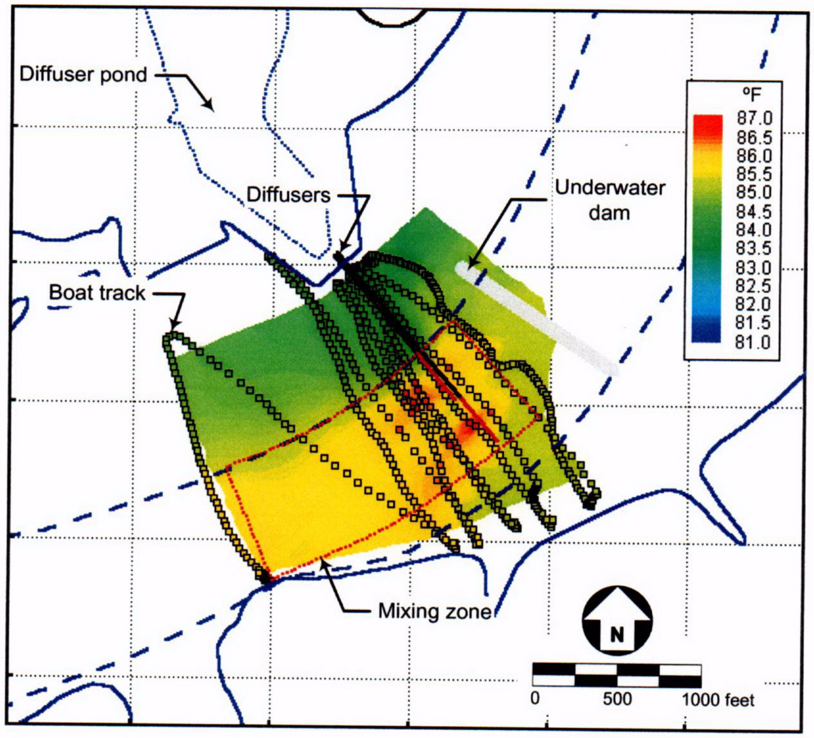
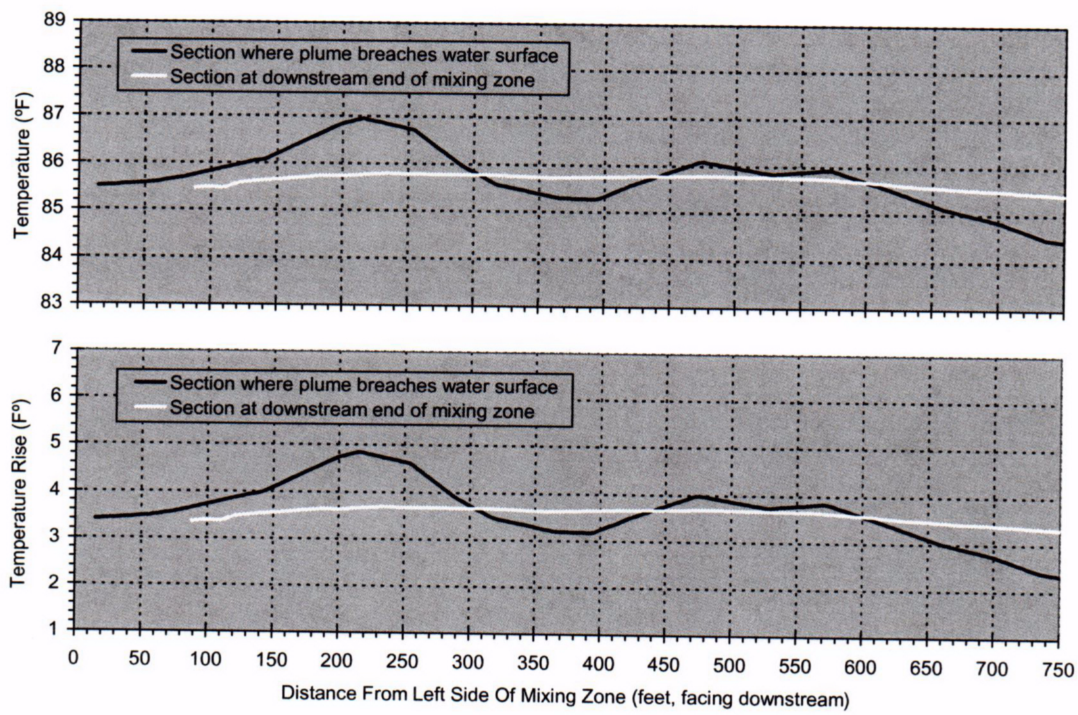
DRAFT



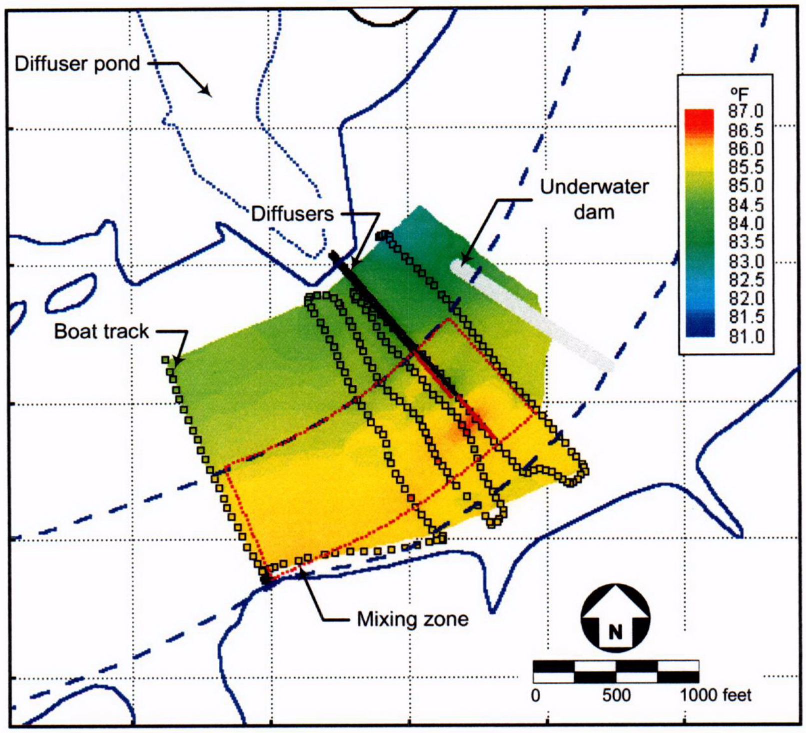
(a) Water Temperature Distribution at 5-Foot Depth



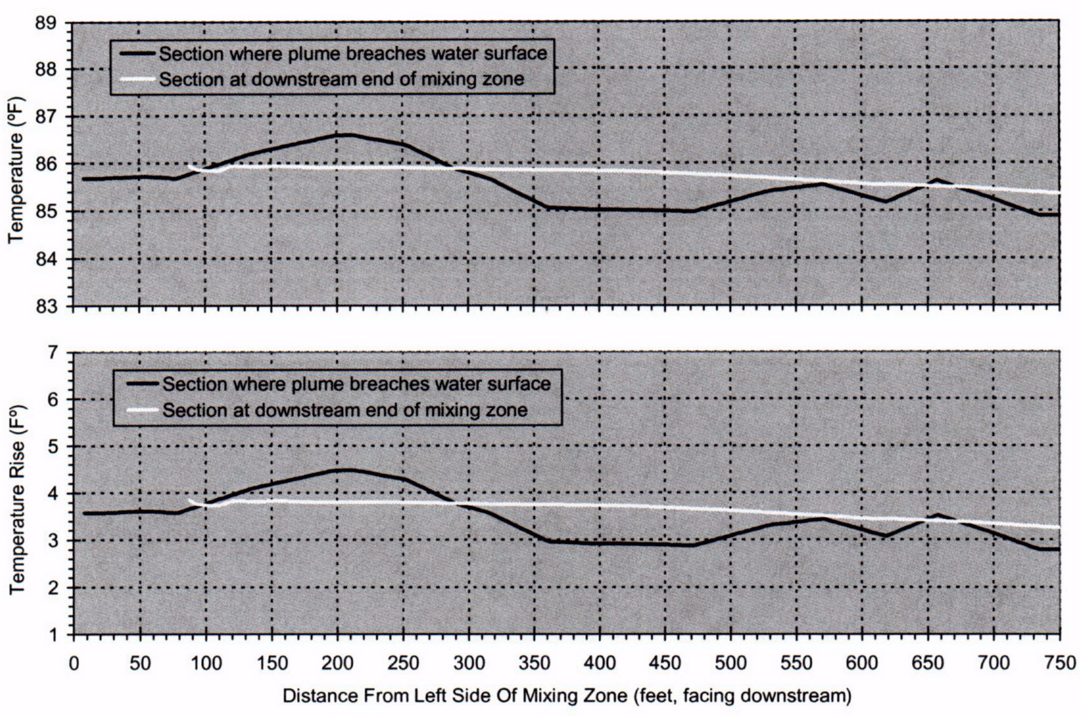
(b) Water Temperatures Across Mixing Zone at 5-Foot Depth

Figure 10. Water Temperature Measurements from Field Study of August 2, 2000, Pass 1

C11



(a) Water Temperature Distribution at 5-Foot Depth



(b) Water Temperatures Across Mixing Zone at 5-Foot Depth

Figure 11. Water Temperature Measurements from Field Study of August 2, 2000, Pass 2

C12

an accuracy of about ±0.25 F° and a response time of about 0.7 second. Based on the boat speed and sampling frequency, the sensor readings represent near-instantaneous temperatures taken at intervals roughly every four to six feet along the boat tracks. It is emphasized that although the plots in Figure 8 through Figure 11 were created from instantaneous measurements, they do not represent an instantaneous snapshot of the thermal discharge. Depending on the study, the time required for the boat to traverse the indicated tracks varied between about 65 minutes and 135 minutes. In this manner, due to the time-varying turbulent motions in the flow, the plots represent "blurred" rather than "clear" images of the thermal discharge at the 5-foot depth. If additional data sets were collected, the general location of the thermal discharge would likely remain unchanged. However, the shape of the temperature distributions would shift over distances associated with the size of the dominant turbulent motions in the flow. From a statistical standpoint, the plots represent "probable" rather than "definite" images of the thermal discharge. With this understanding, the following general comments are provided for each field study.

July 24, 1997

The study of July 24, 1997, included a high river discharge, about 40,000 cfs, and a relatively high ambient water temperature, 83.9°F (28.8°C). Stratification was moderate, with water at the channel bottom about 3.6 F° (0.3 C°) cooler than the ambient temperature (5-foot depth). SQN was operating in open mode with both units, discharging about 2470 cfs through both diffusers at a temperature of about 23.4 F° (13.0 C°) above the ambient temperature at Station 13. The following features are noted (Figure 8).

- Even though both diffusers are operating, the thermal discharge seems to breach the 5-foot depth as a single plume in the center of the main channel. It is emphasized that the diffusers are approximately 40 feet below the 5-foot depth. Depending on the magnitude and direction of the mean and turbulent motions in the flow, it is reasonable to expect the plumes at the 5-foot depth to drift from side-to-side in the mixing zone. It seems unlikely, however, that the discharge from each diffuser would coalesce into a single plume. One thought is that perhaps parts of the diffusers were clogged. Such clogging, however, would have produced an unusually high water level in the diffuser pond, which was not observed. Other possible factors include the following:

  - ✓ Due to moderate stratification, parts of the thermal effluent are significantly cooled and reach a level of neutral buoyancy below the 5-foot depth. The high river discharge also would promote mixing and "bending" of the thermal discharge, sweeping it downstream before reaching the 5-foot depth. Perhaps the only parts of the plumes containing sufficient buoyancy to reach the water surface were those in the middle of the river, emerging side-by-side in what appears to be a single plume.

  - ✓ Part of the thermal effluent was undetected in the field study due to undulations in the flow and an insufficient number of measurements in the region where the plumes breach the surface. If undulations temporarily submerge the plume below the 5-foot

depth, and if they occur at a time-scale longer than that for the survey boat to traverse the breaching area, it is possible for part of the plume to go undetected. The first transect downstream of the diffuser was at about 500 feet. Additional transects may have revealed evidence of two plumes (i.e., one plume for each diffuser).

- Due to high river flow, there is a sharp gradient between the upstream ambient temperature and the plume temperature. There is no thermal wedge propagating upstream in the surface layer of the flow.

- The mixing zone maintains the thermal discharge below the NPDES thermal criteria (i.e., max T_d of 30.5°C/86.9°F and max ΔT of 3.0 C°/5.4 F°).

- North and south of the mixing zone, natural heating creates high temperatures in the overbanks (plot "a" of Figure 8). In some areas, the overbank temperature is higher than that in the mixing zone. These results emphasize the difficulty of tracking SQN thermal compliance by measurements at the outer edges of the mixing zone, as was done in the early 1980s, and the strength of using a computed compliance, which keeps an accurate accounting of the amount of heat added to the reservoir by the plant.

At the section where the plume breaches the water surface (plot "b" of Figure 8), the water temperature is below the ambient temperature for all except the center of the plume (i.e., the local temperature rise is less than zero, except near the center of the plume). This is a consequence of stratification. The ambient water temperature measured at the 5-foot depth at Station 13 is 83.9°F (28.8°C); whereas that near the bottom of the main channel is closer to about 80.0°F (23.7°C). Due to the upward flux of the diffuser discharge and entrainment of ambient flow, the cooler bottom water is forced to the surface, yielding temperatures in parts of the mixing zone that are lower than the ambient temperature measured upstream.

March 24, 1999

The study of March 24, 1999, again included a relatively high river discharge, about 35,000 cfs. As a springtime test, however, the ambient water temperature was cooler, 51.8°F (11.0°C), and contained essentially no stratification. SQN was operating in open mode with both units, discharging about 2490 cfs through both diffusers at a temperature about 24.2 F° (13.4 C°) above the ambient temperature at Station 13. The following features are noted (Figure 9).

- Two plumes breach the 5-foot depth, one for each diffuser leg.

- The peak temperature for the diffuser located in the northern side of the main channel is about 2 F° (1.1 °C) warmer than that located in the southern side of the main channel (i.e., at the 5-foot depth where the plumes breach the water surface).

- Due to high river flow, there is a sharp gradient between the upstream ambient temperature and the plume temperatures. There is no thermal wedge propagating upstream in the surface layer of the flow.

- The mixing zone maintains the thermal discharge below the NPDES thermal criteria (i.e., max T_d of 30.5°C/86.9°F and max ΔT of 5.0 C°/9.0 F°).

- For the prevailing river and plant conditions, the thermal plumes appear to spread into the overbank on the north side of the main channel. In part, this may be a consequence of secondary currents created by river curvature. If significant, secondary currents would induce motion toward the inside of the bend in the surface layer of the flow and toward the outside of the bend in the bottom layer of the flow. This could perhaps be the case in Figure 9, wherein the secondary current moves the plumes toward the inside of the bend. On the outside of the bend, the water is cooler perhaps due to upwelling of bottom water moving outward along the bottom of the river. Other factors, however, also may be responsible for this behavior, including the following:

  ✓ Recirculation. A zone of recirculation created by the shoreline protrusion at the diffusers (see Figure 9) may exist. If it exists, such recirculation could entrain thermal effluent from the northern edge of the mixing zone, but at water temperatures below the NPDES criteria. Recirculation of the type shown in Figure 9 would be significant only at higher river discharges.

  ✓ Wind. Other TVA studies have found that wind can have a significant effect on water motions in the surface layer of the flow (TVA, 1998). During the study of March 24, 1999, a sustained wind was blowing out of the south at about 6 mph, perhaps inducing the plume in the surface layer to spread more northward into the right overbank (i.e., compared to quiescent wind conditions).

  ✓ Insufficient data. Note that the boat transects are sparse in the downstream half of the mixing zone. It may be that the plumes also exist in this area, but were not measured. Concurrently, unsteady undulations in the flow, as described above, could also add bias to the survey results.

It is interesting to note that even though the study of July 24, 1997, was conducted at high river flow, it did not appear to exhibit spreading towards the northern overbank as in the study of March 24, 1999 (i.e., compare Figure 8 and Figure 9). In reality, such spreading may exist, albeit unnoticeable in the measurements. Also recall that the study of July 24, 1997, contained moderate stratification, which could perhaps disrupt secondary currents or other spreading processes.

August 2, 2000

The study of August 2, 2000, included a low river discharge, only about 9,000 cfs, with a relatively high ambient water temperature, 82.1°F (27.7°C). Stratification was essentially nonexistent. SQN was generating with both units, but because of the high ambient temperature and low river flow, the plant was operating in helper mode (i.e., cooling towers in service). Under these conditions, the plant was discharging about 2480 cfs through both diffusers at a temperature of about 18.1 F° (10.1 C°) above the ambient temperature at Station 13. Two passes were made with the survey boat, an early morning pass (Pass 1—Figure 10) and a late morning pass (Pass 2—Figure 11). The following features are noted.

- Two plumes breach the 5-foot depth, one for each diffuser leg. The plumes emerge within 500 feet of the diffusers and are evenly spaced in the mixing zone.

- For Pass 1, the peak temperature for the diffuser located in the northern side of the main channel is about 1 F° (0.6 °C) cooler than that located in the southern side of the main channel (i.e., at the 5-foot depth where the plumes breach the water surface). Note that this is opposite of that which was observed in the test of March 24, 1999.

- For Pass 2, the peak temperatures at the 5-foot depth, where the plumes breach the water surface, are about 0.4 F° (0.2 °C) cooler than those for Pass 1. The peak temperature for the northern side of the main channel is still about 1 F° (0.6 °C) cooler than that for the southern side of the main channel. Also note that the number of boat transects for Pass 2 are less than that for Pass 1, which somewhat diminishes the confidence in the resolution of the plume shown in Figure 10.

- Due to low river flow, the plume in the surface layer of the flow forms a thermal wedge that propagates upstream of the diffuser.

- The mixing zone maintains the thermal discharge below the NPDES thermal criteria (i.e., max T_d of 30.5°C/86.9°F and max ΔT of 3.0 C°/5.4 F°).

- The thermal plumes spread into areas outside of the mixing zone, but at levels below the NPDES thermal criteria.

Under the current NPDES permit, effective August 2001, two field studies have been performed. These include a summer study on July 27, 2002, and a spring study on April 23, 2003. However, in contrast to those summaries above, these studies included instream measurements only at the downstream end of the mixing zone, the results of which are given in Table 1. The purpose of these studies was to collect information for calibration of the numerical model used for the computed compliance and did not include measurements to assess the three-dimensional extent of the thermal plumes in and around the mixing zone.

4.0 NEW STUDIES

Overall, the field studies performed since the startup of SQN have provided valuable information about the three-dimensional extent and other characteristics of the plumes created by the thermal discharge from the multiport diffusers. For the conditions examined, all the studies appear to confirm the adequacy of the mixing zone for diluting the plant thermal effluent. However, the studies have not included the full range of plant and river conditions as summarized in Table 2. Also, they are not without concern. In particular, based on previous discussions, the following items are noted:

- The field measurements did not encompass the full extent of the mixing zone. Downstream of the diffusers, the mixing zone, as defined in the NPDES permit, includes the full depth of flow. Yet, in all but one study (July 24, 1981), the measurements were limited only to the upper 7 feet of the water column. In part, this is justified by the action of buoyancy, which forces the thermal effluent to the surface layer of the flow, and subsequently by the NPDES monitoring criteria, which requires measurements only at depths of 3 feet, 5 feet, and 7 feet (1.0 meter, 1.5 meters, and 2.0 meters). However, it leaves to speculation the three-dimensional extent of the thermal plumes for cases where the thermal discharge does not fully breach the surface layer of the flow, such as the field studies of May 14, 1982, and July 24, 1997, both of which contain significant stratification.

- Most of the field measurements were conducted at time-scales that create blurred images of the thermal plumes that can perhaps obscure and dominant features of the flow.

Perhaps most important, the studies performed thus far have not contained measurements needed to fully address the issues identified in the NPDES permit effective August 2001. In particular, the studies did not include time-series data of the type that allows a comparison of the extent of the thermal plumes based on 1-hour averaging vs. 24-hour averaging. The ambient temperature study requires an examination of *"the major factors contributing to the interaction between main channel and overbank flows."* This calls for measurements and evaluations in both these regions for a variety of plant and river operating conditions. The mixing zone study requires an examination of *"the impact of hydro peaking operations on the behavior of the thermal plume."* This calls for measurements and evaluations of the dynamical (i.e., time-varying) behavior of the plumes as they wander back and forth in the mixing zone in response to changes in the river flow.

To provide full completion of the requirements for hydrothermal studies as given in the NPDES permit effective August 2001, as well as those before, new studies are needed. Due to the wide range of possible operating conditions for the plant and river system, it is proposed herein to update the recommendations given in Table 2 using three-dimensional numerical models of the reach of Chickamauga Reservoir including SQN. The models will be calibrated using any existing data of sufficient quality and new data from additional field studies of the main channel, overbanks, and mixing zone. After calibration, the numerical models will be used to assess other

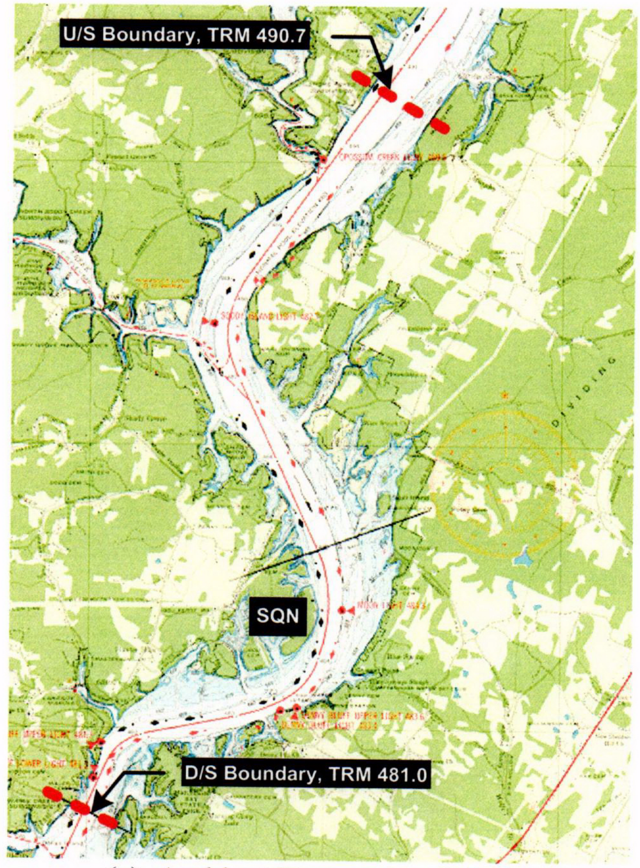
conditions of interest (i.e., in lieu of continued field studies). Described in the following sections are the basic plans for developing the models and performing the related field studies.

4.1 Numerical Models

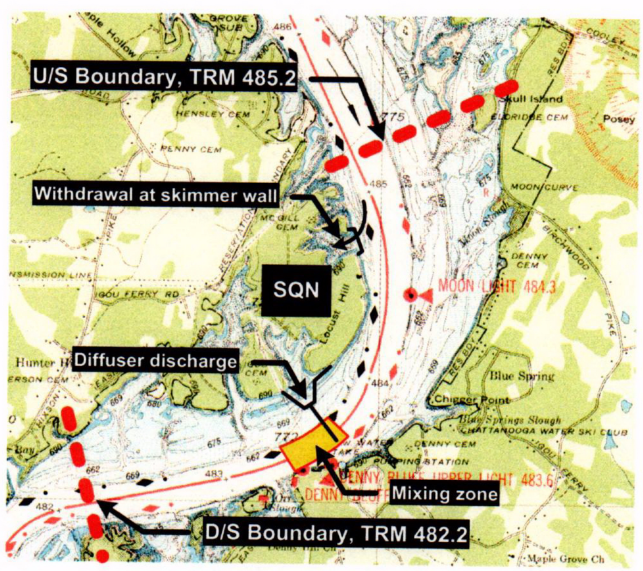
Two numerical models are currently envisioned for SQN, one to examine interactions between the main channel and overbank (ambient temperature model) and one to examine the thermal plumes in the mixing zone (mixing zone model). The ambient temperature model will encompass a 10-mile reach of the river from about Tennessee River Mile (TRM) 481.0 to TRM 490.7. The mixing zone model will encompass a 3-mile reach from about TRM 482.2 to TRM 485.2. The model boundaries are illustrated in Figure 12. Formulations for the numerical models will follow the example of work recently completed for modeling the thermal discharge from the TVA Browns Ferry Nuclear Plant (Lin and Hecker, 2002). In general, the models will include the solution in three dimensions of the governing equations of flow over a computational grid of size appropriate to resolve the major factors of concern. The model development will occur in phases. The initial phase will include steady-state formulations of only the river, incorporating the effects of turbulence and the natural reservoir geometry (main channel, overbanks and river curvature). The second phase will incorporate the withdrawal and mixing zones created by operation of SQN, but with no changes in heat. In the model, this will be accomplished by removing water through openings representing the plant intake skimmer wall and adding water through slots situated on the channel bottom representing the multiport diffusers. The geometry of the skimmer wall, underwater dam, and cylindrical diffusers will be represented in the model. For the purpose of the new studies, the next and final phase will incorporate the effects of heat (i.e., buoyancy), represented by stratification in the ambient river flow and thermal input from the atmosphere and SQN. The thermal impact from SQN will be simulated by an appropriate increase in water temperature between that removed at the intake skimmer wall and that added through the diffuser slots.

In final form, the formulations will include the following processes, all of which have been items of speculation in previous observations and measurements:

- Mean and turbulent interactions between main channel and overbanks.
- Secondary flows due to river curvature.
- Wakes and zones of recirculation due to shoreline protrusions.
- Entrainment and dilution of the thermal plumes, including:
  - ✓ Variations in mixing of the plumes due to cold vs. warm ambient water temperature.
  - ✓ Variations in the propagation of plumes due to river flow (i.e., upstream vs. downstream propagation of thermal effluent).



(a) Ambient Temperature Model



(a) Mixing Zone Model

Figure 12. Boundaries for Numerical Models

C13

✓ Variations in the plume depth due to the effects of stratification (i.e., surface vs. submerged levels of neutral buoyancy of thermal effluent).

4.2 Ambient Temperature Field Studies

The goals of the ambient temperature field study, as stated in the NPDES permit of August 2001, are to determine:

- The major factors contributing to the interaction between main channel and overbank flows.

- The impact of these flows on water temperatures in the thermal mixing zone.

- The optimal location of monitors to record the ambient temperature.

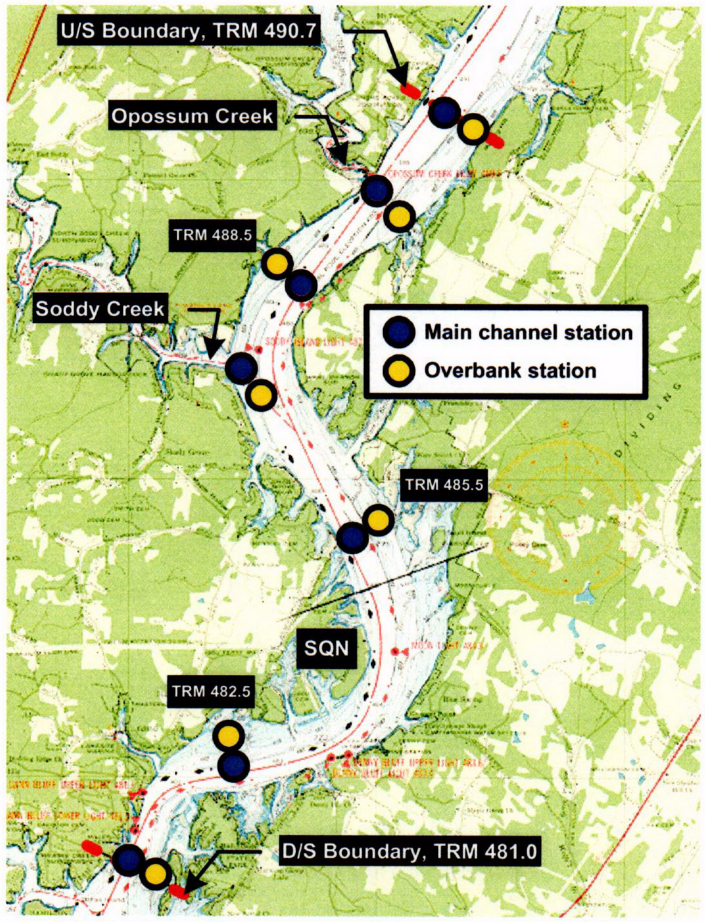
These goals will be achieved by taking hydrothermal and meteorological time-series measurements of key parameters at key locations, and then performing correlation analyses among the measurements to determine the level of dependence among the various parameters. Of particular interest are correlations during events containing spikes in the ambient river temperature. Also of interest are events where there appears to be a large amount of natural heating (or cooling) between the upstream temperature monitor (i.e., Station 13) and the diffuser mixing zone. For all parameters, the time-series measurements will be analyzed to examine behaviors based on 1-hour and 24-hour averaging.

The key hydrothermal and meteorological parameters for the filed studies include water temperature, water velocity, reservoir water surface elevation, air temperature, humidity, wind speed, and wind direction. Operating conditions for SQN and the river system also are required. In general, all but the water temperature and water velocity are currently measured by instrumentation provided by the control systems for SQN and the river system. Water temperature measurements, as required by the SQN NPDES permit, also are available; however, these measurements are not provided at locations appropriate for a detailed examination of main channel and overbank flows and the impacts on ambient water temperature. Under these conditions, the supplemental instrumentation summarized below will be used in the ambient temperature field studies.

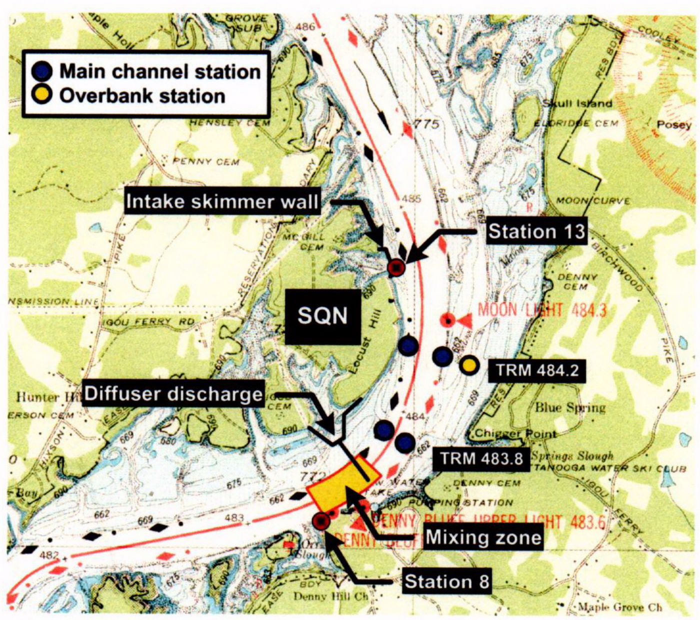
Water Temperature

To analyze the interaction between the overbanks and main channel, water temperature measurements will be made at a number of stations temporarily deployed in the reach of Chickamauga Reservoir represented in the ambient temperature model. A preliminary plan for station locations is shown in Figure 13. In general, the stations will be deployed as pairs, one in the overbank, and one nearby in the main channel. One set of stations will be located each at the upstream and downstream boundaries of the study reach. Other sets will be located at sections

DRAFT



(a) Stations Upstream and Downstream of SQN



(b) Stations Between SQN Skimmer Wall and Mixing Zone

Figure 13. Temporary Stations for Ambient Temperature Field Studies

C14

containing large overbanks near TRM 482.5, TRM 485.5, and TRM 488.5. Stations also will be located near the outfalls for Soddy Creek and Opossum Creek, both of which may provide sources of warm water leading to spiking of the ambient temperature at SQN. To evaluate the optimal location for monitoring ambient temperature, several stations will be deployed between the SQN intake skimmer wall and the diffuser mixing zone. These will include stations near the outer edges of the main channel, immediately upstream of the mixing zone, and in the overbank area opposite the plant.

Altogether, approximately twenty temporary water temperature stations will be deployed. The stations will include thermistors and data loggers at selected depths from near the water surface to the reservoir bottom. Among these will be the compliance depths of 3 feet, 5 feet, and 7 feet (1.0 meter, 1.5 meters, and 2.0 meters). The accuracy of the measurements will be about ±0.3 F°. The data loggers will collect and store measurements about every five minutes throughout the test period.

Water Velocity

Water velocities will be measured by two methods, using surface drogues and using an Acoustic Doppler Current Profiler (ADCP). The surface drogues will be deployed at waypoints along selected river cross sections near a few of the water temperature stations shown in Figure 13. About eighteen drogues will be used. Each drogue will be fitted with a combined Global Positioning System (GPS) receiver and data logger. The GPS location of the drogues will be recoded about every 10 seconds as they drift downstream through the overbank and main channel areas of the flow. After passing through the defined study area, the drogue track data will be downloaded from the GPS units to a computer and plotted on a base map using Geographic Information System (GIS) software. This information will yield the pattern of flow in the surface layer of the reservoir. Approximate surface velocities will be determined based on the distance traveled by the drogues between consecutive GPS readings.

The ADCP will be used to measure the three-dimensional velocity from the water surface to the reservoir bottom at selected profile locations. The specific measurement locations will focus on selected regions of the temperature pairs shown in Figure 13. Each velocity profile will include collecting data over a period of time sufficient to sample the dominant turbulent undulations in the flow. Based on previous experience, this will encompass recording time-series data at each measurement location for at least five minutes. The measurements will sample the velocities in cells of incremental depth of about 1.64 feet (0.5-meter) throughout the water column. The confidence of the average velocities obtained from the ADCP readings will depend on statistics of the time-series data.

Study Period

The ambient temperature field studies will include a deployment of the temporary water temperature stations for a period of seven to ten days. This will encompass typical periods of

weekday and weekend hydro peaking operations. In contrast, measurements for water velocity cannot be made "in parallel" at all desired profile locations. Because only one unit is available, ADCP measurements will be made "in series" from location to location. In a similar fashion, drogues cannot feasibly be deployed simultaneously throughout the study region. Thus, to provide a common basis for comparing data, the velocity measurements will be made in one single day with a steady river flow. This day will be selected within the overall test period (i.e., seven to ten days) and will require special scheduling of hydro releases from Chickamauga Dam, Watts Bar Dam, and perhaps Hiwassee River. Data at steady flow also is needed to calibrate the numerical models and to simplify, for the purpose of analysis, the complexity of hydrothermal phenomena responsible for interactions between the main channel and overbank flows.

4.3 Mixing Zone Field Studies

The goals of the mixing zone field study, as stated in the NPDES permit of August 2001, are to determine:

- The impact of hydro peaking operations on the behavior of the thermal plume.
- The need to redefine the extent of the mixing zone.

As before, these goals will be achieved by taking hydrothermal and meteorological time-series measurements and performing correlation analyses among the measurements to determine the level of dependence among the various parameters. Of particular interest is the dynamic behavior of the thermal plume from each diffuser, based both on a 1-hour averaging and 24-hour averaging. The key hydrothermal and meteorological parameters for the mixing zone study are basically the same as those for the ambient temperature study. Supplemental instrumentation again will be provided for water temperature and water velocity, as summarized below.

Water Temperature

To analyze the dynamic behavior of the thermal plumes, water temperature measurements will be made at a number of stations temporarily deployed in and around the mixing zone. A preliminary plan for station locations is shown in Figure 14. Note that Figure 14 is a schematic—the actual mixing zone follows the curvature of the main channel. The mixing zone will include twenty-five stations. The stations will be positioned along five longitudinal transects—the left and right sides of the mixing zone, the centerline of the mixing zone, and the centerline of the multiport outlets for each diffuser. Each transect will include five water temperature stations—one each at the upstream and downstream ends of the mixing zone, one at the centerline of the diffusers, and two between the diffusers and the downstream end of the mixing zone. The concentration of sensors will be greater in the region where the thermal discharge is likely to breach the water surface and contain a larger temperature. Six additional stations will be positioned in surrounding ambient areas upstream and downstream of the mixing zone. Each station will include thermistors and data loggers at selected depths from near the

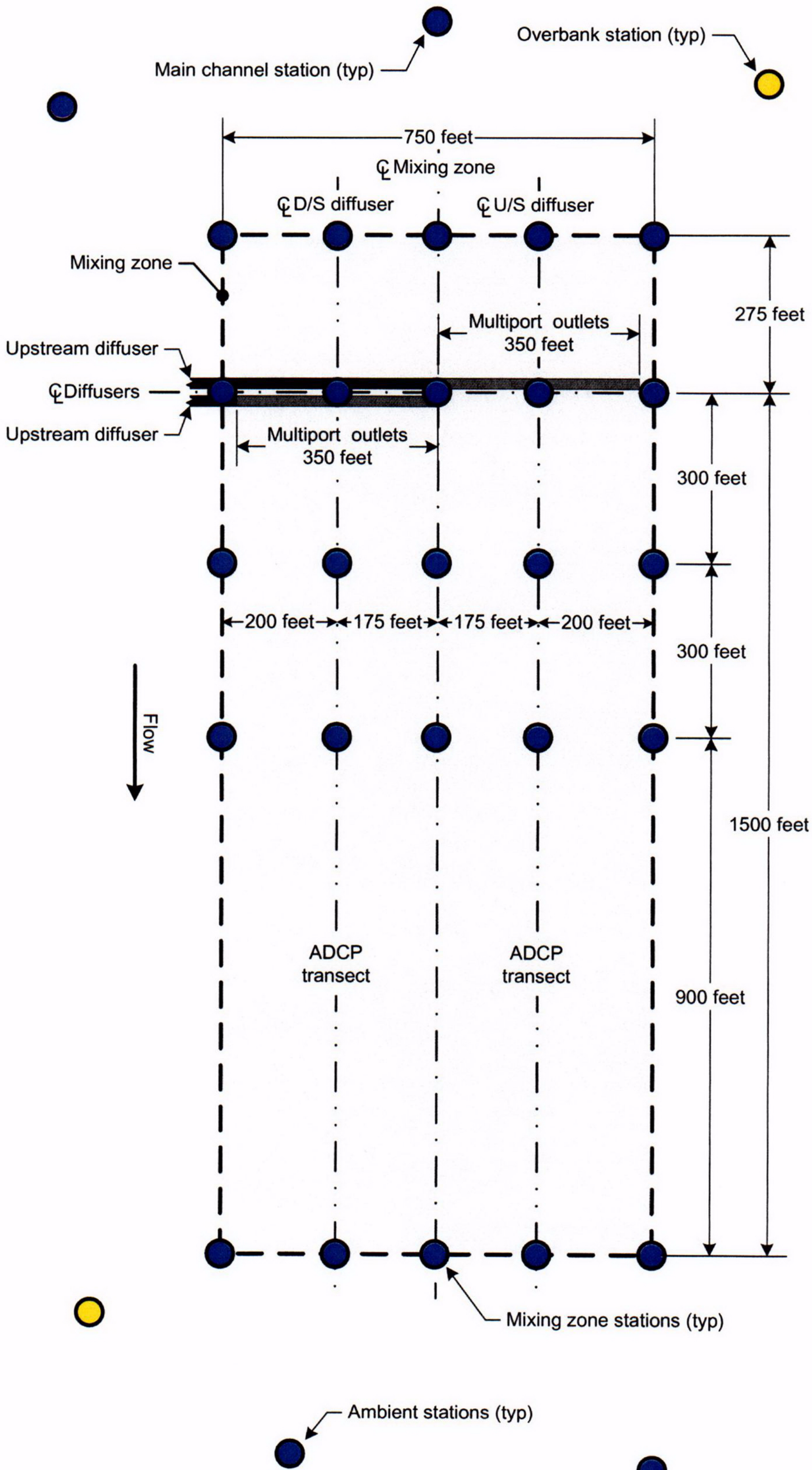


Figure 14. Temporary Stations for Mixing Zone Field Studies

C15

water surface to the reservoir bottom. Among these will be the compliance depths of 3 feet, 5 feet, and 7 feet (1.0 meter, 1.5 meters, and 2.0 meters). The accuracy and sampling frequency of the thermistors will be the same as that for the ambient temperature studies (i.e., ±0.3 F° and about five minutes).

Altogether, the arrangement in Figure 14 will include about 200 water temperature sensors throughout the mixing zone. Monitoring will include both the upstream and downstream portions of the mixing zone. In contrast to previous studies, measurements will be made not only in the surface region of the reservoir, but throughout the depth of flow. Furthermore, the sensors will all be synchronized so that measurements will be made simultaneously. In this fashion, readings at a particular point in time will closely represent a clear snapshot of the thermal discharge rather than an image blurred by the time required to make point by point measurements, as in previous field studies. At the same time, it is emphasized that the layout in Figure 14 yet has limitations. For example, for the spacing shown, it theoretically is possible for "hot spots" of size smaller than about 200 feet to pass undetected between adjacent temperature stations. It is unlikely, though, that the random turbulent bursts of the thermal discharge will pass out of the mixing zone without encountering at least one of the temperature stations. Nevertheless, to provide information about the thermal plumes between temperature stations, measurements using trolling sensors of the type used to produce the images in Figure 8 through Figure 11 will be used during special steady flow tests to be conducted during the study period. These tests are described in more detail below. It is also anticipated that the numerical model, once calibrated, will be able to provide additional understanding on the behavior of the thermal discharge for length scales less than 200 feet.

Water Velocity

Water velocities will again be measured using surface drogues and the ADCP. These measurements will be carried out during a period of steady flow and will be the primary source of data for calibration of the mixing zone model. The surface drogues will be equipped with GPS receivers and deployed at waypoints along a cross section upstream of the mixing zone. After passing downstream beyond the mixing zone, the drogue tracks will be downloaded to yield the pattern of flow. As before, surface velocities will be determined based on the distance traveled by the drogues between consecutive GPS readings.

The ADCP will be used to measure the three-dimensional velocity from the water surface to the reservoir bottom along two longitudinal transects, one each along the centerline of the multiport diffuser outlets (Figure 14). Measurement locations will be spaced close together near the diffuser, where mixing is intense, and farther apart near the downstream end of the mixing zone, where mixing is mild. Each velocity profile again will include the collection of data over a period of about five minutes, sampling velocities in cells of incremental depth about 1.64 feet (0.5-meter).

In contrast to the ambient temperature field studies, the diffuser jets will create much higher levels of turbulence than that found in normal channel flow. Due to these high levels, high

frequency measurements will be needed to obtain average velocities suitable for calibration of the mixing zone model. The ADCP will provide time-series measurements at about 2.5 Hertz, which is fully suitable for resolving the larger turbulent undulations in the flow. In terms of model calibration, it also is best to obtain temperature data at the same location as the velocity measurements. Thus, alongside the ADCP, a string of thermistors will be lowered into the flow. These thermistors have a faster response time than those of Figure 14 and will be sampled at rate of about 0.5 Hertz, which again is fully suitable for obtaining good time-averaged temperature readings.

Study Period

The mixing zone field studies will also include a deployment of the temporary water temperature stations for a period of seven to ten days. This will encompass typical periods of weekday and weekend hydro peaking operations. During these periods, data from the stations will allow the development of animations of the behavior of the thermal effluent due to unsteady variations in the river flow. It should be noted that this deployment will require a 24-hour field crew to tend the temperature stations. In contrast to the ambient temperature studies, the mixing zone studies will include stations in the center of the navigation channel. During the deployment, communications links with the navigation locks at Chickamauga Dam and Watts Bar Dam will be used to determine when tows will be passing through the study area. The temperature stations will be temporarily moved out of the navigation channel during these times. The field crew also will also need to caution other small watercraft in the area.

The velocity measurements again will be made with a steady river flow. In this case, due to the large effect of river flow on dilution of the thermal effluent, two steady flow tests will be performed—one with high river discharge, between 30,000 cfs and 40,000 cfs, and one with low river discharge, between 7500 and 15,000 cfs. As before, the days for the steady flow tests will be selected within the overall deployment period and will require special scheduling of hydro releases from Chickamauga Dam, Watts Bar Dam, and perhaps Hiwassee River. It is emphasized that certain aspects of the field conditions will not be controllable during the steady flow tests, such as meteorology. In general, however, heat added to the receiving water by SQN will dominate over that from the atmosphere. Since the plant will be operating in a steady manner throughout the tests, the behavior of the mixing zone, for all practical purposes, will be near steady, if sufficient time is given to establish steady river conditions.

4.4 Schedule

Planning for the new studies has been ongoing since the summer of 2002. Work on developing the numerical models commenced in October 2002 and also is ongoing. The current schedule for the field studies is shown in Figure 15. As required by the NPDES permit of August 2001, the studies will include both summer and winter hydrothermal regimes. The summer studies will be conducted in the latter half of July and the first half of August (i.e., 2003), when the ambient water temperature is usually the highest. The winter studies will be conducted in the latter half

of January and the first half of February (i.e., 2004), when the ambient water temperature is usually the lowest. For each period, measurements for the ambient temperature study will be conducted first. The temporary water temperature stations will be deployed as shown in Figure 13, with one day set aside for testing at steady flow, as described above. Following in this, the water temperature stations will be moved to the mixing zone, as illustrated in Figure 14. The measurements will then commence for the mixing zone study, with two days set aside for testing at steady flow, again as described above.

Analyses of the field study data will commence immediately following the tests. The final results of the numerical modeling and data analyses are currently expected in September 2004. It is emphasized that field studies can be impacted by weather as well as unexpected restrictions due to other requirements of the river system. The studies may be delayed if boating conditions are unsafe or if the desired operating conditions for SQN or the river are temporarily unobtainable. Proper notification will be given for any changes in the schedule as summarized herein.

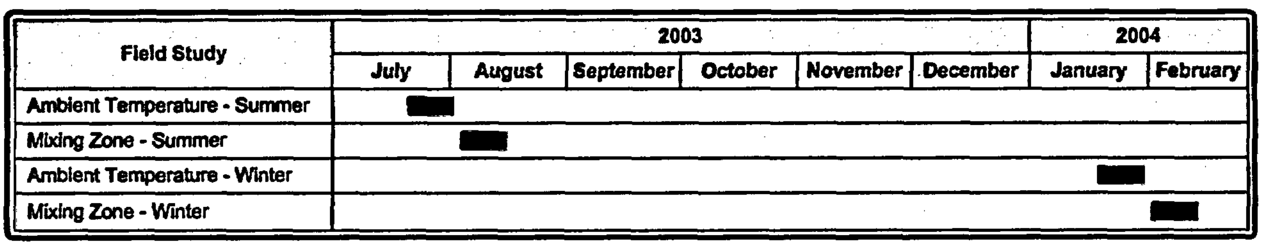


Figure 15. Schedule for New Field Studies

DRAFT

5.0 REFERENCES

Harleman, Donald R.F., Lawrence C. Hall, and T. Gray Curtis (1968), "Thermal Diffusion of Condenser Water in a River During Steady and Unsteady Flows with Application to the TVA Browns Ferry Nuclear Plant," Report No. 111, Massachusetts Institute of Technology, Department of Civil Engineering, Hydrodynamics Laboratory, September 1968.

Lin, Fangbiao, and George E. Hecker (2002), "3-D Numerical Modeling of Thermal Discharge From Browns Ferry Nuclear Plant," Alden Research Laboratory, Inc., June 2002.

TDWPC (1987), Letter from Philip L. Stewart, Manager, Chattanooga Field Office, Tennessee Division of Water Pollution Control (TDWPC) to Martin E. Rivers, Director, TVA Environmental Quality, Subject: Sequoyah Nuclear Plant (SQN) – Thermal Monitoring, NPDES TN0026450, January 12, 1987.

TVA (1972), "Prediction and Control of Water Temperatures in Wheeler Reservoir During Operation of the Browns Ferry Nuclear Plant," Advance Report No. 14, Division of Water Control Planning, Engineering Laboratory, April 1972.

TVA (1978), "Effect of Sequoyah Nuclear Plant Discharges on Chickamauga Lake Water Temperatures" Report No. WM28-1-45-101, Division of Water Management, Water Systems Development Branch, April 1978.

TVA (1979a), "Temperature Monitoring, Sequoyah Nuclear Plant," submitted to EPA February 13, 1979.

TVA (1979b), "Verification of Predictions of Sequoyah Nuclear Plant Effects on Water Temperature," submitted to EPA February 13, 1979.

TVA (1979c), "Model Study and Analysis of Sequoyah Nuclear Plant Submerged Multiport Diffuser," Report No. WM28-1-45-103, Division of Water Management, Water Systems Development Branch, March 1979.

TVA (1982), "A Field Verification of Sequoyah Nuclear Plant Diffuser Performance Model: One-Unit Operation," Report No. WR28-1-45-110, Office of Natural Resources, Division of Air and Water Resources, Water Systems Development Branch, October 1982.

TVA (1983), "Validation of Computerized Thermal Compliance and Plume Development at Sequoyah Nuclear Plant," Report No.WR28-1-45-115, Office of Natural Resources, Division of Air and Water Resources, Water Systems Development Branch, August 1983.

TVA (1984), Letter with short report from Martin E. Rivers, Director, TVA Environmental Quality to Paul E. Davis, Manager, Permit Section, Tennessee Division of Water Management, Subject: Sequoyah Nuclear Plant – NPDES Permit No. TN0026450, June 4, 1984.

TVA (1986), Letter from Martin E. Rivers, Director, TVA Environmental Quality to Philip L. Stewart, Manager, Chattanooga Field Office, Tennessee Division of Water Pollution Control, Subject: Sequoyah Nuclear Plant (SQN) – Water Temperature Monitoring For Compliance With Thermal Water Quality Standards, December 31, 1986.

TVA (1987), "Quality Program For Verification Of Sequoyah Nuclear Plant Thermal Computed Compliance System," Report No. WR28-3-45-134, Office of Natural Resources and Economic Development, Division of Air and Water Resources, Engineering Laboratory, September 1987.

TVA (1989), "A Predictive Section 316(a) Demonstration for an Alternative Winter Thermal Discharge Limit for Sequoyah Nuclear Plant, Chickamauga Reservoir, Tennessee," Report No. TVA/WR/AB--89/11, Resource Development, Nuclear Power, August 1989.

TVA (1996), "A Supplemental 316(a) Demonstration For Alternative Thermal Discharge Limits For Sequoyah Nuclear Plant, Chickamauga Reservoir, Tennessee," Report No. WR96-1-45-145, Resource Group, Engineering Services, Engineering Laboratory, December 1996.

TVA (1998), "1997 Verification of Thermal Discharge for Watts Bar Nuclear Plant," Report No. WR97-2-85-141, Resource Group, Water Management, Engineering Laboratory, January 1998.

DRAFT

TENNESSEE VALLEY AUTHORITY
River System Operations & Environment
River Operations

Study to Confirm the Calibration of the Numerical Model for the Thermal Discharge from Sequoyah Nuclear Plant as Required by NPDES Permit No. TN0026450 of August 2001

WR2003-1-45-149

Prepared by
Walter L. Harper

Norris, Tennessee

June 2003

EXECUTIVE SUMMARY

A system of real-time measurements and computer models is used to verify compliance of Sequoyah Nuclear Plant (SQN) operations with the instream thermal limits contained in the National Pollutant Discharge Elimination System (NPDES) permit. The NPDES permit of August 2001 also requires that a calibration study of the numerical model be used to compute downstream temperatures once per permit cycle.

Temperature data collected at the downstream end of the SQN mixing zone in 11 field surveys performed at SQN between 1982 and 2003, along with measured data from the SQN instream temperature monitoring system were compared with computed downstream temperatures for the same time periods. Sensitivity tests were performed for the two calibration parameters for the diffuser mixing model, effective diffuser slot width, and plume entrainment coefficient. The results showed acceptable agreement between computed and measured temperatures, particularly at river temperatures greater than 75°F. The accuracy at lower river temperatures, although not as good, is still considered acceptable, since instream temperatures resulting from SQN operations do not approach the NPDES limits as closely at lower river temperatures.

DRAFT

CONTENTS

DRAFT

CONTENTS
(continued)

Page

LIST OF FIGURES

LIST OF TABLES

DRAFT

INTRODUCTION

The Sequoyah Nuclear Plant (SQN) was built by the Tennessee Valley Authority (TVA) on the right bank of Chickamauga Reservoir, at Tennessee River Mile (TRM) 484.5. The plant is about 18 miles (29 kilometers) northeast of Chattanooga, Tennessee, and about 13 miles (21 kilometers) upstream of Chickamauga Dam (Figure 1). The reservoir in the vicinity of SQN can be characterized as having a roughly rectangular main channel approximately 900 feet (274 meters) wide and 50 to 60 feet (15 to 18 meters) deep, depending on the pool elevation, with extensive and highly irregular overbank areas which are usually less than 20 feet (6.0 meters) deep (Figure 2).

The two-unit Sequoyah Nuclear Plant has a net generating capacity of 2440 MW_e and an associated waste heat load of 4800 MW_e, or 16.4 x 10^9 Btu/hr. The heat transferred from the steam condensers to the cooling water is dissipated to the atmosphere by way of two natural draft cooling towers, to the river through a two-leg submerged multiport diffuser, or by a combination of both.

Compliance of SQN operation with the instream temperature limits specified in the National Pollutant Discharge Elimination System (NPDES) Permit is based on downstream temperatures which are calculated on a "real-time" basis by a numerical computer model. A calibration study of that model is required by NPDES Permit TN0026450 of August 2001. In particular, Part II, Section G states:

> *The numerical model used to determine compliance with the temperature requirements for Outfall 101 shall be subject of a calibration study once during the permit cycle. The study should be accomplished in time for data to be available for the next permit application for re-issuance of the permit. A report of the study will be presented to the division of Water Pollution Control. Any adjustments to the numerical model to improve its accuracy will not need separate approval from the Division of Water Pollution Control; however, the Division will be notified when such adjustments are made.*

This report documents the findings of the required calibration study.

DRAFT

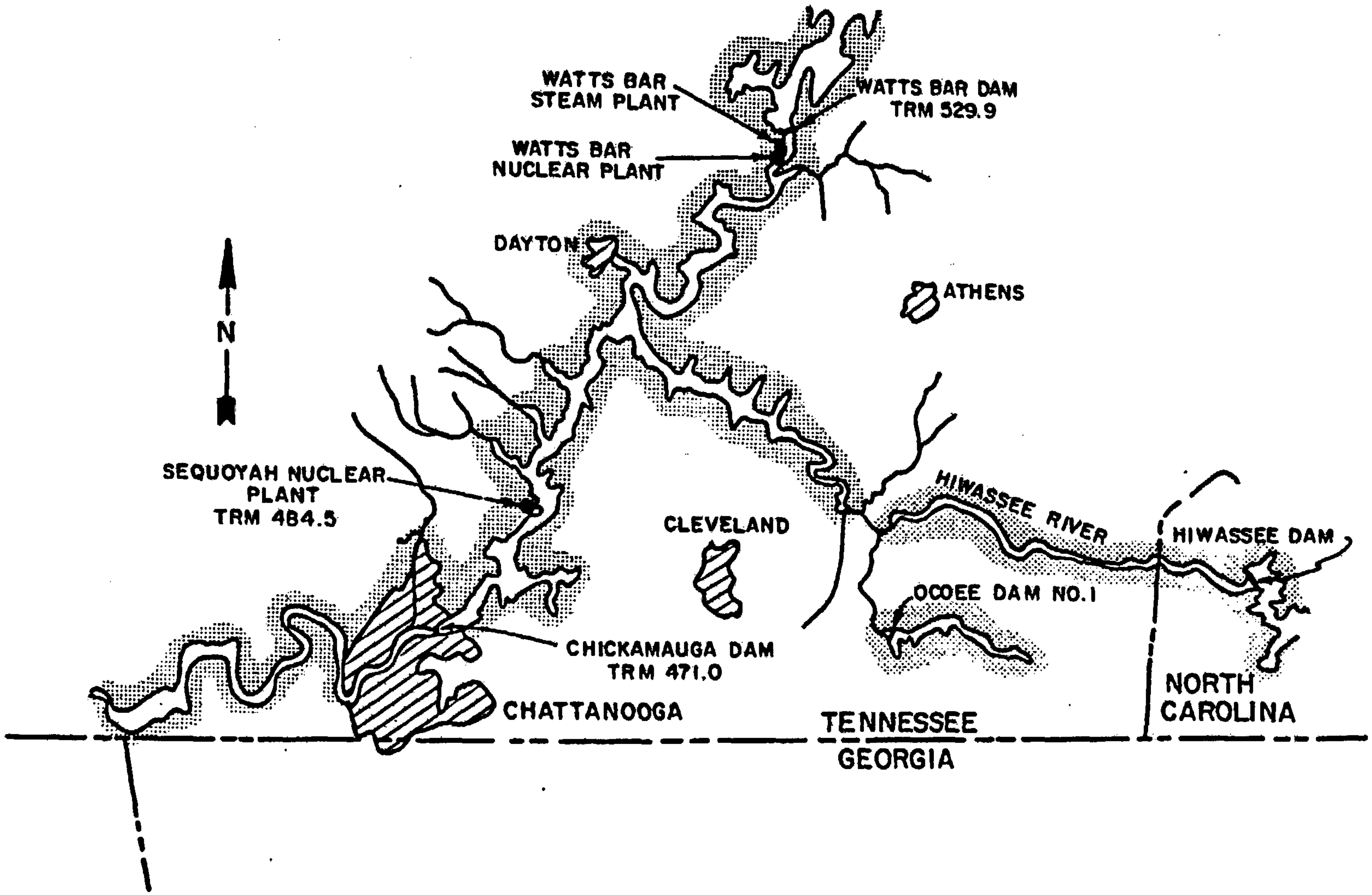


Figure 1. Location of the Sequoyah Nuclear Plant

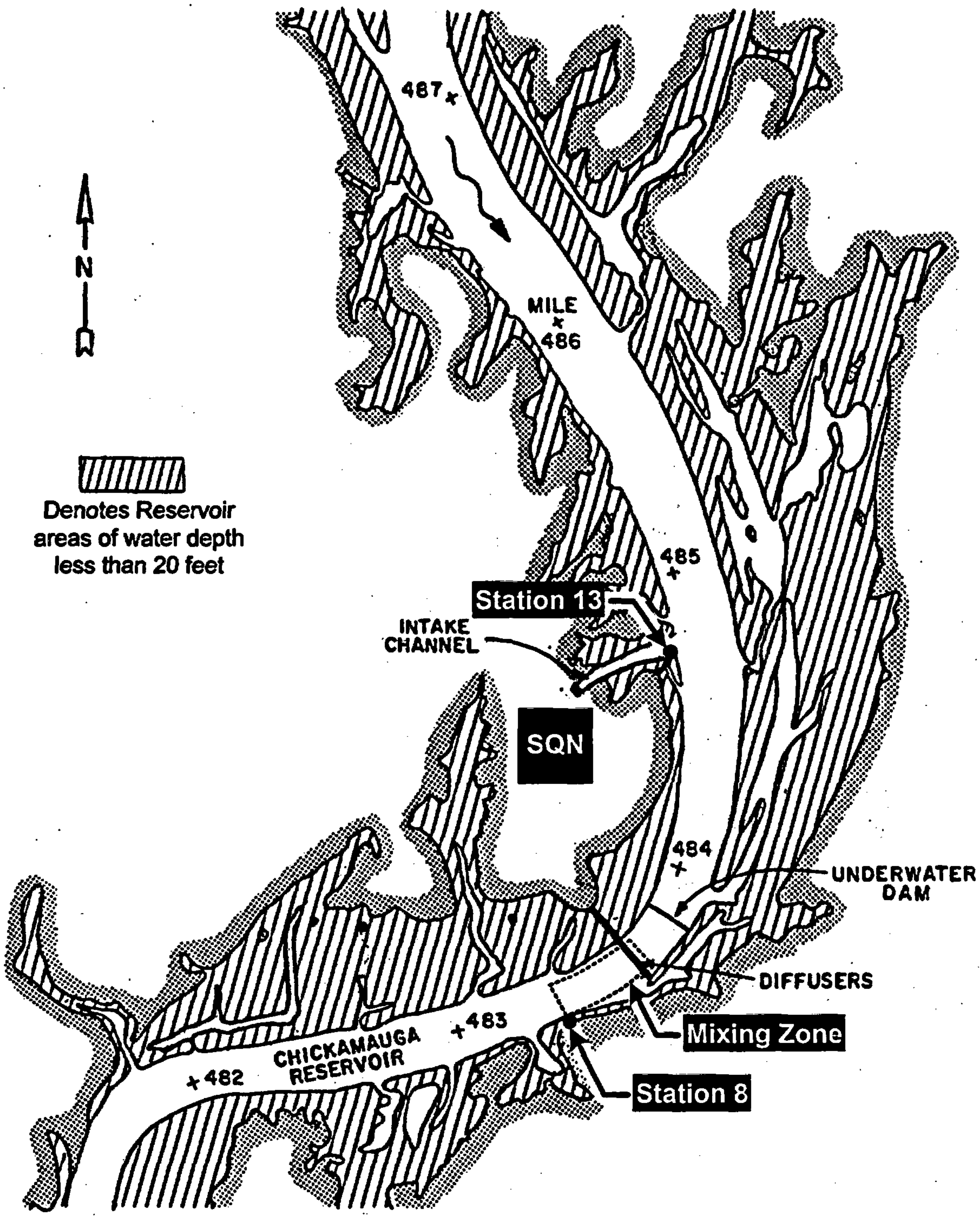


Figure 2. Chickamauga Reservoir in the Vicinity of Sequoyah Nuclear Plant

DRAFT

BACKGROUND

In August 1983, the Tennessee Valley Authority (TVA) reported the results of six field studies of the Sequoyah Nuclear Plant (SQN) diffuser performance under various environmental and plant operating conditions (TVA, 1983a). One purpose of that report was to support the use of computerized compliance as a method for verifying compliance with the thermal limitations in the NPDES Permit for the plant. The field validations from the report showed that the temperature variation that occurs in space and time at the downstream edge of the mixing zone made the use of the two downstream temperature monitors, then in place, inadequate for obtaining a representative cross-sectional average temperature. Because of the necessity to maintain an unobstructed navigation channel, a temperature monitoring station could not be positioned downstream of the mid-point of the diffuser. Instead, two monitors were placed at the edges of the navigation channel, one downstream of either end of the diffuser (Figure 3). It was found that Station 11, at that time located on the right side of the river (looking downstream), was normally not in the main flow path of the discharge plume and did not always show elevated temperatures. Station 11 has subsequently been removed. The remaining downstream monitor, Station 8, may not be in an ideal location because it must also be positioned outside the navigation channel.

In the report, TVA described the use of a dedicated microcomputer to provide real-time assessment of compliance with thermal discharge limitations in Chickamauga Reservoir. The condenser waste heat is discharged to the reservoir through two multiport diffusers located on the riverbed. The procedure for evaluating the effects of the thermal discharge upon the river temperatures requires data gathered at the intake and discharge of the plant and from upstream and downstream dams. A microcomputer, located in the Environmental Data Station (EDS), is used to compute the plant-induced effects upon river temperatures (TVA, 1983b).

The August 1983 report was sent to the Environmental Protection Agency (EPA) and the State of Tennessee (TN) requesting approval to use the computerized compliance as the first method of verifying thermal compliance. The advantages of the method include an improved representation of downstream temperatures (cross-sectional averages) that is at least as good as the instream temperature measurements. The computerized compliance method also provides consistency in the modeling that is used for scheduling upstream and downstream dam releases and SQN operation to meet the thermal limits. The consistency in modeling allows TVA to minimize the number and duration of thermal noncompliances. The operators and schedulers can anticipate undesirable thermal conditions and implement changes that will ensure compliance with the thermal limits in a timely fashion.

The current instream temperature limits for the SQN diffuser (Outfall 101) are summarized in Table 1. Compliance with instream temperature limits are based on computed downstream temperatures at a depth of 5.0 feet. Upstream temperatures are measured at the 5.0-foot depth at monitoring Station 13, located on the SQN intake skimmer wall. A spatial average of measurements at depths of 3.0, 5.0, and 7.0 feet is used as the primary backup downstream temperature measurement in the event of computer failure or invalid or missing input data for the computed downstream temperature.

DRAFT

The model is calibrated by adjusting the plume entrainment coefficient and effective diffuser slot width to achieve the best match of the computed downstream temperatures with field survey measurements and recorded instream monitor data. Higher priority is given to matching data from field surveys, since those measurements are made across the entire width of the plume mixing zone and, therefore, are believed to be more representative of the plume than data from the backup compliance monitor (Station 8), which is limited to the left edge of the mixing zone.

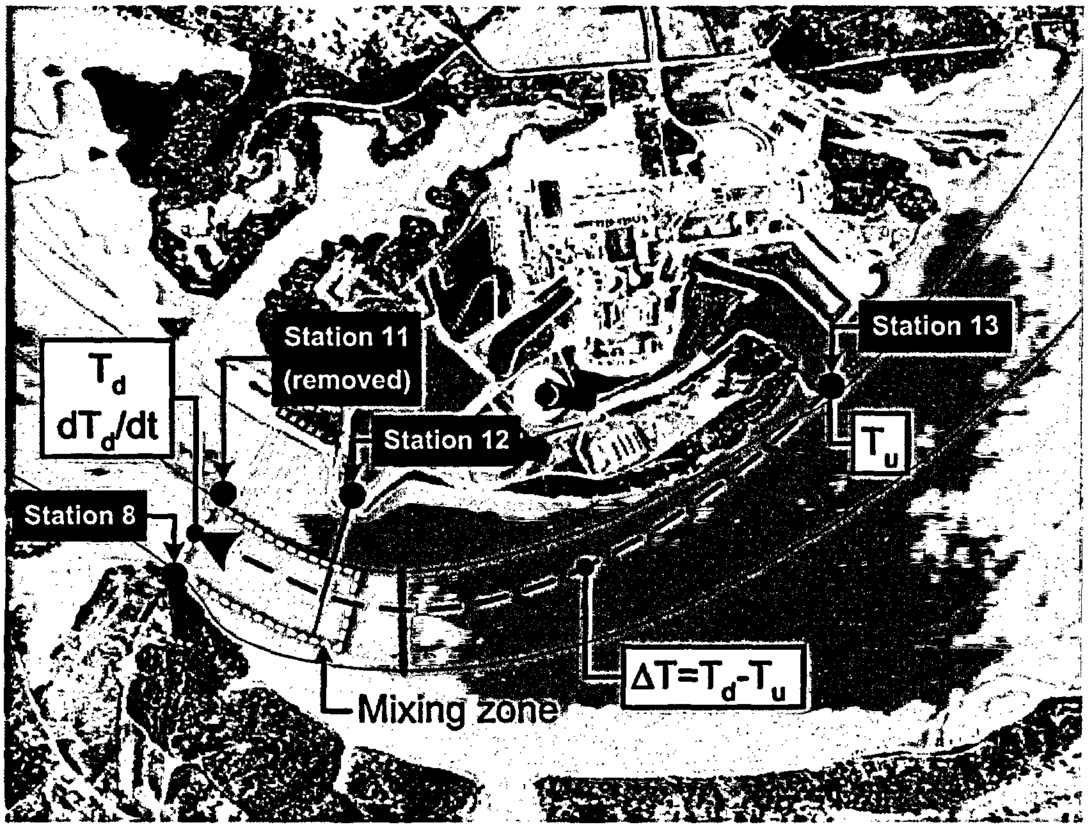


Figure 3. Locations of Instream Temperature Monitors at Sequoyah Nuclear Plant

Table 1. Summary of Instream Thermal Limits for SQN Outfall 101

Type of Limit	Averaging Period (hours)	NPDES Limit[2]
T_{max}[1]	24[3]	86.9°F (30.5°C)[4]
T_{max}[1]	1	93.0°F (33.9°C)
ΔT[1]	24[3]	5.4 / 9.0 F° (3.0/5.0C°)[5]
dT/dt	Mixed[6]	± 3.6 F°/hr (2.0 C°/hr)

Notes:

1. Compliance with the river limitations (river temperature, temperature rise, and rate of temperature change) shall be monitored by means of a numerical model that solves the thermohydrodynamic equations governing the flow and thermal conditions in the reservoir. This numerical model will utilize measured values of the upstream temperature profile, flow, and temperature of the diffuser discharge, releases at Watts Bar and Chickamauga Dams, and the diffuser performance characteristics. In the event that the modeling system described here is out of service, an alternate method will be employed to measure water temperatures at least one time per day. Depth average measurements can be taken at a downstream backup temperature monitor (left bank TRM 483.4) or by grab sampling from boats. Boat sampling will include average 5-foot depth measurements (average of 3-, 5-, and 7-foot depths). Sampling from a boat shall be made outside the skimmer wall and at quarter points and mid-channel at downstream TRM 483.4. Sampling from boats will be used to verify compliance with temperature rise and maximum river temperature limits. The downstream reported value will be a depth (3-, 5-, and 7-foot) and lateral (quarter points and midpoint) average of instream measurements. Monitoring in the alternative mode using boat sampling shall not be required when unsafe boating conditions occur.
2. Compliance with river temperature, temperature rise, and rate of temperature change limitations shall be applicable at the edge of a mixing zone which shall not exceed the following dimensions: (1) a maximum length of 1500 feet downstream of the diffusers, (2) a maximum width of 750 feet, and (3) a maximum length of 275 feet upstream of the diffusers. The depth of the mixing zone measured from the surface varies linearly from the surface 275 feet upstream of the diffusers to the top of the diffuser pipes and extends to the bottom downstream of the diffusers. When the plant is operated in closed mode, the mixing zone shall also include the area of the intake forebay.
3. Daily maximum temperatures for the ambient temperature upstream of the discharge, the downstream river temperature at the edge of the mixing zone, and temperature rise shall be determined from 24-hour average values. The average temperature shall be calculated every 15 minutes using the previous 24 hours of data, thus creating a 'rolling' average. The maximum of the ninety-six averaged observations generated by this procedure shall be reported as the daily maximum value.
4. The maximum 24-hour average river temperature is limited to 30.5°C as a daily maximum. Since the state's criteria makes exception for exceeding the value as a result of natural conditions, where the 24-hour average ambient temperature exceeds 29.4°C and the plant is operated in helper mode (full operation of one cooling tower, at least three lift pumps, per operating unit), the maximum temperature may exceed 30.5°C. In no case shall the plant discharge cause the 1-hour average downstream river temperature to exceed the temperature of 33.9°C without the consent of the permitting authority.
5. The 24-hour average temperature rise shall be computed ninety-six times at 15-minute intervals. The temperature rise is the difference between the upstream ambient 24-hour average river temperature and the 24-hour average downstream temperature at the edge of the mixing zone for that 15-minute interval. The 24-hour average temperature rise shall be limited to 3.0 C° during the months of April through October. The 24-hour average temperature rise shall be limited to 5.0 C° during winter operation months of November through March.
6. The rate of temperature change instream shall be computed at 15-minute intervals based on the current 24-hour average ambient temperature, current 24-hour-hour average river flow, and current values of flow and temperature of water discharging through the diffuser pipes (recorded every 15 minutes). The 1-hour average rate of temperature change shall be calculated for each 15-minute interval by averaging that 15-minute value with the previous four 15-minute values. The 1-hour average rate of temperature change shall be limited to 2 C° per hour.

MODEL SUMMARY

The diffusers at SQN lie submerged at the bottom of the navigation channel of Chickamauga Reservoir. Each diffuser leg is 350 feet long, and contains seventeen 2-inch ports per linear foot of pipe arranged in seventeen rows over an approximately 18 degree arc of the pipe (Figure 4). The two diffuser legs rest on an elevated pad approximately 10 feet above the channel bottom, occupying the 700 feet of navigation channel nearest the plant (left side of the channel, looking downstream). The flow field in the immediate vicinity of the holes is far too complex to be analyzed on a real-time basis with current computer technology. Therefore, a simplifying assumption must be made that the diffuser can be treated as a slot jet with a length equal to that of the perforated sections of the pipe. The width of this assumed slot then becomes one of two empirical constants or relationships which are used to calibrate the model; the other is the coefficient used to compute the entrainment of ambient water at the turbulent boundaries of the plume.

The development of the current diffuser model is described in detail by Benton (2003), and will only be summarized here. The model is a two-dimensional numerical solution of the equations conservation of momentum, mass, and energy for a submerged diffuser in a thermally stratified cross-flow. The governing differential equations are solved by a fourth-order Runge-Kutta scheme, using measured diffuser discharge flow and temperature, upstream temperature profile and river surface elevation, and river flow and velocity computed by a one-dimensional unsteady flow model as boundary conditions. The inputs to the river flow model are measured releases at the upstream and downstream dams (Watts Bar and Chickamauga Hydro Plants) and the measured river surface elevation at SQN.

The downstream temperature and instream temperature rise are computed at 15-minute intervals, using instantaneous values of measured diffuser discharge flow and temperature, upstream temperature profile, and river elevation, and computed river flow, which is, in turn based on measured upstream and downstream hydro releases. All computations are performed once every 15 minutes. One-hour and 24-hour averages are computed from the 15-minute solution results. The one-hour averages are based on the last four 15-minute values, while the 24-hour averages are based on the last ninety-six 15-minute values.

The rate of instream temperature change is computed differently, being computed at 15-minute intervals based on the current 24-hour average ambient temperature, current 24-hour average river flow, and current values of flow and temperature of water discharging through the diffuser pipes. This method was adopted in August 2001, in order to distinguish between rate of instream temperature change due to changes in SQN operations (i.e., changes in discharge flow and/or temperature) and non-SQN induced temperature changes such as passage past the plant of "packets" of water which have been raised to higher than normal ambient surface temperatures in upstream shallow embayments and then flushed downstream by unsteady river flows. Prior to this change, SQN was held accountable for numerous temperature "spikes" over which it had no control and very little influence.

DRAFT

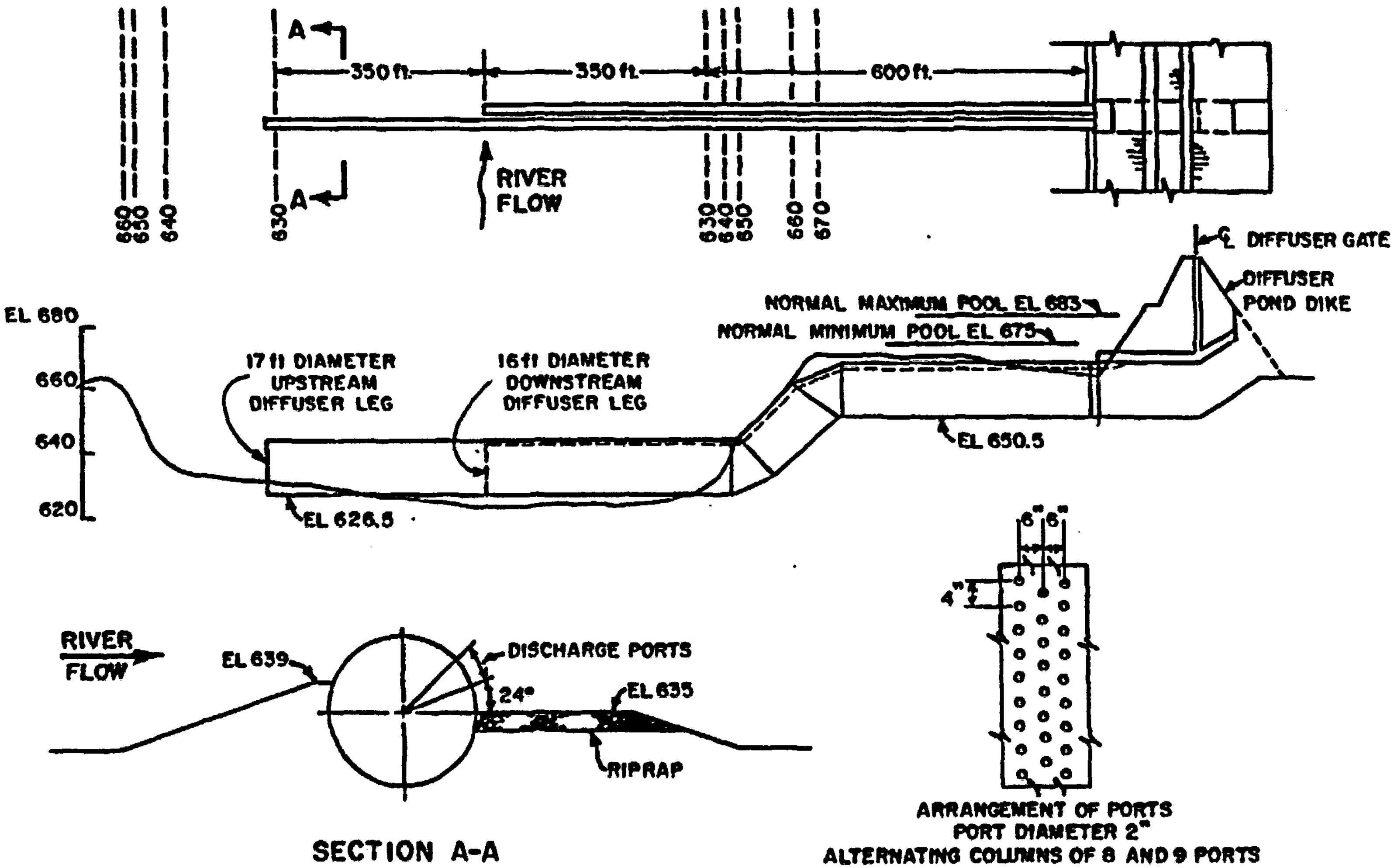


Figure 4. Sequoyah Nuclear Plant Diffuser Design Details

CALIBRATION

Previous Calibrations and Field Surveys

Calibrations and/or field surveys were performed in 1981, 1982, 1983, 1987, 1996, 1997, 1999, 2000, 2002, and 2003. On July 24, 1981, TVA conducted a test under one unit SQN operation (TVA, 1982). Ambient temperatures ranged from 82.4°F (28°C) at the surface to 78.8°F (26°C) in the bottom layers. The diffuser discharge was 1240 cfs at a temperature of about 102.2°F (39°C). Adequate agreement was achieved with measured data and model projections. In cases where there were discrepancies, the model under-predicted the observed dilutions (over-predicted temperatures).

Between April 1982 and May 1983, six field surveys were performed to acquire data for validation of the computed compliance technique (TVA, 1983a). Only one SQN unit was operating during the March 1983 test; the other five tests were for two-unit operation. The results of the simulation program compared favorably with the field-measured downstream temperatures. On average, the discrepancy between the measured and computed downstream temperatures was 0.4 F° (0.22 C°). Considering that the accuracy of the temperature sensors is 0.25 F° (±0.14 C°), the agreement between the field measurements and the computer model is quite close. A similar comparison of the monitored temperatures with the measured lateral averages revealed that the discrepancy for Station 8 was 0.79 F° (0.44 C°) and for Station 11 was 0.65 F° (0.36 C°). Consequently, it was concluded that the computerized compliance method not only provides an accurate representation of the downstream temperature, but also is superior to the monitored approach. The results of these surveys are shown in Table 2.

In 1987, TVA released a report describing the field surveys in support of SQN computed compliance validation and calibration which had been performed up to that date (TVA, 1987). In addition, a table was introduced which described the ambient and operational conditions for which field surveys had been performed or were still needed. This table indicated combinations of river flow, time of year, and number of operating units, showing which tests had been performed, and assigning relative priorities for tests which were still needed.

New Calibration Data

Since March 1996, six field surveys have been performed to measure downstream temperatures with various river flows and at different times of year. The results of these surveys are shown in Table 3.

Diffuser Slot Width

The effective slot width for a multiport diffuser of the type at SQN can logically be assumed to fall somewhere between the width of a rectangle with the same length as the perforated diffuser section and area equal to the total area of the ports, and that a rectangle of the same length, but

Table 2. Thermal Surveys at Sequoyah Nuclear Plant from April 1982 through March 1983

DATE	TIME	River		(All temperature data in these columns are hourly averages.)				
				T-Upstream	T-Downstream		Temp Rise	
		Flow cfs	Elev ft	Measured °F	Measured °F	Computed °F	Measured F°	Computed F°
04/04/1982	0900 CST	19900	676.46	56.8	61.9	61.0	5.1	4.2
04/04/1982	1000 CST	19800	676.46	56.7	60.1	61.1	3.4	4.4
04/04/1982	1100 CST	19600	676.47	56.7	61.2	61.0	4.5	4.3
04/04/1982	1200 CST	19700	676.50	57.2	61.9	61.4	4.7	4.2
04/04/1982	1300 CST	19700	676.45	57.4	62.2	61.5	4.8	4.1
05/14/1982	0900 CDT	7200	682.43	74.5	71.8	74.5	-2.7	0.0
05/14/1982	1100 CDT	9100	682.40	73.4	71.8	73.4	-1.6	0.0
05/14/1982	1300 CDT	6300	682.42	72.1	73.6	72.1	1.5	0.0
09/02/1982	1400 CDT	38500	680.30	78.1	80.1	79.8	2.0	1.7
11/10/1982	1300 CST	36200	677.57	59.0	60.1	60.3	1.1	1.3
11/10/1982	1400 CST	31600	677.59	59.0	60.6	60.6	1.6	1.6
11/10/1982	1500 CST	32300	677.58	59.0	60.4	60.5	1.4	1.5
03/31/1983	1100 CST	9800	676.34	51.4	54.3	54.3	2.9	2.9
03/31/1983	1200 CST	9400	676.34	50.4	54.7	54.2	4.3	3.8
03/31/1983	1300 CST	9300	676.34	52.5	54.5	54.4	2.0	1.9
03/31/1983	1400 CST	9500	676.34	51.4	54.9	54.4	3.5	3.0
03/31/1983	1500 CST	9400	676.36	51.4	54.9	54.4	3.5	3.0

Table 3. Thermal Surveys at Sequoyah Nuclear Plant from March 1996 through April 2003

DATE	TIME	River		(All temperature data in these columns are hourly averages.)				
				T-Upstream	T-Downstream		Temp Rise	
		Flow cfs	Elev ft	Measured °F	Measured °F	Computed °F	Measured F°	Computed F°
3/1/1996	0929 – 1059 CST	42456	676.96	45.9	48.8	47.0	2.9	1.1
	1344 – 1444 CST	28136	677.04	46.2	50.2	49.0	4.0	2.8
	1444 – 1559 CST	21962	677.00	46.1	51.4	50.6	5.3	4.5
	1629 – 1659 CST	20280	677.00	46.0	51.5	50.9	5.5	4.9
7/24/1997	1356 – 1548 CDT	40441	682.57	83.5	84.7	84.2	1.2	0.6
3/24/1999	1137 – 1251 CST	35731	677.46	51.9	54.5	53.2	2.7	1.3
8/2/2000	0744 – 0959 CDT	12472	682.20	82.1	85.1	85.2	3.0	3.2
	0959 – 1103 CDT	8624	682.20	82.1	85.3	85.3	3.1	3.2
7/27/2002	1133 – 1251 CDT	17231	682.37	84.0	86.6	86.1	2.6	2.1
4/23/2003	1328 – 1444 CDT	34178	682.53	63.7	64.2	64.2	0.5	0.5

with area equal to the arc length of the perforated section of the diffuser. For the SQN diffuser, this slot width would be between 0.37 and 2.67 feet. Five slot widths ranging in equal increments from 0.37 foot to 3.437 feet were evaluated and compared with 27 measured data points from field surveys. The results, shown in Figure 5, were relatively insensitive to the assumed initial slot width, with only slightly better agreement with measured data being attained for the larger widths. The nominal arc length of the perforated section of the diffuser (2.67 feet) is therefore used as the diffuser slot width in the model.

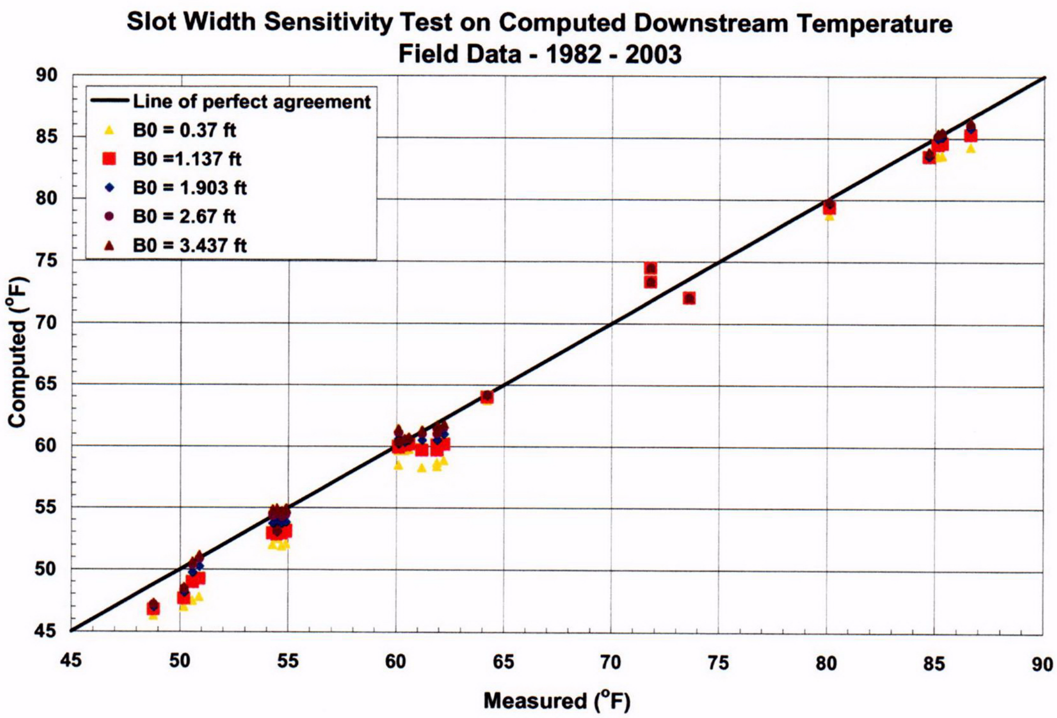


Figure 5. Sensitivity of Computed Downstream Temperature to Diffuser Effective Slot Width

Plume Entrainment Coefficient

Two empirical relationships for the plume entrainment coefficient were evaluated. The first, proposed by McIntosh, was inferred for a slot diffuser from a relationship for the entrainment coefficient from the data reported by TVA (1983a).

$$\alpha = \begin{cases} 0.27, F_r < 0.75 \\ 0.27 / F_r^{2.5}, 0.75 \le F_r \le 1.00 \\ 0.55, F_r > 1.00 \end{cases}. \quad (1)$$

The densimetric Froude number, F_r, is determined by

C16

$$F_r = w_0 / \sqrt{g B_0 |\rho_p - \rho_0| / \rho_0}\,, \tag{2}$$

where w_0 is the initial discharge mass flux; g is the gravitational constant; B_0 is the diffuser slot width; ρ_p is the density of the diffuser discharge, and ρ_0 is the density of the ambient river water at the discharge depth.

The second entrainment coefficient, based on laboratory data, was developed by Benton in 1986 and is given by

$$\alpha = 0.31 + 1.69(1 + tanh(6.5430 \times rmf - 2.0584))/2\,, \tag{3}$$

where

$$rmf = U^3 / b\,, \tag{4}$$

and

$$b = Q_0 \times (g/l) \times ((\rho_0 - \rho_p)/\rho_0)\,, \tag{5}$$

where U is the ambient river velocity; Q_0 is the diffuser discharge flow rate, and l is the length of the ported section of the diffuser.

Figure 6 shows the comparison with measured data of downstream temperatures computed with the McIntosh and Benton entrainment coefficients (i.e., Equation 1 and Equation 3, respectively). Both entrainment coefficients result in relatively close matches with the measured data. Although the McIntosh coefficient seems to perform better at low ambient river temperatures, temperatures computed using the Benton coefficient more closely match measured downstream temperatures at higher river temperatures. Since the accuracy of the computation is more critical at temperatures approaching the NPDES limit, the Benton coefficient is currently used in the compliance monitoring program.

Results of Updated Calibration

Computed and measured downstream temperatures for the 27 downstream temperature data points collected in SQN field surveys since March 1982 are shown in Figure 7. The average discrepancy between the measured and computed downstream temperatures was 0.68 F° (0.38 C°). For downstream temperatures above 75°F, the average discrepancy improved to 0.40 F° (0.22 C°).

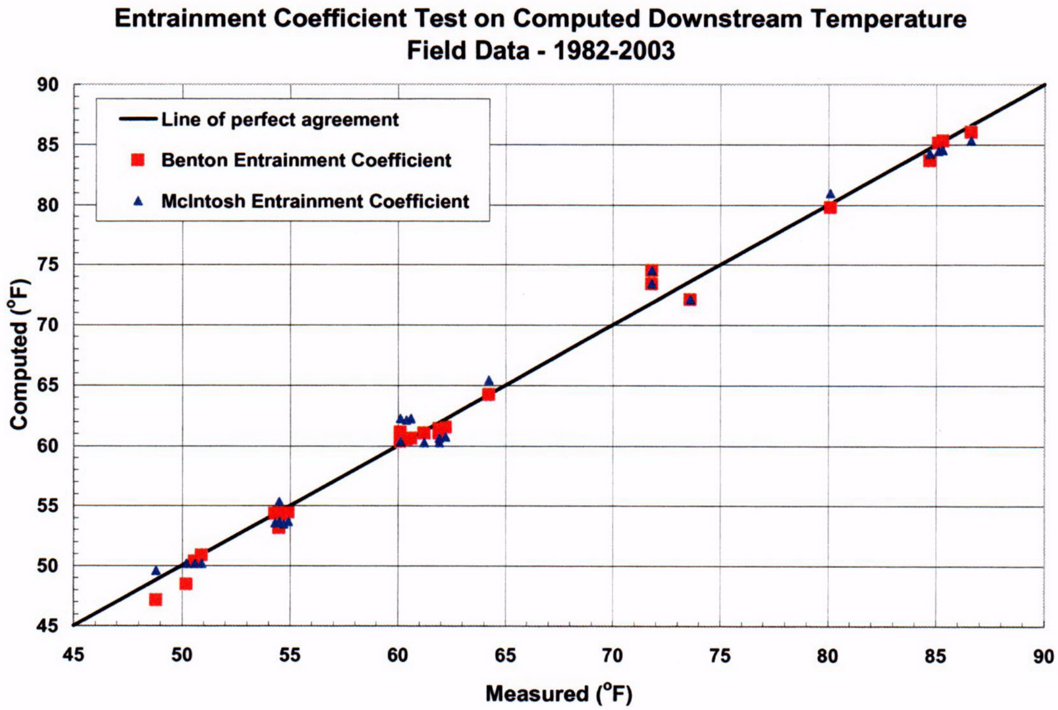


Figure 6. Sensitivity of Computed Downstream Temperature to Plume Entrainment Coefficient

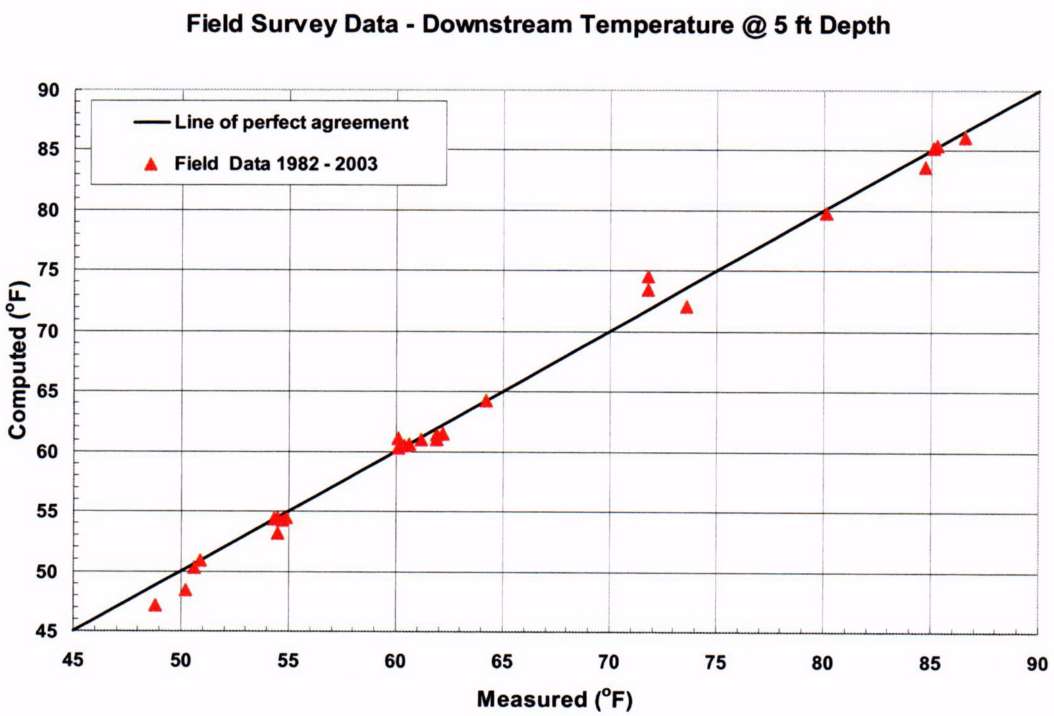


Figure 7. Comparison of Computed and Measured Downstream Temperatures for Field Studies from April 1982 through April 2003

Measured downstream 24-hour averaged temperatures from the downstream temperature monitor (Station 8) are compared to computed values in Figure 8. The figure shows data collected since the adoption of the 24-hour averaging period in August 2001 through mid-October 2002. The data includes a period in December 2001, when one of the temperature probes began to fail, resulting in erroneously high measured temperatures. The overall average discrepancy between the measured and computed 24-hour averaged downstream temperatures was 0.63 F° (0.35 C°), and was 0.31 F° (0.17 C°) for downstream temperatures above 75°F. Measured downstream hourly averaged temperatures from the same time period are compared to computed values in Figure 9. As should be expected, the temperature data are much more widely scattered for the hourly averaged temperatures. The average discrepancy between the measured and computed hourly averaged downstream temperatures was 0.94 F° (0.52 C°) for the full range of river temperatures, decreasing to 0.55 F° (0.31 C°) for downstream temperatures above 75°F.

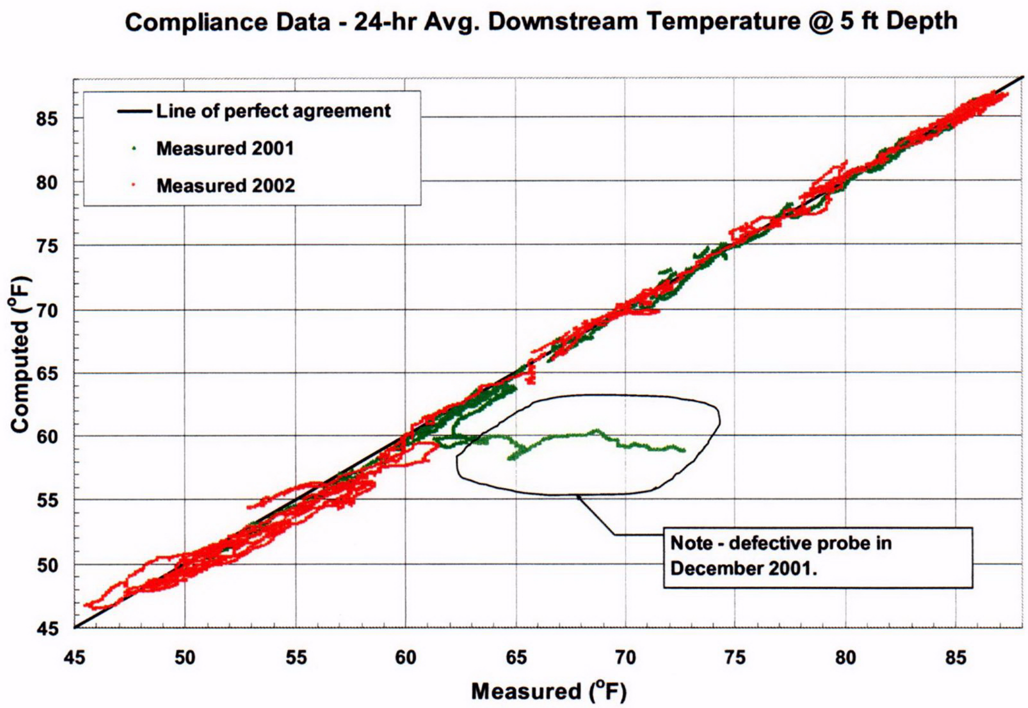


Figure 8. Comparison of Computed and Measured 24-Hour Averaged Downstream Temperatures from Compliance Monitoring Records for 8/09/2001 through 10/15/2002

C18

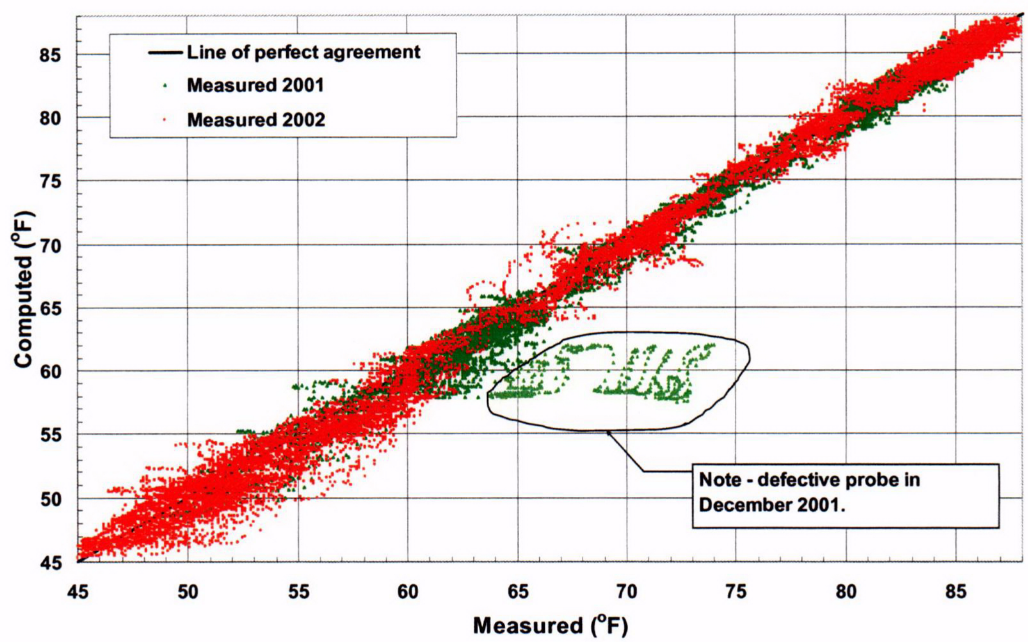


Figure 9. Comparison of Computed and Measured Hourly Averaged Downstream Temperatures from Compliance Monitoring Records for 8/09/2001 through 10/15/2002

CONCLUSIONS

The model appears to compute the temperature at the downstream end of the mixing zone with sufficient accuracy for use as the primary method of verifying thermal compliance. The current calibration appears to be more accurate at higher river temperatures than at lower temperatures. This is considered acceptable, since the accuracy is more critical as the downstream temperatures approach the NPDES instream limit(s). Any future calibration efforts intended to improve accuracy at lower river temperatures should place a high priority on maintaining accuracy at the more critical higher river temperatures.

REFERENCES

1. TVA (1982), "A Field Verification of Sequoyah Nuclear Plant Diffuser Performance Model One-Unit Operation," Report No. WR28-1-45-110, TVA Division of Air and Water Resources, Water Systems Development Branch, October 1982.

2. TVA (1983a), "Validation of Computerized Thermal Compliance and Plume Development at Sequoyah Nuclear Plant," Report No. WR28-1-45-115, Tennessee Valley Authority, Division of Air and Water Resources, Water Systems Development Branch, August 1983.

3. TVA (1983b), Real-Time Computation of Compliance with Thermal Water Quality Standards, Proceedings of Microcomputers in Civil Engineering, University of Central Florida, Orlando, Florida, November 1983.

4. TVA (1987), "Quality Program for Verification of Sequoyah Nuclear Plant Thermal Computed Compliance System," Report No. WR28-3-45-134, Tennessee Valley Authority, Office of Natural Resources and Economic Development, Division of Air and Water Resources, September 1987.

5. Benton, Dudley J. (2003), "Development of a Two-Dimensional Plume Model," Dynamic Solutions, LLC, Knoxville, Tennessee, May 2003.

June 6, 2003

Stephanie Howard, SB 2A-SQN

SEQUOYAH NUCLEAR PLANT DIFFUSER DISCHARGE CALIBRATION

As required by NPDES Permit TN0026450 for Sequoyah Nuclear Plant effective August 8, 2001, we have updated the calibration for the discharge through the plant diffusers. Part III, Section G of the permit states that *"The permittee shall calibrate the flowrate characteristics through the diffusers on a schedule of at least once every two years."* During the current permit cycle, three tests were conducted to measure the head and discharge for the diffusers, on October 10, 2001, July 27, 2002, and April 23, 2003. A summary of all tests from 1986 through 2003 is given in Attachment 1. Based on a regression analysis, the recommended new rating curve for computing the diffuser discharge is given in Attachment 2. Using this rating curve, the mean square error between the measured and computed discharge is about 5.7 percent. The compliance model and forecast model will be updated with the new curve as soon as possible.

It also is noted that the permit states *"For this permit period, such calibration shall be coordinated with the evaluation of the numerical modeling."* To fulfill this requirement, the river temperature at the downstream end of the diffuser mixing zone also was measured in two of the recent tests, those of July 27, 2002, and April 23, 2003. The results of these measurements will be provided in a separate report summarizing the results of a calibration study of the compliance model, also required by Part III, Section G of the permit.

If you have any questions regarding this work, please call Meihuei Lee at 423-632-1897.

Paul N. Hopping

Paul N. Hopping
Technical Specialist
River Operations
LAB 2C-N

PNH:CP
Attachments
cc (Attachments):
Alan Gordon, OPS 3C-SQN
Ann Hurt, SB 2A-SQN
Kate Kalember, LAB 2C-N
Meihuei Lee, LAB 2C-N
Michael McCall, LAB 2C-N
Files, WT 10C-K

Attachment 1

Calibration Data for SQN Diffuser Discharge, 1986 – 2003

Test Date	Number Of Pumps		Field Measurements				
			Discharge Measurement Method [(A)]	Water Surface Elevation [(B)]		Diffuser Head H	Diffuser Discharge Q
				Diffuser Pond	River		
	CCW	ERCW		(feet MSL)	(feet MSL)	(feet)	(cfs)
12/18/1986	2	4	MM	678.03	677.00	1.03	889
12/17/1986	3	4	MM	678.46	676.90	1.56	1,297
12/18/1986	4	4	MM	680.41	676.90	3.51	1,686
12/19/1986	6	4	MM	683.53	677.17	6.36	2,490
03/28/1989	5	4	MM	680.80	676.46	4.34	2,015
03/29/1989	5	4	MM	680.82	676.35	4.47	2,161
03/22/1990	2	3	MM	678.44	677.27	1.17	943
04/05/1990	3	4	MM	680.57	678.54	2.03	1,470
10/05/1990	3	4	MM	682.30	680.20	2.10	1,457
12/19/1990	6	4	MM	682.54	676.26	6.28	2,350
04/03/1991	6	4	MM	684.20	678.18	6.02	2,511
05/22/1991	6	4	MM	688.70	682.60	6.10	2,451
12/10/1991	5	4	MM	682.70	677.90	4.80	2,213
04/10/1992	2	3	MM	680.13	679.12	1.01	879
02/18/1994 [(C)]	2	3	MM	679.42	678.13	1.29	871
06/14/1994	6	4	MM	688.50	682.00	6.50	2,507
04/03/1997 [(D)]	3	3	MM	679.50	677.30	2.20	1,223
05/23/1997	6	3	MM	688.40	681.80	6.60	2,551
05/06/1998	6	3	ADCP	688.20	681.70	6.50	2,345
05/11/1999	6	3	ADCP	689.20	682.60	6.60	2,274
10/10/2001	6	3	ADCP	687.10	680.30	6.80	2,359
07/272002	6	4	ADCP	689.40	682.40	7.00	2,759
04/23/2003	3	4	ADCP	684.05	682.20	1.85	1,552

Notes:

(A) MM=Marsh-McBirney instrumentation. ADCP=Acoustic Doppler Current Profiler instrumentation.

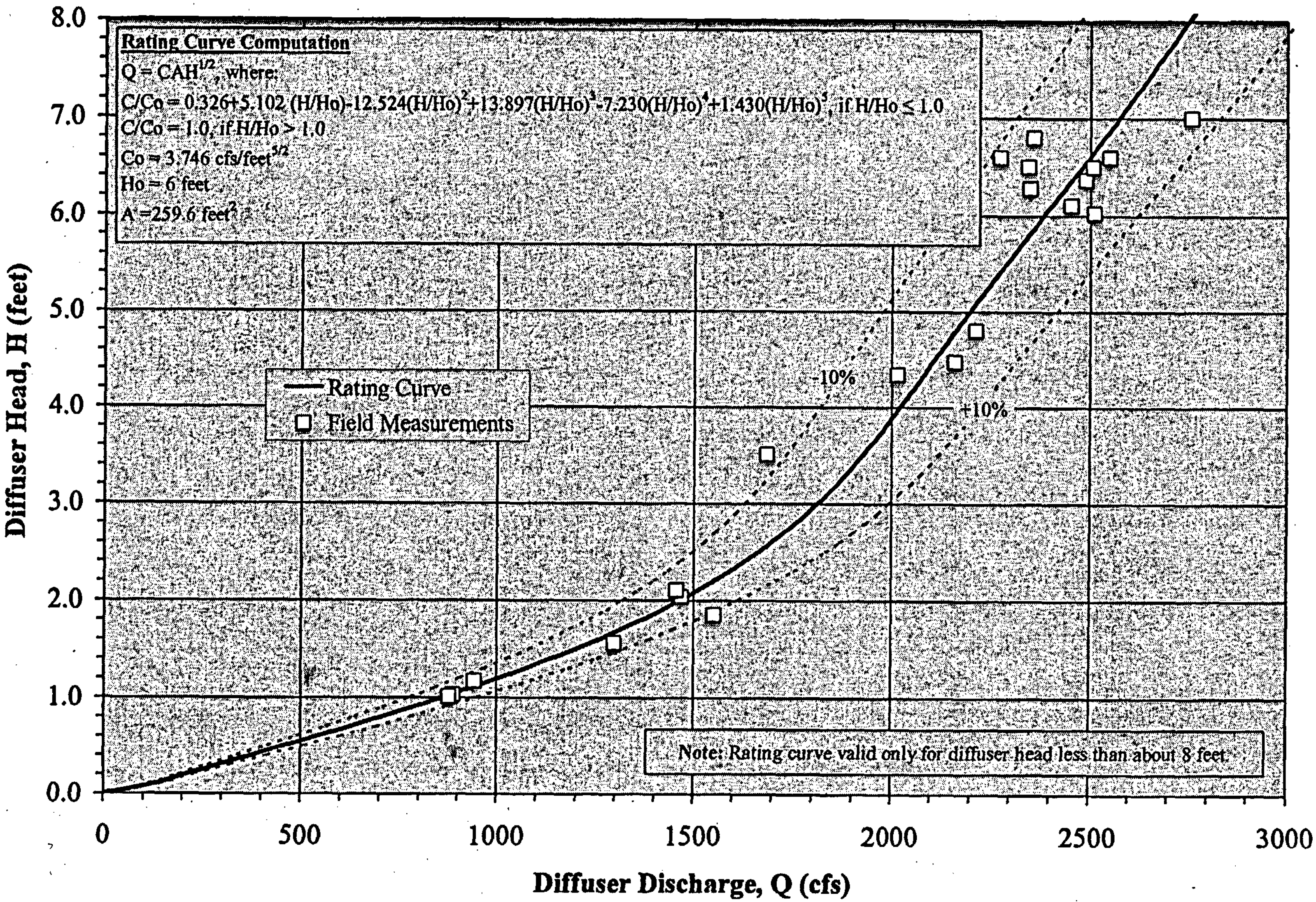
(B) The diffuser pond and river water surface elevations were recorded by instrumentation of the SQN Environmental Data Station. MSL=Mean Sea Level.

(C) The test for 02/18/94 was performed after high rainfall and under very windy conditions. Due to the potential bias of these conditions, the resulting measurements are not used to determine the head-discharge rating curve for the diffuser discharge.

(D) The test of 04/03/97 included a malfunction of the Marsh-McBirney compass, which prohibited the collection of data for flow direction. The diffuser discharge is based on an assumed flow direction. Due to the potential bias of this assumption, the resulting measurements are not used to determine the head-discharge rating curve for the diffuser discharge.

Attachment 2

Rating Curve for SQN Diffuser Discharge



PREVIOUS PERMIT LIMITS AND MONITORING REQUIREMENTS (continued)

PERMIT LIMITS

OUTFALL 110

Condenser Cooling Water, Essential Raw Cooling Water, Raw Cooling Waters, and Storm Water Runoff

	EFFLUENT LIMITATIONS				MONITORING REQUIREMENTS	
	MONTHLY		DAILY			
EFFLUENT CHARACTERISTIC	AVG. CONC. (mg/l)	AVG. AMNT. (lb/day)	MAX. CONC. (mg/l)	MAX. AMNT. (lb/day)	MSRMNT. FRQNCY.	SAMPLE TYPE
pH	Range 6.0 - 9.0		Range 6.0 - 9.0		1/7	Grab
TEMPERATURE	--		38.3 Deg.C		1/Day	Mult.Grabs 2/
CHLORINE (Ttl.Res.)	--	--	0.10	--	1/7 1/	Mult.Grabs 2/

Limitations and monitoring requirements are applicable only during periods of closed-mode operation.

There shall be no distinct discharge of floating scum, solids, oil sheen, visible foam, and other floating matter in other than trace amounts.

Samples taken in compliance with the monitoring requirements specified above shall be taken at the following location(s): Recycled cooling water flow prior to entering the Intake Forebay.

1/ Monitoring frequency shall be increased to 1/Day multiple grab any time the discharge is occurring and fish distress or mortality is observed in the Intake Forebay.

2/ Multiple Grabs shall consist of four grab samples collected during one shift each day.