See Figure 3 for a photo of an operating fogging nozzle.

The PLC interface panel will display the ambient relative humidity, dry bulb temperature, wet bulb temperature, stage in operation, water flow rate, overcooling or undercooling set point, and alarm status.

Balance-of-Plant Design Considerations

The primary issues addressed during detailed design were location for equipment, source of demineralized water for the fogging skids, storage of the demineralized water, procurement schedules, and controls philosophy.

The major equipment necessary for this project included the inlet fogging skids, water treatment equipment, water storage tanks, and water forwarding pumps. Refer to the site arrangement drawings for Wheaton and French Island, Figure 4 and Figure 5, respectively. A flow diagram for the fogging system at Wheaton is shown in Figure 6.

Due to access requirements around the combustion turbines at Wheaton, the inlet fogging skids and other equipment could not be placed adjacent to the turbine inlet ducts. The skids were placed across the plant road but near as possible to each of the turbines to minimize the piping from each skid to the fogging nozzles. The MEE fogging skids were 12 feet x 12 feet and required 480 volt power and demineralized water. Further description of the fogging skids is included above.

The size of the water storage tanks at the sites were determined using the expected maximum water usage of the fogging system based on historical ASHRAE temperature data. The demineralizer selected could not treat enough water to keep up with the demand of all six turbines operating at full fogging capacity. The tanks are filled each night and the demineralizer put in service any time the fogging system is in service. The water storage requirements were set at 60,000 gallons for Wheaton and 20,000 gallons for French Island. The project considered steel tanks, bladder tanks, fiberglass tanks, and even tanker trucks for water storage. The fiberglass tanks were selected for the project because the tanks could be fabricated and on-site in time for startup. The tanks were shop fabricated and trucked to the site ready to be set in place.

A permanent demineralizer was considered but quickly rejected due to the large capital costs for a system that would be utilized for only a small fraction of the plant's operating hours. A leased modular-type demineralization system was selected. The modular system allows customization of the system based on the raw water quality. The modular system was specified to have enough capacity to provide demineralized water after depletion of one of the cation, anion, or mixed bed vessels. The system was delivered to site, and the vessels were set on timbers and connected using large diameter hoses provided with the system. An exhausted vessel can be disconnected and replaced by the vendor within 48 hours to prevent a system outage due to lack of water. The leased equipment was contracted for the typical duration of the summer peak electrical demand, June 15 to September 15.

The location of the nozzle manifold in the inlet duct was selected based on consideration of duct configuration, silencer locations, access, and residence time of the fog prior to ingestion by the compressor.

As described above, the fogging system from MEE is a self-controlled unit. The plant control system provides a signal to the controls on the fogging skid to enable the system. The plant operator must make the decision to enable the inlet fogging and then the fogging system becomes self-controlled.

The power source for the supply to the fogging skids is a new 480 volt disconnect installed on each CT's auxiliary transformer. The power was then distributed to the loads on the skid by a transformer and power panel.

Underground piping was utilized to eliminate interferences caused by above grade piping. The low pressure piping from the storage tanks to the fogging skids was stainless steel to prevent corrosion due to attack by the highly oxygenated demineralized water. High pressure hydraulic hose was used to route the underground high pressure water from the skids to the fogging nozzles. The hose was chosen to reduce the chance of underground leaks. In the event of a leak, the hose could be pulled out and a new hose inserted into the underground conduit. The hose is also resistant to damage from water freezing in the line.

The entire water system is designed to be drained to prevent damage during freezing weather. Couplings were provided to allow draining of the nozzle manifold and to allow compressed air blow-out of the underground hoses. For photos of the site, see Figures 7 through 11.

Schedule

Due to permit constraints, construction at the Wheaton and French Island plants did not commence until the week of May 24, 1999. In two and a half weeks, startup testing for the first MEE pump skid was performed. The successful completion of this fast track construction project was achieved due to the efforts of NSP's construction superintendents, Mr. Paul E. Donaldson and Mr. Tim Becker and the general contractor K'nG Mechanical, managed by Mr. Keith Nuutinen.

The expedited schedule required the construction crews to operate on two ten-hour shifts, including weekends.

Results

During the week of June 7, 1999, the initial startup tests for the inlet fogging system commenced at the Wheaton Plant. Operational tests were conducted with the units in operation the following week. The test procedure required the CT units to be initially operated at base load and then increased to peak load. The inlet fogging systems were initiated and readings were recorded for capacity and weather data. The test period lasted 60 to 80 minutes for each unit and resulted in capacity gains of 6 to 8 percent. The tests at Wheaton were conducted with dry bulb temperatures in the mid sixties to low seventies with relative humidity in the high 30 percent range.

At the end of the week, operational tests were conducted at the French Island Plant with similar weather conditions. Capacity increases exceeded 8 percent for both units.

As a result of the tests, operating protocol was established to operate the inlet fogging systems only with the units at base load.

Project Summary

The following items were identified during construction and initial operation as methods to improve the implementation of inlet fogging at other NSP facilities:

- Carefully review nozzle positions relative to flow (45 degrees from vertical in direction of air flow) for GE 7B frames.
- Add inlet duct drains at strategic locations to prevent pooling of demineralized water and possible corrosion of inlet duct.
- Coat bottom of inlet ducts based on results of inspection.
- Increase distance between bottom nozzle header and duct floor for GE 7Bs (tendency to pool water on duct floor).
- Ensure nozzles and supply lines are properly drained and/or blown out with air prior to winter season in northern climates.

The inlet fogging systems were relatively simple to operate and maintain during the summer of 1999. Combustion turbine capacity increases due to inlet fogging matched those experienced during startup testing (6 to 9 percent).

Reference

ASHRAE, *1997 ASHRAE Handbook - Fundamentals I-P Edition*, published by ASHRAE, Atlanta, 1997.

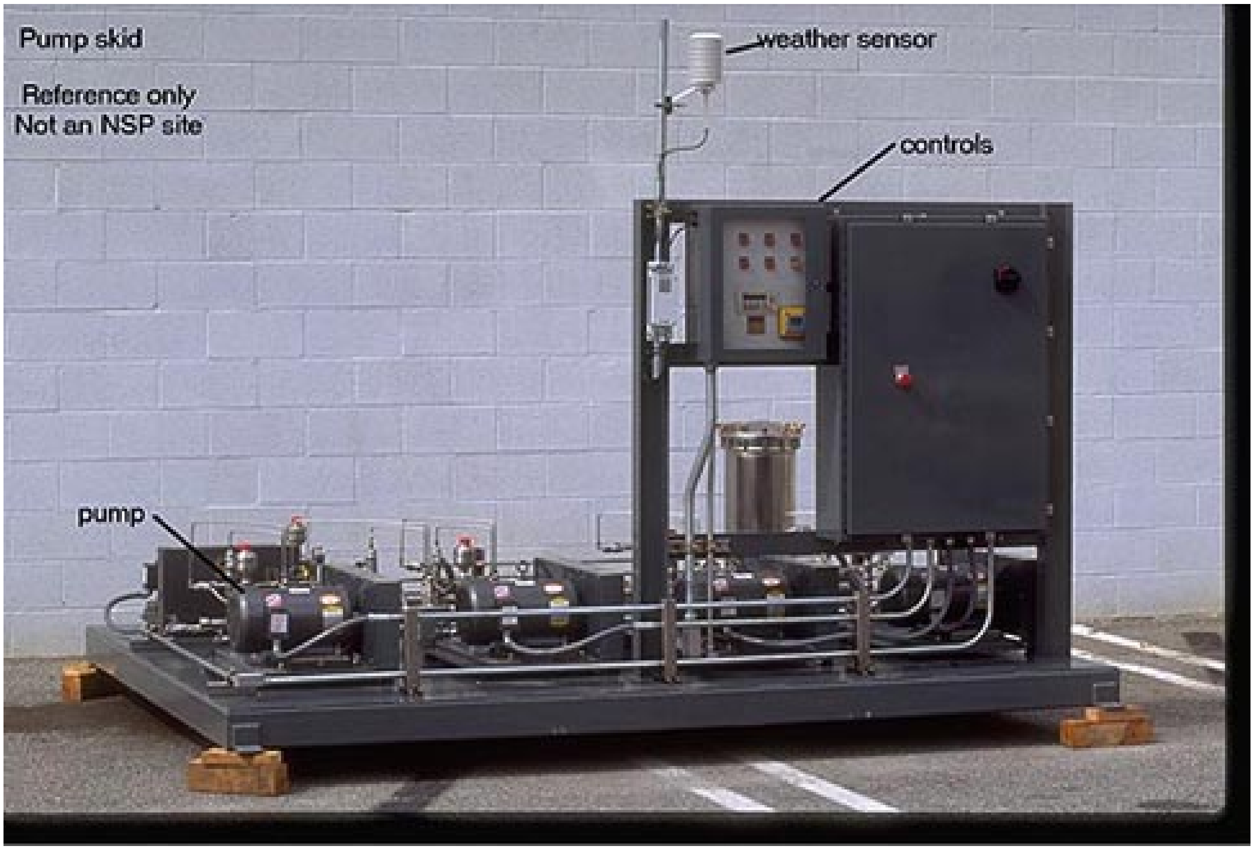

Figure 1. Pump Skid

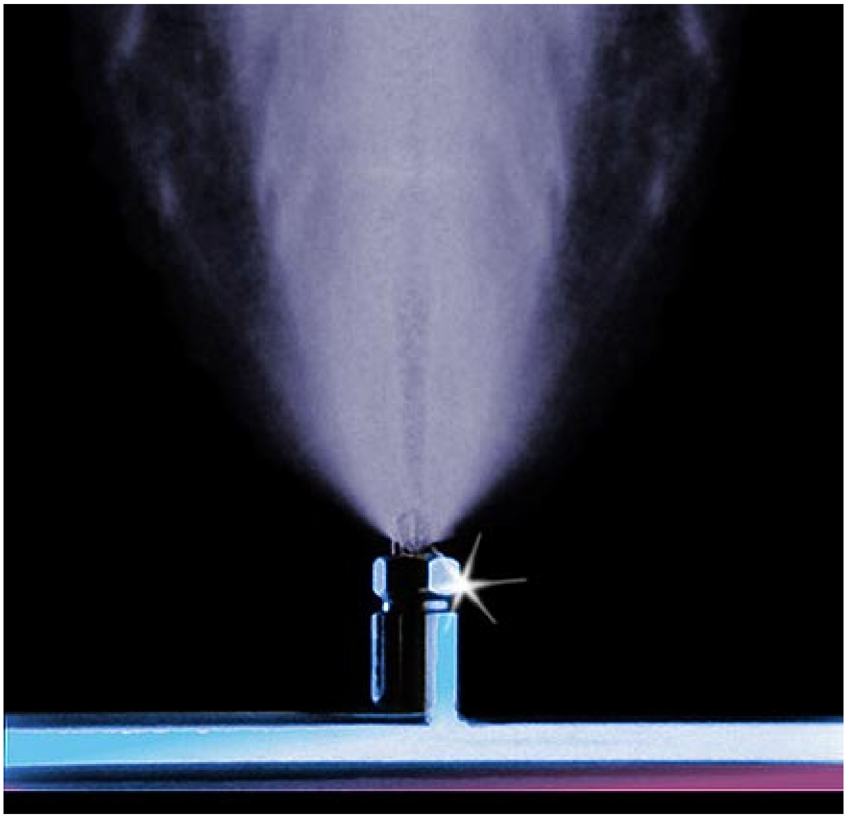

Figure 2. Fogging Nozzle

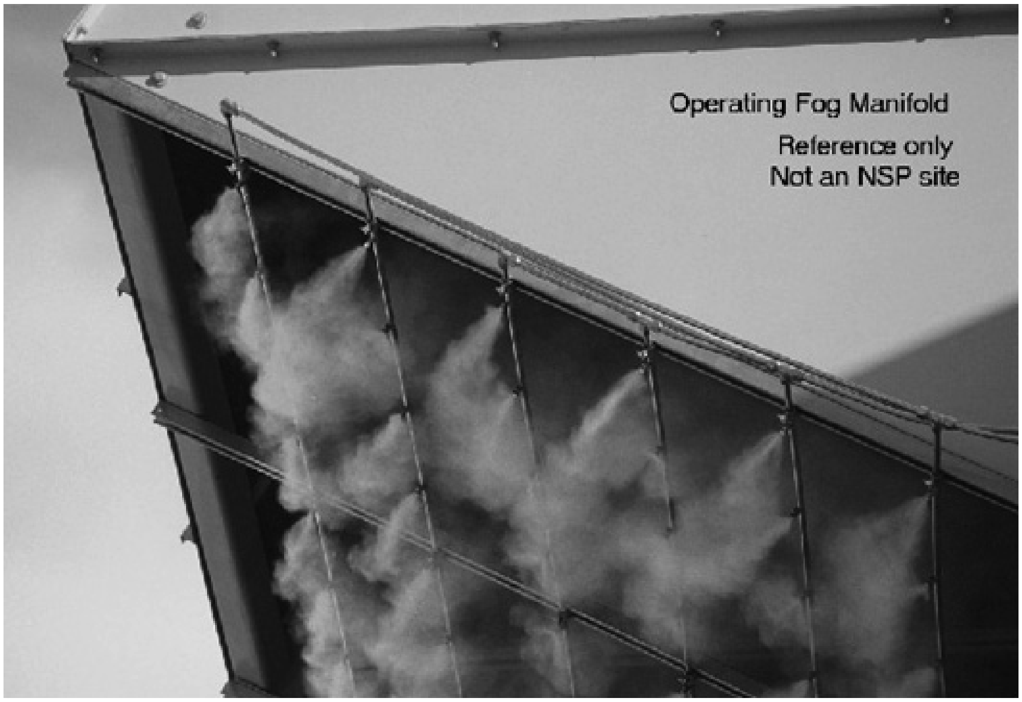

Figure 3. Operating Fogging Nozzle

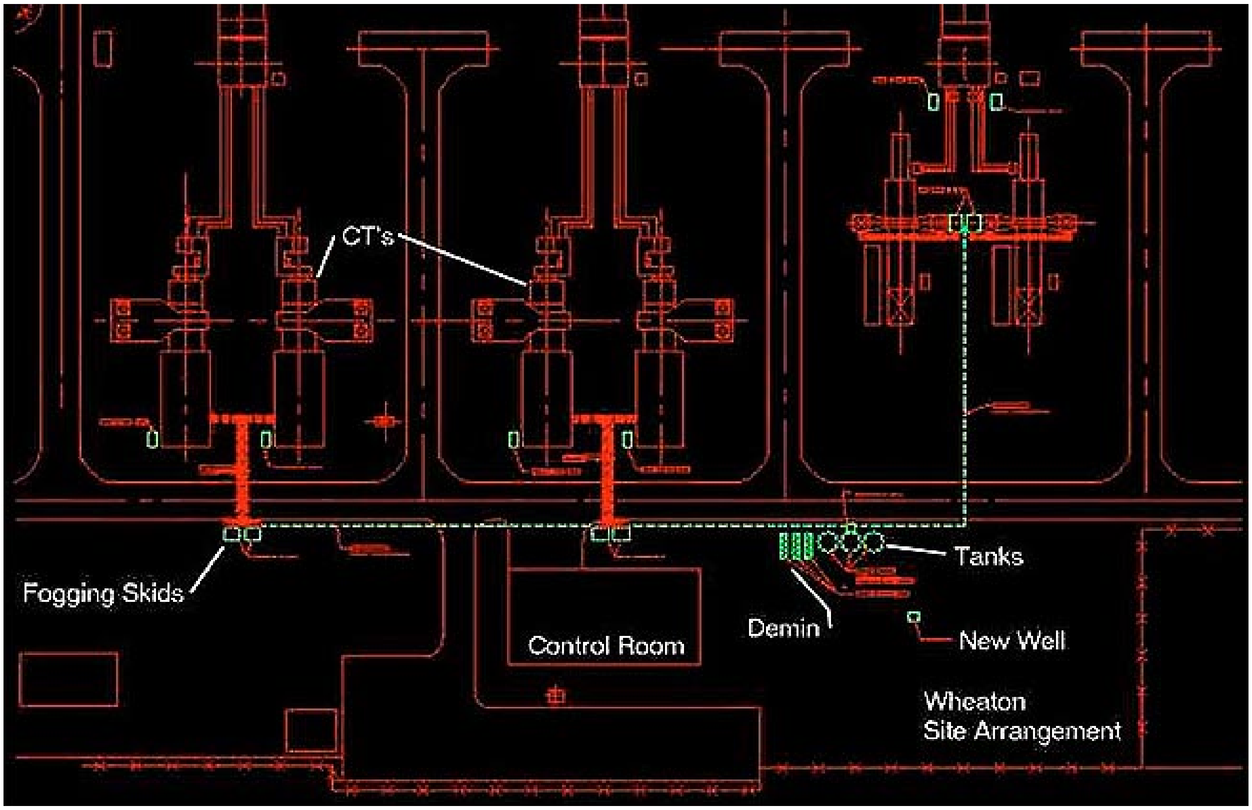

Figure 4. Wheaton Site Arrangement

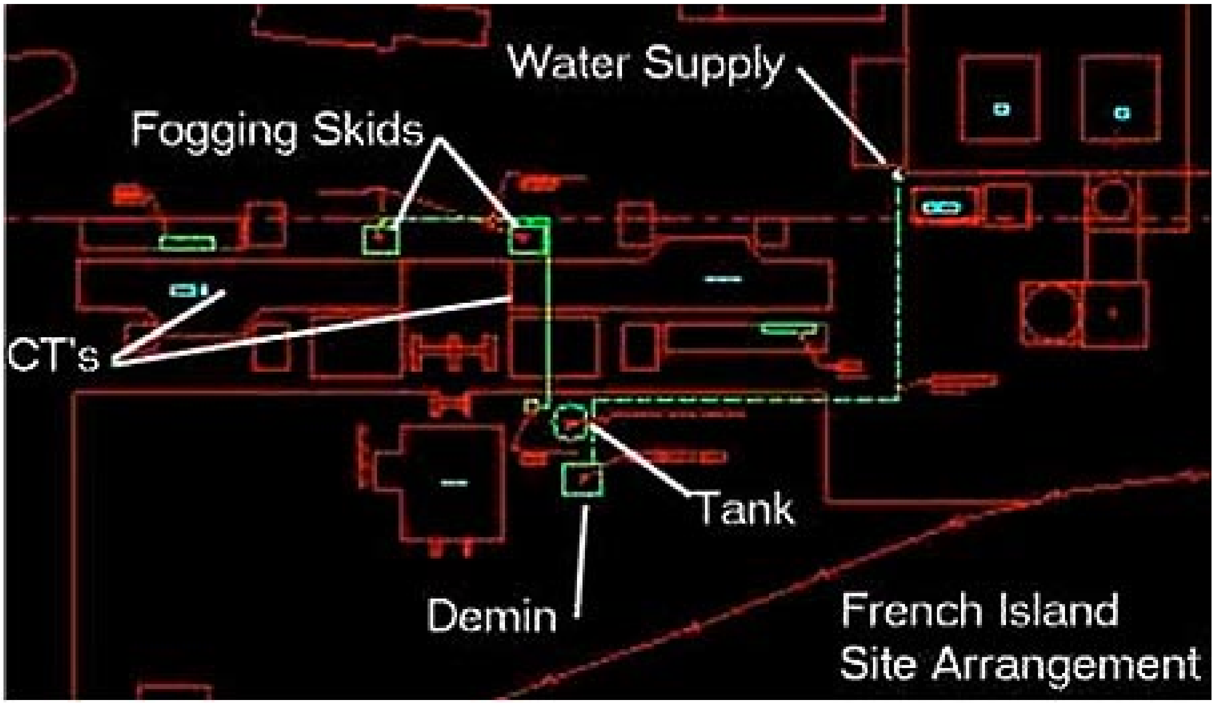

Figure 5. French Island Site Arrangement

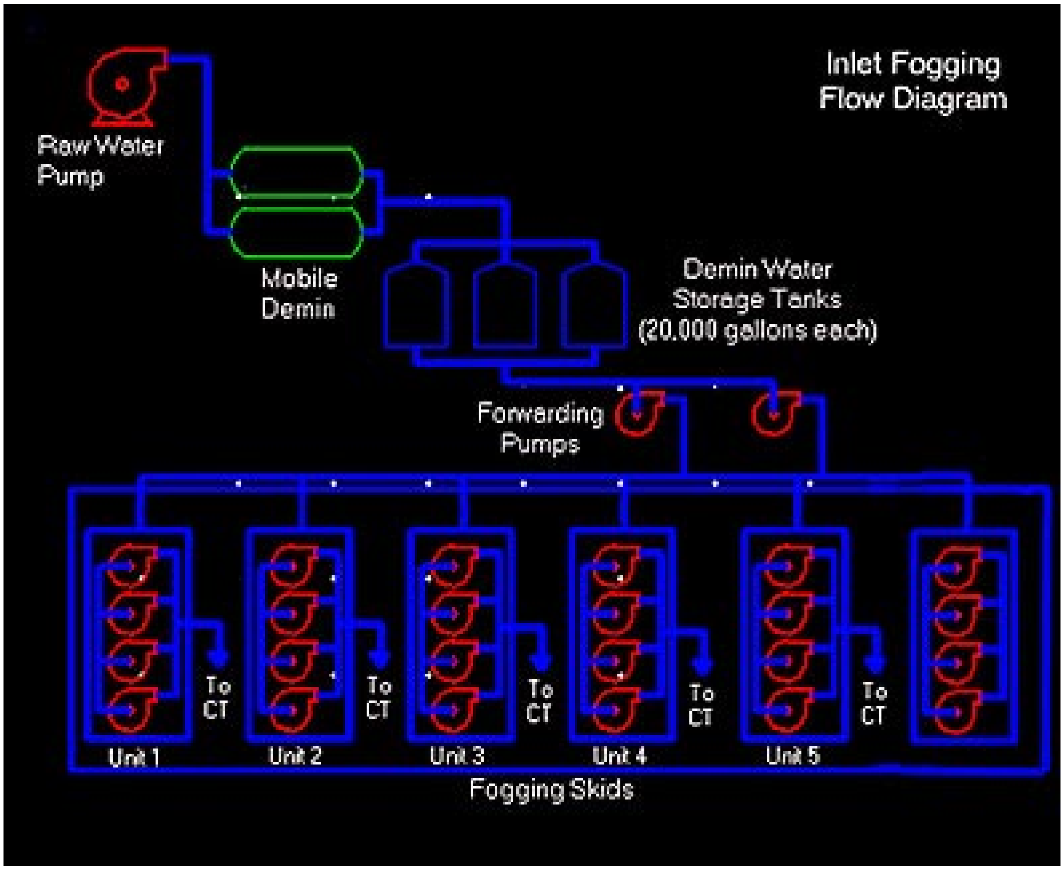

Figure 6. Inlet Fogging Flow Diagram (Wheaton)

Figure 7. Mobile Demineralizer Vessels

Figure 8. Storage Tanks

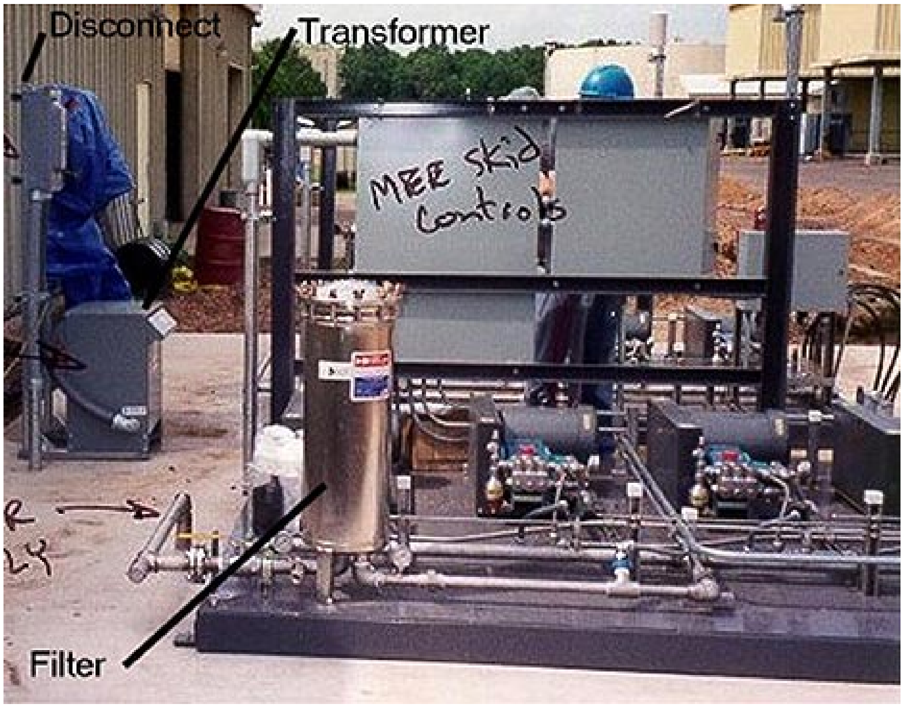

Figure 9. MEE Skid Controls

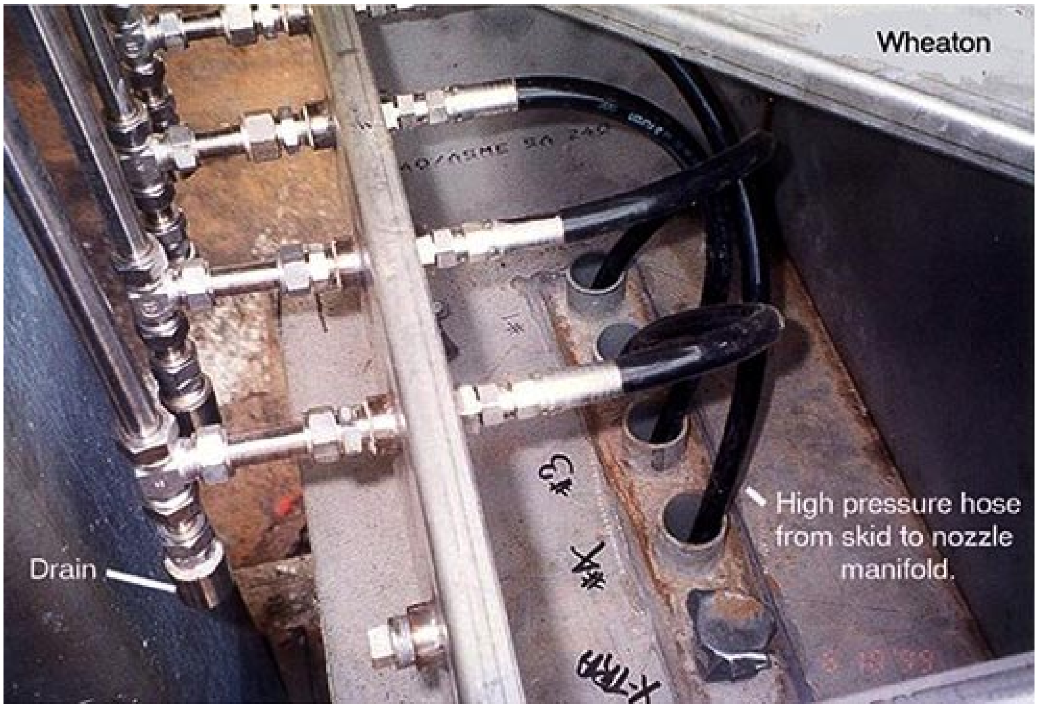

Figure 10. Skid and Nozzle Manifold

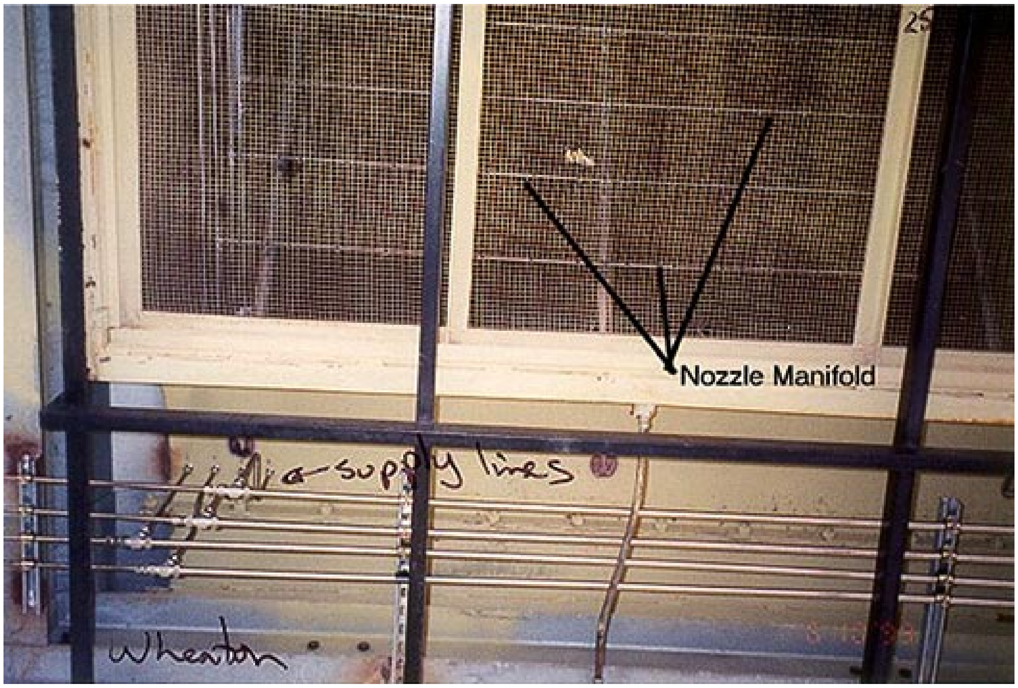

Figure 11. Nozzle Manifold