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COOLING TOWER PLUME ABATEMENT AT CHICAGO'S O'HARE AIRPORT

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Introduction

Repeated expansion of Chicago's O'Hare Airport, over several years, had resulted in evaporative (wet) cooling towers being situated between the FAA control tower and the airport taxiways/runways. Three towers were located at this site, one crosssflow and two counterflow. These cooling towers serve a chilled water plant. Visible plume, produced by these towers during certain ambient conditions, could hinder visibility between the control tower and the taxiways/runways. This situation was recognized as being both undesirable and potentially dangerous; therefore, a project was initiated to study, evaluate and implement a means of eliminating visible cooling tower plume from the subject site.

The City of Chicago and their consulting engineer Black & Veatch understood that in order for their concerns about visible plume to be taken seriously by a cooling tower manufacturer, they must specify that a plume abatement test be performed in addition to a thermal performance test. These tests, of course, would be performed by a CTI licensed independent test agency. A plume abatement test performed by an independent party would make this project unique as currently there are no industry standards for testing plume abated cooling towers against the manufacturer's plume abatement guarantee. Details associated with the plume abatement and performance testing of the cooling tower are discussed in later paragraphs.

It was recognized, at the outset of the project, that during periods when visible plume was a problem the plant heat load was not at its peak. Consequently, it would be possible to replace one of the existing towers with some type of plume abatement cooling tower that alone would serve the chiller plant during ambient conditions that were conducive to visible plume production. A few alternatives were studied, they included:

1) An evaporative cooling tower outfitted with natural gas burners at the discharge stack.
2) A series water path, series air path, wet/dry plume abatement cooling tower. (SPWD)
3) A series water path, parallel air path, wet/dry plume abatement cooling tower (PPWD)

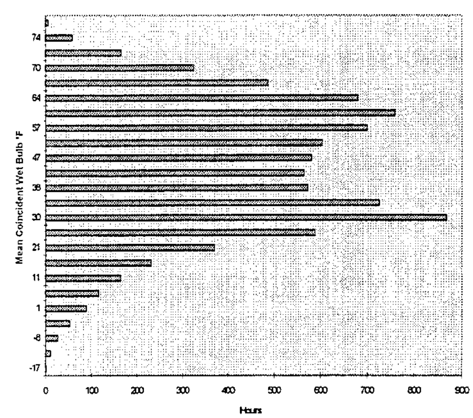
Before a study of alternatives could begin it was necessary to establish thermal design conditions for both the peak (summer) heat rejection condition and for the plume abatement (winter) condition.

Thermal Design Conditions

Figure 1 depicts, for O'Hare Airport, the hours of occurrence at stated mean coincident wet bulb. A 78°F (99th percentile) wet bulb with a 1°F recirculation allowance was chosen for the thermal design condition. Thus, the cooling tower was to cool 6000 gpm/cell from 95°F to 85°F at a 79°F wet bulb.

It was the goal of the City of Chicago and Black & Veatch that this new cooling tower be capable of operating under most weather conditions without producing a visible plume. Consequently, a plume abatement condition of 4°F wet bulb coincident with a 5°F dry bulb was established. This condition is a 3.5 percentile condition.

Figure 1: Chicago Weather



Recognizing that the heat load during the winter months is about 75% of design heat load, the cooling tower specification required that the tower cool 6000 gpm/cell from 82.5°F to 75°F at a wet bulb/dry bulb of 4°F/5°F, with no visible plume. See reference no. 1 for a discussion about methods for selection of a plume abatement design point.

Alternatives

Gas Burners at Fan Discharge:

Natural gas burners installed around the cooling tower fan discharge can be used for plume abatement. Such an arrangement is in fact used at the Dallas/Fort Worth Airport. This alternative was not, however, practical at this jobsite as the number of hours annually requiring plume abatement would result in substantial fuel consumption.

SPWD:

Although this configuration was an option, it has several drawbacks [1]: 1) Dissolved solids contained in drift from the wet section deposit on the coils. 2) Because there is a single air path for both summer and winter modes of operation, there is an ever present increase in air resistance (and fan power) due to the coil. 3) Except at low relative humidities, the driving force for heat rejection in the coils is reduced due to the increased dry bulb temperature of the air leaving the wet section.

PPWD:

Figure 2 illustrates the configuration and psychrometrics associated with a parallel air path, series water path wet/dry tower. This configuration was chosen for economic, operational and maintenance reasons that will be elaborated on in later paragraphs.

The City and their consultant recognized that when a PPWD tower is operated in plume abatement mode it is imperative that there be an acceptable level of mixing between the wet and dry air streams. Consequently, a decision was made to specify that testing be performed on a scale model to verify that the respective air streams could be adequately mixed. Model testing is discussed later.

The Cooling Tower Design

A transverse cross section of the cooling tower design is shown in figure 3. The tower was equipped with galvanized steel louvered dampers on both the wet section and dry section air inlets. Dry section dampers permit operation of the tower in a primarily evaporative mode when plume formation is not likely and maximum cooling is required. Wet section dampers allow for maximum plume abatement.

The tower design was influenced by factors other than the thermal and plume design conditions. These factors included: 1) Length, width and height restrictions associated with the site. 2) Access to the dampers and coils for inspection and maintenance. 3) Operational flexibility so that the tower could be operated to minimize energy consumption or maximize plume abatement. 4) Reliability under harsh atmospheric conditions, particularly ice and freezing temperatures.

<u>Factors Influencing the Design</u>

Site Restrictions:

Refer to Figure 4 for a site plan and note that the cooling tower location is between taxiways/runways and the control tower. A plan area restriction of 40' x 225' was specified along with a height restriction of 46'. The height restriction was stipulated to keep the cooling tower from obstructing the line of sight between the control tower and the taxiways/runways. The site restrictions pushed the cooling tower design to a counterflow configuration with the wet section air inlet partially below grade.

Access to Coils and Dampers:

Finned tube coil bundles, air dampers and damper actuators require routine inspection and maintenance. The outside surface of the coils had to be accessible for pressure washing, and the inside of the tubes needed to be accessible for cleaning either by rodding or pressure wash. Consequently, access hatches through the fan deck were provided along with access ways between the coils and dampers so that maintenance on the dry section could be accomplished. The wet section dampers are accessible from the ground with a step ladder.

Operational Flexibility:

The degree of variation in ambient conditions and to a lesser extent the reduction in heat load during winter conditions made the prospect of using a variable frequency drive on the fan motors attractive. Significant reductions in energy consumption can be obtained by operating a cooling tower fan motor with a variable frequency drive [2]. The cooling tower controls system was set up to allow the fan speed to be controlled by a temperature sensor in the condenser water supply line. When the fan speed is so controlled the tower operates in an "energy saving" mode. The fan draws only enough power to provide set-point temperature cold water. Obviously, this mode of operation is influenced by the damper settings. The most efficient way to operate the tower, for the sole purpose of obtaining set-point temperature cold water, is for the wet section dampers to be full open and the dry section dampers to be completely closed.

Although condenser water supply temperature and energy savings are important, at this site, visible plume is the primary concern. Figure 5 is a graph of required fan speed vs. wet bulb temperature for the subject cooling tower to obtain 85°F cold water with the dry dampers completely closed. The graph also indicates the wet bulb temperature at which visible plume would begin to form at various ambient relative humidities. Obviously, below a certain ambient wet bulb temperature it is necessary to open the dry section dampers to abate tower plume.

All dampers are outfitted with electric actuators. The actuators are signaled from a control panel inside the chilled water plant. It is possible, from the control panel, to set the dampers at any position. Normally, however, the dry section dampers are either fully opened or closed. The blade position of the top half of the wet section dampers can be controlled by the temperature sensor in the condenser water supply line. When the upper wet section dampers are controlled this way, if the dry section dampers are open, the tower is operating in a mode that will minimize visible plume. The fan speed must be set manually.

Thus, there are two ways to set the controls to operate the tower. The tower can be controlled to maximize energy savings without regard to plume, this mode of operation is acceptable when atmospheric conditions are not conducive to visible plume. The tower can, also, be controlled to minimize visible plume at the expense of energy consumption. It is possible to override the control system so as to control the fan speed and damper positions manually.

Reliability:

This jobsite experiences a significant amount of freezing weather accompanied by frozen precipitation. So, it was important that the tower design details account for such conditions. The louvered dampers and actuators were of primary concern.

Electric damper actuators were chosen instead of pneumatic because the air lines that power pneumatic actuators are susceptible to freezing. Even with the best air dryers eventually the air lines will freeze. Such an occurrence would render part or all of the damper actuators inoperable, not an acceptable possibility.

Both the wet and dry section damper panels are approximately 12' x 12', in face area. The dry section dampers are normally operated on a seasonal basis, opened in the late fall and closed in the early spring. So, ice formation on the dry section louvers is not as great of a concern as it is on the wet section louvers because the dry dampers are moved primarily in above freezing weather. Each dry section damper panel is operated by a single actuator. It was anticipated that the wet section dampers might be repositioned frequently during freezing weather. Therefore, each wet section damper panel is divided into an upper and low half, each half can be opened or closed independently of the other half. The respective half of each wet section damper panel is served by its own actuator. This damper/actuator arrangement reduces the potential ice load that each wet section damper actuator would have to work against. Several other special design details were incorporated into the louvered damper blades and frames to reduce the potential for ice build-up.

Structure

The cooling tower shell is reinforced concrete. Tower internals (fill, spray system, eliminators) rest on or are suspended from reinforced concrete beams.

Coils

The coils bundles are two pass with vertical tubes. The tubes are stainless steel with tension wound footed aluminum fins. Coil headers are welded steel, hot dip galvanized after fabrication.

Hydraulics

Water is delivered to the cooling tower via headers which extend the length of the tower and are routed through the passage located between the dry section dampers and the coils. Water moves through the coil, which operates in a siphon loop, and is then delivered to the spray system and fill. The siphon loop in the coil is initiated with the aid of a vent manifold system rather than a vacuum pump[1]. The vent manifold system also facilitates draining of the coil at shutdown. The vent manifold system and the electrically powered damper actuators removed any need for heat tracing on this installation. Heat tracing is used in some applications to prevent pneumatic and vacuum lines from freezing.

Design Verification

Scale Modeling of Wet/Dry Air Stream Mixing

A 1/7 scale model of one cell of the full scale design was built to simulate mixing of the wet and dry air streams. An illustration of the scale model and associated psychrometrics is shown in figure 6. The model was made by extending the plenum of a small induced draft counterflow cooling tower. A rectangular opening was then cut into two opposing sidewalls of the model plenum to simulate air flow through the tower dry section. The dry air stream of the scale model, unlike the full scale tower, did not include a coil. Ambient air pulled into the plenum along the dry air path of the model was not heated. Verification of air mixing was the sole purpose of the model. All air inlets of the model were equipped with dampers. The model was tested as follows: A heat load was applied to the wet section of the tower. The flow rate and temperature of the water going to the model were measured. The temperature of the water leaving the tower was measured. Wet and dry bulb temperatures of the air entering both the wet and dry sections of the model were measured. Air velocities in the wet section air inlets and in the fan discharge were measured. Wet bulb temperatures at the fan discharge were measured.

Knowing the velocities and air properties at the fan discharge and at the wet section air inlet made it possible to calculate the mass airflow rates through the fan, wet section and dry section of the model. The wet bulb temperature of the air leaving the wet section of the tower was computed from a mass heat balance using the boundaries of the wet section as the control volume. If the model was operated so that the ratio of its wet and dry section mass airflow rates was about the same as that anticipated through the full scale tower, then the maximum discharge wet bulb from the fan could be predicted. This prediction was based on model data, calculated air properties for the tower at the condition being analyzed and the observation that the geometry of the model's psychrometrics should be similar to that of the tower.

Model testing indicated that the level of air mixing was probably acceptable but it could be enhanced by adding mixing baffles to plenum of the tower. Therefore, baffles were included in the plenum of the constructed tower.

<u>Acceptance Test - Thermal Performance</u>

An acceptance test was performed by an independent test agency to verify that the completed cooling tower was conforming with the conditions of the performance guarantee. Those conditions were: 6000 gpm/cell, 95-85-79 at 125 bhp. The test was executed in accordance with the regulations outlined by CTI ATC-105. The cooling tower was found to be in compliance with the performance guarantee. It should be noted that when testing a wet/dry tower the entering air dry bulb temperature becomes a significant parameter. Such is not the case for a strictly wet tower.

<u>Acceptance Test - Plume Abatement Compliance</u>

There are no industry standards, at the time this paper is being written, for testing plume abated cooling towers against the manufacturer's plume abatement guarantee. There is now , however, a draft test procedure being considered by the CTI. The test procedure that was prepared by the manufacturer and approved by the City of Chicago and their consultant was compatible with the draft procedure that is currently under CTI consideration. This test procedure in a slightly abbreviated form follows:

Test Procedure:

Conditions and Instrumentation

Test conditions and variations thereof, for the plume compliance test (PCT) shall generally comply with the latest edition of the *Cooling Tower Institute Acceptance Test Code for Water-Cooling Towers (ATC-105).* The following are stipulations on the conditions for the PCT that differ from ACT-105:

1. Inlet wet bulb temperature above 32°F. Below 32°F, there is difficulty in maintaining an ice bulb for a reliable measurement.

2. Average wind velocity not to exceed 7 mph with one minute gusts up to 10 mph. Slightly more restrictive than ATC-105 due to the nature of measurements taken at the fan discharge.

Tower Operation

1. Fan speed at or above 75% of full speed for the duration of the test.

2. Dry section dampers shall be in the full open position.

3. Wet section dampers set to give approximately 75°F cold water for the duration of the test.

4. Test range within 30% of plume abatement range.

5. Fan blades shall be pitched to draw within 5% of the density corrected design fan brake horsepower at full speed. This was verified during thermal performance test.

Measurements

1. Water flow rate to the tower shall be measured by traversing the condenser water return line with a Pitot tube attached to an air-over-water manometer.

2. Hot water temperature shall be measured at flowing wells in the condenser water return line.
3. Cold water temperature shall be measured at flowing wells on the discharge side of the

circulating water pumps.

4. Inlet air wet bulb temperature measured per ATC-105.

5. Inlet air dry bulb temperature measured per ATC-105.

6. Barometric pressure measured per ATC-105.

7. The fan discharge air wet bulb and dry bulb temperatures, and the fan discharge air velocity along with coincident angle shall be measured at stations on two perpendicular diameters at or near the discharge plane of the fan stack. A maximum of ten measurement stations along each diameter shall be located at the center of equal area rings. Because of the size of the instruments and the proximity of the first and last stations to the edge of the fan cylinder, it may not be possible to obtain ten stations.

Evaluation of Results

The data from the discharge air measurements is averaged for each of the stations. Enthalpy, specific volume and humidity ratio are determined for each station based on these averages. This information, in conjunction with the averaged vertical velocities at each station, are be used to calculate a mass/energy balance. The resultant weighted enthalpy and humidity ratio define the average effluent condition.

$$h_{avg} = \frac{\sum \dot{m}_i \cdot h_i}{\sum \dot{m}_i}$$

$$w_{avg} = \frac{\sum \dot{m}_i \cdot w_i}{\sum \dot{m}_i}$$

$\dot{m}_i$ = mass flow rate through ith area

$\dot{h}_i$ = enthalpy of ith area

v_i = vertical component of velocity in ith area

w_i = humidity ratio in ith area

The average test effluent air condition is plotted on a psychrometric chart. The average test inlet air condition is plotted and a line is drawn between it and the average test effluent air condition. This line describes, graphically, the mixing process above the fan during the test.

The manufacturer's effluent air properties curves are crossplotted to determine the predicted fan discharge wet bulb and dry bulb temperatures at the test conditions. See figure 7 for an example of the manufacturer's effluent air properties curve. A line is drawn on the psychrometric chart between the predicted fan discharge properties and the average inlet air condition. This line is the predicted mix line at test conditions. If the test mix line coincides or is to the right of the predicted mix line, then the plume abatement guarantee has been fulfilled.

Execution of the Test:

The plume abatement verification test followed the procedure previously described. One cell of the tower was tested as being representative of any cell or all cells collectively. Figure 8 shows the results of the test, the test and predicted fan mix lines are plotted along with the averaged air properties of each point sampled from the fan discharge. The tower was shown to be in compliance with the manufacturer's plume abatement guarantee.

Conclusion

The cooling tower industry's term for reducing the visibility of a cooling tower's discharge air stream is plume abatement. The word abate means to reduce in amount, intensity or otherwise. Plume abatement is a subjective matter and, therefore, difficult to quantify. An acceptable level of plume abatement can vary from jobsite to jobsite and observer to observer.

The City of Chicago chose to require the highest level of plume abatement at the O'Hare Airport site and see that compliance with their specifications was verified. Thorough review of figure 8 illustrates how seriously this requirement was taken. Not only is the test mix line below the predicted mix line, all averaged air properties at each sampling station of the fan discharge are below the predicted mix line.

References

1. Lindahl, Paul A. and Jameson, Randall W., Plume Abatement and Water Conservation with the Wet/Dry Cooling Tower, The Marley Cooling Tower Co., 1993, CTI TP93-01

2. Immell, William F., Variable Speed Fan Drives for Cooling Towers, The Marley Cooling Tower Co., 1996. CTI TP96-03

3. Monjoie, Michel and Libert, Jean-Pierre, Testing Procedures for Wet/Dry Plume Abatement Cooling Towers, Hamon-Sobelco, 1994, CTI TP94-15

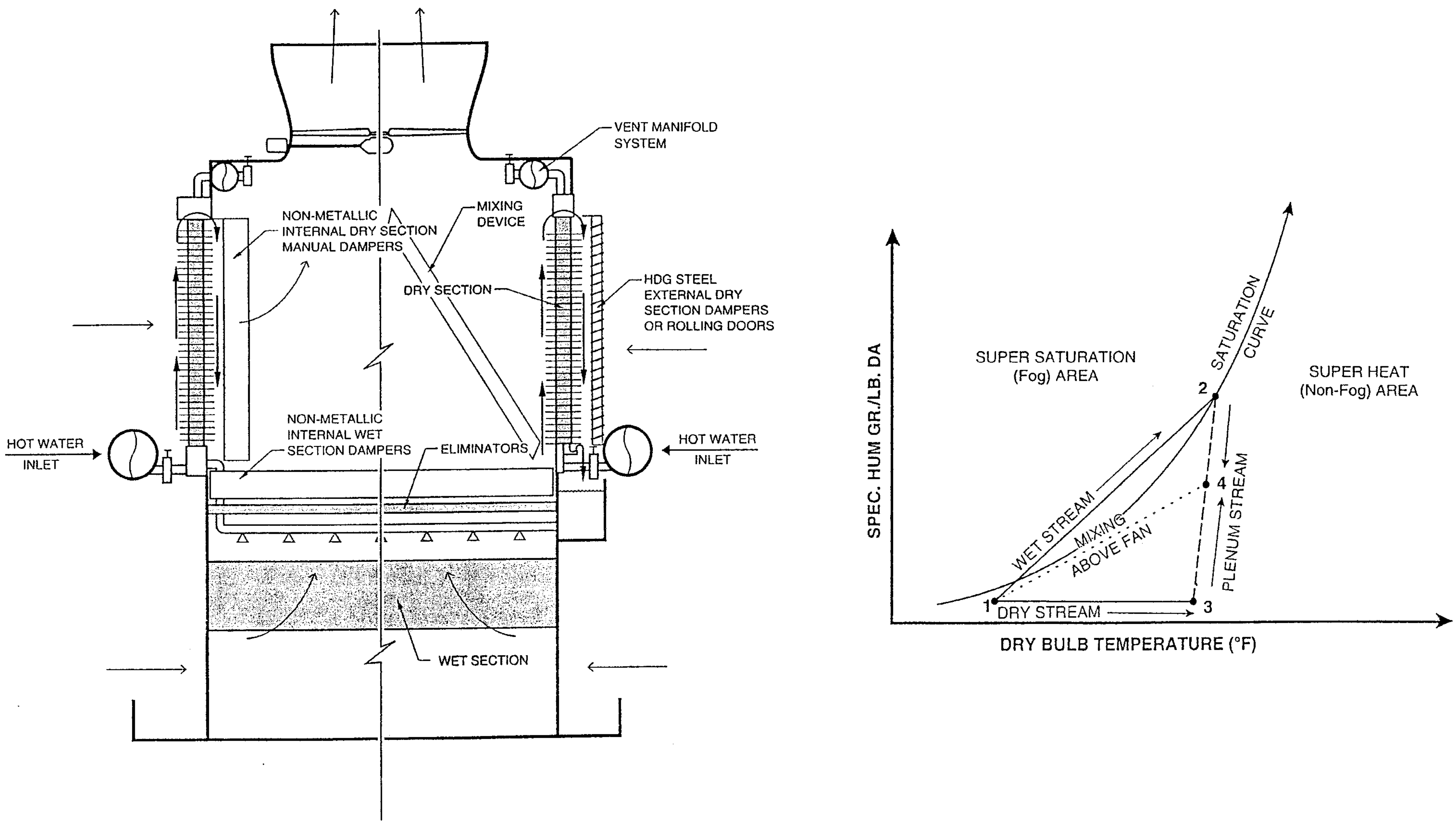


Figure 2: Configuration and Psychrometrics for a Series Water Path Parallel Air Path Wet/Dry Cooling Tower

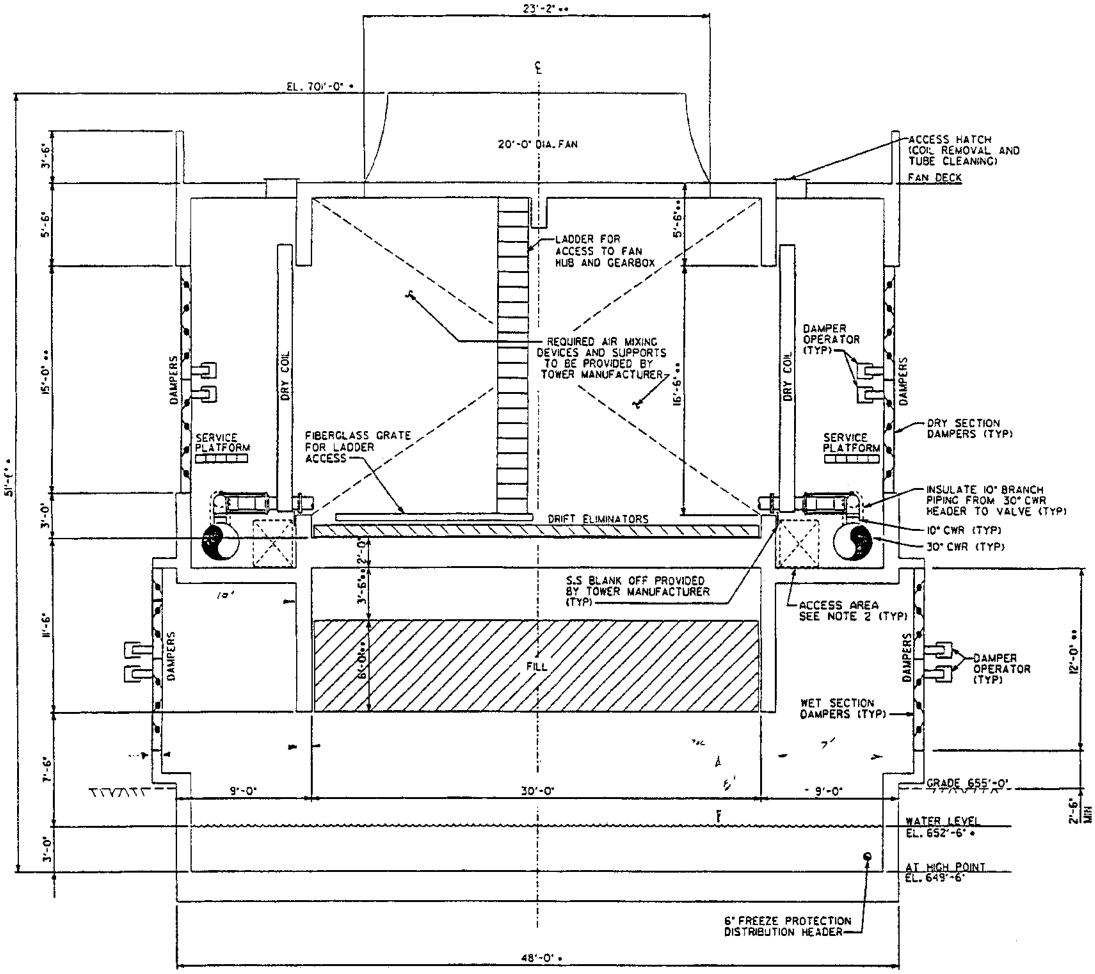


FIGURE 3: Transverse Cross Section of Cooling Tower Design

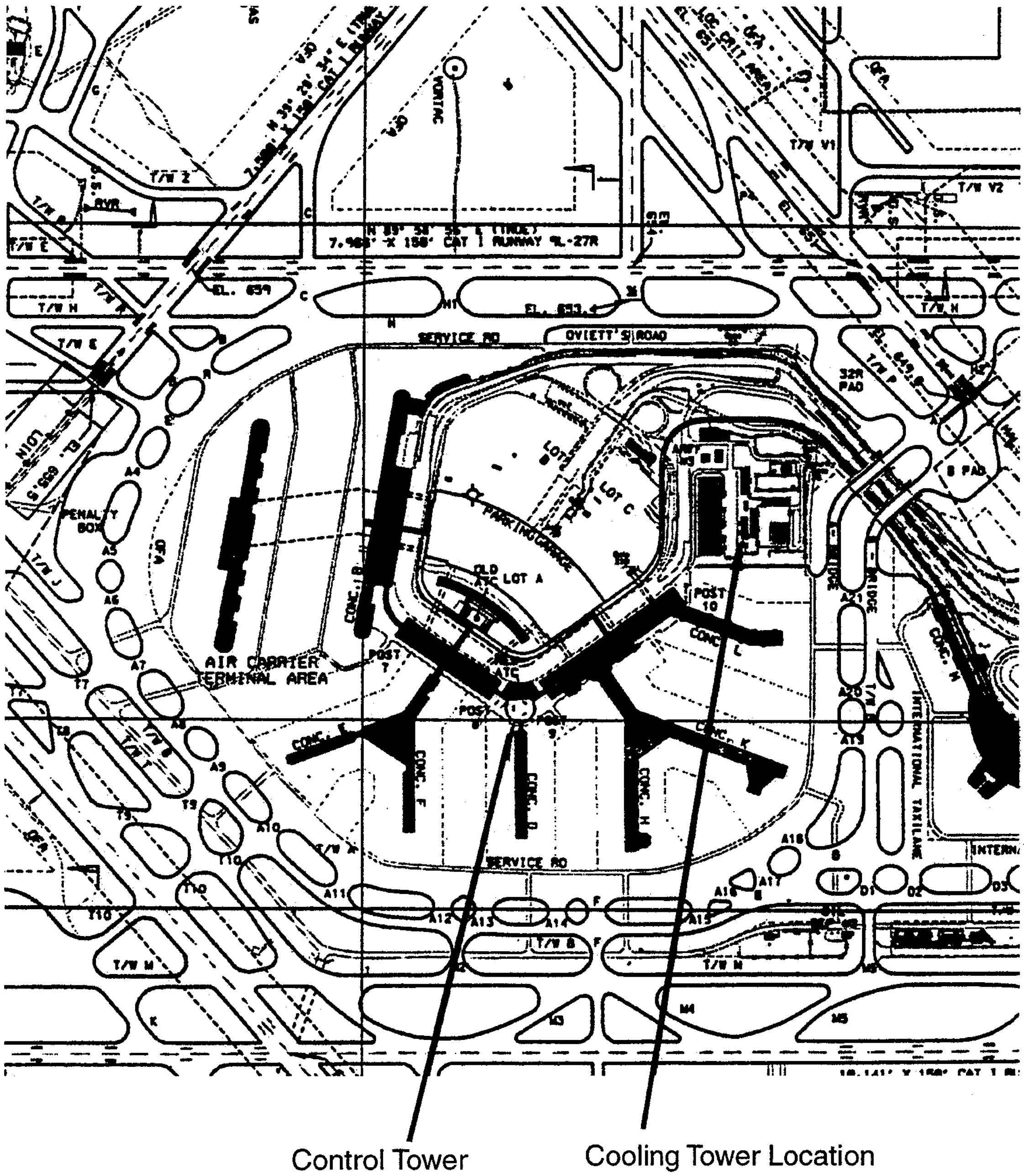


Figure 4: Site Plan View

Figure 5

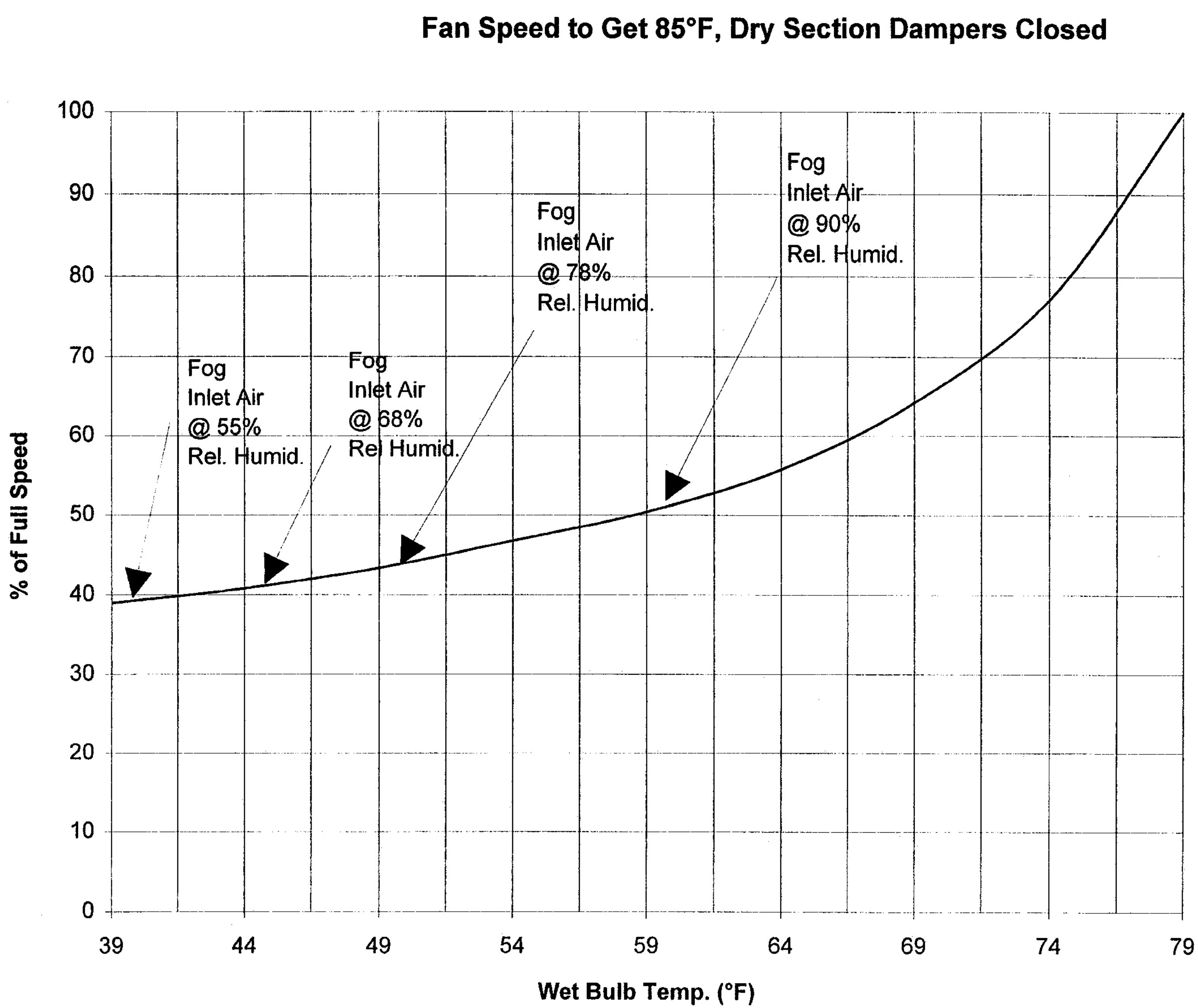


FIGURE 5: Fan Speed to Get 85°F, Dry Section Dampers Closed

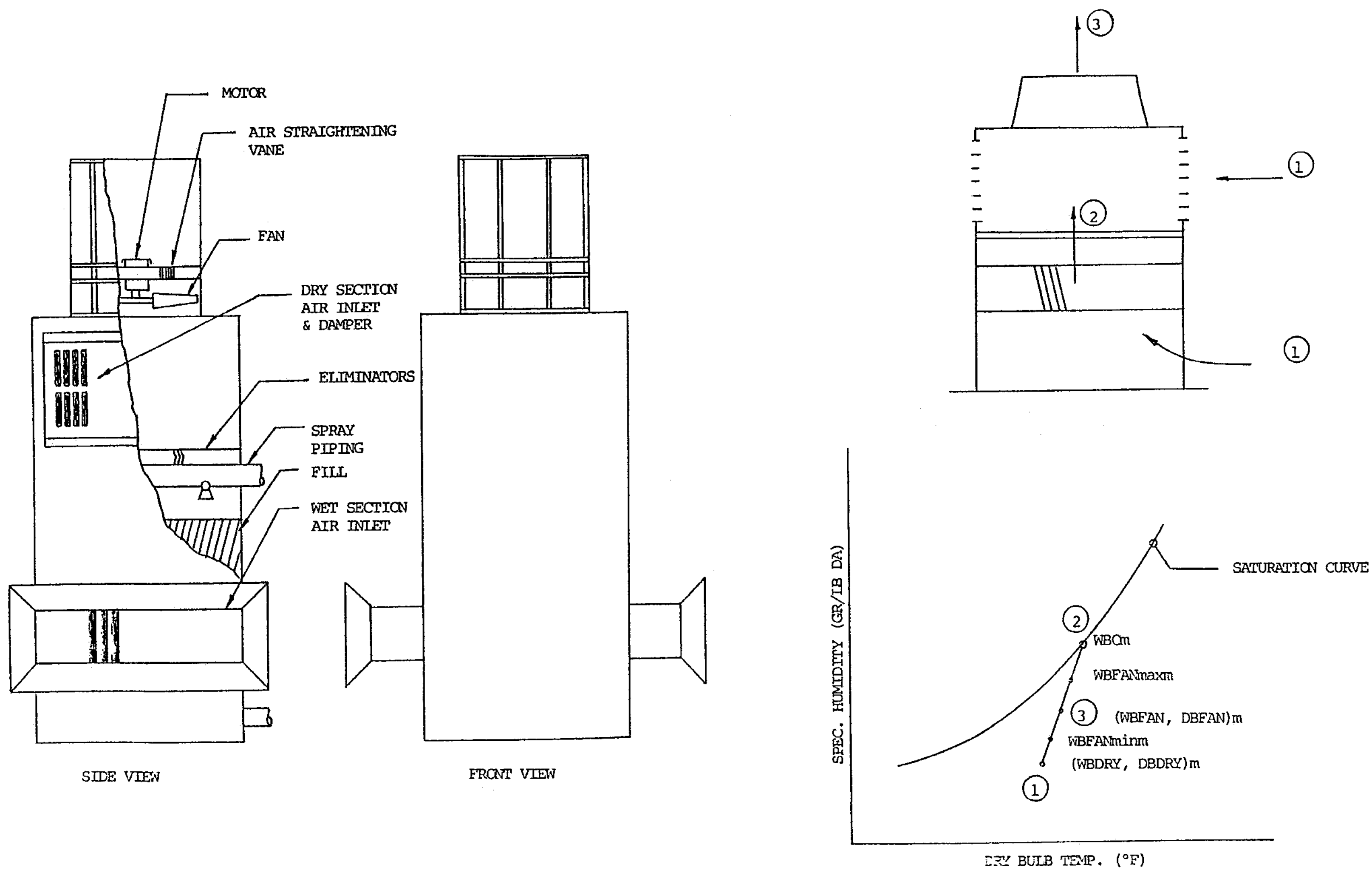
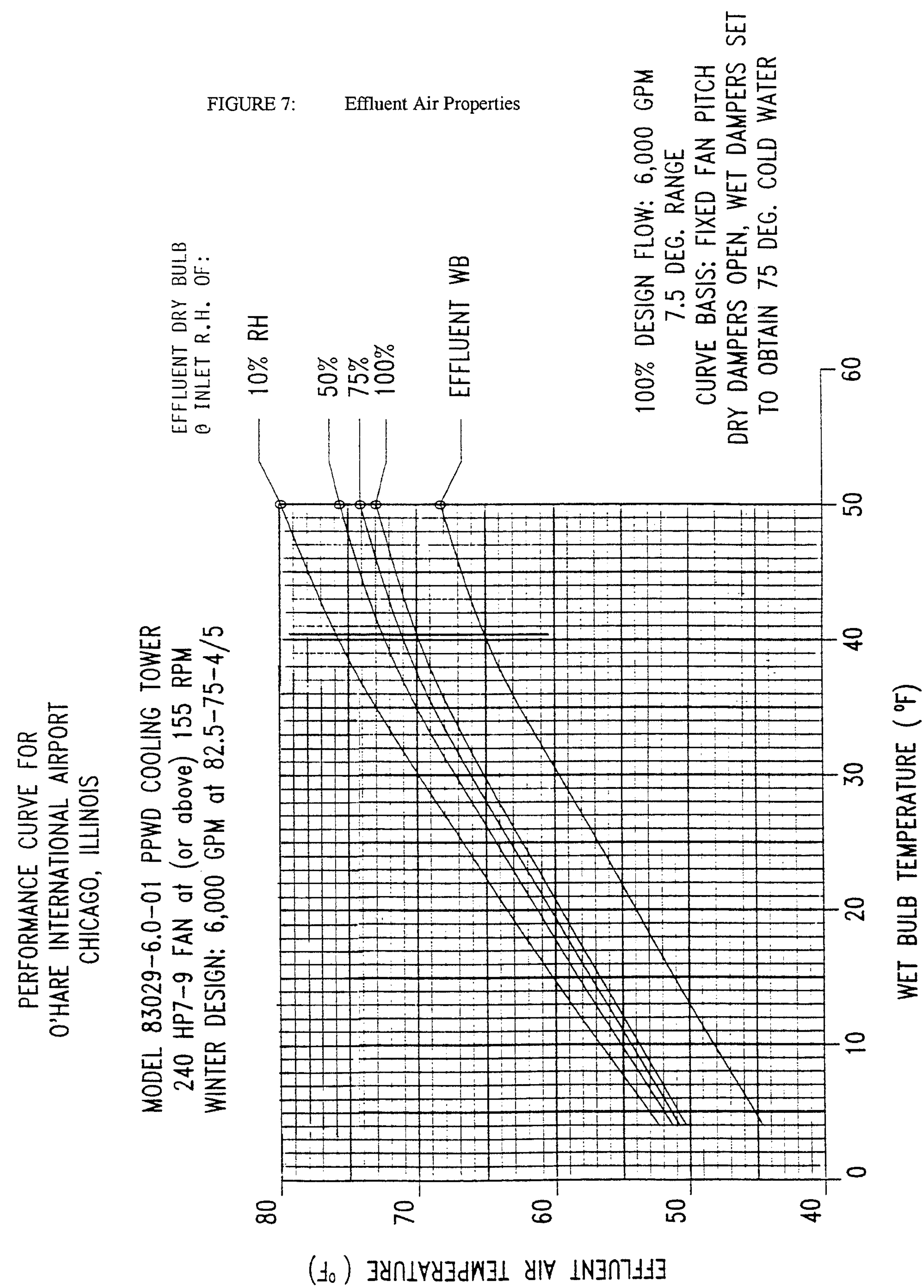


Figure 6: Scale Model for Verification of Air Mixing with Associated Psychrometics.

FIGURE 7: Effluent Air Properties



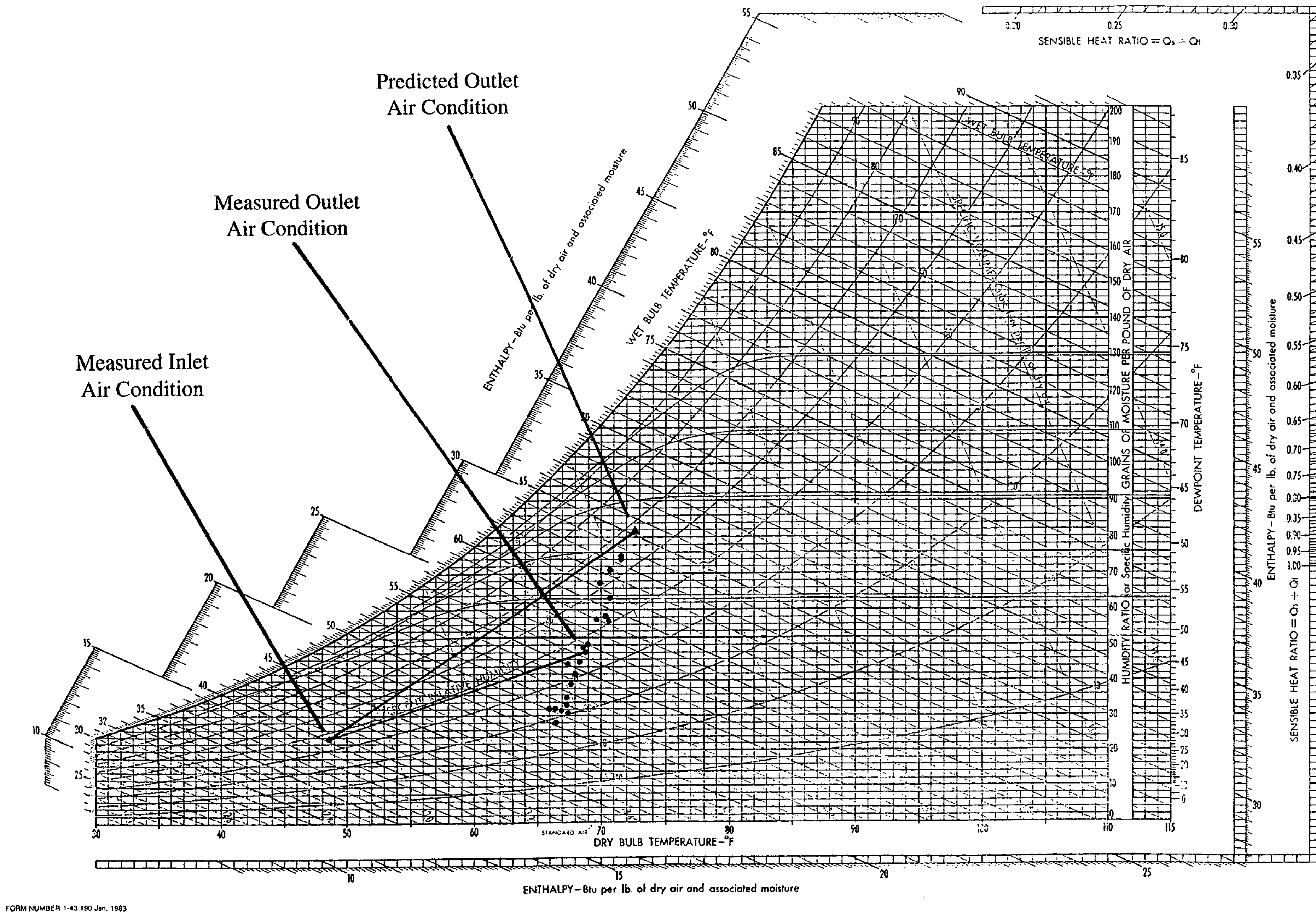


Figure 8: Plume Abatement Test Results