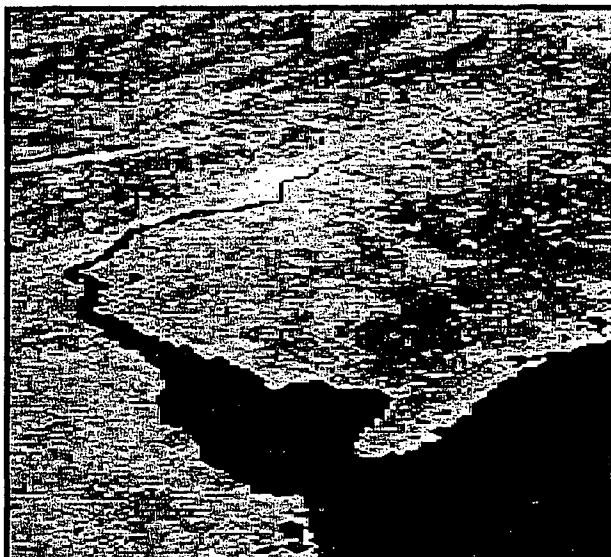
FINAL REPORT

HYDROTHERMAL MODELING ANALYSIS FOR THE HOPE CREEK GENERATING STATION EXTENDED POWER UPRATE PROJECT

Volume 1: Main Report plus Appendices A and B (supporting data)



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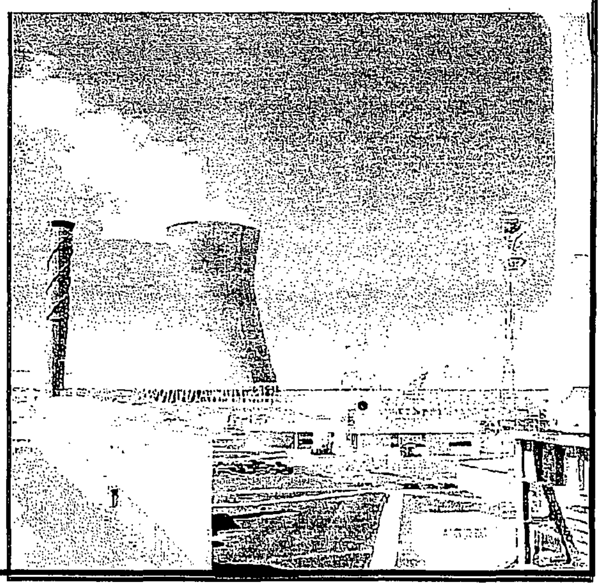

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EXECUTIVE SUMMARY

PSEG Nuclear LLC is planning an Extended Power Uprate (EPU) Project for the Hope Creek Generating Station – a nuclear-powered electric-generating facility located in Lower Alloways Creek Township, Salem County, New Jersey. This report provides an assessment of the Project's potential thermal impacts on Delaware Estuary receiving waters. To this end, a numerical plume-dilution model (CORMIX1) was adapted to the study area. Model application considered a range of ambient receiving-water conditions, meteorological conditions and projected discharge conditions, but focused on scenarios of critical (minimum-dilution) conditions. Under such conditions, results indicate that Station-induced temperature increases for the planned EPU Project will not exceed relevant water quality standards.

1. INTRODUCTION

1.1 Background

Hope Creek Generating Station (HCGS or the Station) is a nuclear-powered electric-generating facility owned and operated by PSEG Nuclear LLC (PSEG). The Station is located adjacent to the Delaware Estuary in Lower Alloways Creek Township, Salem County, New Jersey (Figures 1 and 2). The Station's electrical output is approximately 1,049 megawatts-electric (Mwe) net Maximum Dependable Capacity (MDC).

PSEG is planning to increase the electrical output of this facility by a maximum of 20% above its original licensed thermal power (OLTP) of 3,293 megawatts thermal (MWth) in an Extended Power Uprate (EPU) Project. This Project includes replacement of the Station's steam turbine, replacement of two of the main transformers, and reconfiguration of the reactor core fuel load. In addition, PSEG has modified the Hope Creek Cooling Tower (HCCT) to improve its thermal performance.

The EPU Project, and to a lesser extent the HCCT improvements, will change the characteristics of thermal discharges from the Station. Accordingly, PSEG requested that an assessment be made of the effects of such changes on the temperature regime of the Delaware Estuary.

1.2 Objectives

The primary objective of this study is to characterize potential water temperature increases in the adjacent Delaware Estuary due to the Station's thermal discharges under post-EPU conditions. Specifically, the goal is to forecast the spatial distribution of induced temperature increases and dilutions within the Station's discharge plume over a range of ambient receiving-water conditions, meteorological conditions and post-EPU discharge conditions. To this end, a numerical plume-dilution model is adapted to the study area and used to simulate excess water temperatures over a range of ambient current speeds, ambient water densities and projected (i.e., post-EPU) blowdown flows, blowdown temperatures and blowdown densities.

2. SITE CHARACTERISTICS

2.1 Environmental Setting

The HCGS is located adjacent to the Delaware Estuary on Artificial Island, New Jersey -- about 50 miles northwest of the mouth of the Estuary (Figure 2). The estuarine channel adjacent to the Station consists of a relatively deep (approximately 40 ft) and narrow (approximately 1,300 ft wide) navigation channel flanked by relatively broad shelves (Figure 2). On the New Jersey side of the navigation channel, mean low water (MLW) depths are fairly uniform and typically about 20 ft (Figure 2).

Compared to the wider lower Estuary, the local receiving waters are characterized by relatively high current speeds and turbidity levels (PSEG, 1999). Ambient tidal currents in the study area are predominantly semi-diurnal, with a period of 12.42 hrs. According to the NOAA/NOS Tidal Current Tables, maximum flood tidal current speeds of 1.08 m/sec -- and maximum ebb tidal current speeds of 1.39 m/sec -- occur in the center navigation channel (Baker Range) located approximately 6,600 ft (2,012) offshore from the HCGS discharge. Weaker current speeds are observed in the broad, shallower region adjacent to the Station (Figure 2). For example, during the Salem Generating Station Permit Renewal Project (PSEG, 1999), maximum mid-depth current speeds of about 0.76 m/sec (2.5 ft/sec) were observed approximately 462 m offshore of the HCGS (Figure 3). The pattern observed at this location indicates a prolonged ebbing tide, with an instantaneous current speed of approximately 0.46 m/sec (1.5 ft/sec) occurring approximately 1 hour before low-slack tide (Figure 3).

Water temperatures in the study area vary seasonally over a wide range, from about 0°C to nearly 30°C. Figure 4 is a record of water temperatures measured at both the Station's intake and approximately 2 miles up-estuary at the USGS' monitoring station at Reedy Island (Figure 2). Note that the Reedy Island Station provides representative background water temperature variations for this analysis, and that maximum background temperatures are typically about 29°C.

2.2 Regulatory Limits

The Station is located within the Delaware River Basin Commission's (DRBC's) Zone 5 of the Delaware Estuary. In DRBC Zone 5, Station-induced water temperature increases are not allowed to exceed 4°F (2.2 °C) above ambient temperatures from September to May (non-summer months), and 1.5°F (0.8°C) from June to August (summer months), or a maximum of 86°F (30°C), whichever is less, except in a designated heat dissipation area (HDA). The designated HDA for the Hope Creek cooling tower discharge extends 1,500 ft offshore, 2,500 ft up-estuary and 2,500 ft down-estuary from the point of discharge (DRBC, 1984). The EPU Project's compliance with these HDA limits is the focus of the present analysis. Compliance with other thermal discharge limits imposed by the Station's NJPDES Permit (i.e., for maximum daily average discharge temperatures and maximum daily average heat rejection rates) is addressed in Appendix A.

2.3 Hope Creek Generating Station

The Station uses a closed-loop cooling system to dissipate heat from its condenser to the atmosphere. The cooling system includes four (4) circulating water pumps, each rated at 138,000 gallons per minute (gpm); a natural-draft cooling tower; four (4) service water pumps; and a blowdown return line.

The circulating water pumps pass cooling water through the Station's condenser. They have a total design capacity of 552,000 gpm (4 x 138,000 gpm = 552,000 gpm). The condenser transfers heat from the hot steam exhausted from the turbine-generator to the cooler circulating water. The heat transfer condenses the steam and increases the temperature of the circulating water. The temperature increase of the circulating water across the condensers is called the "cooling range." The Station's current actual cooling range is approximately 27.0°F (15°C) at a circulating water rate of approximately 610,000 gpm. The EPU Project is expected to increase the cooling range approximately to 32.3°F (17.9°C) for a circulating water flow of approximately 610,000 gpm.

After leaving the condensers, the heated circulating water is directed to a flow distribution system located within the Station's single, hyperbolic cooling tower (the HCCT). The flow distribution system enhances evaporation and generates an intense rainfall-like pattern of small water droplets, which evaporate as they fall through the HCCT. The evaporation saturates and warms the surrounding air and cools the water droplets. The warm-moist air rises to the top of the tower and causes the cooler ambient air to be drawn in at the base of the cooling tower. This process sets up a natural draft and a counter-flowing system of rising warm-moist air and falling water droplets.

Most of the cooling water not lost to evaporation is collected in the cooling tower basin. Due to evaporation, these waters may become concentrated in dissolved solids. Some cooling water is discharged continuously back to the Estuary to maintain acceptable concentrations of solids in the cooling system. This discharge is referred to as "blowdown." Typically, the average concentration of solids in the blowdown water is less than 1.3 times that in the makeup water. Blowdown occurs as a gravity flow over a concrete broad-crested weir and is discharged to the Estuary through a 48-inch submerged pipe (Figure 5).

Water that is lost to evaporation and blowdown is replaced by estuarine water that is supplied by service water pumps that are monitored by PSEG. The water provided by the service water pumps is commonly called "makeup." Blowdown flow equals the difference between the makeup flow and the evaporation rate.

Evaporative losses from HCCT are a function of meteorological conditions (primarily, the wet or dry bulb temperature and relative humidity), the cooling range and the circulating water flow rate. The EPU Project will increase evaporation and, therefore, the concentration of the total dissolved solids (TDS) in the circulating water. PSEG estimates that evaporative losses for the EPU Project will be approximately 20% greater than evaporative losses based on the original design and OLTP. In turn, average TDS concentrations in the cooling water (and blowdown) will increase approximately 9%

above levels based on original design conditions. Thus, blowdown after the EPU Project will tend to be at a lower rate -- and a higher density -- than before the EPU Project. Depending on the ambient water temperature, ambient TDS concentrations, cooling range and meteorological conditions, the density of the blowdown may be greater than, or less than, the density of the receiving water.

Makeup waters are brackish and exhibit a wide range of salinity, with a typical range of 0 to 20 parts per thousand (ppt). Auxiliary cooling requirements, and the Estuary's temperature, determine the service water flow rate. When the estuarine temperature is less than approximately 70°F, the average service water flow rate typically is approximately 37,000 gpm, which is supplied by two service water pumps. When the estuarine temperature exceeds approximately 70°F, the average service water flow rate is approximately 52,000 gpm, which is supplied by three service water pumps. Typically, two service water pumps are operated from November through April, three service water pumps are operated from June through September, and two or three service water pumps are operated in May and October.

3. MODEL ADAPTATION

3.1 Model Selection

The model selected for this study is the CORMIX1 model from the most recent update of the Cornell Mixing Zone Expert System (CORMIX-GI version 4.2 GT). CORMIX is a simulation and decision support system for environmental impact assessment of mixing zones resulting from continuous point source discharges (Jirka et al., 1996). CORMIX development began in 1986 at the DeFrees Hydraulics Laboratory at Cornell University under contract from the U.S. EPA Environmental Research Laboratory, Athens, GA; (Dr. Thomas Barnwell, Program Officer). Initial development yielded the CORMIX1 subsystem for single-port, sub-surface discharges (Doneker and Jirka, 1990). CORMIX1 predicts the geometry and dilution characteristics of the effluent flow resulting from a submerged single-port diffuser discharge, of arbitrary density (positively, neutrally, or negatively buoyant), into an ambient receiving water body that may be stagnant or flowing and have ambient density stratification of different types. Other system features were gradually added in the ensuing years, including separate subsystems for multi-port and surface discharges (CORMIX2 and CORMIX3). An updated users manual (Jirka et al., 1996) for the various subsystems was developed at Cornell in 1996 under a cooperative agreement with the U.S. EPA.

Today, CORMIX is a widely accepted modeling algorithm used throughout the U.S. and abroad. A new CORMIX user interface was developed by a private firm to ease model input and to enhance model output display (http://www.mixzon.com/mixzon.html).

3.2 Model Input

Model input consists of two types. The first type consists of fixed model-input parameters that represent ambient bathymetry, outfall orientation and outfall configuration. Since no design changes are planned for the subject outfall, these input parameters do not change for each model simulation. The second type of model input consists of variable data representing ambient hydrographic conditions (i.e., ambient current speeds, ambient water density) and effluent data (e.g., discharge rate, discharge excess temperature, effluent density). These inputs variables change when the model is used to simulate scenarios of varying ambient conditions and discharge conditions.

3.2.1 Fixed Model Input Parameters

Table 1 lists model-input parameters selected for this study. CORMIX requires that the actual cross-section of the receiving waterbody be characterized ("schematized") by an "equivalent" rectangular channel that is either bounded or unbounded laterally. In this case, a *bounded* estuarine cross section is specified. Next, the user must specify whether the assumed channel appears to be fairly straight and uniform, moderately meandering or highly irregular. CORMIX increases the internal turbulent diffusivity, and associated far-field (i.e., passive) mixing process, for meandering and irregular channels. In this case, a fairly straight and uniform channel is assumed so as to provide a conservative simulation of far-field mixing.

The assumed "equivalent" rectangular cross section at mean low tide is illustrated in Figure 6. As recommended in the CORMIX guidance documents (Jirka et al., 1996), the assumed rectangular cross section neglects shallow bank areas. Also, more weight is given to the cross sections that are close to the discharge location since these will likely have the greatest effect on near-field processes. The specified average depth (HA) of the equivalent rectangular cross section is 5 m at mean low water (MLW), since this represents typical average depths in the near-field region (Figure 6). Given an actual cross-sectional area of 24,482 m^2, the corresponding equivalent channel width (BS) at MLW is calculated as 4,896 m (i.e., the cross-sectional area divided by the average depth).

Next, CORMIX requires specification of a representative local water depth in the general discharge location, HD. Here, the local depth (HD) is not allowed to differ from the average depth (HA) by more than 30%. Based on the plotted bathymetry (Figure 6) and the 30% constraint, a representative local depth of 3.7 m at MLW is selected. This corresponds approximately to the midpoint elevation of the sloping embankment that supports the outfall pipe (Figure 5).

CORMIX requires specification of outfall orientation and configuration data, including the location of the nearest bank (left or right) as seen by an observer looking downstream in the flow direction. Here, the correct specification is "left" for an ebbing tide and "right" for a flooding tide. Next, the distance to the nearest bank is specified as 3.048 m (10 ft). Also, a vertical discharge angle of approximately –3.4 degrees is assumed (based on Figure 5), along with a specified horizontal discharge angle of 270 degrees (corresponding to the discharge pipe pointing to the right of an ebbing flow). In addition, the port diameter is specified as 1.22 m (4 ft), corresponding to the diameter of the subject outfall pipe. Finally, the specified height of the port center above the "equivalent" (i.e., flat) bottom is specified as 1 m. For the specified 1.22-m-diameter outfall, this corresponds to an invert elevation of about 0.4 m above the local bottom. This near-bottom location provides a reasonable schematization of the actual sloping embankment that supports the outfall pipe (Figure 5).

A typical value of 0.025 is specified for the bottom friction coefficient (mannings n). Also, a nominal wind speed value of 1 m/sec is specified, similar to the conservative 2-m/sec value recommended in the CORMIX users manual.

Finally, the specified pollutant type is "heated," and *a most conservative atmospheric heat-loss coefficient value of 0.0 is specified.*

3.2.2 Model Input Variables

In this application, CORMIX requires specification of five input variables: (1) ambient current speeds; (2) discharge excess temperatures; (3) effluent flow rates; (4) ambient water densities; and (5) effluent densities. As Figure 3 comprises the only available current meter data for the adjacent receiving waters, ambient current speeds recorded during the near-slack intervals were used as input for the model scenarios. Available data for the remaining input variables are summarized in Tables 2 and 3, along with information regarding their sources, sampling frequency and calculation methods. In this analysis, both ambient and meteorological variables were analyzed for a recent decade (i.e., January 1, 1991- December 31, 2001) in order to capture a representative range of ambient conditions.

Model inputs for discharge excess temperature were developed based on estimated (post-EPU) blowdown temperatures and ambient water temperatures (as represented by Reedy Island water temperature data). In this analysis, available ambient water temperature data collected by the USGS at Reedy Island were compiled for the period January 1, 1991 - December 31, 2001 (Appendix B, Figure B1). Also, a synthetic record of blowdown temperatures was assembled by PSEG (Appendix A) based on local meteorological data for the selected period and cooling tower performance curves developed for the EPU Project (Figure B2). Next, daily discharge excess temperatures were computed by subtracting the ambient temperatures from the synthetic record of blowdown temperatures (Figure B3).

Model inputs for effluent flow rates (i.e., blowdown flows) were calculated based on prescribed makeup flows and estimated evaporation rates for the EPU Project. As noted above, records indicate that when ambient water temperatures are below approximately 70°F, typically an average service water flow rate of approximately 37,000 gpm is supplied by two pumps; when ambient water temperatures are above approximately 70°F, typically an average service water flow rate of approximately 52,000 gpm is supplied by three pumps. Thus, model-input make flows were prescribed as these two values. The hourly evaporation rates for this period (Figure B4) were calculated by PSEG (Appendix A) based on local meteorological data for the selected period and cooling tower performance curves derived for the HCGS. Hourly blowdown flows were computed by subtracting the synthesized evaporation rates from the specified makeup flow rates (Figure B5).

Ambient salinities for the selected period were computed based on daily water temperature data and conductivity data collected by the USGS at Reedy Island over the selected period (Figure B6). Resulting conductivity and temperature data were converted to corresponding daily salinity and ambient density data (Figure B7) using a standard oceanographic algorithm (UNESCO, 1981). Corresponding total dissolved solids concentrations were computed by applying a conversion factor of 1.005 to the computed salinities.

Model inputs for effluent density were developed based on the synthesized records of blowdown temperatures and corresponding effluent salinities. As noted above, a record of hourly blowdown temperatures was synthesized based on local meteorological data for the selected period and cooling tower performance curves developed for the EPU Project. Next, corresponding effluent salinities were computed based on calculated daily ambient salinity data at Reedy Island over the same period and estimated hourly cycles of concentration for the HCGS. The latter was computed as the ratio of the makeup flow divided by the blowdown flow (Figure B8). The resulting set of blowdown temperatures and effluent salinities were converted to hourly effluent densities (Figure B9) over the selected period (UNESCO, 1981).

3.3 Model Scenario Development

The model scenarios developed for the EPU Project specify combinations of the five model-input variables that regulate plume dilution: (1) ambient current speed; (2) discharge excess temperatures; (3) effluent flow rate; (4) ambient density; and (5) effluent density. Overall, the scenarios consist of particular combinations of these variables that represent a range of ambient and discharge conditions, including worst-case (e.g., minimum-dilution or maximum-discharge) conditions. Statistical uncertainty in estimates of absolute worst-case ambient conditions is generally large in coastal waterways. Often, reliable estimations are obtained based on lowest (or, in some cases, highest) tenth-percentile values of an input variable on a cumulative frequency distribution curve (USEPA, 1985). Using this approach, individual model scenarios were developed using combinations of lowest (or, where more conservative, highest) 10^{th}-percentile monthly values for each of the five model-input variables. It should be noted that the *joint* occurrence of the five selected model-input variables would be very unlikely (i.e., well below the 10% individual probabilities). Thus, a truly conservative set of model scenario inputs was developed.

For example, minimum dilution levels may be anticipated under slack-tide conditions (i.e., zero current speeds). However, due to wind forcing effects and non-uniform flow patterns, zero tidal current speeds rarely, if ever, occur and never persist (e.g., Figure 3). Consequently, zero current speeds are not representative inputs to steady-state plume-dilution models such as CORMIX. Lowest 10^{th}-percentile ambient current speed recommended in the EPA guidance provide a more representative model input for scenario analyses.

As noted above, the only available current speed data for the study area are plotted in Figure 3. A visual inspection of the mid-depth (10-ft-deep) record indicates that ambient current speeds of approximately 0.75 ft/sec (0.23 m/sec) are exceeded except for a very brief period around each slack tide. A graphical analysis of this record indicates that currents of this magnitude are exceeded approximately 96% of the time. Hence 0.23 m/sec was selected as a representative critical ambient current speed for plume-dilution modeling. Note that this value is comparable to the 0.25-m/sec-value assumed in a previous dye-tracer and modeling study conducted on the Station's thermal plume (LMS, 1992).

Next, the assembled time series (Appendix B) for discharge excess temperature, blowdown flows, ambient densities and effluent densities were analyzed statistically to yield empirical distributions and corresponding monthly percentile statistics. For example, a cumulative frequency distribution (and monthly percentile statistics) of discharge excess temperatures was derived (Table 4) from the hourly time series of calculated discharge excess temperatures (Figure B3). This analysis yielded representative model scenario inputs for the critical discharge excess temperatures (e.g., highest 10th-percentile discharge excess temperatures for each month, Figure 7).

Likewise, a cumulative frequency distribution (and percentile statistics) of blowdown flows was derived (Table 5) based on the assembled blowdown flow data set (Figure B5). This analysis yielded representative model scenario inputs for critical, post-EPU effluent flow rates (e.g., highest 10th-percentile blowdown flows, Figure 8).

From a dynamical standpoint, the buoyancy of a discharge plume exerts an important control on plume dilution. Indeed, it is well known that negatively buoyant plumes tend to become bottom-attached in estuaries, thereby limiting dilution levels. Accordingly a cumulative frequency distribution (and percentile statistics) was derived (Table 6) from the computed *difference* between the computed daily effluent densities (Figure B9) and ambient densities (Figure B7). This analysis yielded representative model scenario inputs for a negatively (or positively) buoyant plume (e.g., highest 10th-percentile negatively buoyant values, Figure 9).

Critical 10th-percentile statistics described above were computed separately for each month based on ambient and meteorological data for the selected time period (January 1, 1991-December 31, 2001). Results are summarized in Table 7. The computed statistics allowed for an initial screening of critical conditions and relevant model scenarios.

As tabulated, the computed critical (i.e., highest 10th-percentile) discharge excess temperature is highest (20.46°C) for the month of January, with February ranking a close second. Moreover, corresponding blowdown flows and density differences are comparable for both months. Thus, these months were selected initially as candidate months for a model scenario screening analysis for the non-summer months.

Likewise, the computed critical discharge excess temperature for the summer months is highest (9.62°C) for June, with July ranking a more distant second (6.83°C) followed by August (6.62°C). Note that a more stringent water quality standard (0.8°C vs. 2.2°C at the edge of the HDA) is promulgated for these three months. For these reasons, these three months were selected initially as candidate months for a model scenario screening analysis for the summer months.

Additional spring and fall monthly scenarios for the non-summer period were not included since the maximum discharge excess temperature for these remaining months was only 16.12°C (in April) – well below the corresponding 20.46°C value for the month of January. Note that the 2.2°C-allowable temperature increase that applies for January also applies for the remaining spring and fall months.

The critical input variables for the months of January, February, June, July and August were assembled as model input and listed in Table 8. Corresponding fixed input parameters for these initial scenarios are listed in Table 1 and are described in section 3.2.1. Using these inputs, CORMIX1 was run for each initial scenario, and corresponding model output was compiled in Appendix C. Simulated maximum excess temperatures at the edge of the Station's HDA (i.e., 2,500 ft down-estuary) are presented in Table 9. As indicated, the winter and summer months having the highest discharge excess temperature (i.e., January and June) exhibited the highest excess temperatures at the edge of the HDA. Thus, these months were selected for further model scenario analyses.

While model results presented in the previous section focused on strict regulatory compliance at the edge of the HDA, this section describes model results in detail for both the January and June scenarios.

3.4 Model Scenario Analyses

3.4.1 Model Scenario Analysis for January

Figure 10 displays the simulated trajectory (upper panel) and excess temperature distribution along the plume centerline (lower panel) for the January scenario. A physical description of the simulated dilution pattern is as follows. First, the subject discharge consists of a submerged, negatively buoyant effluent issuing nearly horizontally into the ambient cross-flow. Upon entering the receiving-waters, the initial momentum of the discharge dominates the flow in relation to the limited layer depth, and the simulated discharge plume consists of a bottom-attached jet. The simulated discharge plume becomes unstable and full vertical mixing occurs. The subject plume is diluted rapidly down-estuary -- from an initial discharge excess temperature of 20.46°C down to an excess temperature of 2.69°C (i.e., 7.6-fold dilution) at the edge of the near-field located 14.09 m (46.2 ft) down-estuary. The plume trajectory parallels the shoreline, with the plume centerline located approximately 17 m (55.8 ft) from the shoreline at the edge of the near-field region.

Beyond this point, the plume becomes passive and far-field dilution is less rapid. The plume is advected by the ambient cross-flow, and the plume spreads laterally due to turbulent diffusion processes. At a distance of about 71 m (233 ft), the excess temperature is reduced to the water quality standard level of 2.2°C (i.e., 9.3-fold dilution). At the edge of the HDA, the excess temperature is reduced to 0.54°C (i.e., 35.9-fold dilution) and is well below the standard.

To provide a more conservative estimate, the January scenario simulation was repeated with the ambient current assumed to be *unsteady*, but equivalent to the specified 0.75ft/sec (0.2286 m/sec) value at 1 hour after slack tide (Table 10). Also, a peak current speed of 2.5 ft/sec (0.76 m/sec) was assumed. With these inputs, the model simulated re-entrainment of the plume (Figure 10). That is, it simulated an additional build-up of excess temperatures near the discharge due to the return of a diluted plume after tidal reversal. Unfortunately, this re-entrainment effect can only be simulated over a limited distance from the discharge (Nash, 1995). In this case, this corresponds to about 345 m (1,130 ft) down-estuary. The simulated excess temperature at the plume centerline is 1.57°C – already in compliance with the 2.2°C standard. Thus, it is clear from Figure 10 that the subject discharge would be in compliance whether or not re-entrainment is included in the simulation.

3.4.2 Model Scenario Analysis for June

Figure 11 displays the simulated trajectory (upper panel) and excess temperature distribution along the plume centerline (lower panel) for the June scenario. As illustrated, the simulated dilution pattern for the June scenario is similar to the pattern for January.

Physically, the subject discharge consists of a submerged, negatively buoyant effluent issuing nearly horizontally into the ambient cross-flow. Upon entering the receiving-waters, the initial momentum of the discharge dominates the flow in relation to the limited layer depth, and the simulated discharge plume consists of a bottom-attached jet. The simulated discharge plume becomes unstable and full vertical mixing occurs. The subject plume is diluted rapidly down-estuary -- from an initial discharge excess temperature of 9.62°C down to an excess temperature of 1.55°C (i.e., 6.2-fold dilution) at the edge of the near-field located 10.1 m (33.1 ft) down-estuary. The plume trajectory parallels the shoreline, with the plume centerline located approximately 21.3 m (70.0 ft) from the shoreline at the edge of the near-field region.

Beyond this point, the plume becomes passive and far-field dilution is less rapid. The plume is advected by the ambient cross-flow, and the plume spreads laterally due to turbulent diffusion processes. At a distance of about 340 m (1,115 ft), the excess temperature is reduced to the water quality standard level of 0.8°C (i.e., 12.0-fold dilution). At the edge of the HDA, the excess temperature is reduced to 0.47°C (i.e., 20.5-fold dilution) and is below the 0.8°C standard.

To provide a more conservative estimate, the June scenario simulation was also repeated with the ambient current assumed to be *unsteady* (Nash, 1995), but equivalent to the specified 0.75 ft/sec (0.23 m/sec) value at 1 hour after slack tide (Table 10). Also, a peak current speed of 2.5 ft/sec (0.76 m/sec) was assumed. With these inputs, the model again simulated re-entrainment of the plume (Figure 11). Unfortunately, this re-entrainment effect can only be simulated over a limited distance from the discharge (Nash, 1995). In this case, this corresponds to about 358 m (1,174 ft) down-estuary. At this point, the simulated excess temperature is 0.987°C or about 1.28 times higher than the simulated temperature without re-entrainment. Applying this same proportion at the edge of the HDA, the simulated excess temperature would be increased from 0.47°C (without re-entrainment) to 0.60°C (with re-entrainment) and, thus, would still be in compliance.

4. MODEL SENSITIVITY ANALYSIS

The results indicate that the Station's post-EPU thermal plume would comply with relevant water quality standards under the specified critical input conditions. However, a range of conditions (both more stringent and less stringent) should be examined to further characterize plume dilution.

A series of model sensitivity runs were conducted for the two scenario months (January and June). These sensitivity runs considered a range of possible values for the five input variables: ambient current speed, discharge excess temperature, effluent flow rate, ambient water density and effluent density.

4.1 Model Sensitivity Analysis for January

Four sets of model sensitivity runs were conducted for the month of January. Each set simulated effects of changing one of the following variables: (1) ambient current speed; (2) discharge excess temperature; (3) effluent flow; and (4) initial buoyancy, as represented by effluent density minus ambient density. Note that model-input parameter values for these simulations were fixed to those listed in Table 1, while only one variable listed for January in Table 8 was varied within a given set, or two variables in the case of the density difference sensitivity (Table 11). Corresponding model output is compiled in Appendix D and simulated maximum excess temperatures at the edge of the HDA are plotted in Figures 12-15.

Figure 12 displays resulting model sensitivity to variations in the specified ambient current speed, with all other input parameters and variables held fixed to values prescribed for January in Tables 1 and 8. Typically, near-field dilution levels decrease (and excess temperatures increase) markedly as ambient current speeds decrease. In this case (Figure 3), minimum current speeds observed at mid-depth are typically 0.5 ft/sec (0.15 m/sec). Figure 12 indicates that the Station's thermal plume under post-EPU conditions would comply with the 2.2 °C maximum-allowable increase even for such low current speeds.

Figure 13 displays model sensitivity to variations in the discharge excess temperature, with all other input parameters and variables held fixed to values prescribed for January in Tables 1 and 8. As illustrated, the model proved insensitive to the range of prescribed discharge excess temperature, which varied from 17.95°C (50^{th} percentile for January) to 21.13°C (highest 95^{th} percentile). Likewise, the model proved insensitive (Figure 14) to blowdown flow rates varying from 52.65 cfs (lowest 10^{th} percentile) to 55.60 (highest 10^{th} percentile). In both cases, the simulated maximum excess temperature at the edge of the HDA fell well below the 2.2°C standard limit.

Finally, model sensitivity to the density difference (effluent minus ambient) for the month of January is displayed in Figure 15. Note that selected density differences for these sensitivity simulations are listed in Table 11, along with their corresponding instantaneous ambient and effluent densities. Results indicate that even as the density difference (for a negatively buoyant plume) is increased from the highest 10^{th} percentile value (0.4151 kg/m^3) to the highest 5^{th} percentile value (0.6205 kg/m^3), the simulated maximum excess temperature at the edge of the HDA falls well below the 2.2 °C standard. Similar results apply for a positively buoyant plume (Appendix D, last section).

Overall, the model sensitivity analysis for January indicates no anticipated exceedances of the 2.2°C standard for any reasonable change in selected input values. Since the model indicates that January is the most critical non-summer month, this result implies that other non-summer months would also be in compliance under post-EPU conditions.

4.2 Model Sensitivity Analysis for June

Four sets of model sensitivity runs were conducted for the month of June. Again, each set simulated effects of changing one of the following variables: (1) ambient current speed; (2) discharge excess temperature; (3) effluent flow; and (4) effluent density minus ambient density. Corresponding model output is compiled in Appendix E and simulated maximum excess temperatures at the edge of the HDA are plotted in Figures 16-19.

Figure 16 displays resulting model sensitivity to variations in the specified ambient current speed, with all other input parameters and variables held fixed to values prescribed for June in Tables 1 and 8 (column 3). Typically, near-field dilution levels decrease (and excess temperatures increase) markedly as ambient current speeds decrease. Figure 16 indicates that as the prescribed ambient current speed is decreased below the specified value of 0.23 m/sec (a value exceeded about 96% of the time) to 0.20 m/sec, the simulated maximum excess temperature at the edge of the HDA increases from 0.41°C to 0.50°C and is still below the 0.8°C maximum allowable increase. With re-entrainment included for the 0.20 m/sec case, the model predicts a maximum excess temperature of 1.14°C at a down-estuary distance of 1,059 ft (323 m) – about 1.23 times higher than the corresponding temperature simulated without re-entrainment (0.92°C). Applying this same factor at the edge of the HDA (i.e., at 2,500 ft down-estuary), the simulated excess temperature for the 0.20 m/sec case is still below the 0.8°C maximum allowable increase (i.e., 1.23 times 0.5°C or 0.62°C). For lower ambient current speeds, the model predicts a smaller near-field region and an unstable far-field region where results are deemed unreliable.

Figure 17 displays model sensitivity to variations in the discharge excess temperature, with all other input parameters and variables held fixed to values prescribed for June in Tables 1 and 8. As illustrated, the simulated excess temperatures fell below the 0.8°C standard for the range of prescribed discharge excess temperature, which varied from 6.87°C (50th percentile for June) to 10.35°C (highest 95th percentile). Also, the model proved insensitive (Figure 18) to blowdown flow rates varying from 80.53 cfs (lowest 5th percentile) to 84.31 cfs (highest 10th percentile). In both cases, the simulated maximum excess temperature at the edge of the HDA fell below the 0.8°C standard limit. Similar results apply for a positively buoyant plume (Appendix E, last section).

Finally, model sensitivity to the density difference (effluent minus ambient) for the month of June is displayed in Figure 19. Note that selected density differences for these sensitivity simulations are listed in Table 11, along with their corresponding instantaneous ambient and effluent densities. Results indicate that even as the density difference (for a negatively buoyant plume) is increased from the highest 10th percentile value (0.6114 kg/m^3) to the highest 5th percentile value (0.8784 kg/m^3), the simulated maximum excess temperature at the edge of the HDA falls below the 0.8 C standard limit.

Overall, the model sensitivity analysis for June indicates no anticipated exceedances of the 0.8°C standard for any reasonable change in selected input values. Since the model indicates that June is the most critical summer month, this result implies that other summer months would also be in compliance under post-EPU conditions.

Moreover, since discharge excess temperatures are markedly less severe for the remaining spring and fall months, all months are anticipated to be in compliance under post-EPU conditions.

5. SUMMARY AND CONCLUSIONS

As the Extended Power Uprate (EPU) Project will increase the electrical output of PSEG's Hope Creek Generating Station by a maximum of 20% above its originally licensed thermal power (OLTP), an assessment of the Project's potential thermal impacts on Delaware Estuary receiving waters was requested. To this end, a numerical plume-dilution model was adapted to the study area and used to forecast potential water temperature increases in the adjacent Estuary under post-EPU operating conditions.

The CORMIX1 model was adapted to the study area using two types of model input: (1) fixed model-input input parameters that represent ambient bathymetry, outfall orientation and outfall configuration; and (2) variable model-input data representing ambient hydrographic conditions (i.e., ambient current speeds, ambient water density) and effluent data (e.g., discharge rate, discharge excess temperature, effluent density). A representative database of model-input variables was developed for each month using available ambient hydrographic data provided by the USGS and effluent data that was calculated by PSEG based on local meteorological data and thermodynamic performance curves developed for the Station's EPU Project.

Model scenarios were developed from this database using an established statistical approach that combined lowest (or, where more conservative, highest) 10th-percentile monthly values for key model-input variables. Jointly, these "critical-condition" variables provided a conservative set of model scenarios. A model screening analysis of these scenarios indicated that the winter and summer months having the highest discharge excess temperature (i.e., January and June) exhibited the highest excess temperatures at the edge of the allowed HDA for the Station. Thus, these months were selected for further model scenario analyses.

Water quality standards promulgated for the receiving waters limit water temperature increases to 4°F (2.2 °C) above ambient temperatures from September to May, and 1.5°F (0.8°C) from June to August, and a maximum temperature of 86°F (30°C), whichever is less, except in a designated heat dissipation area (HDA) that extends 1,500 ft offshore, 2,500 ft up estuary and 2,500 ft down estuary from the point of discharge. The model analysis of the January Scenario indicated that at a down-estuary distance of about 71 m (233 ft), the excess temperature was reduced to the water quality standard of 2.2°C (i.e., 9.3-fold dilution), while at the edge of the HDA, the excess temperature was reduced well below the standard to 0.57°C (i.e., 35.9-fold dilution). Including effects of plume re-entrainment, the model indicates that the Station's post-EPU discharge would still be in compliance with the standard.

Likewise. the model analysis of the June Scenario indicated that at a down-estuary distance of about 340 m (1,115 ft), the excess temperature was reduced to the water quality standard of 0.8°C (i.e., 12.0-fold dilution), while at the edge of the HDA, the excess temperature was reduced to 0.47°C (i.e., 20.5-fold dilution) and was below the 0.8°C standard limit. Including effects of plume re-entrainment, the model suggests that the Station's post-EPU discharge would still be in compliance with the standard.

Next, to further characterize the results, a series of model sensitivity runs were conducted for the January and June scenarios. These sensitivity runs considered a wider range of input variables (both more stringent and less stringent). Results for January indicated that the Station's thermal plume, under post-EPU conditions, would comply with the 2.2°C standard even for typical minimum observed current speeds equal to 0.5 ft/sec (0.15 m/sec). Also, the model proved insensitive to the range of prescribed discharge excess temperature, which varied systematically from 17.95°C (50th percentile for January) to 21.13°C (highest 95th percentile). Also, the model proved insensitive (Figure 14) to blowdown flow rates varying from 52.65 cfs (lowest 10th percentile) to 55.60 (highest 10th percentile). In both cases, the simulated maximum excess temperature at the edge of the HDA fell well below the 2.2°C standard limit. Overall, the model sensitivity analysis for January indicates no anticipated exceedances of the 2.2°C maximum-allowable increase for any reasonable change in selected input values. Since the model indicates that January is the most critical winter month, this result implies that other winter months would also be in compliance under post-EPU conditions.

Results of sensitivity runs for June indicated that the Station's thermal plume, under post-EPU conditions, would comply with the 0.8°C standard even as the prescribed ambient current speed is decreased below 0.23 m/sec (a value exceeded about 96% of the time) to 0.20 m/sec. Also, the simulated excess temperatures fell below the 0.8°C standard for the range of prescribed discharge excess temperature, which varied from 6.87°C (highest 50th percentile for June) to 10.35°C (highest 95th percentile). Also, the model proved insensitive (Figure 18) to blowdown flow rates varying from 80.53 cfs (lowest 5th percentile) to 84.31 cfs (highest 10th percentile). In both cases, the simulated maximum excess temperature at the edge of the HDA fell below the 0.8°C standard limit. Also, as the density difference was increased from the highest 10th percentile value (0.6114 kg/m^3) to the highest 5th percentile value (0.8784 kg/m^3), the simulated maximum excess temperature at the edge of the HDA fell below the 0.8°C maximum-allowable increase.

Overall, the model sensitivity analysis for June indicates no anticipated exceedances of the 0.8°C standard for any reasonable change in selected input values. Since the model indicates that January is the most critical winter month, this result implies that other winter months would also be in compliance under post-EPU conditions. Moreover, since discharge excess temperatures are markedly less severe for the remaining spring and fall months, all months are anticipated to be in compliance under post-EPU conditions

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TABLES

Table 1: Selected model input parameters (fixed for January, February, June, July and August scenarios)

AMBIENT DATA	FIXED MODEL INPUT
Cross-section	bounded
appearance	Regular
equivalent channel width (m)	4896
average depth (m)	5
discharge depth(m)	3.7
Ambient currents	steady
mannings n	0.025
wind speed(m/s)	1
EFFLUENT DATA	**FIXED MODEL INPUT**
pollutant type	Heated
heat loss coefficient	0
DISCHARGE DATA	**FIXED MODEL INPUT**
nearest bank on	left
distance to nearest bank (m)	3.048
vertical discharge angle (deg)	-3.4
horizontal discharge angle (deg)	270
port diameter (m)	1.22
port height (m)	1

Table 2: Background information on model-input ambient variables and related computed variables

	AMBIENT VARIABLES				MODEL INPUT
	Ambient Temperature (C)	Specific Conductance (umohs)	Ambient Salinity (psu)	TDS (ppt)	Ambient Density (kg/m^3)
Location	Reedy Island	Reedy Island	Reedy Island	Reedy Island	Reedy Island
Source	USGS	USGS	NA Calculated	NA Calculated	NA Calculated
Dates	January 1, 1991 - December 31, 2001	January 1, 1991 - December 31, 2001	January 1, 1991 - December 31, 2001	January 1, 1990 - April 30, 2003	January 1, 1991 - December 31, 2001
Sampling Interval	Hourly	Daily	Daily	Daily	Daily
Notes	USGS PA office provided	USGS PA office and USGS web site provided	NA calculated based on daily Reedy Island Specific Conductance	NA calculated based on daily Reedy Island Salinity times a factor of 1.005	NA Calculated based on daily Reedy Island Salinity and Ambient Water Temps in UNESCO formula

Table 3: Background information on model-input discharge variables and related computed variables

	DISCHARGE VARIABLES						
		MODEL INPUT			MODEL INPUT		MODEL INPUT
	Blowdown Temperature (C)	**Delta T (C)**	**Evaporation Rate (GPM)**	**Make-Up Flow Rate (GPM)**	**Blow-Down Flow Rate (CFS)**	**Cycles of Concentration (ratio)**	**Discharge Density (kg/m^3)**
Location	Hope Creek GS	Hope Creek GS	Artificial Island	Hope Creek GS	Hope Creek GS	Hope Creek GS	Hope Creek GS
Source	PSEG	Najarian Calculated	PSEG	PSEG	Najarian Calculated	Najarian Calculated	Najarian Calculated
Dates	January 1, 1991 - December 31, 2001	January 1, 1991 - December 31, 2001	January 1, 1991 - December 31, 2001	October - May: 37,000 gpm for <70F May - October: 52,000 gpm for >70F	January 1, 1991 - December 31, 2001	January 1, 1991 - December 31, 2001	January 1, 1991 - December 31, 2001
Sampling Interval	Hourly	Hourly	Hourly		Hourly	Hourly	Hourly
Notes	PSEG provided using relative humidity measured at Artificial Island and EPU rating curves	NA calculated as blowdown temperature minus ambient temperature	PSEG provided based on data from MET station on Artificial Island	PSEG provided flow rates based on make-up water temperature	NA calculated as make-up flow rate minus evaporation rate	NA calculated as make-up flow rate divided by blowdown flow rate	NA calculated as Reedy Isl salinity times cycles of con. and blowdown temps in UNESCO formula

Table 4: Monthly percentiles of hourly discharge excess temperature (Delta T discharge) for the EPU project. The excess temperature was calculated as EPU blowdown temperature (provided by PSEG, Appendix A) minus ambient temperature measured at Reedy Island by the USGS from 1991 to 2001.

Delta T %-tile	Jan. (C)	Feb. (C)	Mar. (C)	Apr. (C)	May (C)	Jun. (C)	Jul. (C)	Aug. (C)	Sep. (C)	Oct. (C)	Nov. (C)	Dec. (C)
5%	15.20	15.80	13.42	9.87	6.45	3.69	2.36	2.33	2.43	5.24	8.75	11.58
10%	15.60	16.24	13.99	10.54	7.06	4.30	2.86	2.86	3.34	5.97	9.40	12.41
15%	15.90	16.60	14.40	11.02	7.48	4.83	3.26	3.28	3.83	6.50	9.93	12.94
20%	16.18	16.88	14.77	11.42	7.85	5.20	3.56	3.57	4.17	7.00	10.35	13.38
25%	16.50	17.17	15.17	11.75	8.23	5.53	3.79	3.79	4.46	7.43	10.73	13.77
50%	17.95	18.19	16.48	13.28	9.76	6.87	4.82	4.79	5.75	9.00	12.32	15.34
75%	19.47	19.21	17.71	14.83	11.18	8.29	5.93	5.79	7.17	10.44	14.27	16.64
80%	19.78	19.53	18.06	15.21	11.57	8.68	6.25	6.04	7.47	10.75	14.71	16.97
85%	20.11	19.82	18.45	15.63	12.01	9.08	6.52	6.29	7.89	11.06	15.09	17.34
90%	20.46	20.21	18.96	16.12	12.52	9.62	6.83	6.62	8.29	11.49	15.69	17.92
95%	21.13	20.87	19.60	16.83	13.10	10.35	7.24	7.04	8.84	12.11	16.58	18.79
Min.	14.04	14.52	10.87	7.63	2.13	0.65	-1.02	-0.61	-0.84	2.47	6.37	8.63
Max.	24.35	24.57	22.89	19.29	16.71	14.32	9.28	9.03	11.12	14.91	20.39	22.20
Mean	18.03	18.24	16.46	13.31	9.75	6.92	4.84	4.76	5.77	8.87	12.50	15.25
Count	3469	2942	5926	6307	6263	6300	6840	5922	6142	6939	6181	4937

Table 5: Monthly percentiles of hourly effluent flow rates (blowdown) for the EPU project. The effluent flow rate was calculated as the make-up flow rate minus the EPU cooling tower evaporation rate from 1991 to 2001 based on data provided by PSEG. When ambient water temperatures are below approximately 70°F, typically an average service water flow rate of approximately 37,000 gpm is supplied by two pumps; when ambient water temperatures are above approximately 70°F, typically an average service water flow rate of approximately 52,000 gpm is supplied by three pumps. During the two transition months (i.e., May and October), the lower of the two pumping rates was prescribed to provide a relatively high cycles of concentration and effluent density.

Make-up Flow Rates

River Temp <70 F (21.1 C): **37,000gpm = 82.44cfs**

River Temp >/=70 F (21.1 C): **52,000gpm = 115.86**

Effluent (Blow-down)	Make-up Pump Rate = 37,000 gpm					Make-up Pump Rate = 52,000 gpm				Pump Rate = 37,000 gpm		
Flow	Jan.	Feb.	Mar.	Apr.	May	Jun.	Jul.	Aug.	Sep.	Oct.	Nov.	Dec.
%-tile	(cfs)	(cfs)	(cfs)	(cfs)	(cfs)	(cfs)	(cfs)	(cfs)	(cfs)	(cfs)	(cfs)	(cfs)
5%	52.01	51.52	50.56	49.16	47.75	80.53	80.32	80.69	81.46	49.22	50.43	51.39
10%	52.65	52.14	51.40	49.92	48.38	80.98	80.71	81.07	81.88	49.72	51.01	52.04
15%	53.03	52.64	51.92	50.35	48.82	81.35	81.01	81.32	82.18	50.05	51.35	52.43
20%	53.29	52.93	52.25	50.69	49.18	81.67	81.24	81.55	82.42	50.31	51.59	52.76
25%	53.54	53.18	52.52	51.02	49.45	81.93	81.46	81.74	82.61	50.53	51.78	53.03
50%	54.32	54.09	53.51	52.11	50.59	82.82	82.32	82.59	83.41	51.37	52.75	53.89
75%	55.04	54.87	54.38	53.10	51.54	83.60	83.04	83.26	84.17	52.30	53.81	54.59
80%	55.20	55.04	54.57	53.33	51.76	83.78	83.20	83.40	84.37	52.51	54.02	54.74
85%	55.38	55.24	54.80	53.56	51.99	84.00	83.36	83.59	84.61	52.74	54.25	54.88
90%	55.60	55.43	55.07	53.84	52.30	84.31	83.56	83.78	84.92	53.08	54.52	55.08
95%	55.90	55.74	55.43	54.21	52.67	84.73	83.83	84.08	85.40	53.56	54.83	55.38
Min.	49.62	48.95	46.70	47.04	45.96	79.17	79.13	79.50	79.64	46.42	47.87	48.64
Max.	56.31	56.34	56.25	56.19	54.49	86.68	84.74	85.37	87.01	55.38	56.18	56.33

Table 6: Monthly percentiles of hourly density difference (delta rho = effluent density minus ambient density) for the EPU project. Delta rho was calculated as EPU effluent density minus ambient density based on data from 1991 to 2001.

Delta Rho %-tile	Jan. Kg/m^3	Feb. Kg/m^3	Mar. Kg/m^3	Apr. Kg/m^3	May Kg/m^3	Jun. Kg/m^3	Jul. Kg/m^3	Aug. Kg/m^3	Sep. Kg/m^3	Oct. Kg/m^3	Nov. Kg/m^3	Dec. Kg/m^3
5%	-2.1746	-2.0334	-2.8035	-3.0770	-2.3198	-1.9980	-1.0857	-1.1008	-0.9040	-1.3853	-1.6168	-2.2194
10%	-1.8555	-1.8199	-2.5050	-2.7871	-2.0022	-1.7599	-0.8264	-0.8541	-0.6127	-0.5178	-1.4098	-1.9308
25%	-1.4625	-1.3712	-1.9021	-2.2621	-1.5440	-1.2935	-0.3901	-0.3120	-0.1669	0.4434	-0.4628	-1.1446
50%	-1.0542	-0.6936	-1.3279	-1.5892	-0.9039	-0.6688	0.1289	0.3183	0.4300	1.1140	0.5228	-0.1810
75%	-0.0039	0.1343	-0.6609	-0.9076	-0.2095	-0.0017	0.7416	0.9789	0.9673	1.7097	1.4527	0.6880
90%	0.4151	0.5028	-0.0406	-0.4896	0.4797	0.6114	1.1938	1.6069	1.4840	2.2388	2.3130	1.2826
95%	0.6205	0.6878	0.2783	-0.3301	0.8802	0.8784	1.4680	2.0386	1.7816	2.5251	2.7824	1.5092
Min.	-3.1458	-2.7462	-4.2795	-4.0881	-3.7600	-3.0949	-1.9495	-2.1204	-1.6653	-3.0876	-3.0734	-3.2775
Max.	1.5176	1.7139	1.5246	0.3406	1.5831	1.8848	2.4127	3.1084	2.5745	4.1421	3.7474	2.2580
Mean	-0.8488	-0.6375	-1.2851	-1.6211	-0.8450	-0.6351	0.1673	0.3603	0.4269	0.9776	0.5009	-0.2505
Count	3232	2854	5835	5645	5797	6251	6756	5843	6110	6951	5947	4960

Table 7: Summary of critical model input variables derived for each month

Month	highest 10th-percentile initial excess temperature (deg C)	Water quality standard at edge of HDA (deg C)	highest 10th-percentile effluent flow (cfs)	lowest 10th-percentile ambient current speed (m/sec)	highest 10th-percentile density difference* (kg/m³)	ambient density (kg/m³)	effluent density (kg/m³)
January	**20.46**	**2.2**	55.6	0.2286	0.4151	1005.5051	1005.9202
February	20.21	2.2	55.43	0.2286	0.5028	1005.5267	1006.0295
March	18.96	2.2	55.07	0.2286	-0.0406	1005.3252	1005.2847
April	16.12	2.2	53.84	0.2286	-0.4896	1002.2789	1001.7894
May	12.52	2.2	52.30	0.2286	0.4797	1003.2748	1003.7545
June	**9.62**	**0.8**	84.31	0.2286	0.6114	1002.9706	1003.5820
July	6.83	0.8	83.56	0.2286	1.1938	1002.1329	1003.3264
August	6.62	0.8	83.78	0.2286	1.6069	1004.2245	1005.8316
September	8.29	2.2	84.92	0.2286	1.4840	1005.6281	1007.1119
October	11.49	2.2	53.08	0.2286	2.2388	1004.6256	1006.8644
November	15.69	2.2	54.52	0.2286	2.3130	1008.2840	1010.5971
December	17.92	2.2	55.08	0.2286	1.2826	1006.1497	1007.4323

* Effluent density minus ambient density

Table 8: Selected model input variables for each screening scenario

	SCENARIO				
	1	2	3	4	5
Month:	**January**	**February**	**June**	**July**	**August**
EFFLUENT DATA					
Highest 10th-percentile initial discharge excess temp. (deg C)	20.46	20.21	9.62	6.83	6.62
Highest 10th-percentile flow rate	55.6	55.43	84.31	83.56	83.78
Highest 10th-percentile effluent density(kg/m3)	1005.9202	1006.0295	1003.582	1003.3264	1005.8316
AMBIENT DATA					
Instantaneous velocity (m/sec)	0.2286	0.2286	0.2286	0.2286	0.2286
Surface/Bottom water density	1005.5051	1005.5267	1002.9706	1002.1329	1004.2245
Corresponding highest 10th-percentile of effluent density minus ambient density**	0.4151	0.5028	0.6114	1.1935	1.6071

Notes:
***Not a required input variable (for reference, only)**
** Not a direct input variable (computed internally by model)

Table 9: Results of model simulations of excess temperature at edge of HDA for 5 selected months.

Month	Scenario	Highest 10th percentile initial excess temperature (deg C)	Water quality standard at edge of HDA (deg C)	Simulated maximum excess temperature at edge of HDA* (deg C)
January	**1**	**20.46**	**2.2**	**0.57**
February	2	20.21	2.2	0.51
June	**3**	**9.62**	**0.8**	**0.47**
July	4	6.83	0.8	0.40
August	5	6.62	0.8	0.42

* Edge of HDA located 2,500 feet down-estuary

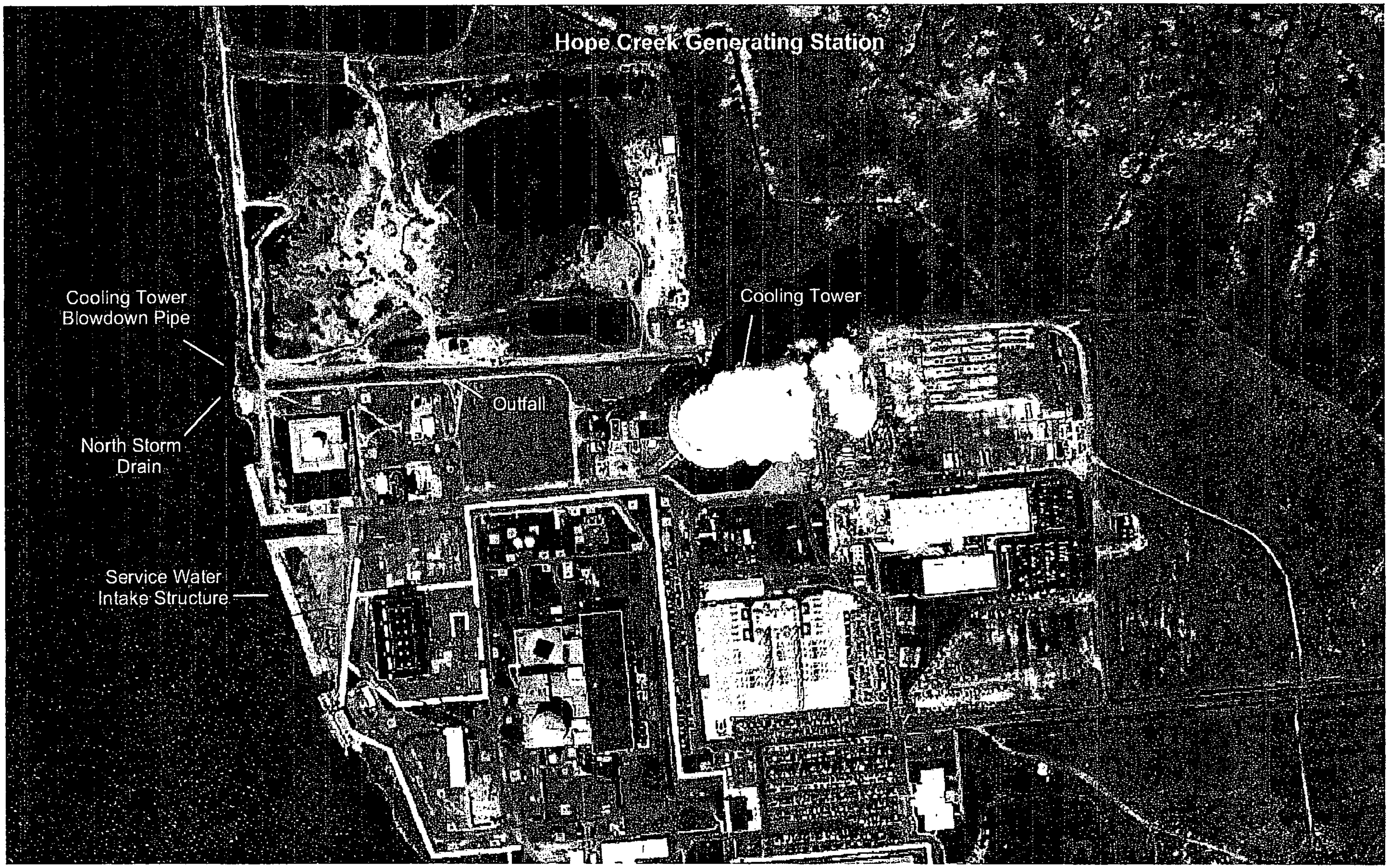
Table 10: Additional model inputs for re-entrainment simulations (fixed for each scenario)

	SCENARIO	
	1	**3**
Month	January	June
AMBIENT DATA		
Ambient currents	steady and unsteady	steady and unsteady
Tidal period (hr)	12.4	12.4
Maximum velocity (m/sec)	0.76	0.76
Instantaneous velocity (m/sec)	0.2286	0.2286
Time after slack (hr) for prescribed instantaneous velocity	1	1

Table 11: Monthly percentiles of hourly effluent, ambient and delta rho densities for the EPU project for the two scenario months (January and June).

January					June				
Delta Rho %-tile	Discharge Density Kg/m3	Ambient Density Kg/m3	Delta Rho Kg/m3	Buoyancy $(\rho_a-\rho_d)/\rho_a$	Delta Rho %-tile	Discharge Density Kg/m3	Ambient Density Kg/m3	Delta Rho Kg/m3	Buoyancy $(\rho_a-\rho_d)/\rho_a$
5%	999.1931	1001.3673	-2.1746	0.00217	5%	996.2121	998.2103	-1.9980	0.00200
10%	999.6118	1001.4673	-1.8555	0.00185	10%	996.4175	998.1774	-1.7599	0.00176
25%	1000.2220	1001.6845	-1.4625	0.00146	25%	998.7865	1000.0800	-1.2935	0.00129
50%	1001.3744	1002.4290	-1.0542	0.00105	50%	1000.6829	1001.3517	-0.6688	0.00067
75%	1005.9002	1005.9041	-0.0039	0.00000	75%	1001.6379	1001.6396	-0.0017	0.00000
80%	1004.9872	1004.8420	0.1451	-0.00014	80%	1001.6909	1001.5165	0.1744	-0.00017
85%	1005.8255	1005.5692	0.2572	-0.00026	85%	1002.3522	1001.9880	0.3630	-0.00036
90%	1005.9202	1005.5051	0.4151	-0.00041	90%	1003.5820	1002.9706	0.6114	-0.00061
95%	1007.0295	1006.4089	0.6205	-0.00062	95%	1001.7901	1000.9128	0.8784	-0.00088
Min.	997.2524	1000.1830	-3.1458	-0.00151	Min.	995.4971	997.5958	-3.0949	-0.00188
Max.	1009.1061	1007.6357	1.5176	0.00314	Max.	1005.2106	1003.7184	1.8848	0.00309
Mean	1002.2276	1003.0764	-0.8488	0.00085	Mean	1000.0297	1000.6648	-0.6351	0.00064
Count	3232	3232	3232	3232	Count	6251	6251	6251	6251

FIGURES



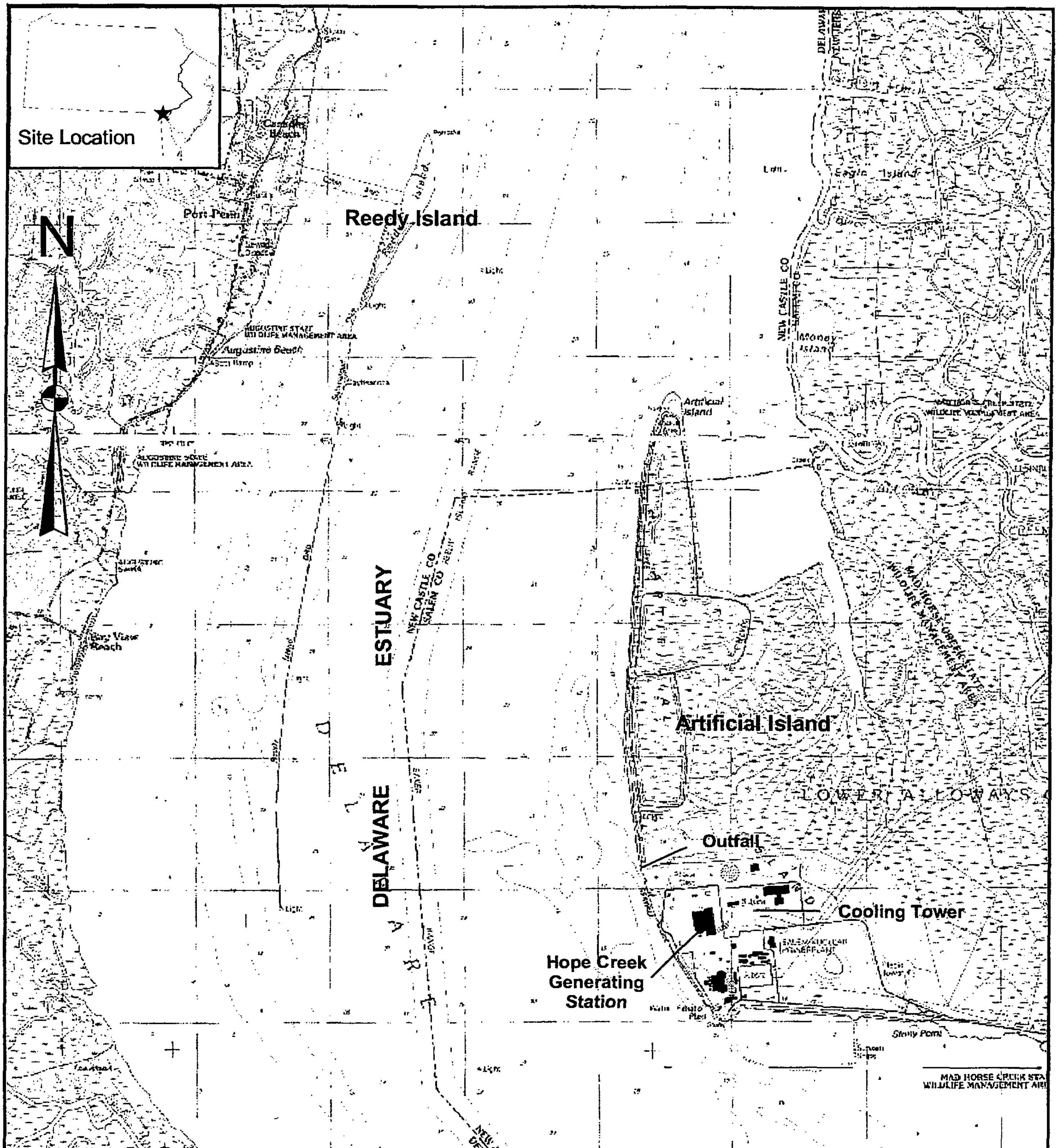
Najarian Associates
Engineers • Planners • Scientists • Surveyors

Figure 1
Aerial View of Site

0 500 1,000 Feet

0 250 500 Meters

N



Hope Creek Generating Station

2,000 0 2,000 4,000

Feet

Najarian Associates

Engineers · Planners · Scientists · Surveyors

One Industrial Way West, Eatontown, New Jersey 07724

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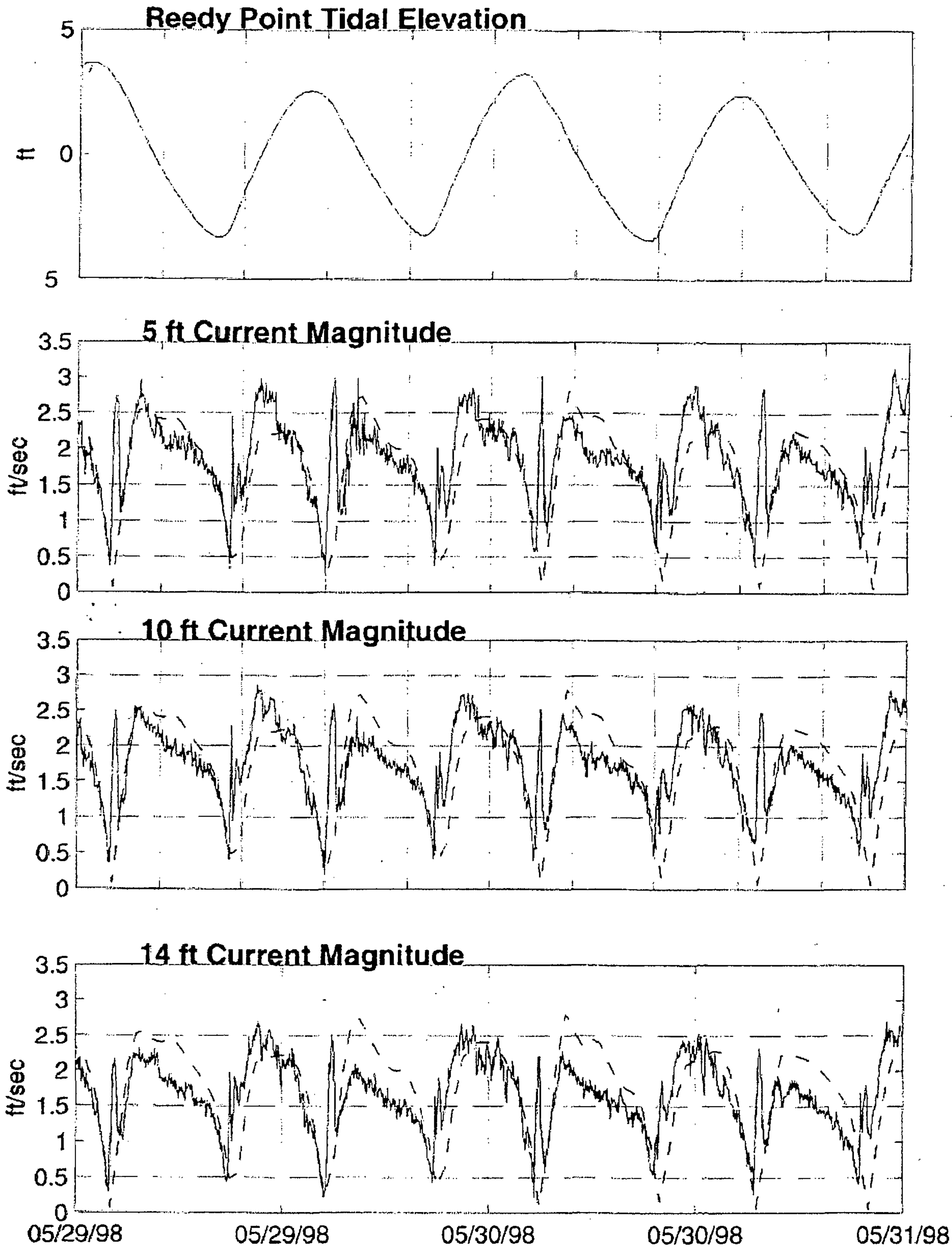


Figure 3: Time series of sea level at Salem Barge Slip (upper panel) and current velocity collected at near-surface, mid-depth and near-bottom levels measured with an ADCP during the Salem Generating Station Permit Renewal Project (lower three panels). Dashed line represents previous hydrodynamic model simulations. (From PSE&G, 1999)

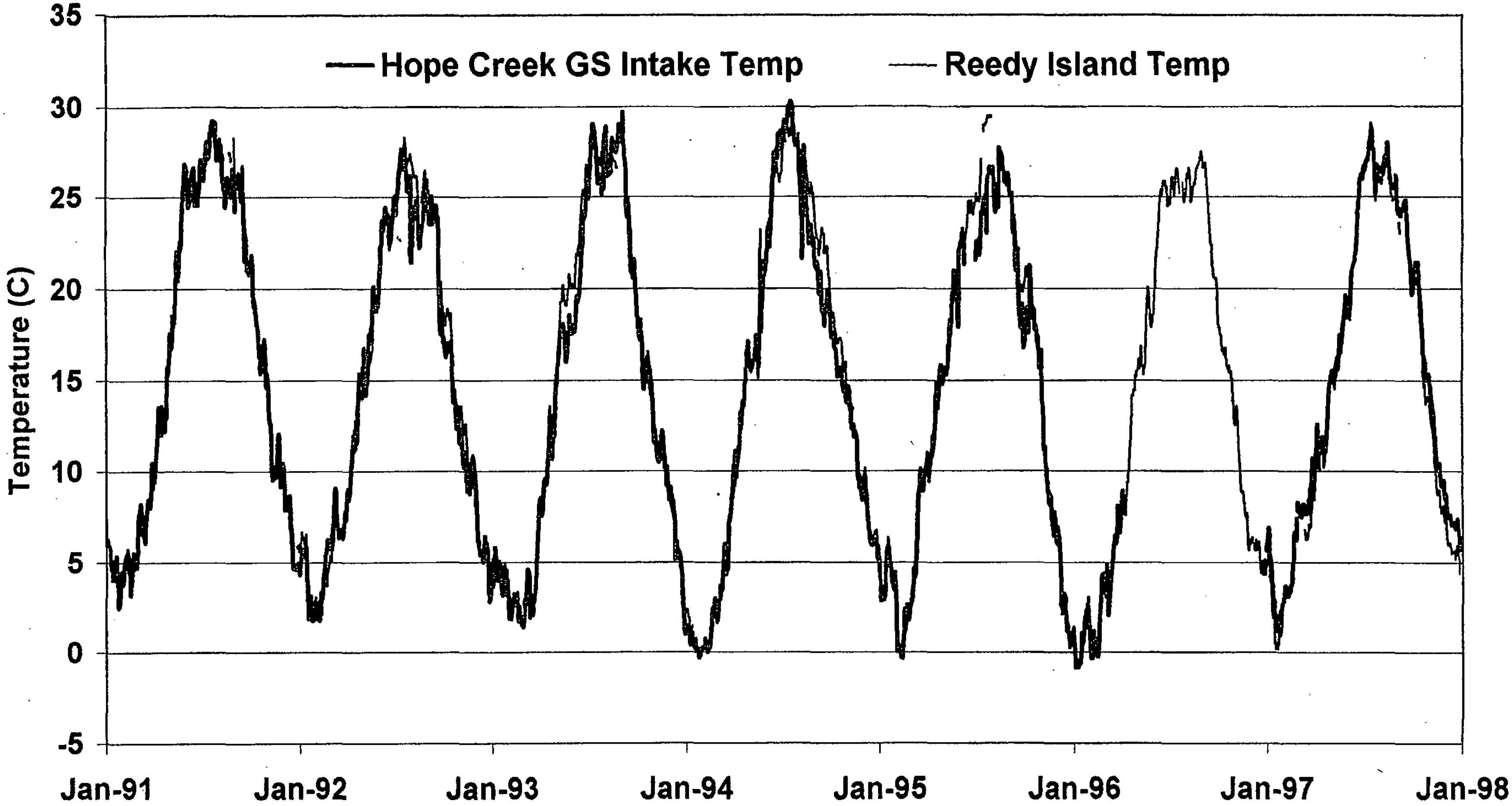
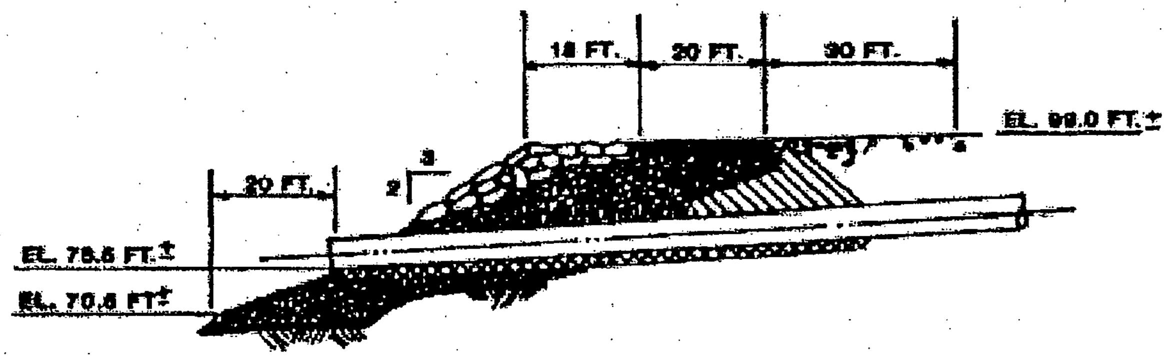


Figure 4: Time series of intake (make-up) and ambient water temperatures.

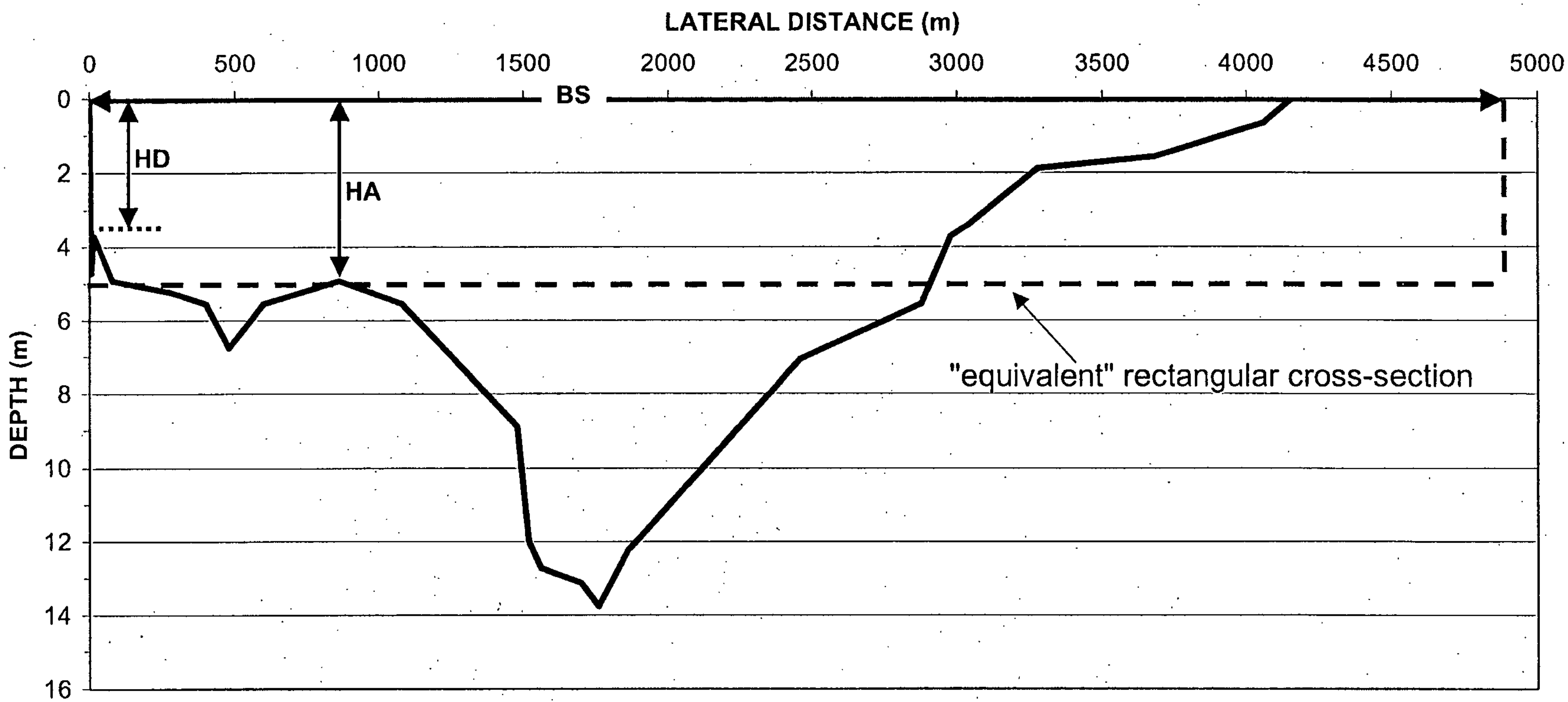
f:\job\6295\figures\Figure 4 - Daily Reedy Island & HCGS Intake Temps.xls



Note: Elevations given in Public Service Datum (PSD)
PSD 89.0 ft = 0.0 MSL

Figure 5: Outfall configuration for blowdown from Hope Creek Cooling Tower.

ESTUARINE CROSS-SECTION AT MEAN LOW WATER (MLW)



Cross-Sectional Area = 24,482 m^2
HD = Actual Depth Below MLW in General Discharge Location = 3.7 m (12.1 ft)
HA = "Average" Depth Below MLW = 5m
BS = Average Width = 4,896 m

Figure 6: Idealized estuarine cross section at mean low water.

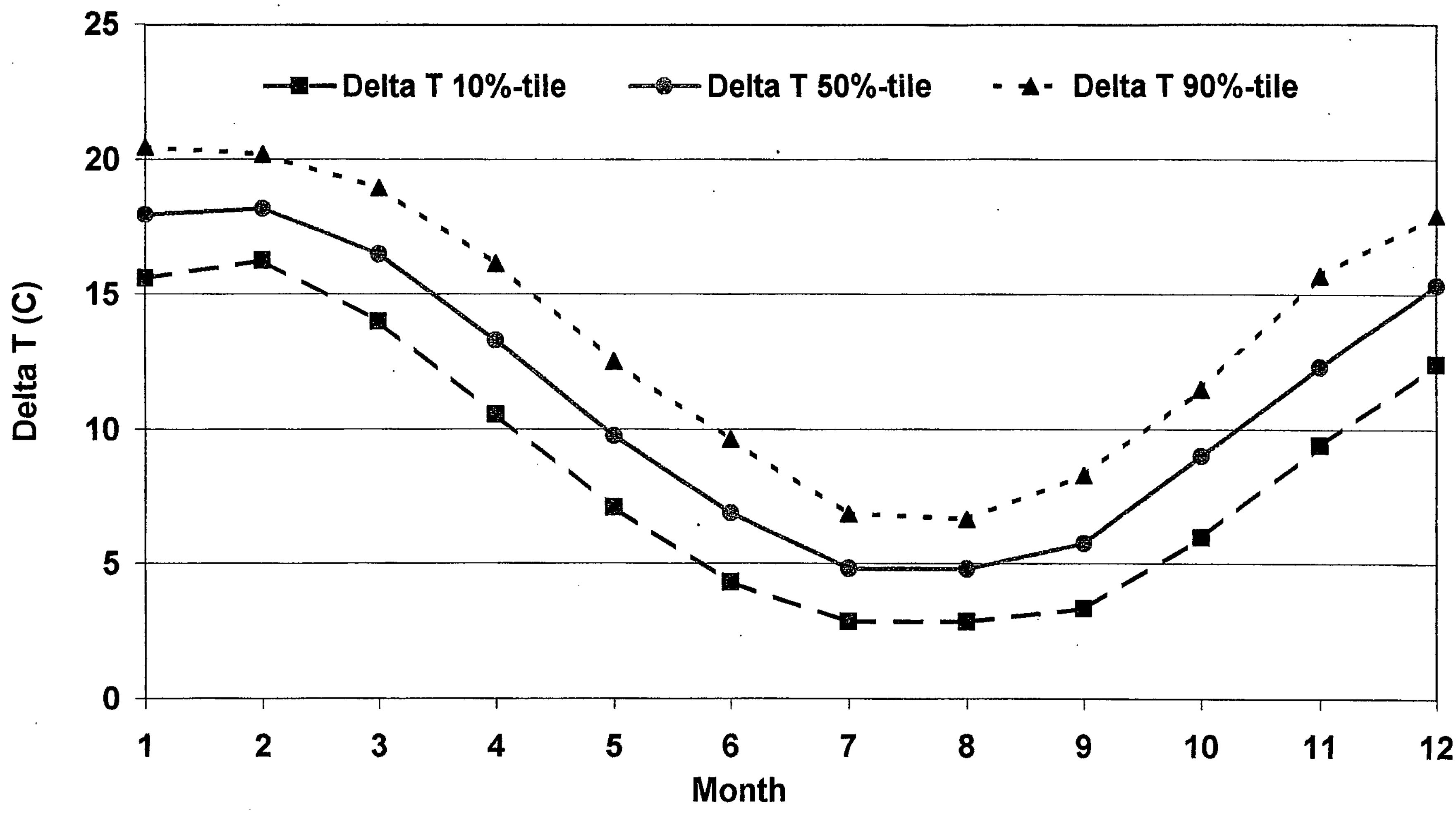


Figure 7: Percentiles of discharge excess temperature for each month.

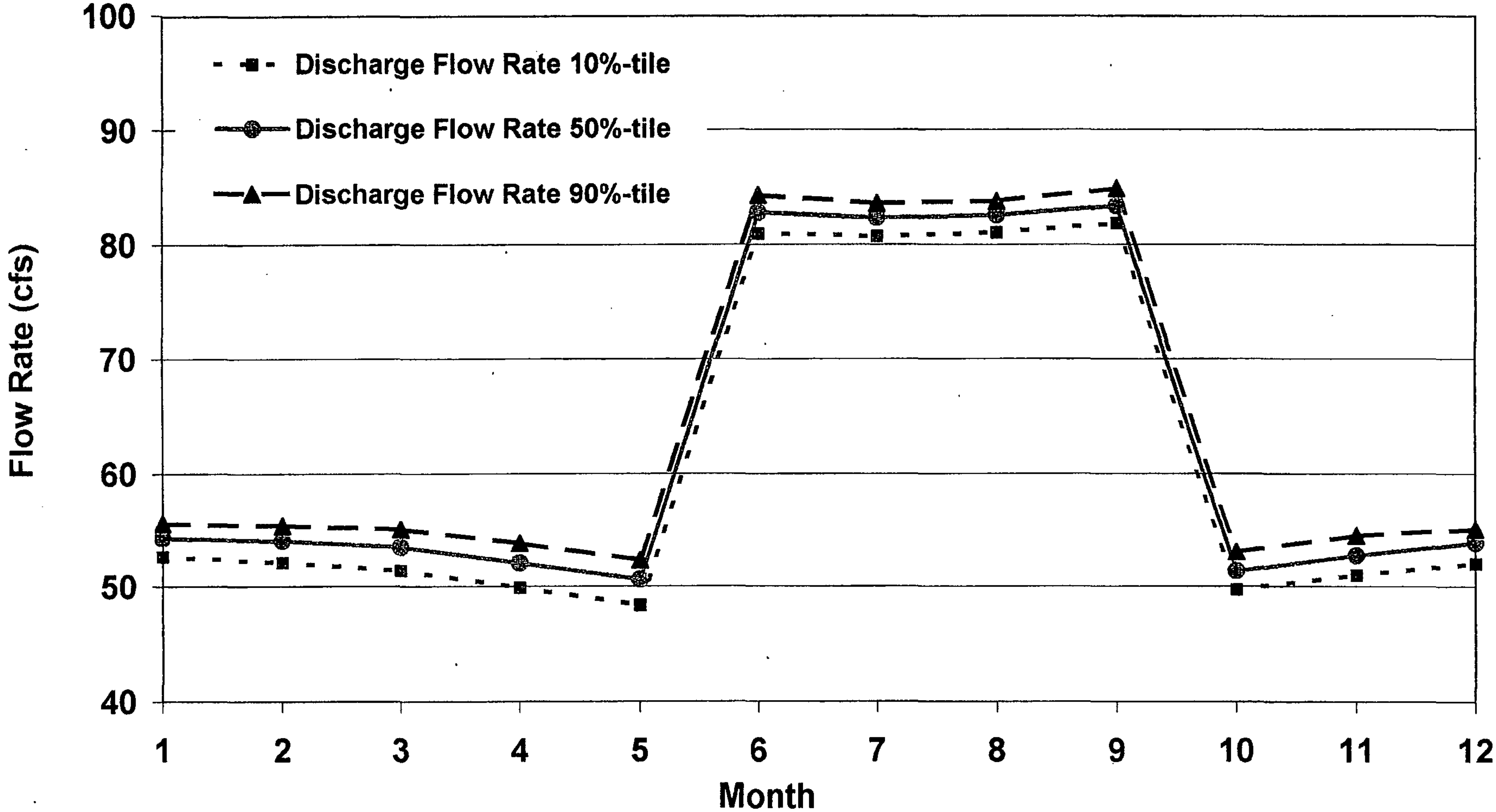


Figure 8: Percentiles of blowdown flows for each month.

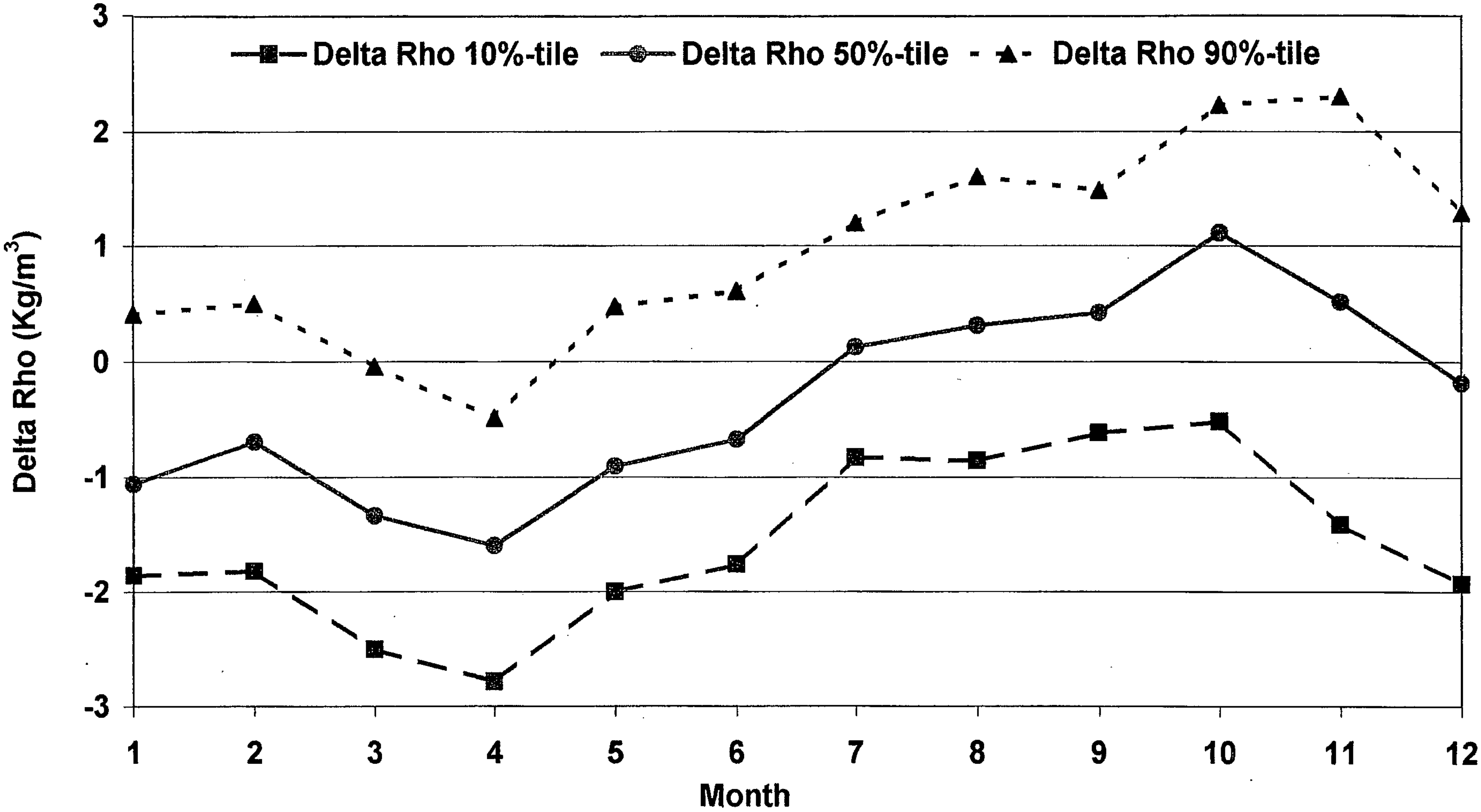
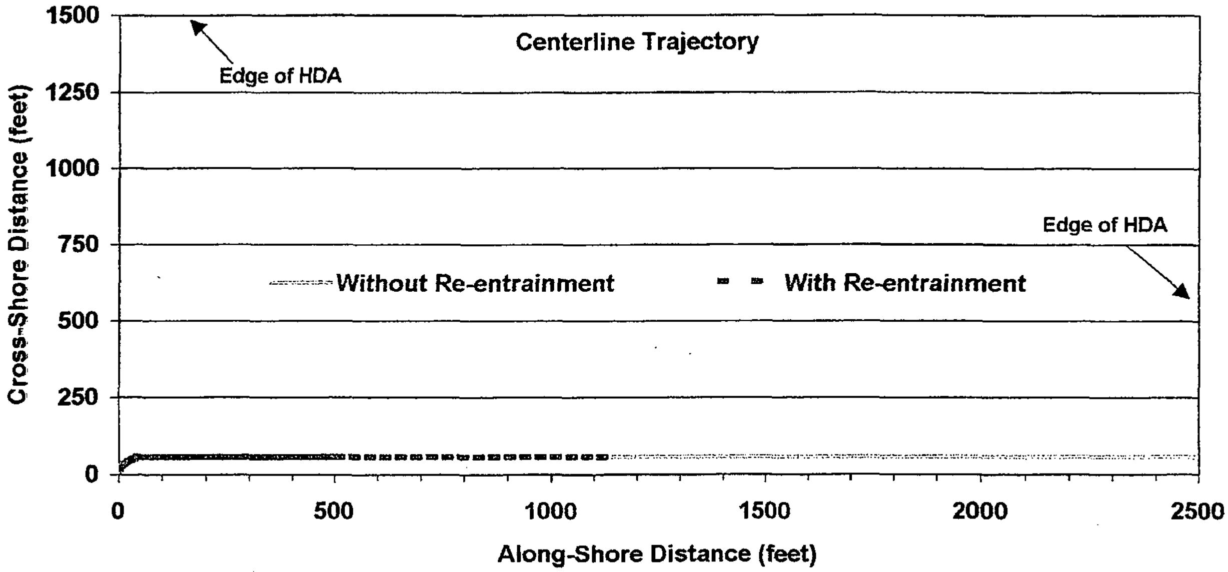


Figure 9: Percentiles of density difference for each month.



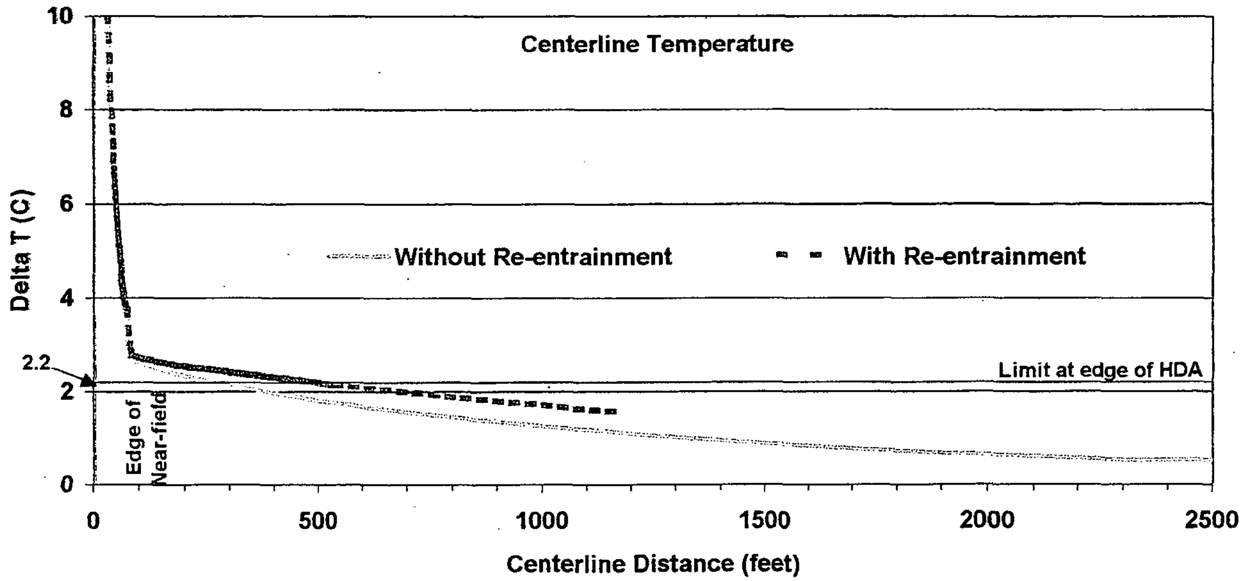


Figure 10: Simulated centerline trajectory (upper panel) and centerline excess temperatures (lower panel) for the January scenario.

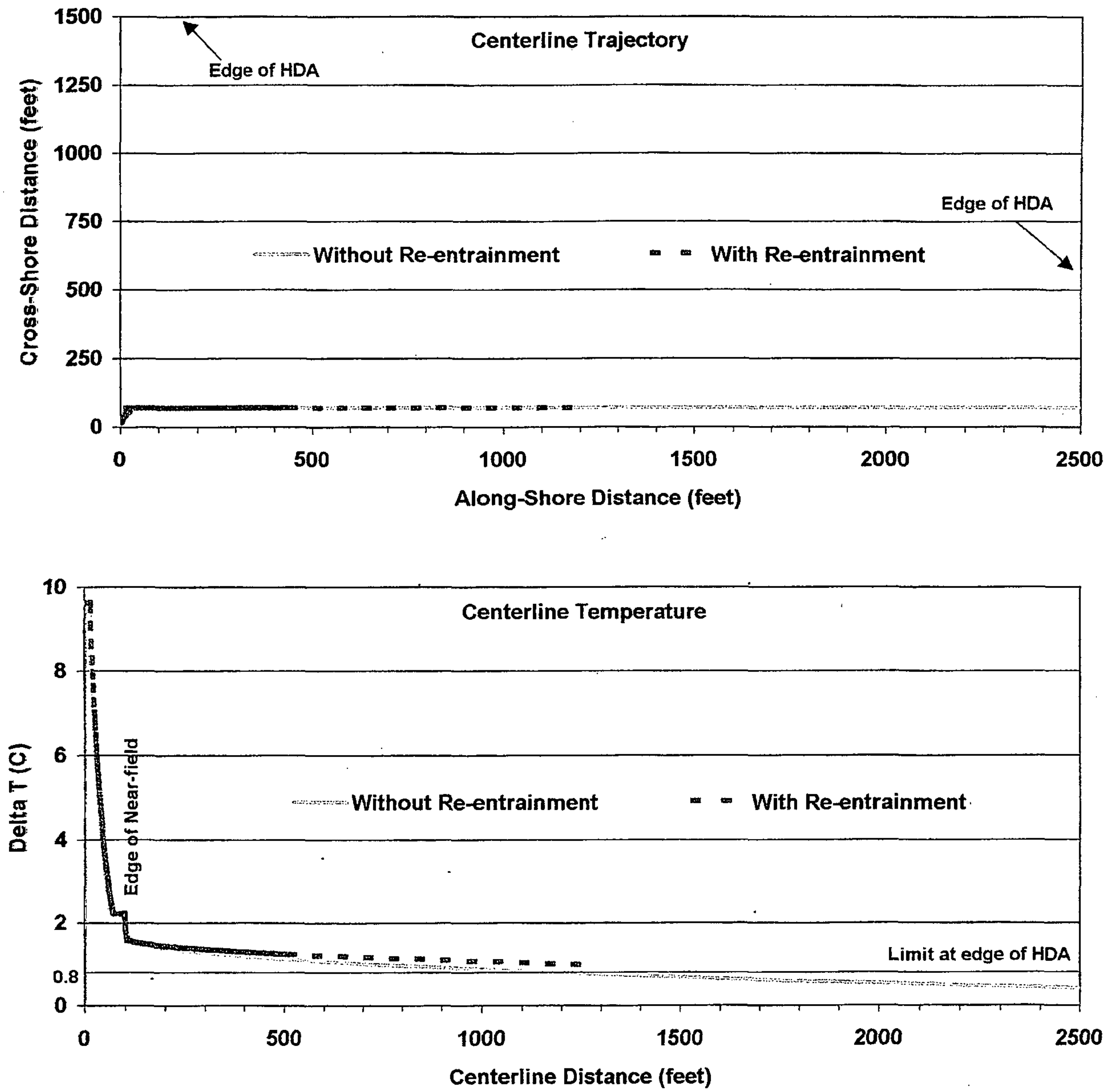


Figure 11 : Simulated centerline trajectory (upper panel) and centerline excess temperatures (lower panel) for the June scenario.

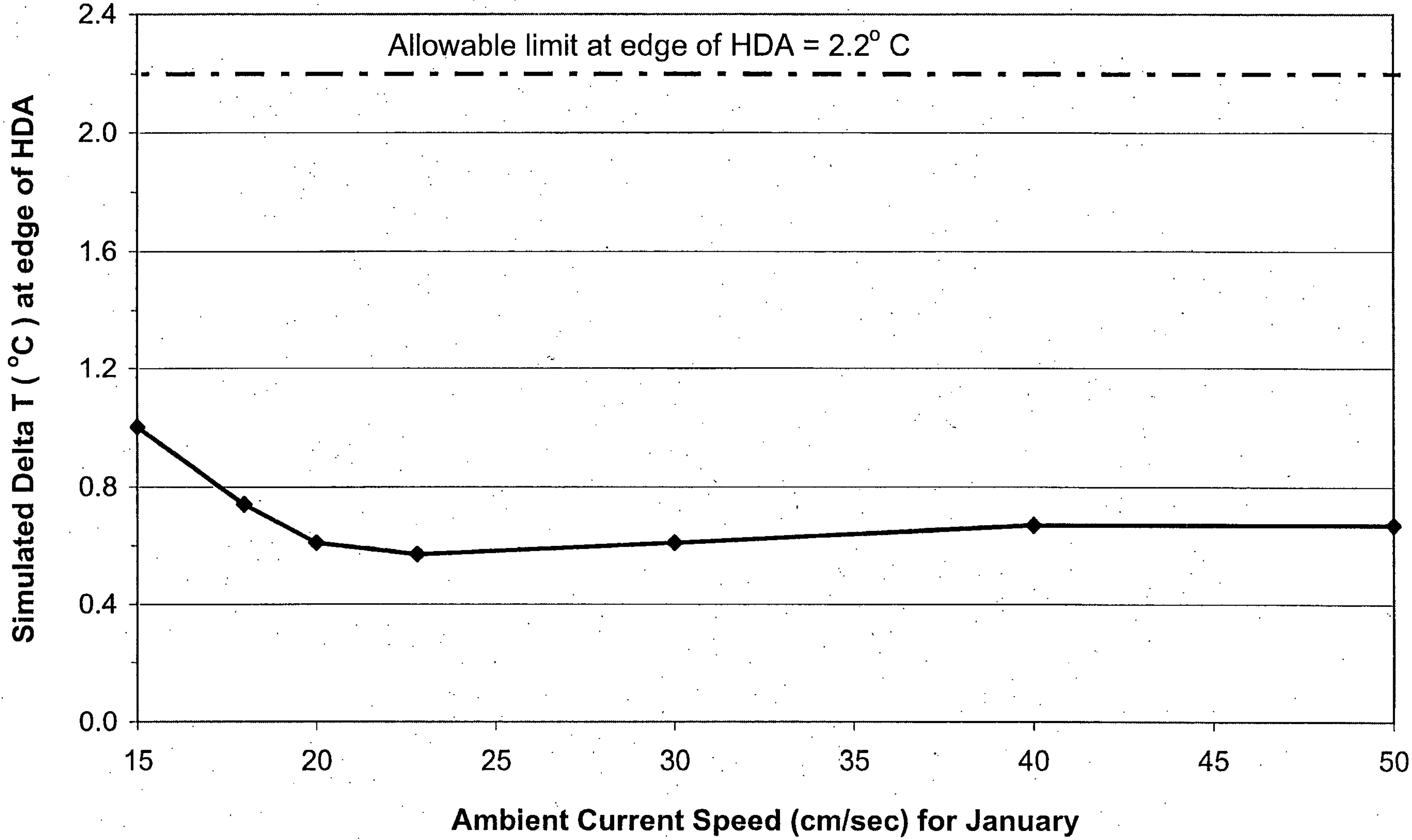


Figure 12: Model sensitivity to ambient current speed for January Scenario.

f:\job\6295\figures\Figure 12 - Velocity Sensitivity-January.xls

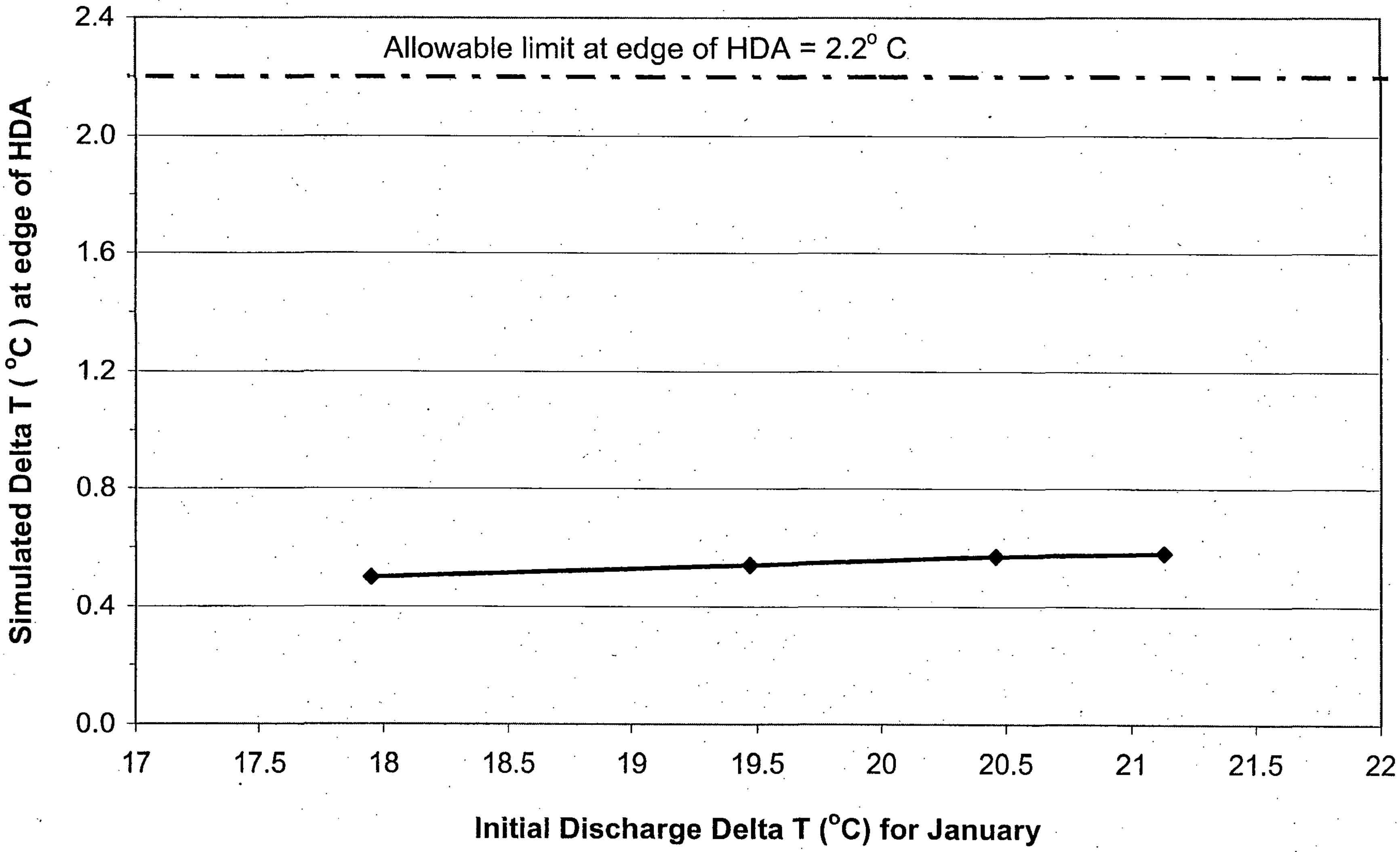


Figure 13: Model sensitivity to initial discharge excess temperature for January Scenario.

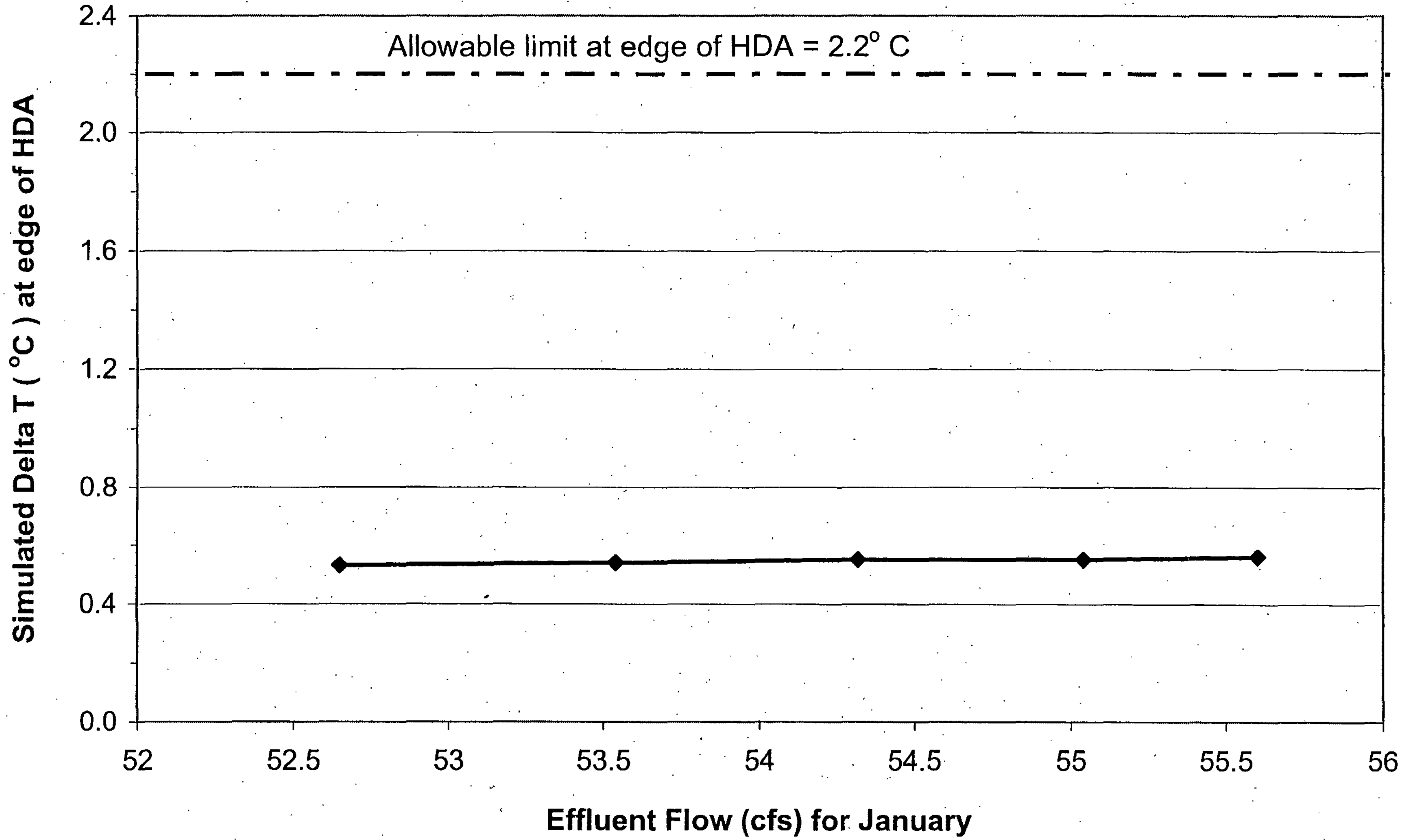


Figure 14: Model sensitivity to blowdown (effluent) flow for January Scenario.

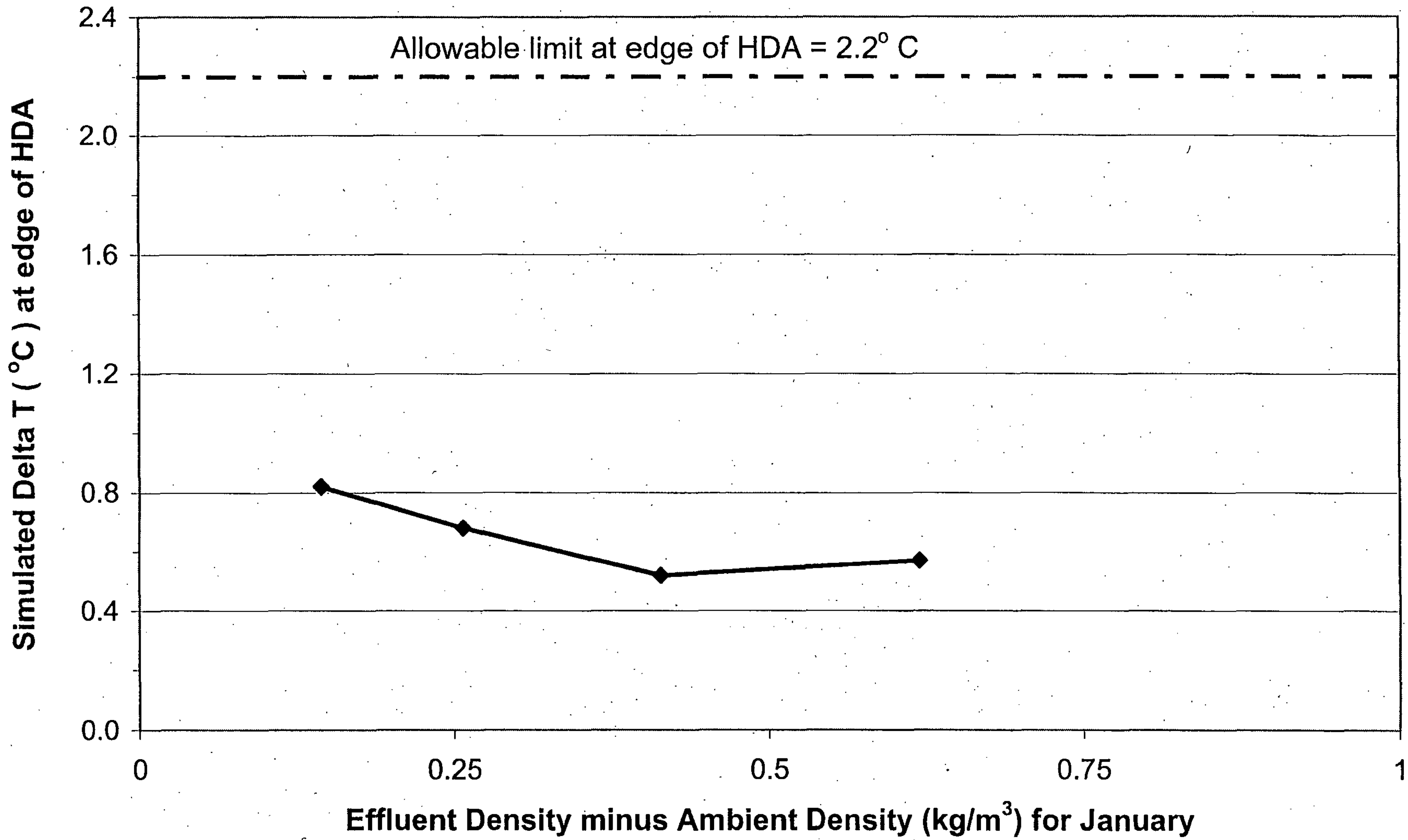


Figure 15: Model sensitivity to density difference for the January Scenario.

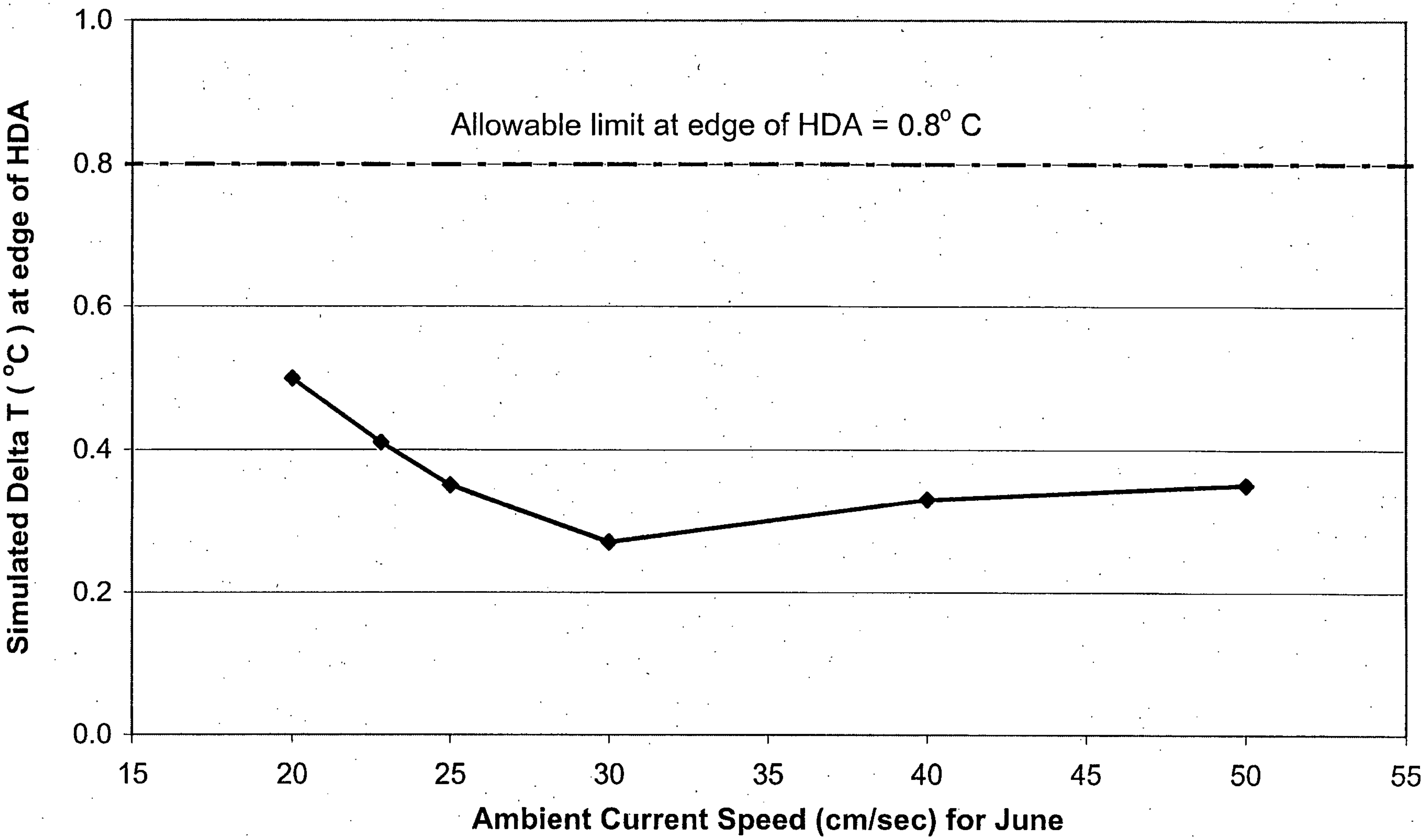


Figure 16: Model sensitivity to ambient current speed for June Scenario.

f:\job\6295\figures\Figure 16 -Velocity Sensitivity-June.xls

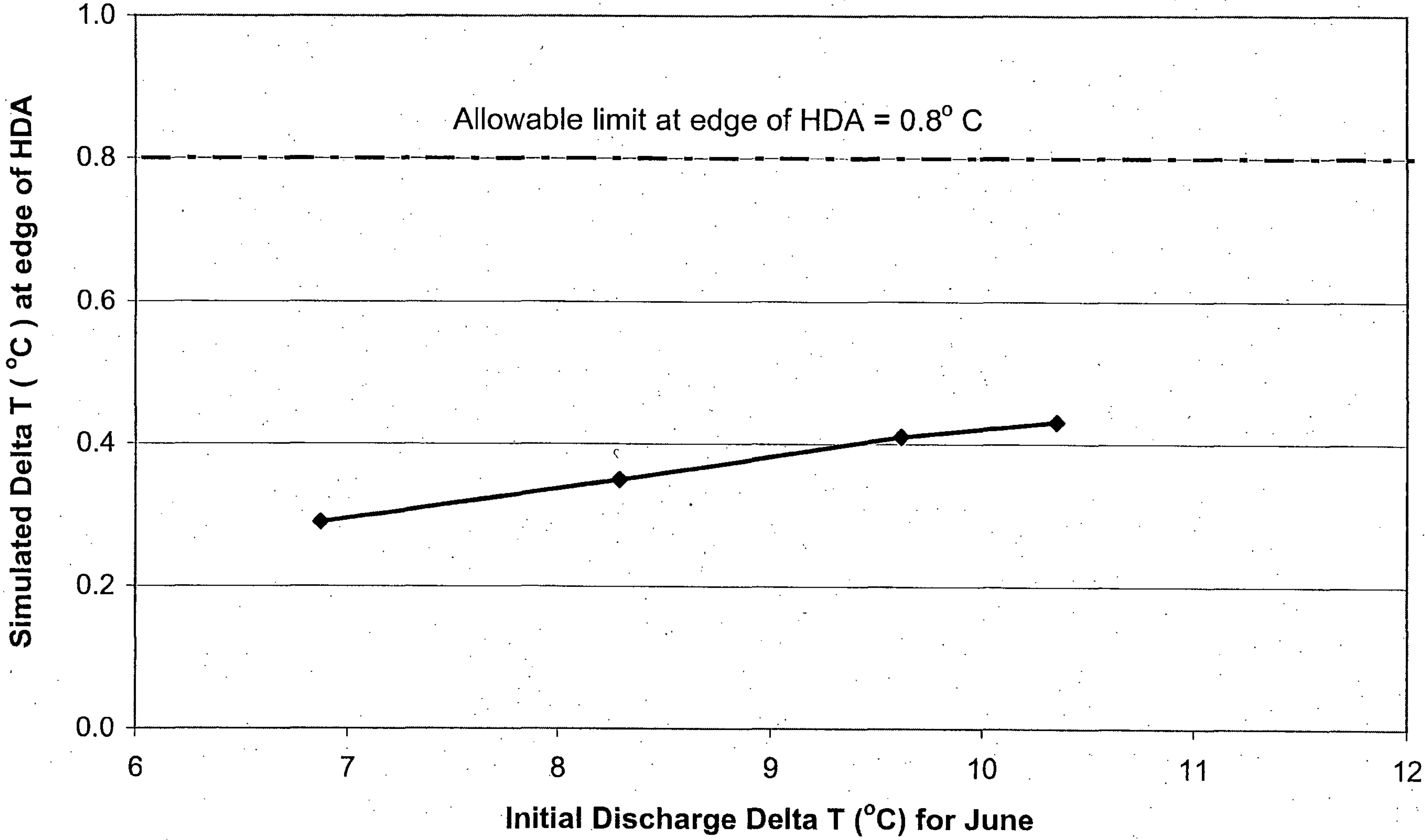


Figure 17: Model sensitivity to initial discharge excess temperature for June Scenario.

f:\job\6295\figures\Figure 17 -Delta T Sensitivity-June.xls

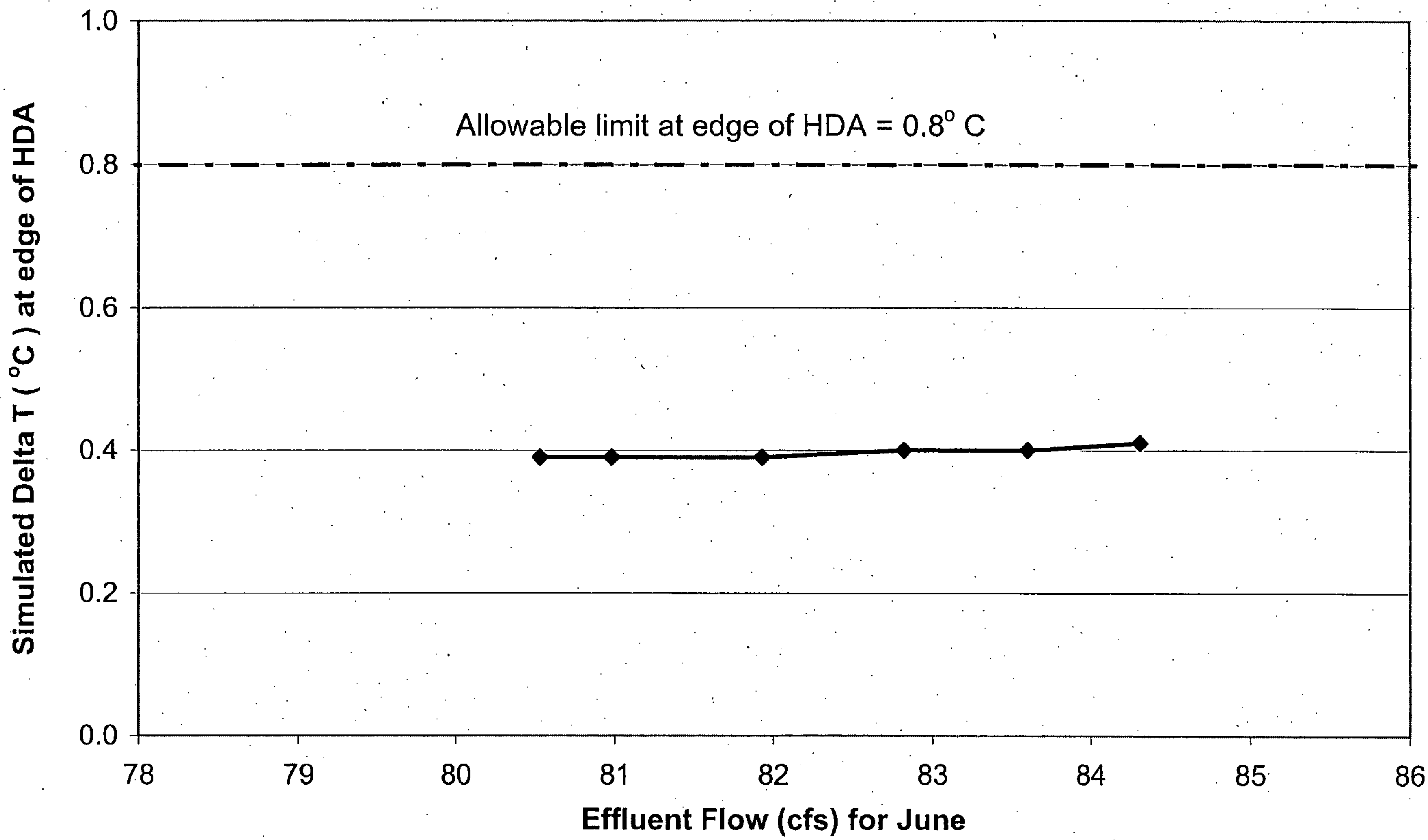


Figure 18: Model sensitivity to blowdown flow for June Scenario.

f:\job\6295\figures\Figure 18 -Effluent Flow Sensitivity-June.xls

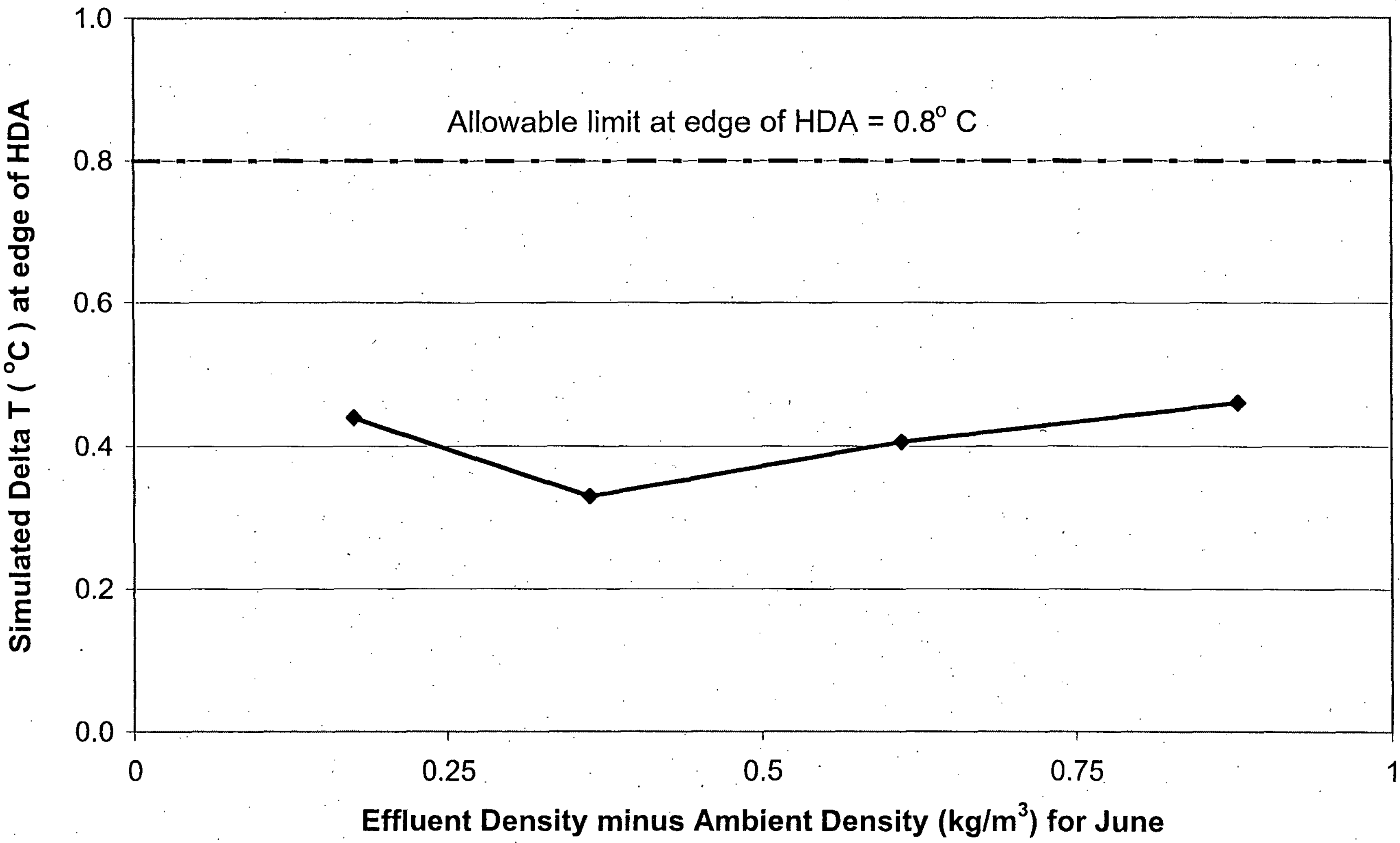


Figure 19: Model sensitivity to density difference for June Scenario.

f:\job\6295\figures\Figure 19 -Delta Rho Sensitivity-June.xls

Appendix A

Calculations of Post-EPU Blowdown Flow, Temperature, and Heat Rejection Rate

Calculations of Post-EPU
Blowdown Flow, Temperature, and Heat Rejection Rate

The EPU Project will increase the amount of heat to Hope Creek Cooling Tower (HCCT) by approximately 20% over the original design value. This appendix summarizes the methodology and inputs that PSEG Service Corporation (PSEG) used to generate synthetic long-term records of hourly blowdown temperatures, evaporation rates and blowdown flows for post-EPU operations. PSEG and Najarian Associates, Inc. (Najarian) used these records to assess compliance with existing thermal effluent limits in the New Jersey Pollutant Discharge Elimination System (NJPDES) permit (NJ0025411) for Hope Creek Generating Station (HCGS).[1] PSEG calculated the maximum daily average discharge temperature and heat for the non-summer (September through May) and summer months (June through August). Najarian calculated the maximum post-EPU ΔTs at the edge of the HDA using PSEG's sythethic record of blowdown temperatures and evaporation rates for the period 1991 through 2001 (Table 3). The time-series of blowdown temperatures and evaporation rates are shown in Figures B-2 and B-4, respectively. Tables 4, 5 and 6 provide percentile values of hourly discharge ΔT, hourly blowdown flow, and hourly density differences between blowdown and makeup, respectively, that Najarian computed using PSEG's estimates of evaporation rates, makeup flow rates, and blowdown temperatures and Najarian's estimates of ambient (makeup) water temperature and salinity for 1991 through 2001.

Blowdown Flow

Blowdown flow equals the service water flow (namely, the makeup flow) minus losses due to evaporation. This section summarizes the procedures and assumptions PSEG used to create synthetic records of hourly makeup flow and evaporation rates.

Makeup flow is primarily a function of the cooling requirements of the Station's auxiliary equipment and is supplied by service water pumps. The EPU project will not require changes to the auxiliary equipment or its operation. Thus, pre-EPU and post-EPU makeup flows are equivalent.

PSEG examined the operation of the service water pumps during 1998 by comparing service water flow and intake temperature (Figure A-1). Typically, two service water pumps are used when the intake temperature is less than 70°F. Otherwise, three service water pumps are used. The average makeup flow is approximately 36,625 gpm when two pumps are operating, and approximately 51,479 gpm when three pumps are operating.

[1] The NJPDES permit for HCGS imposes thermal limits on the blowdown from HCCT. The maximum daily average discharge temperature cannot exceed 97.1°F, except on days with adverse meteorological conditions (AMCs). On days with AMCs, the limit is replaced by a monitoring requirement. An AMC occurs when the relative humidity is below 60% <u>and</u> the wet bulb temperature exceeds 76°F for a period of greater than 60 minutes. During the summer months, the maximum daily average heat rejection rate cannot exceed 534 MMBTU/hr, and the temperature increase (ΔT) at the edge of the Heat Dissipation Area (HDA) for HCGS cannot exceed 1.5°F. During the non-summer months, the maximum daily average heat rejection rate cannot exceed 662 MMBTU/hr, and ΔT at the edge of the HDA cannot exceed 4.0°F.

Because the variations in makeup flow around the averages are small (≈ 2,000 gpm) in comparison to the average flow, they were ignored. In addition, PSEG assumed that the pattern for 1998 is typical of normal year-to-year operations because the service water system will not be modified for the EPU and routine maintenance is not expected to significantly alter service water flow rates.

PSEG estimated the seasonal variation in service water flow by comparing intake water temperatures versus calendar month (Figure A-2). In June, July, August and September, the intake water temperature equals or exceeds 70°F. Thus, service water pumps during these four months were assumed to provide a constant flow of 51,479 gpm. In November through April, the makeup water temperature is less than 70°F. Accordingly, the service water pumps during these six months were assumed to provide a constant flow of 36,625 gpm. For May and October, the water temperature is less than 70°F approximately 50% of the time. Thus, the makeup rate for both months is almost evenly divided between 36,625 gpm and 51,479 gpm.

Evaporation losses from HCCT are not constant and vary in response to changing meteorological conditions, cooling range[2], and circulating water flow rate[3]. This variability can have a significant effect on blowdown temperatures and flow rates. A synthetic record of hourly evaporation losses was calculated using thermal performance curves for post-EPU operations[4], and a 23-year record (1979 – 2001) of hourly meteorological measurements (i.e., dry bulb temperature, dew point temperature, and atmospheric pressure) made at Salem Generating Station (Salem). Post-EPU operations are a cooling range and circulating water flow rate of 32.3°F and 612,000 gpm, respectively.

The thermal performance curves relate evaporation losses (expressed in gallons per minute, gpm) to wet bulb temperature, relative humidity, cooling range, and circulating water flow. Revised post-EPU performance curves for three cooling ranges (29.0°F, 30.6°F and 40.0°F) at a circulating water flow rate of 612,000 gpm are shown in Figures A-3, A-4 and A-5, respectively. Calculating the evaporation rate for each hour of the period of record involved computing the hourly value for relative humidity from the set of meteorological observations for that hour, reading the performance curves to obtain the evaporation rate for each of the three cooling ranges (29.0°F, 30.6°F and 40.0°F)[5],

---

[2] Cooling range equals the temperature of heated water leaving the condenser minus the temperature of the water entering the condenser.

[3] HCGS estimates circulating water flow from thermal performance data. These estimates can exhibit some variability. At the time of this analysis, the circulating flow rate was between 610,000 to 613,000 gpm. The EPU Project will not require modifications to the circulating water flow system. For purposes of characterizing the blowdown, a constant value of 612,000 gpm was assumed.

[4] The thermal performance curves also account for work that was completed in 2003 and additional work to improve HCCT's spray distribution system and to replace missing or deteriorating fill.

[5] An automated procedure for reading the curves was developed to expedite the process. Tables of evaporation rate versus relative humidity and wet bulb temperature were constructed. Quadratic interpolation was used to calculate evaporation rates for combinations of relative humidity and wet bulb temperature falling between tabulated entries.

and applying quadratic interpolation to estimate the evaporation rate at the post-EPU cooling range (32.3°F). A calculation was performed for each hour having a recorded wet bulb temperature, dry bulb temperature, dew point and atmospheric pressure. As part of this process, the hourly value for relative humidity was derived from the set of meteorological observations. If any of the four meteorological measurements were not available, the evaporation loss for that hour was considered "missing." The results were assembled in Microsoft EXCEL workbooks (see enclosed compact disk) containing the hourly meteorological observations, the computed relative humidity, the computed evaporation, and blowdown temperature (which is discussed in the following section.) Table A-1 summarizes the makeup flow rates, and the monthly average values evaporation rates for post-EPU conditions.

Blowdown Temperature
Hourly values of post-EPU blowdown temperatures were calculated using the 23-year record of meteorological observations at Salem, and thermal cooling tower performance curves that express cold-water temperature (namely, the blowdown temperature) as a function of wet bulb temperature and relative humidity. Figures A-6, A-7 and A-8 show the curves for a circulating flow rate of 612,000 gpm and cooling ranges of 29.0°F, 30.6°F, and 40.0°F, respectively.

An hourly blowdown temperature was calculated for each hour of the long-term record having a measured dew point, dry bulb temperature, wet bulb temperature and atmospheric pressure to develop a synthetic record. If any of the four meteorological measurements were not available, the blowdown temperature for that hour was considered "missing." The calculation required reading the cold-water temperature for each of the curves in Figures A-6, A-7 and A-8[6], and then using quadratic interpolation to obtain the cold-water temperature for the post-EPU cooling range. The results are included in the above-mentioned Micorsoft EXCEL workbooks.

Inspection of the long-term synthetic blowdown temperature record indicated that the hourly blowdown temperature infrequently exceeds 97.1°F. The number of predicted occurrences are few (i.e. 5) and of very short duration (i.e. 1 to 4 hours). The maximum hourly blowdown temperature is 98.4°F. The meteorological conditions associated with this result are a relative humidity of 64% and a wet bulb temperature of 84.2°F. Although the wet bulb temperature exceeded the design values, this is not an AMC because the relative humidity was within the design specifications (i.e. > 60%). Because the blowdown temperature at least for one hour exceeded the daily average, additional calculations were made to determine daily average blowdown heat for use in assessing compliance with the permits limitations, which are expressed as a daily average.

---

[6] An automated procedure for reading the curves was developed to expedite the process. Tables of cold water temperature versus relative humidity and wet bulb temperature were constructed. Quadratic interpolation was used to calculate cold water temperature for combinations of relative humidity and wet bulb temperature falling between tabulated entries.

The long-term hourly record of calculated post-EPU blowdown temperatures was used to estimate the expected maximum daily average blowdown temperature when AMCs are ignored and when AMCs are considered. An average blowdown temperature was made for each day with no more than 14 "missing" values of blowdown temperature. The maximum daily average temperature for the period of record is 94.6°F. The maximum daily average for days with no AMCs is 94.1°F. These results indicate that the EPU-Project will not require a revision to the existing NJPDES permit for HCGS because neither maximum exceeds the current limitation on blowdown temperature (i.e. 97.1°F as a daily average).

Blowdown Heat

Blowdown heat is computed using the following equation:

$$\textbf{Heat} = \mathbf{K} \times (\mathbf{T}_{\textbf{blowdown}} - \mathbf{T}_{\textbf{service water intake}}) \times \mathbf{Q}_{\textbf{blowdown}}$$

where K is a units constant, $T_{blowdown}$ is the temperature of the blowdown, $T_{service\ water\ intake}$ is the intake temperature of the service water, and $Q_{blowdown}$ is the blowdown flow. A synthetic record of hourly estimates of blowdown heat (MMBTU/Hr) was constructed using the synthetic records of blowdown flow and temperature, and intake water temperatures measured at Salem Generating Station between 1987 and 2001. The latter were assumed to be a reasonable approximation of the intake temperature of HCGS's service water. For the May and October heat calculations, the higher of the service water flow rates (51,479 gpm) was used to approximate $Q_{blowdown}$.

For the non-summer period, the maximum hourly blowdown heat is 556 MMBtu/hr, which is less than the current limitation (662 Mmbtu/hr, as a daily average). Similarly, for the summer period, the maximum hourly blowdown is 440 MMBtu/hr, which is less than the current limitation (534 MMBtu/hr, as a daily average). In addition, a daily average value of blowdown heat was calculated for each day having at least 11 hours with an estimated blowdown flow, blowdown temperature, and intake temperature at Salem. The maximum value is 499 MMBTU/hr for the non-summer period and 376 MMBtu/hr for the summer period. These results indicate that the EPU-Project will not require revising the heat limitations in the existing NJPDES.

Table A-1

Monthly Average Post-EPU Hope Creek Cooling Tower Makeup and Blowdown Flows

Parameter	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Makeup (gpm) (See Note 1)	36,625	36,625	36,625	36,625	36,625 51,479	51,479	51,479	51,479	51,479	36,625 51,479	36,625	36,625
Ave. $E_{Post\text{-}EPU}$ (gpm)	10,185	10,315	10,642	11,278	11,994	12,571	12,849	12,716	12,274	11,542	10,894	10,430

Note 1: The hourly makeup flow rate is assumed to be constant for all months except May and October. For May and October, the hourly makeup flow rate equals 36,625 gpm or 51,479 gpm approximately 50% of the time.

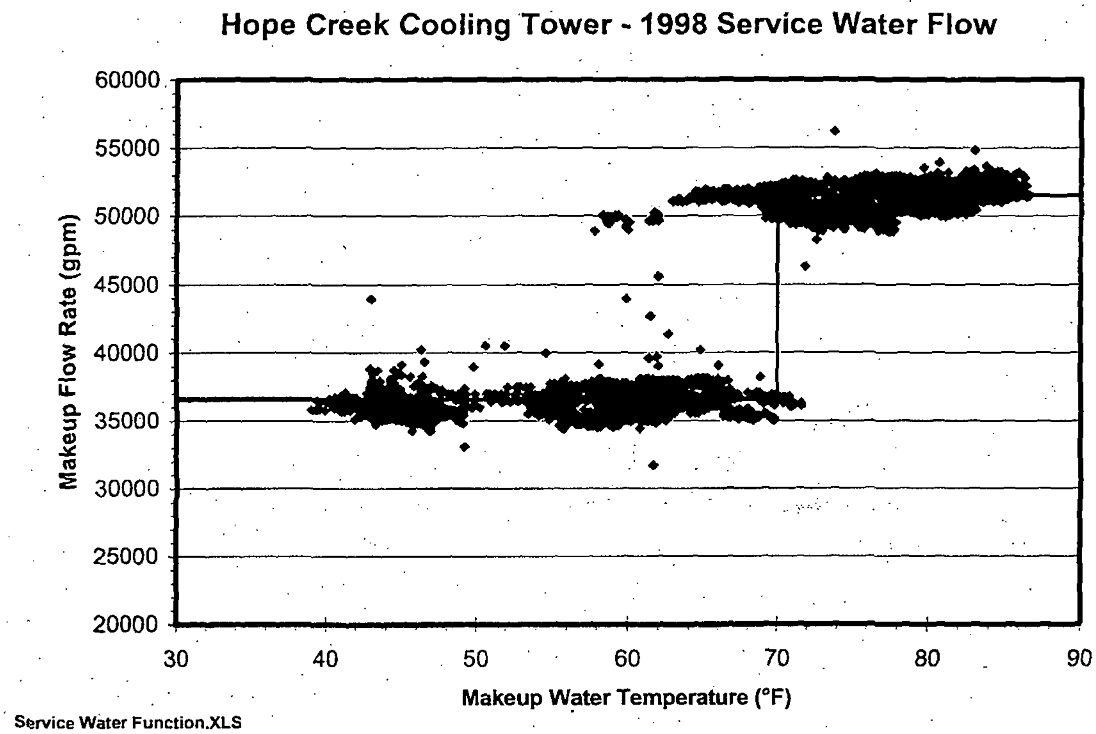


Figure A-1. Relationship between Makeup Flow and Makeup Temperature for Hope Creek Cooling Tower - 1998

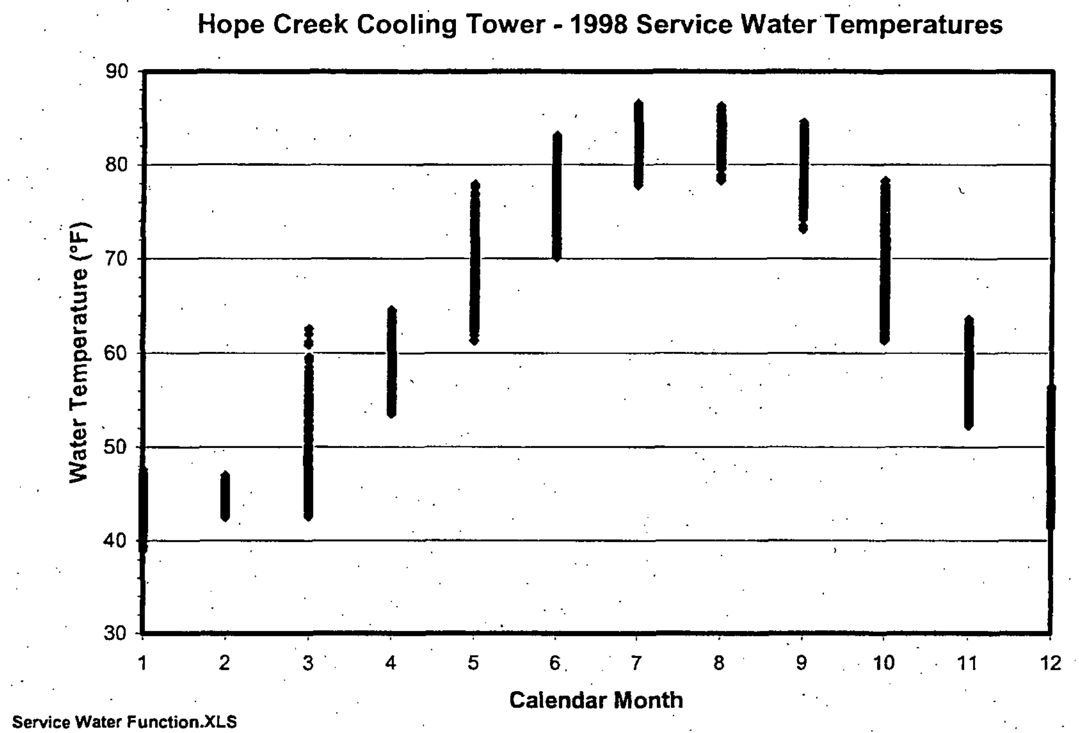


Figure A-2. Relationship between Makeup Flow for Hope Creek Cooling Tower and Calendar Month - 1998

Figure A-3

PSEG Nuclear LLC
Hope Creek Generating Station
Cooling Tower Evaporation Rate Curves
Curve No. JCA-PSEG-EVAP-006
April 13, 2003

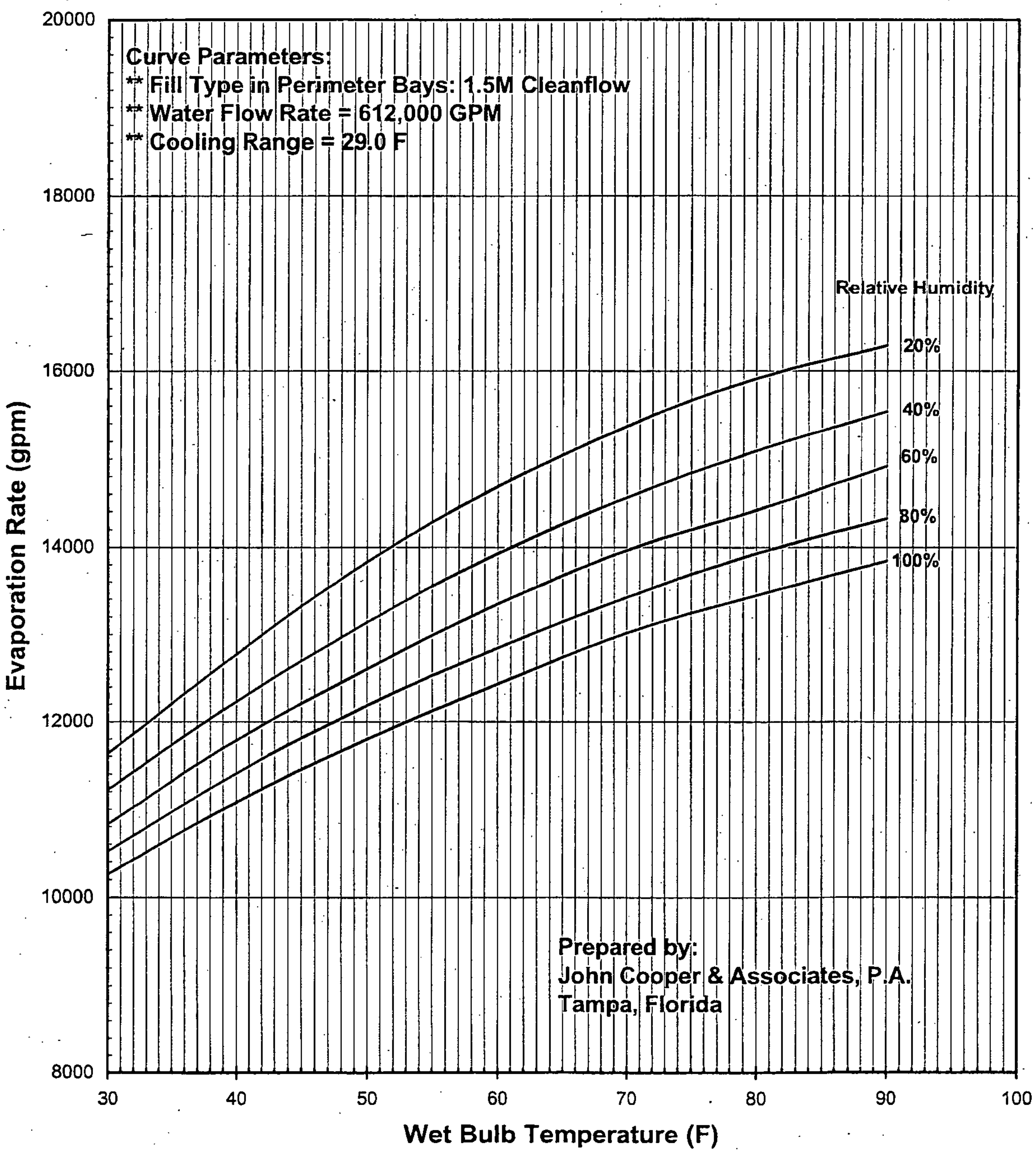


Figure A-4

PSEG Nuclear LLC
Hope Creek Generating Station
Cooling Tower Evaporation Rate Curves
Curve No. JCA-PSEG-EVAP-007
April 13, 2003

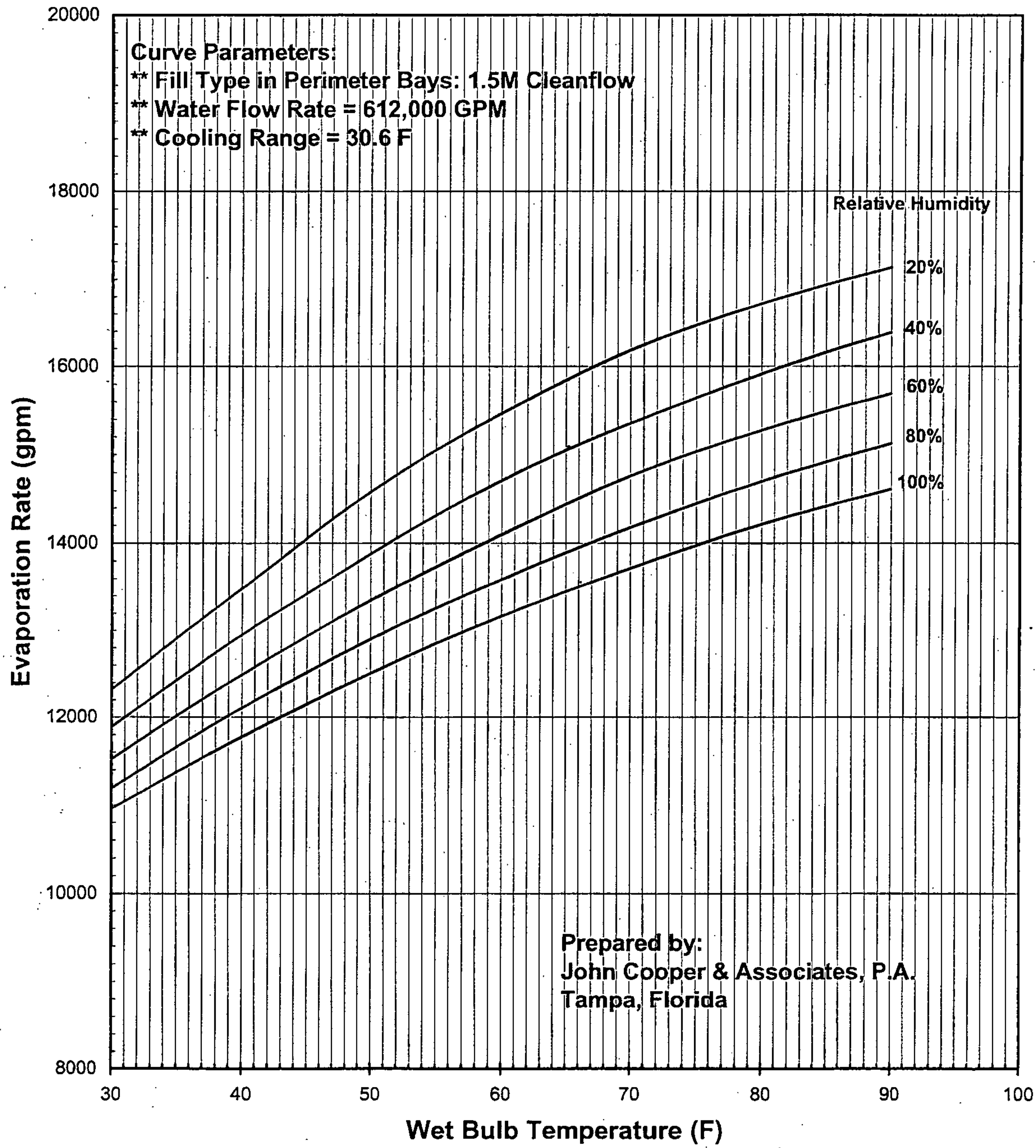


Figure A-5

PSEG Nuclear LLC
Hope Creek Generating Station
Cooling Tower Evaporation Rate Curves
Curve No. JCA-PSEG-EVAP-008
April 13, 2003

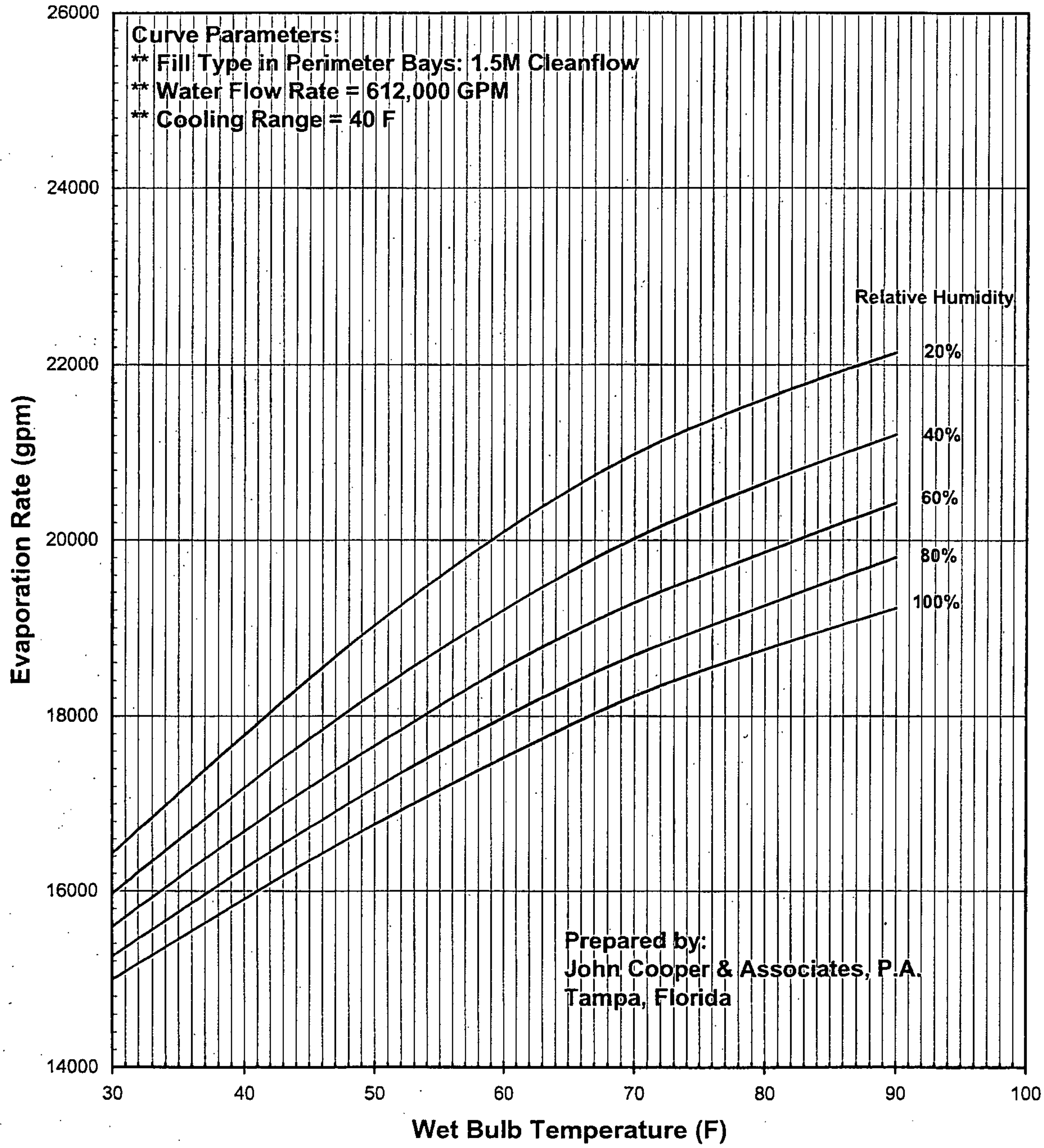


Figure A-6

PSEG Nuclear LLC
Hope Creek Generating Station
Cooling Tower Thermal Performance Curves
Curve No. JCA-PSEG-CWT-006
April 13, 2003

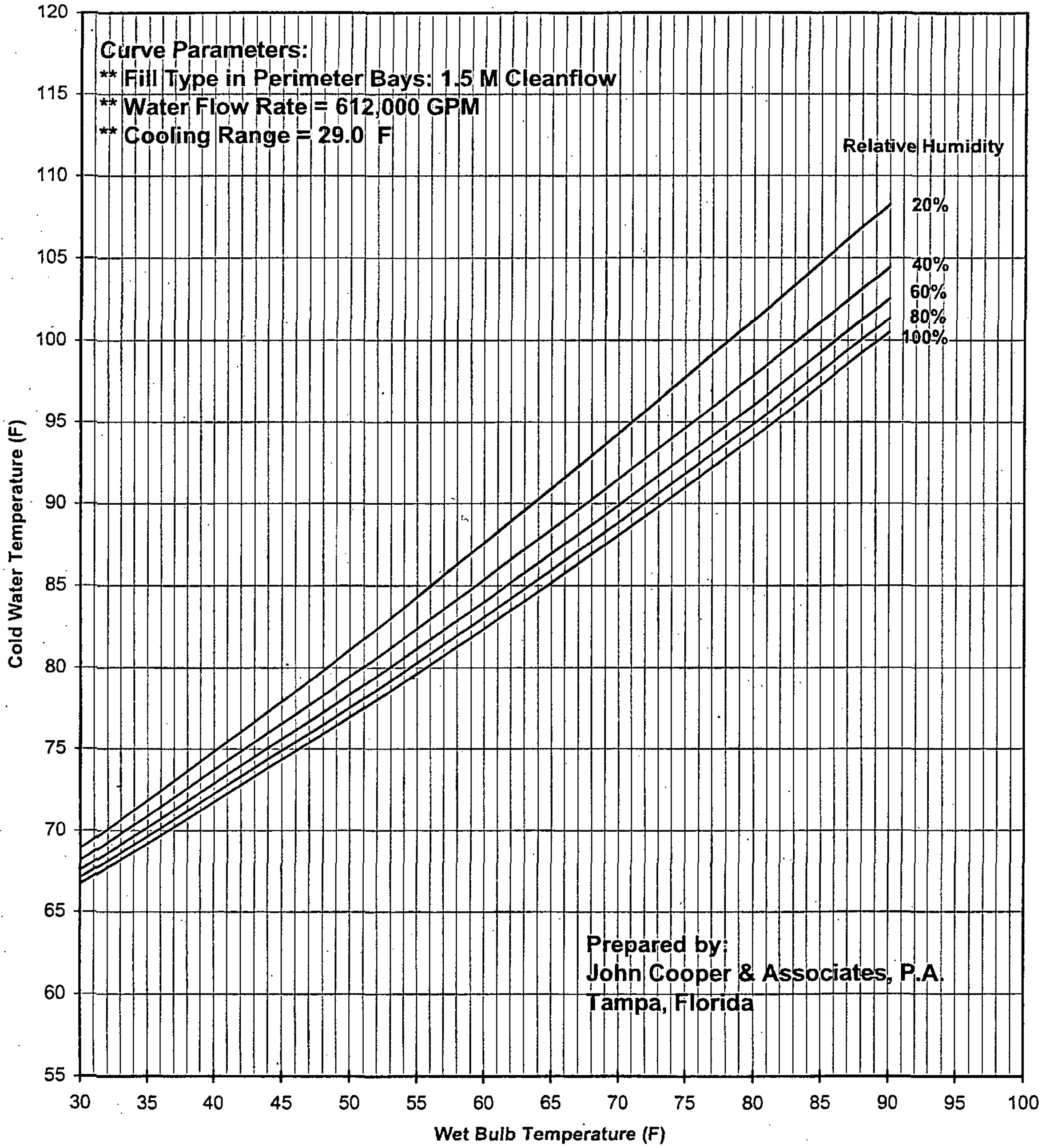


Figure A-7

PSEG Nuclear LLC
Hope Creek Generating Station
Cooling Tower Thermal Performance Curves
Curve No. JCA-PSEG-CWT-007
April 13, 2003

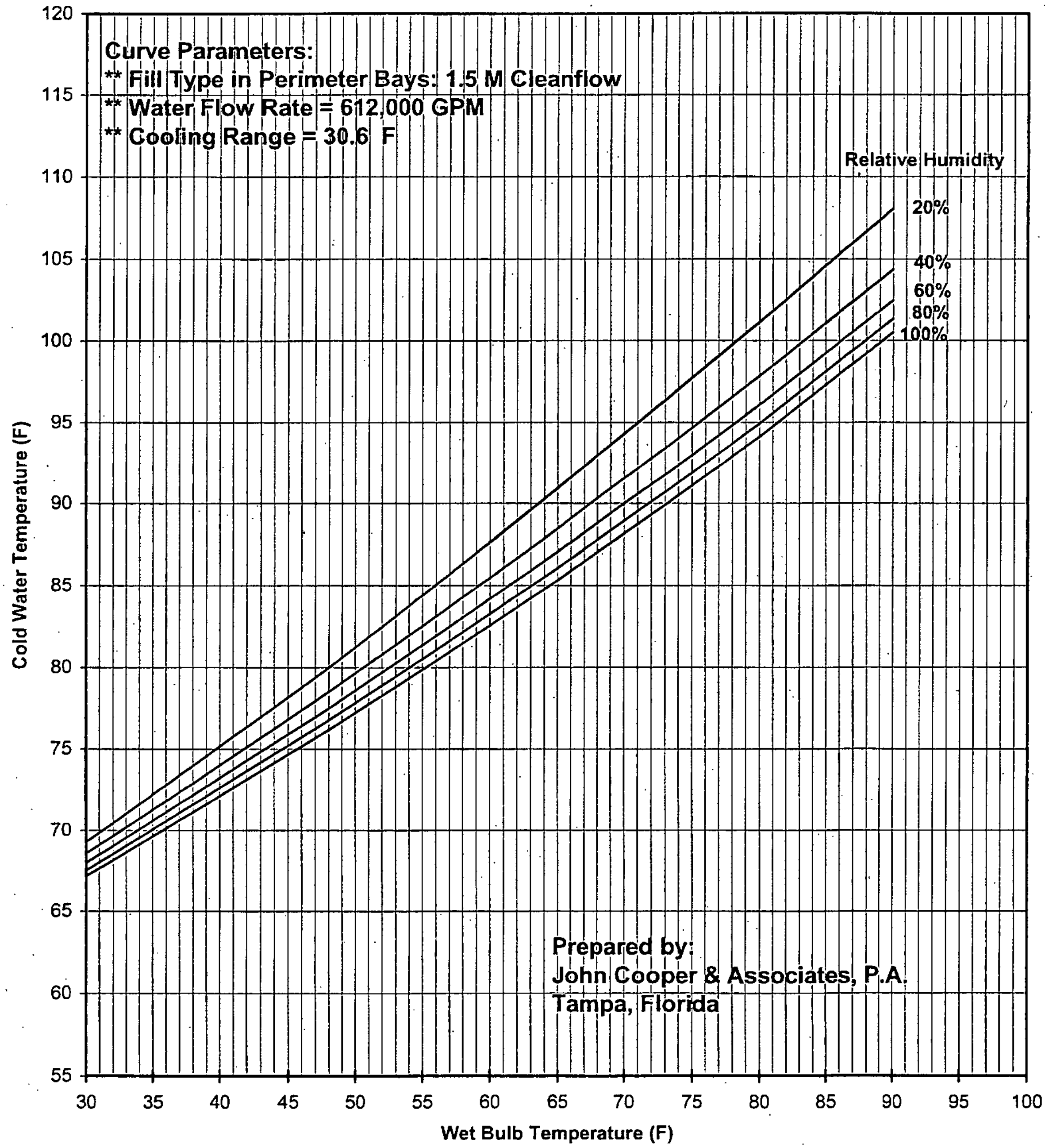
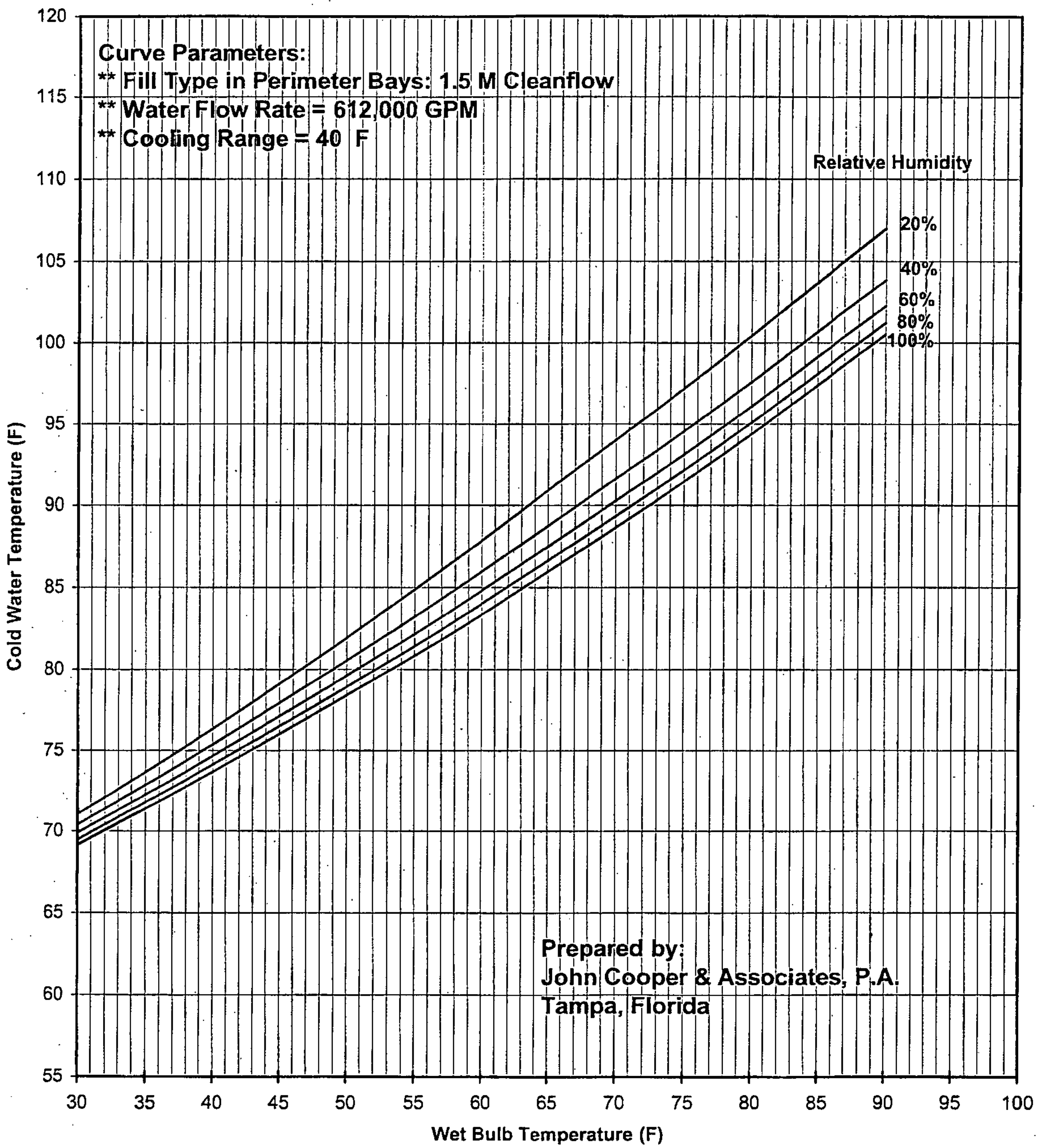


Figure A-8

PSEG Nuclear LLC
Hope Creek Generating Station
Cooling Tower Thermal Performance Curves
Curve No. JCA-PSEG-CWT-008
April 13, 2003



Appendix B

Time series of model inputs and related variables

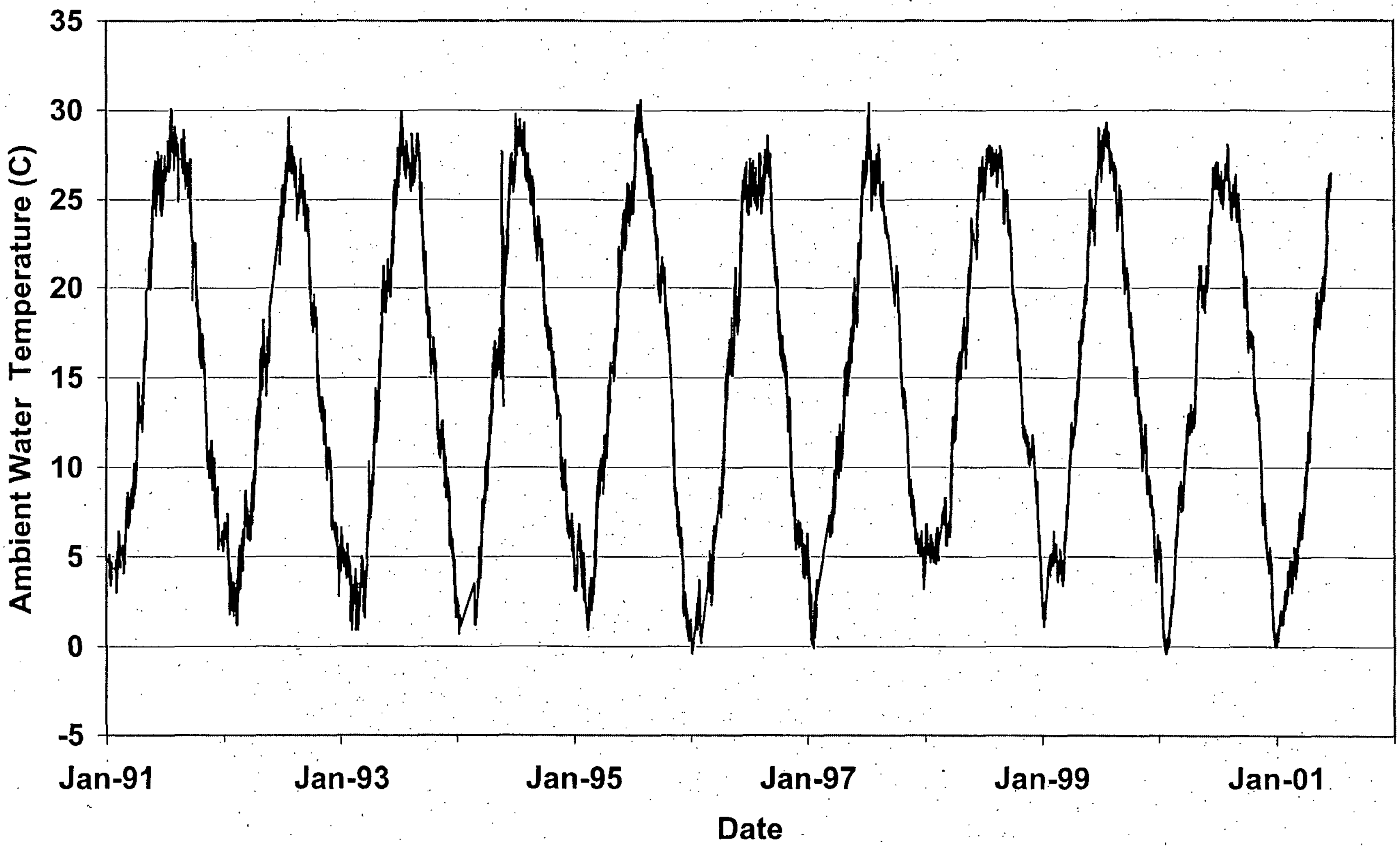


Figure B1: Hourly ambient water temperatures measured at Reedy Island by the USGS.

f:\job\6295\figures\Figure B1 - Hourly Reedy Island Water Temp - 1991 - 2001.xls

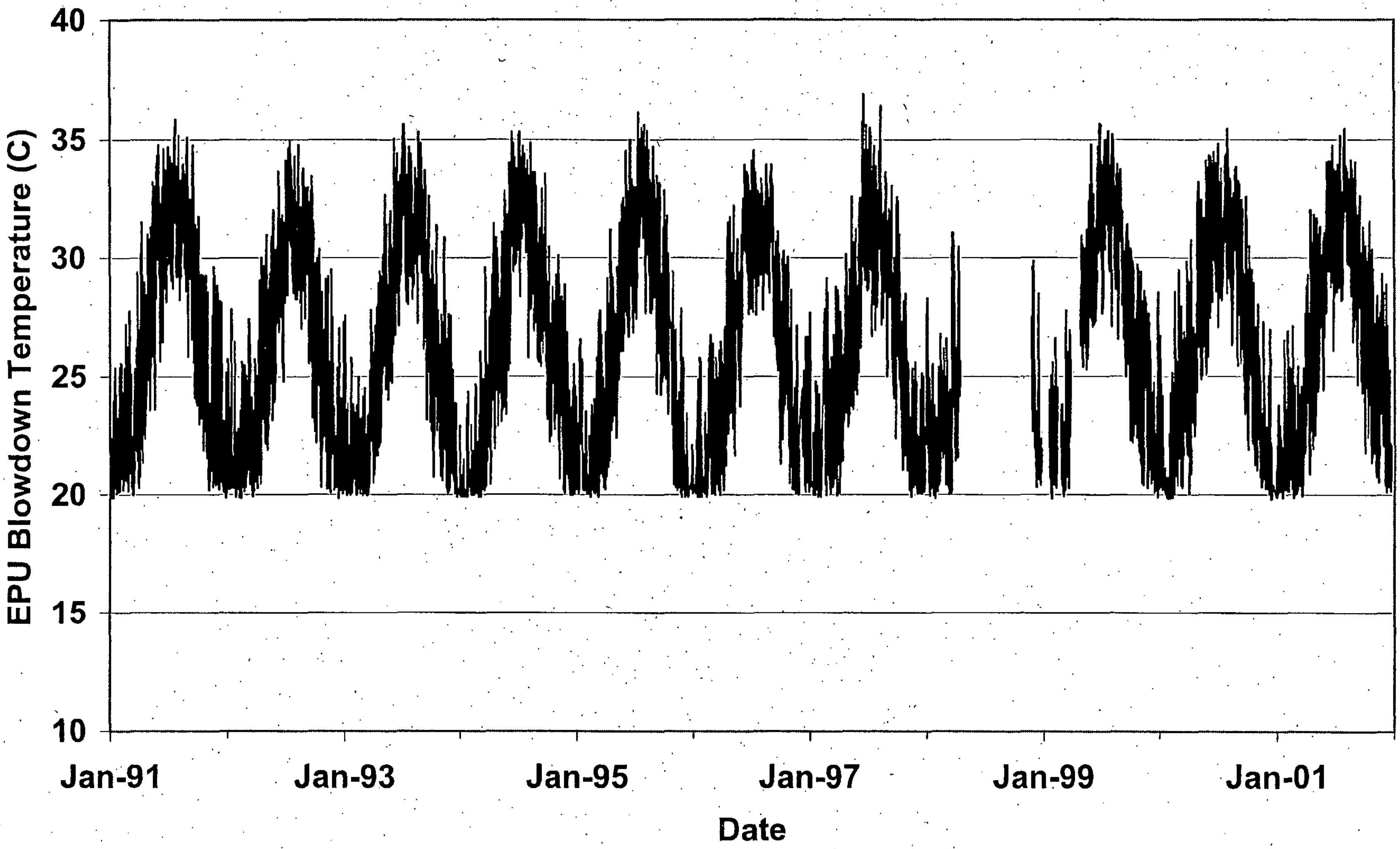


Figure B2: Hourly blowdown temperatures calculated for the EPU project.

f:\job\6295\figures\Figure B2 - EPU Hourly Blowdown Temp 1991 - 2001.xls

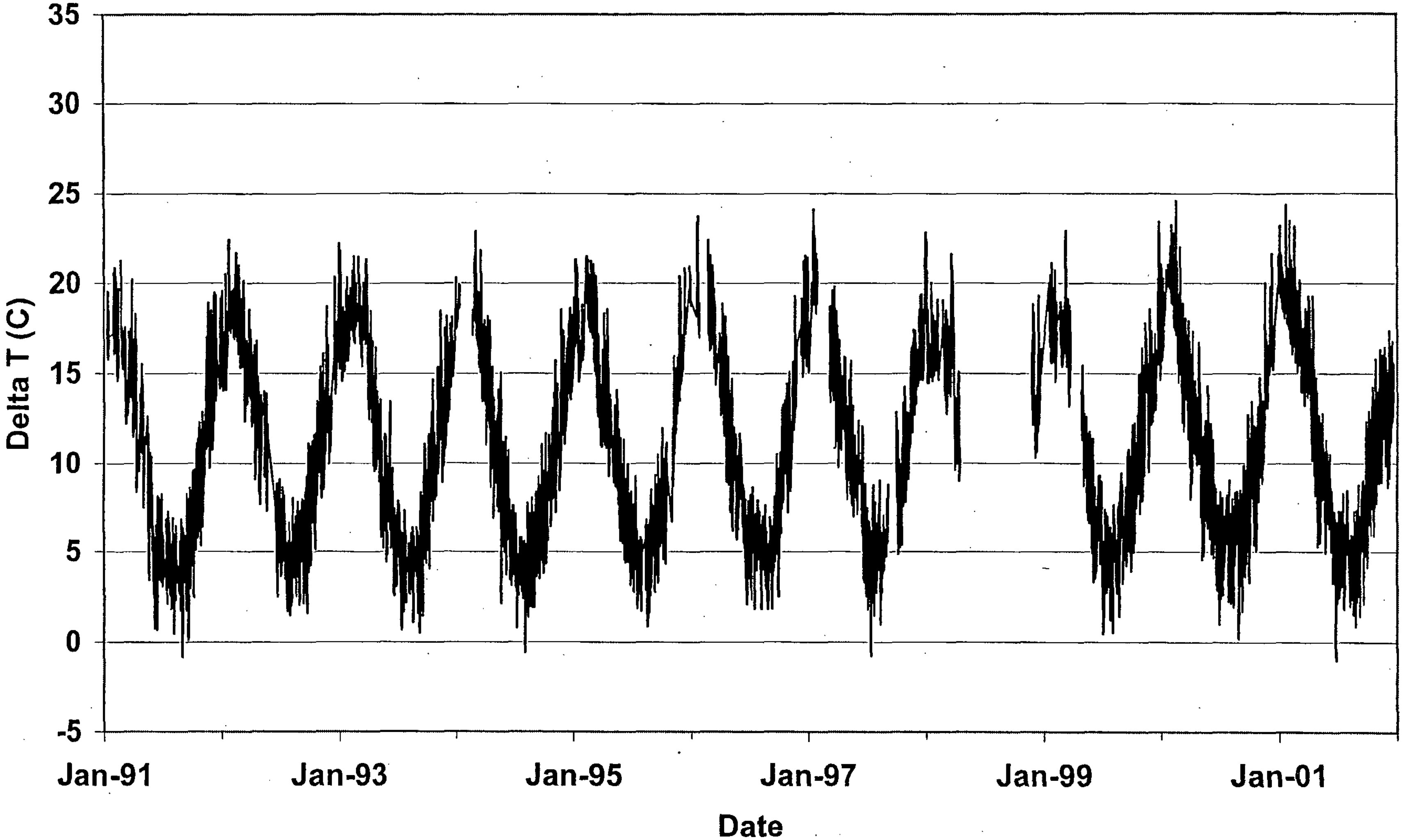


Figure B3: Hourly Delta T discharge (i.e., blowdown temperatures - ambient temperatures) calculated for the EPU project.

f:\job\6295\figures\Figure B3 - EPU Hourly Delta T 1991 - 2001.xls

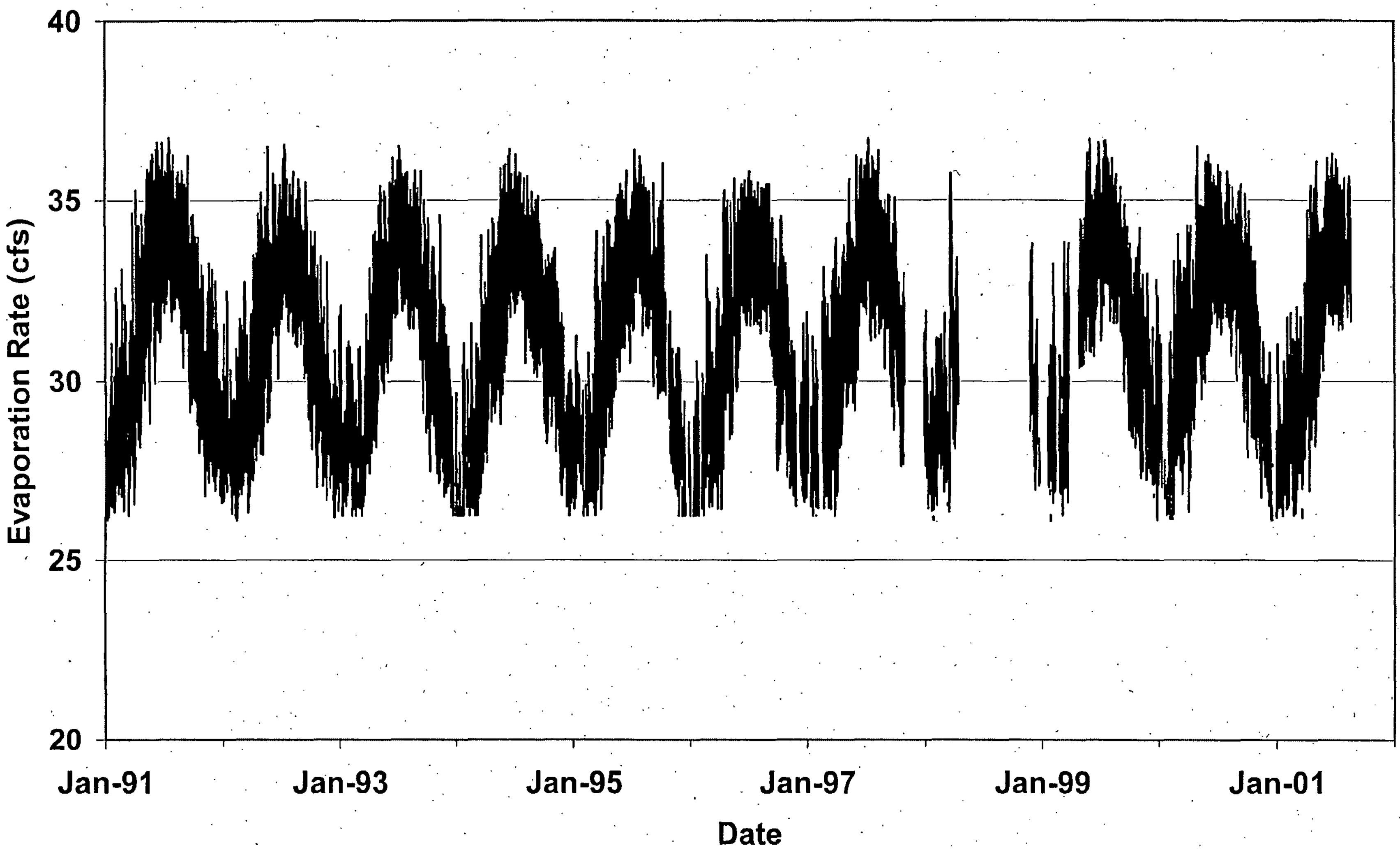


Figure B4: Hourly calculated evaporation rates for the EPU project.

f:\job\6295\figures\Figure B4 - EPU Evaporation Rate 1991 - 2001.xls

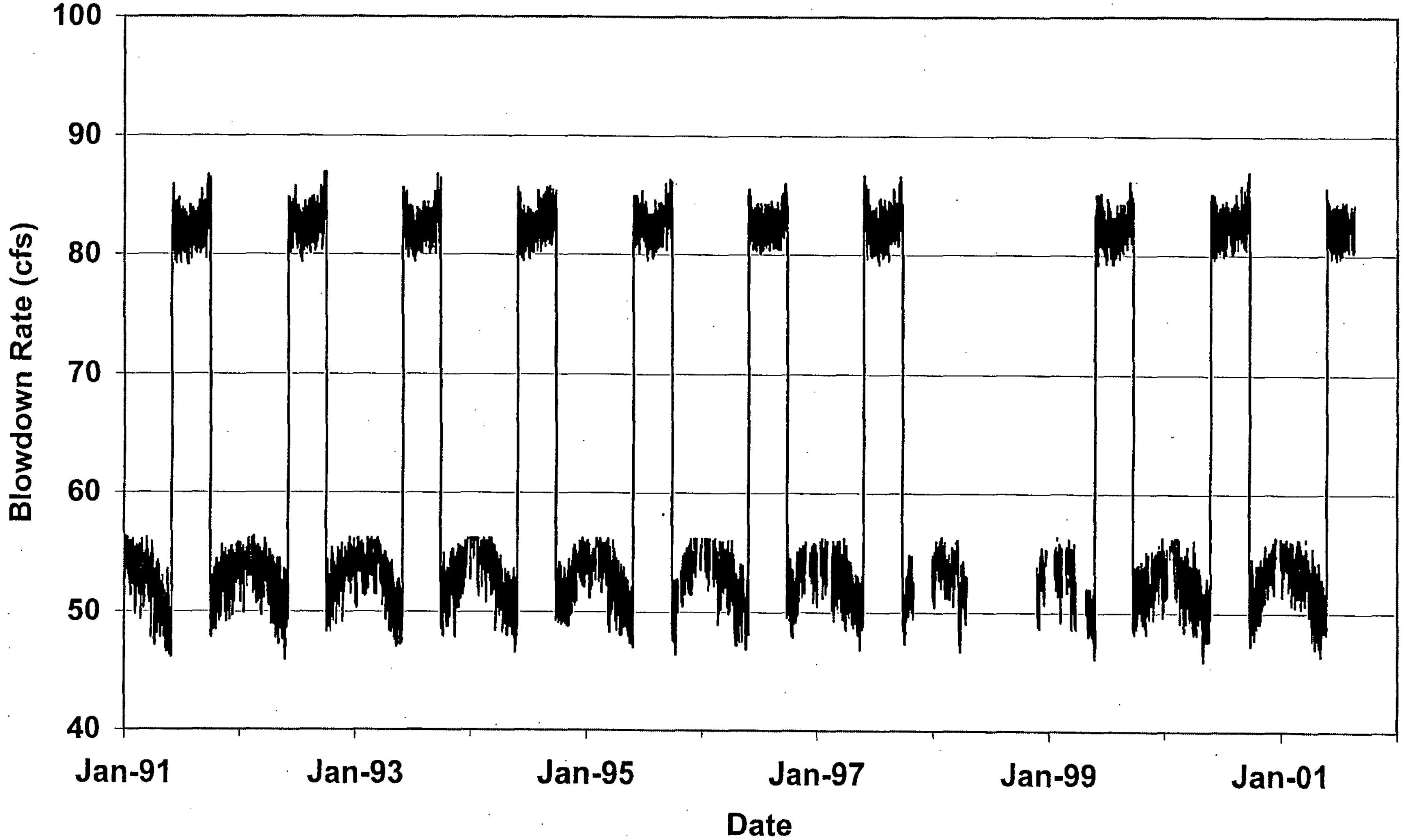


Figure B5: Hourly calculated blowdown (i.e., discharge=makeup - evaporation) rates for the EPU project.

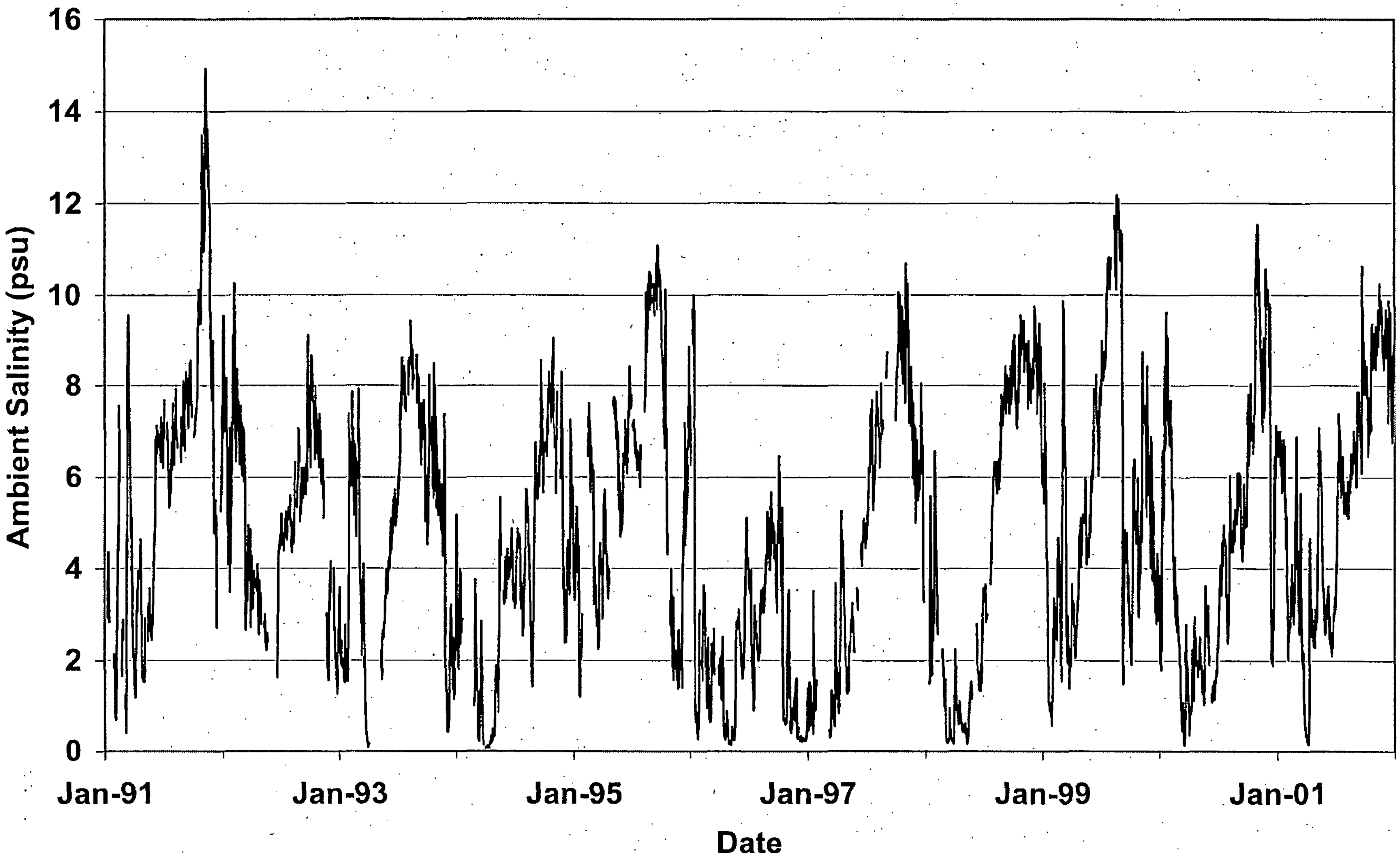


Figure B6: Daily average ambient salinity calculated from daily average water temperature and specific conductance data measured by USGS at Reedy Island.

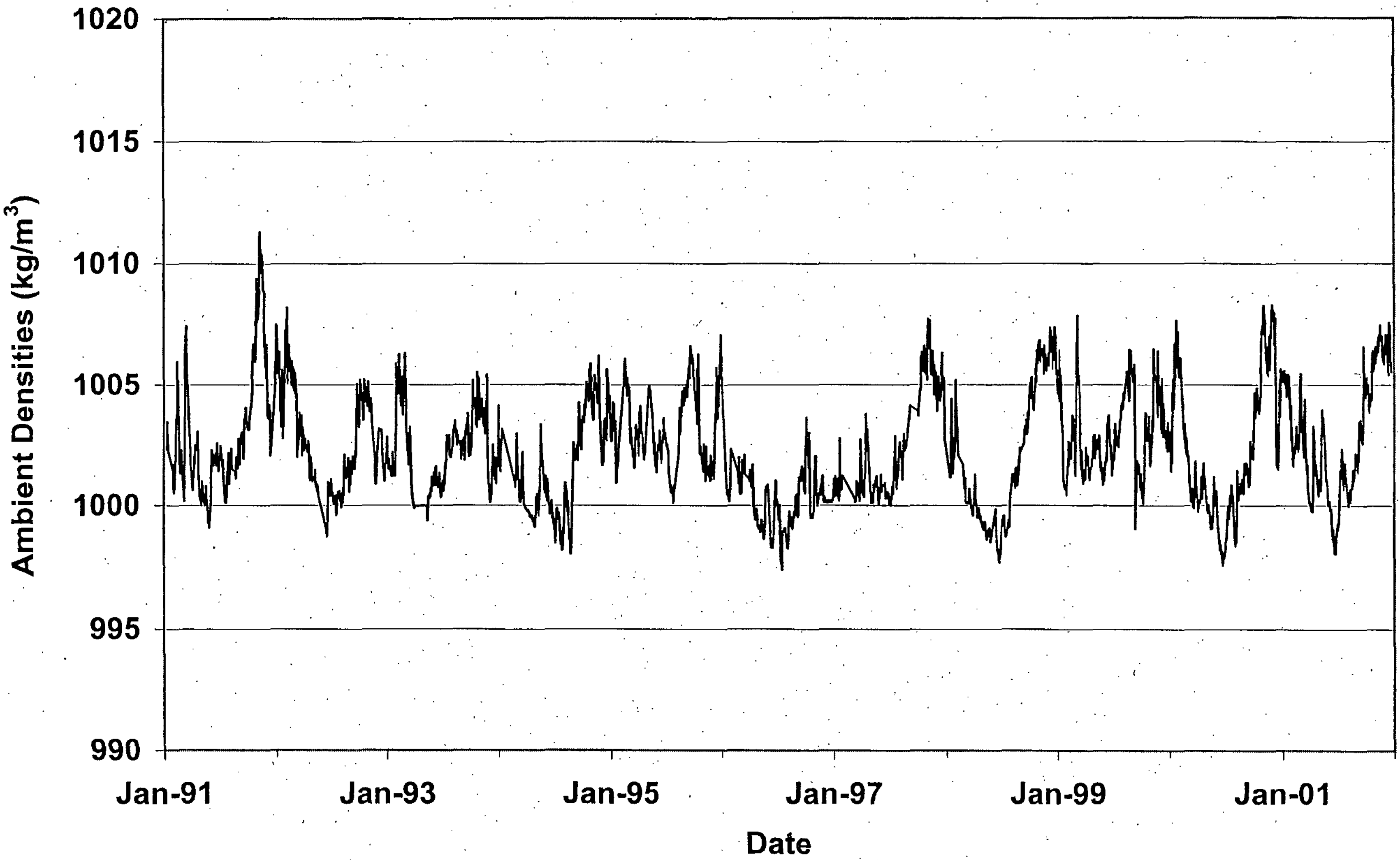


Figure B7: Daily calculated ambient densities.

f:\job\6295\figures\Figure B7 - Daily Ambient Density 1991-2001.xls

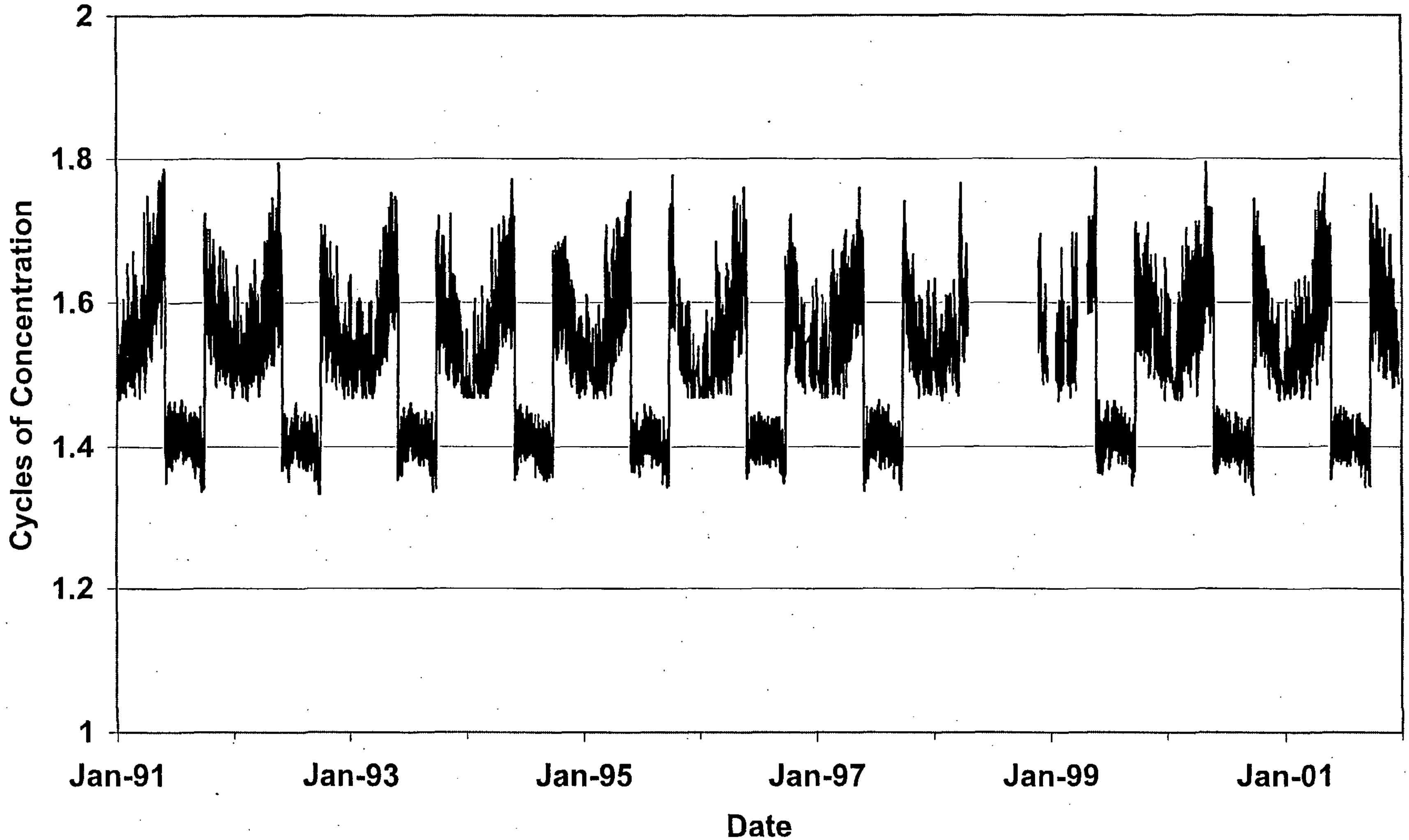


Figure B8: Hourly cycles of concentration (make-up flow rate / blowdown flow rate) for the EPU project.

f:\job\6295\figures\Figure B8 - Cycles of Concentration 1991-2001.xls

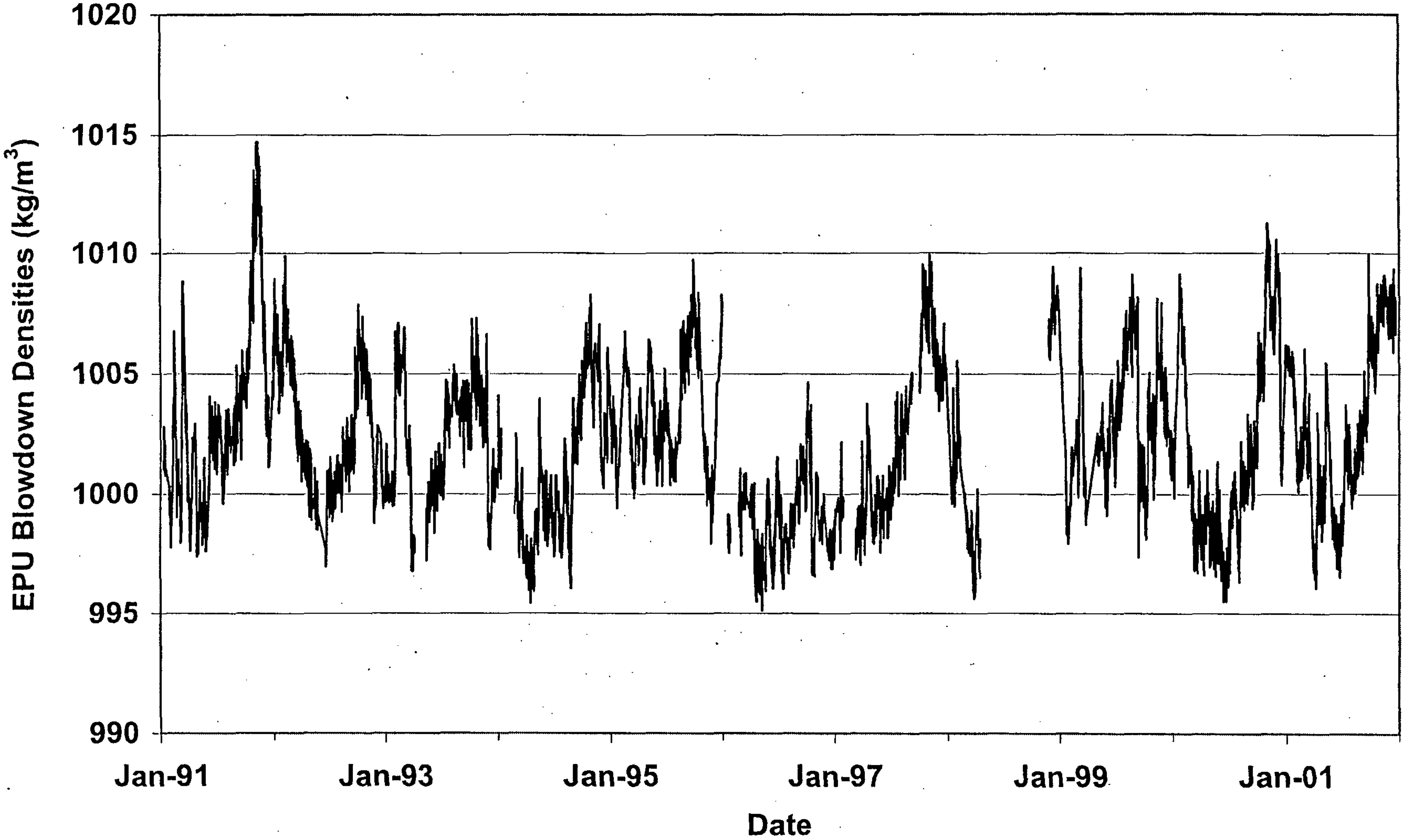


Figure B9: Hourly blowdown densities calculated for the EPU project.