Prepared for

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MIXING ZONE REQUEST
WILLIAM STATES LEE III NUCLEAR STATION
NPDES PERMIT
CHEROKEE COUNTY, SOUTH CAROLINA

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1. INTRODUCTION

Duke Energy Carolinas, LLC (Duke Energy) is making application to the South Carolina Department of Health and Environmental Control (SCDHEC) for a National Pollutant Discharge Elimination System (NPDES) permit for its proposed new William States Lee III Nuclear Generating Station (Lee Nuclear Station) to be constructed in Cherokee County near Gaffney, South Carolina.

This document presents background and technical information supporting formal requests to SCDHEC for Thermal and Whole Effluent Toxicity (WET) mixing zones for the Lee Nuclear Station effluent discharge to the Broad River pursuant to Rule 61-68 (Water Classifications and Standards) Section C.10.

1.1 Facility Description

Lee Nuclear Station will be a twin reactor facility with a total electric generating capacity of approximately 2,200 MWe. A Combined Construction and Operating License (COL) application was prepared for the facility in accordance with U.S. Nuclear Regulatory Commission (NRC) regulations, and submitted to NRC at the end of 2007. Plans are for Lee Nuclear Station to be operational by 2022.

Lee Nuclear Station will use as its primary cooling water source waterbody, an existing impoundment on the Broad River created by the Ninety-Nine Islands Hydroelectric Project. The Ninety-Nine Islands impoundment/reservoir (Ninety-Nine Islands) covers about 430 acres and has a total storage capacity of about 2,300 acre-feet (ac-ft) [Reference 1; Chapter 2]. The reservoir is characterized by three hydrographic areas, the main river channel and two backwater areas that have developed because of sedimentation patterns since impoundment of the river. The two backwater regions exhibit very little circulation during non-flood periods. Therefore, the average transit time through the reservoir is conservatively estimated from the volume of the reservoir along the main channel excluding the backwater areas. Consequently, a storage volume of 570 ac-ft along the main channel results in an average hydraulic retention time of about 3 hours under annual average flow conditions [Reference 1; Chapter 2].

As further described below, the Ninety-Nine Islands Hydroelectric project is regulated by the Federal Energy Regulatory Commission (FERC) who has specified certain minimum water levels to be met in the reservoir and minimum seasonal flows to be released downstream of Ninety-Nine Islands Dam.

1.2 Operational Discharges to the Broad River

As a twin reactor/unit facility, Lee Nuclear Station will require approximately 35,030 gallons per minute (gpm) (78 cubic feet per second (cfs)) of cooling water withdrawal from the Broad River for its closed-cycle cooling system [Reference 1; Chapter 3 – Figure 3.3-1]. An average of approximately 71 percent (24,800 gpm or 55 cfs) of the withdrawal will be consumptive due to evaporative and drift losses from the cooling towers, with 2,000 gpm (5 cfs) returned to the river as screen wash water. In addition to approximately 18 cfs (8,200 gpm) of cooling tower blowdown discharged to the Broad River, other waste streams of much lesser volume include facility process (< 0.28 cfs [< 125 gpm]) and treated radionuclide wastewaters (< 0.009 cfs [<4 gpm]) [Reference 1; Chapter 3 – Figure 3.3-1]. For the purposes of evaluating Lee Nuclear Station discharges to the Broad River, a total average discharge flow from the final outfall (‘*Outfall 001*’) of 18.3 cfs (8,216 gpm; as associated with two-unit, normal operation) was used in the current analyses of mixing as reported herein.

The plant will discharge approximately 18.3 cfs of cooling water blowdown and treated process waters to the Broad River more than 95 percent of the time. Less than 5 percent of the time, blowdown discharge could be as low as 9 cfs or as high as 64 cfs. The variation in atypical discharge flows are associated respectively with scheduled unit refueling outages and adjusted (lower) cooling tower cycling rates when necessary to manage high total solids originating from the cooling water source waterbody .

Discharge to the Broad River will be via a submerged multi-port diffuser, designated as NPDES outfall 001, attached to the upstream face of the Ninety-Nine Islands dam spillway in the western portion of Ninety-Nine Islands reservoir forebay (Figure 1). The diffuser design (see Section 2) will consist of an 88-foot (ft) long pipe, 36 inches inside diameter and having 64, 4-inch holes (ports) spaced 1.4 ft apart discharging horizontally [Reference 2]. Extending horizontally from west to east along the dam (and <u>parallel</u> to flow), the diffuser will be positioned approximately 750 ft from the west shore near the Ninety-Nine Islands dam trash gate, and submerged in the water column (approximate centerline elevation 499.25 ft above mean sea level (msl)) [Reference 1; Chapter 5 – Figure 5.3-4]. At normal water elevation of 511 ft msl, the centerline of the pipe will be submerged approximately 11.75 ft; total river depth at this location is 21 ft.

Based on FERC-specified management of the Ninety-Nine Islands impoundment (see next section), depth of the submerged diffuser could range seasonally from 9.75 to 11.75 ft (greater during flood flows), with the shallower depth associated with low river flows and pulsed operation of the Ninety-Nine Islands Hydroelectric facility; conditions that occur rarely.

The Lee Nuclear Station cooling water system may potentially reach a discharge temperature of 91°F during critical summertime conditions of high ambient river and air temperatures, and seasonally low flows. However, as presented later, a discharge temperature of 95°F was also considered in the mixing zone modeling as a rare worst case scenario. Duke Energy is requesting the thermal mixing zone associated with the postulated 95°F discharge temperature as this approach provides added conservatism to the compliance format. Maximum discharge temperatures would be expected to occur during extreme summertime conditions when water temperature and ambient air temperatures are at their seasonal highs.

Additional details about the Lee Nuclear Station cooling water and process wastewater system, including a water balance diagram, have been provided on SCDHEC/U. S. Environmental Protection Agency (EPA) Forms 1 and 2D of the primary NPDES application package.

1.3 Ninety-Nine Islands Dam Operations

Duke Energy's Ninety-Nine Islands Dam is located on the Broad River approximately 4.5 river miles downstream from the Cherokee Falls Dam and is operated under a FERC license (FERC Project No. 2331) [Reference 3]. The Ninety-Nine Islands Dam and associated hydroelectric plant were constructed in 1910, and the dam structure is a concrete gravity dam. The facility operates as a modified peaking plant where the reservoir, augmented by inflow, supports daily operation (i.e., there is no appreciable storage volume).

Although initially designed with six hydroelectric power turbine units, currently only Units 1-4 are operable. Units 5 and 6 are not currently operable. Units are numbered sequentially from the east side of the powerhouse beginning with Unit 1. Thus, the two idled units are those located closest to the proposed Lee Nuclear Station discharge diffuser. Range in approximate distance from the end of the proposed discharge diffuser to the turbine units is 130 ft (Unit 6) to 260 ft (Unit 1). Currently, the closest operable unit (Unit 4) is approximately 175 ft from the end of the proposed discharge diffuser. At normal water elevation (511 ft. msl), the centerline elevation of the turbine inlets is approximately 494.1 ft msl [Reference 3], or about 5 ft deeper than the centerline elevation of the proposed Lee Nuclear Station discharge diffuser (499.25 ft msl). Note a trash gate is located adjacent to the powerhouse approximately 70 feet west of Unit 4. It is estimated that the trash gate discharges approximately once a week for 20 to 30 minutes in order to remove leaves and debris. In the fall season the discharge may occur twice a week for 20 to 30 minutes.

During normal river flows, the Ninety-Nine Islands hydroelectric generating units are operated within the FERC license-specified drawdown limits[1] for the reservoir (1 ft below full reservoir (511 ft msl) from March through May and 2 ft below full reservoir from June through February) [Reference 4]. Total hydraulic capacity of the 20 megawatt (MW) Ninety-Nine Islands Dam powerhouse (six units authorized) is 5,220 cfs [Reference 3]. Hydraulic capacity of the four currently operable units (Nos. 1-4; rated at ~14.450 MW total) is 3,510 cfs; thus, as currently configured/operated, the Broad River flows in excess of this amount pass over the dam spillway.

In addition to drawdown limitations, the FERC license for Ninety-Nine Islands Dam also specifies certain seasonally adjusted minimum flows to be maintained below the dam [Reference 4]:

- 966 cfs January through April;
- 725 cfs May, June, and December; and,
- 483 cfs July through November.

If the above-referenced flows cannot be maintained during December through June without dropping below the reservoir level restrictions described above, then at least 483 cfs is required to be released. If there is insufficient water to maintain at least 483

[1] Drawdown limits may be temporarily modified in the event of operating emergencies beyond Duke Energy’s control.

cfs of continuous flow release, the operating license provides that one hydroelectric unit can be operated at its minimum hydraulic output for that portion of every hour that is necessary to release the approximate accumulated inflow, i.e. a pulse flow operational format [Reference 5].

As indicated above, the FERC-specified July through November minimum flow is 483 cfs. Based on analysis of the Broad River period of record flows (85 years) performed by Duke Energy contractor HDR|DTA, flows were greater than 483 cfs 98.2 percent of the time [Reference 6]. Of the 31,046 days that flows were measured by the U.S. Geological Survey (USGS) for the Broad River since 1926, flows less than 483 cfs were recorded for just 545 days (1.8 percent). Consequently, pulsed flow operations of Ninety-Nine Islands hydroelectric power generation are rare events.

1.4 Chronological Summary of Related Modeling Work

There have been a number of numeric modeling efforts conducted as part of the design and NRC licensing of Lee Nuclear Station. These efforts are summarized in the following sections.

1.4.1 Clemson University Study

The thermal discharge to the Broad River was initially evaluated through limited work performed by Clemson University [Reference 7]. The researchers employed simplifying assumptions and analytical calculation methods, in lieu of a three-dimensional model, to identify any “fatal flaws” in the discharge diffuser concept being developed at that time with regard to thermal gain in the Ninety-Nine Islands forebay and downstream of the dam. The results, not meant to be highly definitive, provided gross insight into the potential thermal effects of the Lee Nuclear Station cooling water discharge in the Broad River above and below Ninety-Nine Islands Dam. The Clemson researchers concluded that, based on conservative assumptions, thermal gain above the dam may range from 1.2 to 3.7°F; with a thermal gain of up to 1.7°F predicted for waters below the dam.

1.4.2 Enercon Study

In support of the COL application, additional modeling was conducted by Duke Energy contractor Enercon, which used a more sophisticated modeling approach employing Cornell Mixing Zone Expert (CORMIX) modeling software (Version 4.3) to simulate the thermal plumes above and below Ninety-Nine Islands Dam [Reference 1]. This effort was coupled with a mass balance analysis to determine expected temperature of water discharged by Lee Nuclear Station after mixing with the Broad River water in the Ninety-Nine Islands hydroelectric station turbines.

Results of the CORMIX simulations predicted a small thermal plume that dissipates quickly. Results of the heat balance calculation indicated that the maximum temperature change downstream of Ninety-Nine Islands Dam is expected to be less than 1.4°F.

1.4.3 Computational Fluid Dynamics Modeling

The results of the CORMIX modeling, though more accurate than the Clemson work, still did not consider the important effects on Lee Nuclear Station thermal discharge mixing characteristics brought about due to variation in reservoir bathymetry, flow velocity, and flow vector (direction) in the Ninety-Nine Islands Dam forebay at the diffuser location. Likewise, the hydraulic influences of the Ninety-Nine Islands Dam hydroelectric generating units on thermal plume characteristics were not considered.

In subsequent discussions with regulatory agencies pertaining to the appropriate permitting approach for Lee Nuclear Station, concerns were raised about the mixing behavior of the thermal discharge from the station in the forebay and the potential effect of this discharge on the aquatic community, particularly on the smallmouth bass (*Micropterus dolomieui*) fishery present downstream of Ninety-Nine Islands Dam.

In order to characterize more definitively the Lee Nuclear Station thermal discharge into the hydrodynamically and spatially complex mixing environment present in the Ninety-Nine Islands Reservoir forebay, a more robust modeling approach was needed. As such, three-dimensional Computational Fluid Dynamics (CFD) modeling was conducted [Reference 8].

CFD modeling is based on the Navier-Stokes equations for fluid motion, which are simply an expression of Newton's laws of motion with additional viscous stress terms required to calculate fluid flow [Reference 9]. The equations express the laws of conservation of mass, momentum and energy and are hence a "fundamental" set of equations (i.e. no assumptions are made in forming the basic equation set).

CFD modeling has been used successfully for over 40 years in a variety of industrial and environmental applications. Similar to its use in the current study, the Tennessee

Valley Authority (TVA) used CFD modeling to evaluate the multi-port diffused thermal discharge from its Browns Ferry Nuclear Power Plant to Wheeler Reservoir in north Alabama [Reference 10]. The CFD model allowed TVA to determine thermal plume mixing and temperature rise patterns as well as other hydrodynamic features of the discharge. Notably, TVA found close agreement between CFD model predicted water temperatures and direct temperature measurements at the operating diffusers.

Other examples of CFD environmental applications include the U.S. Department of Energy's Pacific Northwest National Laboratory use of CFD in the hydrodynamic evaluation of the North Fork Dam forebay on the Clackamas River in Oregon and to model the three-dimensional velocity field below Bonneville Dam to enhance fish passage [Reference 11]. CFD has also been used to investigate the increased discharge associated with the re-powering of an existing power plant [Reference 12].

In this initial CFD evaluation of the Lee Nuclear Station thermal discharge, mean annual flow (2,538 cfs[2]), low flow (483 cfs) and extreme low flow (157 cfs) discharge scenarios were conservatively calculated to determine the potential effects of the Lee Nuclear Station cooling water discharge on the Broad River and Ninety-Nine Islands Reservoir environments. Discharge temperatures of 91°F and 95°F were evaluated. In all the cases studied, the maximum temperature rise at the Ninety-Nine Islands hydro turbine intakes was 0.72°F. Therefore, the maximum temperature rise passed through to the Ninety-Nine Islands Dam tailrace would also be 0.72°F. For all other scenarios examined, predicted water temperature rises at the turbines were less than 0.4°F. Based on the minimal temperature rise predicted by the CFD model, the study concluded there would be no substantive changes to the summertime thermal regime that currently exists in the tailrace. Thus, there would be no detrimental impacts to the smallmouth bass fishery.

Modeling of the extreme low flow scenario (157 cfs) also predicted that under certain conditions heat may accumulate in the Ninety-Nine Islands Dam forebay if the pattern of Ninety-Nine Islands hydroelectric station pulsed flow operation is insufficient to fully remove the Lee Nuclear Station heat addition. A pulsed flow operational pattern

[2] At the time that the initial CFD evaluation was performed, 2,538 cfs was the accepted value for mean annual flow. It has since been recalculated based on data from 1926 through 2011 as 2,437 cfs.

matched to 322 cfs was predicted through interpolation to preclude accumulation of heat in the forebay.

1.4.3.1 Presentation of CFD Model Results to SCDHEC

A comprehensive report of the initial CFD thermal modeling, prepared in support of the COL application, was submitted to NRC on 24 September 2009 [Reference 8]. Results were presented directly to SCDHEC on 27 August 2009. Based on SCDHEC feedback regarding apparent accumulation of heat in the Ninety-Nine Islands forebay, additional modeling was performed to further evaluate thermal discharges under critical low flow at times when the Ninety-Nine Islands hydroelectric generating station is operating in pulsed generation mode. The 7Q10 critical low flow of 464 cfs[3] was determined by SCDHEC [Reference 13] to be the appropriate flow value to use for modeling NPDES-permitted discharges to the Broad River from Lee Nuclear Station. The additional CFD modeling was conducted as requested by SCDHEC to: 1) address the issue of heat accumulation in the Ninety-Nine Islands Dam forebay; and 2) to support requests for thermal and whole effluent toxicity (WET) mixing zones in accordance Rule 61-68 (Water Classifications and Standards) Section C.10 [Reference 14].

SCDHEC also requested additional information about the design of the proposed submerged multi-port discharge diffuser; particularly with regard to its efficiency in mixing Lee Nuclear Station discharges with the Broad River receiving waters.

The sections that follow present technical information on optimization of the Lee Nuclear Station discharge diffuser, and supporting information for the Thermal and WET Mixing Zone requests.

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[3] At the time that the initial CFD evaluation was performed, 464 cfs was the accepted value used in the 7Q10 critical low flow simulations. It has since been recalculated based on data from 1926 through 2011 as 438 cfs.

2. DISCHARGE DIFFUSER OPTIMIZATION

Duke Energy contracted with Philip J. Roberts, Ph.D. of Georgia Tech's School of Civil and Environmental Engineering to support design optimization for the Lee Nuclear Station submerged multi-port discharge diffuser [Reference 2]. Dr. Roberts has published extensively on such technical topics as environmental fluid mechanics, mixing and dynamics of rivers, lakes, coastal waters, and estuaries; optimization of outfalls for wastewater discharge; and mathematical models of wastewater fate and transport. Dr. Roberts' work is cited multiple times in EPA's *Technical Support Document for Water Quality-Based Toxics Control* (EPA/505/2-90-001), which is the seminal work upon which permitting of potentially toxic discharges to waters of the United States is based.

The following represents a summary of Dr. Roberts' work in optimizing the design of the Lee Nuclear Station discharge diffuser.

2.1 Design Study Objectives

Dr. Roberts' work focused on the optimization of the Lee Nuclear Station diffuser engineering design to satisfy plant operational parameters, promote efficient mixing of the effluent, and limit temperature rise in the receiving waterbody (Broad River). Performance criteria for the discharge design included achievement of a temperature rise in the river at the water surface near the diffuser of no more than 5°F with a maximum temperature not to exceed 90°F (analysis of mixing needed to address chemical constituents in the discharge was not conducted). While water quality criteria for temperature were used to inform the design of the diffuser, it was not the intent of Dr. Roberts' work to directly address an NPDES compliance-based mixing zone. That objective was addressed by the additional CFD modeling reported herein (see Sections 3 and 4).

2.2 Assessment Methodology

The initial multi-port diffuser design proposed by Duke Energy was a submerged 65-ft-long pipe of 36-inch diameter attached to the upstream face of the Ninety-Nine Islands Dam spillway in the western portion of Ninety-Nine Islands Reservoir forebay. The diffuser was to consist of 16, 3-inch holes (ports) per square foot. For the optimization study, multiple discharge flow rates (9 cfs [4,039 gpm] to 64 cfs [28,725 gpm]), diffuser port depth (6 to 8 ft), diffuser nozzle spacings (1 to 10 ft) and nozzle diameters (3 to 4 inches) were modeled by Dr. Roberts using EPA's Visual Plumes model. Modeling targeted two seasons: (i) winter when differential between monthly average ambient river temperature (44.1°F) and cooling tower blowdown (discharge) temperature (70.4°F) is estimated to be greatest (ΔT=26.3°F); and (ii) in summer when maximum monthly average river temperature and blowdown discharge temperature are at their seasonal highs: 82.3°F and potentially 91°F, respectively. The modeling assumed there was no ambient river flow whatsoever in the forebay into which the discharge was made, an attribute reported as conservative by Dr. Roberts [Reference 2].

The Visual Plumes model predicts the buoyant thermal plume to follow a curved trajectory from the submerged diffuser as it rises to the water surface (ports/nozzles are located on the upstream side of the diffuser, away from the face of the dam). As the plume rises, it entrains ambient water that mixes and dilutes the discharge and reduces the temperature rise. The maximum surface temperature occurs where the jet centerline impacts the water surface [Reference 2]. This impact zone represents the maximum spatial extent of model predictability for surface water temperature (i.e., the model domain extends from the point of port/nozzle discharge to impact of the plume with the water surface).

Visual Plumes consists of a suite of models intended for various purposes. In this case, the UM3 model was considered the most appropriate model [Reference 2]. UM3 is a three-dimensional Lagrangian entrainment model for jets and plumes. External fluid is assumed to be entrained into the rising buoyant thermal plume at a rate proportional to the local plume centerline velocity. The local profiles of velocity, density deficiency, and tracer concentrations are assumed to be self-similar and the equations for conservation of mass and momentum, are integrated over the plume cross-section. The equations are solved numerically to predict plume conditions, including dilution and plume width, along the jet trajectory. If the ports are close together, the plumes may merge. The merging of the thermal plumes is considered in the routines of the UM3 model. Entrainment models are widely used in engineering to predict a wide variety of flows related to wastewater and atmospheric discharges.

2.3 Study Findings

It was determined that a minimum mixing dilution ratio of 5.3 to 1 was needed to meet the applicable thermal water quality criteria (ΔT $\leq$ 5°F and 90°F maximum). All combinations of discharge flow rates, diffuser port spacings and port diameters modeled indicated the needed dilution could be achieved. Based on Dr. Roberts' analysis, the optimally designed submerged, multi-port discharge diffuser (pipe) is approximately 88-ft long with an inside diameter of 36 inches and has 64 4-inch ports spaced 1.4 ft apart. The Visual Plumes model indicates that if the Lee Nuclear Station heated effluent were discharged to the Broad River via a diffuser of this design, the result will be a temperature rise at the water surface (where the buoyant plume emerges) that will always be less than 5°F and have a maximum temperature at the water surface of less than 90°F based on the assumed conditions. The lateral distance from the diffuser port to the point of plume impact with the water surface was estimated to range from 14 ft (9 cfs discharge flow rate) to about 76 ft (64 cfs discharge flow rate).

3. THERMAL MIXING ZONE REQUEST

The Lee Nuclear Station thermal discharge is predicted at times to potentially exceed water quality criteria for temperature (e.g. 90°F). Because the spatial extent of such exceedance in the receiving waterbody is expected to be small, a regulatory mixing zone presents an allowable compliance approach provided requirements specified in Rule 61-68 (Water Classifications and Standards) Section C.10 can be met [Reference 14].

3.1 Background

As indicated previously, Dr. Roberts' work focused on optimizing the design of the submerged multi-port discharge diffuser and not the determination of a regulatory mixing zone. It is important to note, however, that rapid mixing of the Lee Nuclear Station discharge was demonstrated by Dr. Roberts' analysis, with achievement of temperature criteria predicted upon impact of the buoyant plume with the receiving water surface (under the conditions considered).

The limitations of the Visual Plumes model used by Dr. Roberts (as well as the CORMIX model used by Enercon [Reference 1]) to evaluate thermal discharge mixing zones are primarily associated with the orientation of the discharge diffuser parallel to ambient flow along the Ninety-Nine Islands Dam (Figure 1). Typically, a discharge diffuser is oriented perpendicular to flow whereby the discharge from each port/nozzle may be entrained into ambient receiving water unaffected by the discharge. Such orientation provides for efficient mixing of the discharge with the receiving waterbody. The Visual Plumes and CORMIX models are best suited for these conditions.

Constraints imposed by conditions in the Broad River (i.e., heavy debris and sediment accumulation) necessitated placement of the Lee Nuclear Station discharge diffuser along the face of Ninety-Nine Islands Dam, parallel to flow. In the case of diffuser orientation parallel to flow, the discharge from ports located on the "downstream" end of the diffuser entrains the effluent discharged from the "upstream" ports thereby affecting mixing characteristics. This physical phenomenon is accounted for in the CFD approach, since the flow of the thermal discharges parallel with the river flow are included as an integral part of the model and is allowed to mix according to the fundamental laws of fluid motion. The discharge is treated in the CFD model as a mass source at the location of the discharge diffuser, and is allowed to diffuse equally in all directions and mix as the ambient flow dictates. The discharge diffuser is not modeled explicitly with jets emanating from each port, as this has a high “computational overhead” – i.e. it takes significantly longer to run each case in the model. The run times for the mass source discharge approach are several days for each case; it is not practicable to extend this further by explicitly modeling each port. The loss in detail due to using a mass source discharge instead of explicit jets from each port is not significant to the mixing zone calculation – it only has an effect very close to the diffuser before the jets from each port merge.

In the CFD model, a temperature transport model derived from the law of conservation of energy is included. Temperature is transported in the model domain by convection with the water flow, and molecular and turbulent diffusion. It has an influence on the flow profile as the heated water plumes rise – this is included in the calculations using a buoyancy model in the momentum equations. As the temperature and flow fields are interdependent it is essential that the flow, turbulence and temperature equations are calculated simultaneously. Heat can also be lost or gained through the model boundaries. For example, heat lost or gained through the free surface will modify the temperature in the reservoir and this can be included in the calculation by selection of appropriate boundary conditions. It is likely that heating and cooling in the forebay is influenced by river temperature, air temperature, cloud cover, sun elevation, shading by vegetation and other effects. In the absence of full knowledge of these variables, heat loss/gain through the free surface cannot be calculated accurately. Instead, adiabatic conditions were specified at the free surface, which was a reasonable modeling approach and allowed the thermal profile resulting from the cooling water discharge to be studied in isolation from solar and ambient air heating or cooling effects.

3.2 Current Thermal Modeling Effort

Geosyntec Consultants/MMI Engineering (Geosyntec) was contracted by Duke Energy to conduct the necessary calculations/modeling to determine the Lee Nuclear Station thermal discharge mixing characteristics in the Broad River for the purposes of NPDES permitting of the new facility. Based on SCDHEC feedback received at the 27 August 2009 meeting regarding apparent accumulation of heat in the Ninety-Nine Islands forebay, additional modeling was performed to further evaluate thermal discharges under critical low flow at times when the Ninety-Nine Islands hydroelectric generating station is operating in pulsed generation mode. The 7Q10 critical low flow of 438 cfs was determined by SCDHEC [Reference 24] to be the appropriate flow value to use for modeling NPDES-permitted discharges to Broad River from Lee Nuclear Station. This modeling scenario (critical conditions and pulsed flow) was used to estimate spatial boundaries for a thermal mixing zone.

The SCDHEC further indicated their focus will be on the size of the Lee Nuclear Station thermal plume relative to the specified acute mixing zone boundary. Duke Energy has assumed SCDHEC is referring to that portion of the plume/mixing zone where temperatures may potentially exceed 90°F (maximum ambient water quality criterion) as discharge temperatures in excess of 90°F would only be expected to occur during summer - the time when critical low flows in the river (e.g., 7Q10 flows) can also occur. The other component of the state's temperature criteria (adapted from EPA), "*free flowing* [waters] *shall not be increased more than 5°F (2.8°C) above natural temperature conditions*", [Reference 14] is largely based on the objective to "*maintain a well-rounded population of warmwater fishes*" [Reference 15]. In the case of power plant additions, it is further based on the objective to avoid fish lethality resulting from a sudden *drop* in water temperature (should the plant shut down) during winter months when the potential for $\Delta T > 5°F$ to occur is greatest [Reference 2]. As such, the 90°F maximum temperature criterion was selected as the acute condition and the additional CFD modeling was conducted to address this component of the mixing zone request.

Duke Energy is also aware of SCDHEC's interest in temperature differential between the discharge and ambient Broad River as exemplified by the $\Delta T \leq 5°F$ criterion [Reference 14]. A simulation of the $\Delta T \geq 5°F$ under worst-case winter conditions ($\Delta T = 26°F$ at the discharge) at mean annual flow has been run, and the results are presented later in this report. In addition, the previous comprehensive CFD thermal modeling report (see Section 1.4.3) speaks directly to this issue and includes several CFD modeling runs that address plume characteristics of $\Delta T \geq 5°F$. In all cases conservatively modeled, plume spatial dimensions associated with temperatures of $\Delta T \geq 5°F$ are very small. This finding is further supported by Dr. Roberts' additional analysis of the discharge diffuser that indicates the ΔT will always be $< 5°F$ at the point of buoyant plume impact with the water surface [Reference 2].

As is presented in the following text, an approved mixing zone request based upon plume dimensions for the $\geq$ 90°F isotherm associated with a discharge temperature of 95°F will fully encompass the area occupied by that portion of the plume exhibiting $\Delta T \geq 5°F$. This has been shown to be the case in the results presented in this report.

Therefore, as the additional modeling requested by SCDHEC (acute, critical summer condition) is most relevant to the Thermal Mixing Zone request, the results thereof are summarized in the following text.

3.3 Critical Conditions Modeling

The Lee Nuclear Station thermal discharge characteristics under critical condition 7Q10 flow of 438 cfs were conservatively calculated using CFD models. These determined the potential effects of the Lee Nuclear Station cooling water discharge on the Broad River and Ninety-Nine Islands Reservoir forebay environments, particularly with regard to that portion of the thermal plume where temperatures are ≥ 90°F. Under 7Q10 flow conditions, the Ninety-Nine Islands Hydroelectric Generating Station is expected to operate in a pulsed mode format whereby a single turbine is pulsed "on" and "off" over an hourly cycle to comply with the FERC-specified minimum water levels which must be maintained in the impoundment and minimum seasonal flows to be released downstream. The CFD model was configured to address this pulsed mode of operation.

The CFD model used in this study is similar to the earlier work [Reference 8] where a more detailed overview of the model is given. Bathymetry data measured in the Ninety-Nine Islands Reservoir forebay by Duke Energy was used to develop the original CFD model; the model was validated using water column acoustic Doppler velocity and vector data measured by Duke Energy in the reservoir forebay. In the current work, the geometry and computational mesh were changed slightly to reflect the correct position and length of the discharge diffuser (an initial design was used in the previous work), and are shown in Figures 2 through 5 for reference[4].

The model was run in transient mode to capture the pulsed operation of the turbines. As with the previous studies, the diffuser discharge was applied as a mass source at the location of the diffuser and allowed to disperse equally in all directions. This tends to result in a conservative result for the thermal plume as the momentum induced by the multi-port discharge diffuser will be greater in reality than in the model and an increase in momentum will encourage entrainment of ambient water and enhance cooling of the plume. Therefore, the under-representation of momentum in the CFD model is conservative.

[4] Please note that for Figures 4 and 5 the viewer's perspective is from the east bank of Broad River (looking southwesterly), upstream of the dam, and somewhat elevated. This is also true for subsequently-referenced Figures 6-10, 12, 15, 16, 20 and 21.

3.3.1 Methodology

Geosyntec/MMI Engineering uses a variety of classical and computational analysis techniques to assess the performance of fluid systems and processes. For detailed CFD analysis, calculations are made with the general purpose, commercial CFD code ANSYS-CFX Version 14 [Reference 16]. This is the CFD model code selected for the current analysis.

The extent (geometry) of the Ninety-Nine Islands Reservoir/Broad River environment in the CFD models included:

- The Ninety-Nine Islands Dam, forebay, turbine intakes, and Lee Nuclear Station diffuser discharge;
- the backwater areas in the locality of the forebay; and,
- a reach of the Broad River extending approximately 0.5 mile upstream of the forebay.

Total surface area of the modeled domain was approximately 61 acres.

Bathymetry data for the reservoir forebay area and river was provided by Duke Energy contractor, DTA [Reference 17] in the form of point-depth measurements in a series of transects. These point data were interpolated to form the river/reservoir bed in the CFD models. The data received did not include the dam or turbine intakes, which were incorporated into the model by reference to the civil engineering drawings of the Ninety-Nine Islands hydropower station [References 18 and 19]. Similarly the dredged area in front of the turbine intakes, indicated in Figure 4, had to be estimated for the CFD models. The best information at the time the CFD models were built indicated that only the area immediately in front of the turbines would be dredged. In practice, it is likely that the dredged area will be extended from this region, right across to the area of the forebay below the diffuser. Hence in the actual forebay, it is likely that there will be a greater depth of water column unaffected by the thermal plume, which will allow unhindered passage for aquatic life.

The Lee Nuclear Station cooling water discharge was defined in the CFD models based on reference to the Duke Energy drawings of the discharge [References 19 and 20]. The location of the discharge relative to the turbine intakes is shown in Figure 1. Only the discharge diffuser detail was included in the model; the remainder of the discharge pipe work is assumed to have no significant effect on plume behavior.

3.3.1.1 CFD Model Relationship to Dr. Roberts' Diffuser Design Study

It is important to acknowledge that at the time the additional CFD modeling (reported herein) was conducted, Dr. Roberts' work in optimizing the discharge diffuser design had not been completed. It should be noted that that Dr. Roberts used a maximum *monthly* average temperature of 82.3°F and normal discharge temperature of 91°F in his discharge diffuser design optimization study; whereas, the CFD model uses a *daily* average maximum temperature of 88.2°F and both 91°F and 95°F discharge temperatures to evaluate worse case conditions of summer in the determination of mixing zones. These differences are simply the result of independent investigations, conducted at different times, and with differing objectives in mind, and would have no material impact on the CFD model results.

3.3.2 Scenarios Modeled

Three CFD calculations (scenarios or cases) were performed. The first two were relevant to the 90°F plume with the following variables common to both cases:

- River flow rate was set to 438 cfs in accordance with the 7Q10 level specified by SCDHEC for the NPDES permitting [Reference 24] ;

- River temperature (background) was set to 88.2°F as determined from Duke Energy continuous water temperature data collected in the Ninety-Nine Islands forebay during June-August 2008 (when 7Q10 flows might be expected to occur) [Reference 21];

- Turbine flow rate was set to 500 cfs when "on" and 53 cfs when "off" (due to leakage through the turbine penstock);

- Ninety-Nine Islands Hydroelectric Station turbine operation:

  - Only 1 turbine unit is in operation.

  - The unit is "off" for the first 7.4 minutes per hour, flow accumulates in the forebay and only leakage flow passes to the tailrace. The unit is "on" for the remaining 52.6 minutes per hour. These timings were calculated by considering the balance of the river and turbine flow rates only.

- Diffuser discharge rate was set to 18.3 cfs.

The scenarios differed in the temperature of the diffuser discharge. In Scenario 1 the discharge temperature was set to 95°F, while in Scenario 2 it was 91°F.

The third scenario is relevant to the ΔT = 5°F plume. In this case, the following variables were set:

- River flow rate was set to 2,437 cfs [Reference 24] representing mean annual flow.
- River temperature (background) was set to 44.1°F in alignment with the diffuser optimization report [Reference 2].
- Ninety-Nine Islands Hydroelectric Station turbine operation:
  - Turbine Units 1, 3 and 4 in operation.
  - The three turbine units are continually on.
  - The flow rate through units 1 and 3 was set to 1,000 cfs. The flow rate through unit 4 was calculated from mass balance considerations as 455 cfs (2,437 cfs mean annual flow + 18.3 cfs discharge – 2 x 1,000 cfs through units 1 and 3).
- Diffuser discharge rate was set to 18.3 cfs.
- The discharge temperature was set to 70.4°F in alignment with the diffuser optimization report [Reference 2].

3.3.3 Model Results – 90°F Plume

For the 7Q10 river flow rate of 438 cfs, the peaks of the average temperatures at the Ninety-Nine Islands Hydroelectric Station turbine inlet calculated from the CFD model are as follows:

- Scenario 1 (95°F discharge temperature): 88.57°F or 0.37°F above ambient river temperature (88.2°F).

- Scenario 2 (91°F discharge temperature): 88.36°F or 0.16°F above ambient river temperature (88.2°F).

It is apparent from these results that the Lee Nuclear Station thermal discharge will have minimal impact on the thermal regime of the Broad River downstream of the Ninety-Nine Islands Hydroelectric Project.

With regard to the Ninety-Nine Islands Dam forebay, the CFD modeling of two consecutive one-hour cycles demonstrated that heat did not accumulate in the forebay and that steady-state conditions were reached by the end of the second hour of pulsed operation. This was determined to be true for both Scenario 1, and is a feature of Scenario 2 as well, although the thermal plumes are much smaller.

For Scenario 1 (95°F discharge temperature), Figure 6 illustrates the 90°F area by the blue iso-surface 20 minutes into the first cycle modeled. At the end of this first cycle, the plume is virtually identical (see Figure 7). The variation in plume size and shape throughout the cycle is an important consideration in the modeling, and is a feature of Scenario 2 as well, although the thermal plumes are much smaller because the discharge temperature is lower for Scenario 2 (91°F). See Figure 8 and Figure 9 for the thermal plumes for Scenario 2. Note that in this case the plume remains so localized to the diffuser that it is difficult to distinguish in the figures.

The variation in plume volume over two cycles is an important dynamic in the model. At the start of the first cycle, the CFD model requires initial conditions for all flow variables (velocity, temperature etc.). An accurate initialization is achieved by computing a steady-state CFD model with the turbine “on” prior to the running of the transient CFD model. The results from the steady-state model are then used as initial conditions for the transient model. Because the turbine is turned off at the start of the first cycle, the thermal plume increases in size, and even increases when the turbine is turned back on for a short period (this lag is to be expected as the turbine does not immediately influence the entire domain as soon as it is turned on), before returning to approximately the volume from the steady-state simulation. This time-variation in volume repeats during the second cycle. As the plume volume at the end of the second cycle is approximately the same as at the end of the first cycle, the second cycle can be assumed to be the "repeating" cycle and will be representative of the following third, fourth, etc. cycles. A similar pattern was also observed for Scenario 2.

Dimensions of the thermal plume were taken at the end of the second cycle in each case, as this is the best representation of the plume over the hourly cycle. Figures 10 through Figure 13 show the steady-state plumes for Scenarios 1 and 2, respectively. The plan views (Figure 11 and Figure 13) of the plumes provide a perspective of the size of the plume in comparison to the forebay of the dam. A detailed summary of the plume dimensions for each scenario are shown on the table in the following section. The volume of the thermal plume for Scenario 1 is 0.195 ac-ft (8,516 ft^3), while the surface area is 0.060 acres (2,616 ft^2). The cross-section area (see Figure 15) is 710 ft^2 which constitutes 4.5 percent of the forebay cross-sectional area. The maximum plume length, taken from the end of the discharge diffuser, is 138 ft (approximately 13 percent of the width of the Broad River at the forebay of the dam) while the width of the plume is 71 ft. The maximum and average depths are 10.9 ft and 5.3 ft, respectively. The bar chart showing percent of plume volume against depth for this scenario (Figure 14) indicates that the majority of the plume is less than 7 ft depth – in fact, 85% of the plume volume is less than 7 ft depth for Scenario 1.

For Scenario 2 the thermal plume is significantly smaller, as would be expected, with a volume of 0.013 acre-ft (569 ft^3). In this case, the thermal plume is entirely dissipated before reaching the water surface. The cross-section area (see Figure 16) is 92.3 ft^2 which constitutes 0.6 percent of the forebay cross-sectional area. The maximum plume length, calculated from the end of the discharge diffuser, is 89 ft (approximately 9 percent of the forebay length) while the width of the plume is 5 ft. The maximum and average depths are 10.6 ft and 8.4 ft, respectively. The bar chart showing percent of plume volume against depth for this scenario (Figure 17) further indicates that the plume does not reach the water surface.

3.3.4 Model Results – $\Delta T = 5°F$ Plume

The $\Delta T = 5°F$ plume for Scenario 3 is shown on Figure 18. Note that in this scenario, three turbines are "on" (Units 1, 3 and 4), indicated in orange in the figure. As the flow rate for the simulation is much higher (2,437 mean annual flow cfs as opposed to 438 cfs for 7Q10 critical flow) the turbines are not in pulsed mode operation and the plume is more slender than the plumes for scenarios 1 and 2. As anticipated, the plume is much smaller than Scenario 1, with a volume of 0.081 acre-ft (3,548 ft^3). The surface area is zero since the plume dissipates entirely before reaching the surface as was observed for Scenario 2. The plume is still relatively shallow at 7.5 ft average depth and 11.5 ft maximum depth. The shape of the plume also results in a relatively long (138 ft maximum length) but narrow (10.1 ft maximum width) mixing zone.

3.3.5 Results Summary

The CFD model inputs and resulting spatial dimensions of the ≥ 90°F plume under each scenario were determined for the steady-state condition and are summarized on the following table:

	Scenario 1	Scenario 2
River Flow	438 cfs 7Q10 Critical Flow	438 cfs 7Q10 Critical Flow
River Temperature	88.2°F	88.2°F
Discharge Flow	18.3 cfs	18.3 cfs
Discharge Temperature	**95°F**	**91°F**
Dimensions of Steady-state ≥ 90°F Thermal Mixing Zone for Repeating Cycle		
	Scenario 1	**Scenario 2**
- **Volume**	0.195 acre-ft 8,516 ft^3	0.013 acre-ft 589 ft^3
- **Surface area**	0.060 acre 2,616 ft^2	0.0 acre 0 ft^2
- **Cross-Sectional area** o **Percent of forebay**	710 ft^2 4.5 %	92.3 ft^2 0.6 %
- **Average Depth/Thickness**	5.3 ft	8.4 ft
- **Maximum Depth/Thickness**	10.9 ft	10.6 ft
- **Maximum Width**	71 ft	5 ft
- **Maximum Length**[5]	138 ft	89 ft

[5] Calculated from the end of the discharge diffuser.

It is important to note (as detailed in the next section) that proper interpretation of the model results (i.e. spatial attribute) relative to a regulator mixing zone should consider orientation of the diffuser and buoyant properties of the thermal plume.

The CFD model inputs and spatial dimensions of the ΔT ≥ 5°F plume for the steady-state condition are summarized on the table below.

	Scenario 3
River Flow	2,437 cfs Mean Annual Flow
River Temperature	44.1°F
Discharge Flow	18.3 cfs
Discharge Temperature	**70.4°F**
Dimensions of Steady-state ΔT ≥ 5°F Thermal Mixing Zone	
- **Volume**	0.081 acre-ft 3,548 ft^3
- **Surface area**	0 acre 0 ft^2
- **Average Depth/Thickness**	7.5 ft
- **Maximum Depth/Thickness**	11.5 ft
- **Maximum Width**	10.1 ft
- **Maximum Length**[6]	138 ft

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[6] Calculated from the end of the discharge diffuser.

3.4 Relevance to the Thermal Mixing Zone Request

The discussion of the thermal plume and associated mixing zone for Lee Nuclear Station conservatively assumes Scenario 1 conditions with the 95°F discharge temperature under critical low flow (7Q10) conditions, since this is the worst-case scenario out of all the scenarios modeled.

As noted previously, SCDHEC indicated a significant consideration in its analysis will be on the size of the Lee Nuclear Station thermal plume relative to the specified acute mixing zone boundary. Duke Energy has assumed this to be that portion of the plume/mixing zone where temperatures are in excess of the 90°F criterion. This has also been shown to be more onerous than the $\Delta T \geq 5$°F criterion. As the discussion hereafter focuses on the plume area characterized by temperatures $\geq$ 90°F and analogous to the acute mixing zone, the terms "plume" and "mixing zone" are used interchangeably.

Mixing zone boundary conditions set by SCDHEC seek to keep the size of mixing zones to a minimum. According to SCDHEC requirements, acute mixing zones are limited in width to no more than one-tenth (10 percent) of the width of the stream and in length downstream to one-third (33.3 percent) the width of the stream, although alternatives may be considered for larger mixing zones [Reference 22].

Unlike the conventional configuration where the discharge diffuser extends laterally from shore and is positioned perpendicular to the flow, the Lee Nuclear Station discharge diffuser is attached to a dam and oriented parallel to river flow (i.e., flow is along the dam face toward the hydroelectric turbines). These attributes make the direct application of the SCDHEC acute mixing zone length/width proportional dimensions to the Lee Nuclear Station thermal plume somewhat atypical.

For example, given the placement of the discharge diffuser parallel to flow along the face of the Ninety-Nine Islands Dam, it is necessary to define length of the plume/mixing zone as running parallel to the longitudinal centerline of the diffuser pipe (i.e., easterly), and width as perpendicular to the diffuser (i.e., northerly). As such, the maximum downstream length of the buoyant 90°F plume (acute mixing zone) is conservatively estimated to be 138 ft, which is approximately 13 percent of the width of the Broad River at the forebay of the dam (1,031 ft), while the plume width is conservatively estimated to be 71 ft, or 7 percent the width of the stream. Accordingly, the size of the acute thermal mixing zone for the Lee Nuclear Station discharge as conservatively determined by the CFD model falls well within the maximum spatial boundary conditions, for the mixing zones established by SCDHEC.

As an additional check on the plume calculations, some limited CFD model tests were carried out on the diffuser with the 64 ports modeled explicitly rather than the “mass source” approach used here (and described in Section 3.3). This demonstrated that the model with the 64 ports included explicitly, provided enhanced mixing properties and reduction in thermal mixing zone size which were not fully demonstrated by the CFD model used to produce these results reported herein. Hence it was understood that the CFD modeling technique used provides an additional layer of conservatism.

Also, while seasonal temperature data for the Ninety-Nine Islands forebay demonstrate the water column is well mixed and oxygenated all year, the buoyancy of the thermal plume results in an uneven dispersal of heated water vertically in the water column. That is, at the maximum horizontal extent (length) of the ≥ 90°F plume (138 ft), the plume/mixing zone does not extend vertically downward into the water column. Although the maximum depth of the mixing zone (extending from the surface downward) is 10.9 ft, only a very small proportion of the plume is at that depth; 85 percent of the mixing zone volume is found at 7 ft depth or less (Figure 14). The average depth/thickness of the mixing zone is just 5.3 ft. As the average depth is so shallow, there is a significant distance between the mixing zone and the bottom of the forebay where fish may escape or swim around the area.

Given the above discussion, an alternative/analogous approach to evaluate minimization of the size of the Lee Nuclear Station thermal mixing zone relative to the receiving waterbody may be to use the percent cross-sectional area of the forebay occupied by the ≥ 90 °F plume/mixing zone. This approach is fully consistent with SCDHEC mixing zone requirements and EPA guidance [Reference 23], which seeks to limit exposure to fish and other organisms to acute conditions. Using this approach, the cross-sectional area of the plume was determined by positioning an east-west oriented line (aligned with the dam and diffuser) through the thickest part of the vertical plane of the plume. This cross-sectional area of the ≥ 90°F plume (associated with a 95°F discharge temperature) measures 710 ft^2 in size; proportionally, this represents just 4.5 percent of the cross-sectional area of the forebay (Figure 15). Thus, under conservative conditions there is very limited potential exposure to the thermal plume for free-swimming fish or benthic organisms and their passive life stages.

EPA guidance provides that the areal extent and concentration isopleths (for toxics) of a mixing zone must be such that the 1-hour average exposure of organisms passing through the mixing zone is less than the acute criteria [Reference 23]. Though maximum temperature criteria are based on experimental studies using longer averaging periods [Reference 15], the 1-hour average exposure period was used as a conservative means of evaluating, through additional analysis, the potential lethality to passive organisms from exposure to elevated water temperature (> 90°F) in the mixing zone.

The average velocity in the steady-state plume was obtained from the CFD model and divided into the greatest length of the plume (138 ft) to estimate potential travel time through the plume for a passive organism. For Scenario 1, the average velocity was estimated at 0.23 feet per second (ft/s). As such, travel time through the plume was determined to be approximately 10 minutes. For Scenario 2 the average velocity is 0.13 ft/s and the length of the plume is 89 ft, so travel time is 11 minutes. Thus, no passive organisms/life stages will be exposed to water temperatures > 90°F for extended periods of time and any exposures will be well below an hour.

Determination of velocities throughout the plume is a complex exercise given the dynamic conditions in the forebay. However, the analysis is conservative in that the conditions considered (i.e., flow velocities) have been determined for the steady state condition of the plume under rare pulsed-flow conditions. Under typical continuous operation of the Ninety-Nine Islands hydroelectric facility turbines, ambient and turbine-induced flows would be higher and reduce travel time for passive organisms through the mixing zone.

With regard to the downstream extent of the thermal plume, it is important to note that based on the CFD-modeling results (see Section 3.3.3 above), water temperatures greater than 90°F are not predicted to reach the Ninety-Nine Islands hydroelectric turbine inlets and pass downstream to the tailrace under critical conditions. Thus, the acute mixing zone boundary does not extend downstream of the forebay area.

3.5 Thermal Mixing Zone Request

The text provided in this document constitutes Duke Energy's formal request to SCDHEC to authorize a thermal mixing zone for the Lee Nuclear Station thermal discharge to the Broad River. The technical information presented herein fully addresses South Carolina Regulation 61-68 Water Classifications and Standards as they relate to mixing zones for surface waters (Section C.10.); specifically:

- The size of the requested thermal mixing zone has been reasonably minimized based on the proportion of the discharge flow to receiving waterbody critical 7Q10 flow (i.e., approximately 4 percent). This will be accomplished through the active design and construction of a closed-cycle re-circulating cooling water system at Lee Nuclear Station as opposed to an open-cycle, once-through cooling water system.

- The size of the requested mixing zone has been further minimized through the use of a submerged multi-port discharge diffuser that provides rapid mixing of the thermal discharge in the receiving waterbody.

- Considering potential acute thermal affects to aquatic life, under a rare worst case discharge temperature of 95°F concurrent with critical 7Q10 low flow conditions, the areal extent of the ≥ 90°F acute mixing zone is predicted by the conservatively applied CFD modeling to be well within SCDHEC's specified spatial boundaries for such mixing zones of no more than one-tenth (10 percent) of the width of the stream (width) and a length downstream of one-third (33.3 percent) the width of the stream [Reference 22]. The Lee Nuclear Station thermal mixing zone width and length are predicted by the model to be 6 and 19 percent, respectively, of the width of the Broad River at the discharge location.

  Under the same discharge scenario, the cross-sectional area of the ≥ 90°F plume is proportionally 4.5 percent of the total cross-sectional area of the Broad River at the discharge location. In addition, the plume is relatively shallow (85% of the plume is at 7 ft depth or less, and the maximum plume depth is 10.9 ft) so that there is a significant distance between the thermal plume and the bottom of the forebay where fish may escape, or swim under the plume.

Further, the CFD modeling indicates that under the worst case conditions considered, water temperatures ≥ 90°F will not extend to the Ninety-Nine Islands Hydroelectric Station turbine inlets and pass downstream to the tailrace. Notably, maximum temperature rise at the turbine inlets under modeled conditions is predicted to be approximately 0.4°F.

Additionally, travel time for passive organisms through the thermal plume/mixing zone was determined to be approximately 10 minutes for Scenario 1 (95°F discharge temperature), and 11 minutes for Scenario 2 (91°F discharge temperature). Thus, exposure of passive organisms/life stages to water temperatures > 90°F for extended periods of time will not occur under critical conditions.

- Given the small size of the thermal discharge area and acute mixing zone (≥ 90°F) relative to the receiving waterbody, there can be no reasonable expectation that the thermal discharge and requested mixing zone would "*result in undesirable aquatic organisms or a dominance of nuisance species outside of the mixing zone*".

- Given there are no federally-listed endangered or threatened aquatic species or habitats in the Broad River in the vicinity of the discharge [Reference 1], there is no reasonable expectation that the requested thermal mixing zone "*would adversely affect a federally-listed endangered or threatened aquatic species, its habitat, or a proposed or designated critical habitat*".

- Based on the small proportion of the discharge flow to receiving waterbody critical 7Q10 flow (i.e., approximately 4 percent), minimization of the thermal mixing zone to meet SCDHEC spatial requirements for mixing zones, and limited travel time through the plume for passive organisms, the requested thermal mixing zone will allow for safe passage of aquatic organisms and the protection and propagation of a balanced indigenous aquatic community in and on the Broad River.

- The requested mixing zone will not endanger public health and welfare.

The CFD modeling was conservatively applied in this study and demonstrates the minimal impact the Lee Nuclear Station thermal discharge is predicted to have on the thermal regime of the Broad River and Ninety-Nine Islands Reservoir forebay, and associated aquatic communities they support.

Based on the above evidence, Duke Energy requests that SCDHEC authorize a thermal mixing zone as defined for a potential daily average discharge temperature of 95°F, as part of the NPDES permit for the Lee Nuclear Station thermal discharge to the Broad River.

4. WHOLE EFFLUENT TOXICITY MIXING ZONE REQUEST

South Carolina water quality regulations allow mixing zones for discharges to state waters [Reference 14]. A mixing zone is defined in the regulations as:

"…*an area where a discharge undergoes initial dilution and is extended to cover the secondary mixing in the ambient waterbody. A mixing zone is an allocated impact zone where water quality criteria can be exceeded as long as acutely toxic conditions are prevented (except as defined within a Zone of Initial Dilution) and public health and welfare are not endangered.*"

Zone of Initial Dilution is defined as:

"*that minimal area of a mixing zone immediately surrounding the outfall where water quality criteria are not met, provided there is no acute toxicity to drifting organisms and public health and welfare are not endangered.*"

As an applicant for an NPDES point source discharge permit in South Carolina, SCDHEC provided Duke Energy with procedures for requesting a WET Mixing Zone [Reference 22], including a form to be completed and submitted as part of the NPDES permit application package for Lee Nuclear Station. Completion of the form provides SCDHEC with information needed to determine mixing zone size for chemical constituents potentially present in the Lee Nuclear Station discharge and associated WET requirements.

CORMIX is a common water quality model used by SCDHEC and other regulatory permitting agencies to determine mixing zone size and other attributes to establish WET requirements. In the case of the Lee Nuclear Station submerged multi-port discharge diffuser, the orientation of the discharge diffuser parallel to ambient flow along the Ninety-Nine Islands Dam precluded the use of a CORMIX model to determine the mixing zone size (see discussion in Section 3.1). Consequently, Geosyntec used CFD modeling to accomplish this task. The results thereof are summarized in the following text.

4.1 Computational Fluid Dynamics Modeling – Approach

4.1.1 Overview

Modeling was conducted to evaluate mixing characteristics of the discharge with Broad River, and determine spatial dimensions of the mixing zone. The CFD model used was similar to that reported for the thermal discharge analyses (see Section 3). The geometry and computational mesh were unchanged and are shown in Figure 2 through Figure 5 for reference. To evaluate the mixing of the cooling water with the ambient water of the Broad River, a "passive scalar" approach (conceptually similar to a dye tracer) was used in the CFD models, as the concentration of constituents was low enough that they would have no significant effect on the overall flow field. A source for this passive scalar was imposed on the volume representing the discharge diffuser. From the concentration of the passive scalar at each point in the flow field, relative to the initial concentration, the dilution of the diffuser discharge could be determined.

The model was run in transient mode to capture the pulsed operation of the turbines. As with the models described in Section 3, the diffuser discharge was modeled as a mass source at the location of the diffuser and allowed to convect and diffuse equally in all directions, instead of modeling the 64 diffuser discharge ports explicitly. This will tend to result in conservative results for the mixing zones as the momentum induced by the multi-port discharge diffuser will be greater in reality than in the model. This increase in momentum would encourage entrainment of ambient water and enhance mixing. As a result, the under-representation of momentum in the CFD model is conservative.

4.1.2 Definition of Dilution Ratio

To evaluate mixing, a "dilution ratio" was defined that represented the total number of parts of fluid (background plus discharge) to the number of parts of discharge fluid only. Thus, a dilution ratio of one represents fluid that is purely from the discharge, while a dilution ratio of four indicates three parts background to one part discharge fluid. A useful alternative view is that a dilution ratio of one represents a 100 percent concentration of discharge fluid, while a dilution ratio of four indicates a 25 percent concentration. This is particularly useful as the discharge fluid concentration is a direct output of the CFD model, so that the dilution ratio, r, can be calculated using:

$$r = \frac{1}{C_S} \tag{1}$$

where C_s is the concentration of the passive scalar (in the CFD model, the initial passive scalar concentration is 1 so that the above equation holds).

4.1.3 Scenarios Modeled

Similar to modeling of the thermal discharge, the two scenarios modeled in the CFD calculations had the following variables common to both:

- River flow rate was set to the 7Q10 value of 438 cfs specified by SCDHEC for the NPDES permitting [Reference 24];
- River temperature (background) was set to 88.2°F as determined from Duke Energy continuous water temperature data collected in the Ninety-Nine Islands forebay during June-August 2008 (when 7Q10 flows might be expected to occur) [Reference 21];
- Turbine flow rate was set to 500 cfs when "on" and 53 cfs when "off" (due to leakage through the turbine penstock);
- Ninety-Nine Islands Hydroelectric Station turbine operation:
  - Only 1 turbine unit is in operation.
  - The unit is "off" for the first 7.4 minutes per hour, flow accumulates in the forebay and only leakage flow passes to the tailrace. The unit is "on" for the remaining 52.6 minutes per hour. These timings were calculated by considering the balance of the river and turbine flow rates only.
- Lee Nuclear Station discharge rate was set to 18.3 cfs.

The scenarios differed in the temperature of the cooling water discharge which affects water density and associated mixing characteristics. In Scenario 1 the discharge temperature was set to 95°F, while in Scenario 2 it was 91°F.

4.2 Definition of Mixing Zones

Under typical circumstances, SCDHEC requirements [Reference 22] specify that the length of the acute mixing zone (or Zone of Initial Dilution, ZID) extending downstream should not exceed one-third (33.3 percent) the width of the river and the width of the mixing zone should not exceed one-tenth (10 percent) the width of the river. In addition, the chronic mixing zone should not exceed twice (200 percent) the width of the river in length and should not exceed one-third (33.3 percent) the width of the river in width. However, the nature of the flows in this instance is atypical due to the operation of the nearby hydroelectric power station. For example, under 7Q10 flow conditions, the single operating turbine intake is approximately 175 feet from the end of the discharge diffuser. The flow through the turbine intake must contain discharge fluid at an average concentration of approximately 4% (from a simple mass balance calculation of 18 cfs discharge flow and 438 cfs 7Q10 river flow). As the width of the river at this point is approximately 1,031 ft, the cooling water discharge flow can enter the turbine intake well within the limit of the acute mixing zone length of 344 ft (one-third of 1,031 ft). Downstream of the turbine, the river will maintain a concentration of approximately 4% discharge flow.

An alternative definition for the mixing zone is presented that is better suited to the flows in the proximity of the discharge in this case. That is, the volume of fluid with a dilution ratio less than or equal to the lowest value of dilution ratio calculated at a distance from the diffuser pipe equal to the distance from the end of the discharge diffuser to the turbine intake (175 ft)

This approach yields only one value for dilution ratio. It is proposed that this value defines the chronic mixing zone, and the acute mixing zone is not defined.

Considering both modeling scenarios, an appropriate value of dilution ratio that represented the minimum value approaching the turbine intakes was 5, or 20% concentration. The chronic mixing zone was thus defined as the volume less than, or equal to, a dilution ratio of 5.

4.3 Model Results

Contours of dilution ratio (defined as shown in Equation (1)) for Scenario 1 (95°F discharge temperature) are shown on Figure 19. As expected, the low values of dilution ratio are located close to the discharge diffuser, with the higher values (indicating that the fluid is mostly background) much further away. It should be noted that as the turbine switches on and off during the hourly cycle, the shape of the dilution contours change throughout the cycle. The variation is greater for dilution than for the temperature contours considered in the previous section, so it is more representative to present the results in terms the time-average dilution of the second cycle rather than the "steady state" plume. Thus the results shown for the WET mixing zone (Figures 19 – 24), are for the time-averaged plume, where the averaging occurs during the second hourly cycle in the CFD model.

It is also important to note that Figure 19 shows the dilution ratio at the surface of the forebay. As the plume from the diffuser is buoyant and lies close the surface, the values shown in Figure 19 are not representative of the dilution ratio throughout the depth of the forebay. Indeed the average value of dilution ratio at the turbine intake is significantly lower at a value of 100. This helps to demonstrates that the plume and mixing zone are a surface effect and are not as extensive in depth as Figure 19 might be taken to suggest.

Figure 20 shows contours of dilution ratio for Scenario 2 (91°F discharge temperature). The plume in this case is less spread than in Scenario 1. This is due to the difference in discharge temperature in the two scenarios. For Scenario 1 where the discharge temperature is higher, the plume rises to the surface quickly due to its positive buoyancy and then spreads in a relatively thin, shallow layer. The "cooler" discharge in Scenario 2 rises much more slowly and does not spread as rapidly just below the water surface. Therefore, in general, the cooler plume of Scenario 2 is less spread. The differences between the two plumes become greater as the dilution ratio increases. However, the same point as made for Scenario 1 is still applicable that the plume and mixing zone are predominantly surface effects. In Scenario 2 the average value of dilution ratio across the face of the turbine intake is 122.

Plan views of the mixing zone looking from above are shown on Figure 21 for Scenario 1 and Figure 22 for Scenario 2. The boundaries of the mixing zone are shown by the solid purple isosurfaces in each figure; the value of dilution ratio at the boundary of these iso-surfaces is 5 (concentration 20%). As this is the value which has been chosen to define the limit of the chronic mixing zone, Figures 21 and 22 show the extent of the chronic mixing zone for each Scenario.

4.3.1 Spatial Dimensions of the WET Mixing Zone

Figures 23 and 24 repeat the plan views of the mixing zone calculated for Scenario 1 and 2 with more detail of the plumes and less of the surrounding forebay. These figures have been annotated to demonstrate how the surface dimensions of the plumes have been determined. DHEC's normal method to determine plume dimensions is to draw a rectangular box around the plume, with the long sides aligned with the river flow direction and the short sides aligned with the cross-river direction. This has been replicated in Figures 23 and 24. Due to the curvature of the reservoir forebay and angle in the reservoir face the orientation of the rectangular box is somewhat arbitrary. However, in discussion with DHEC [Reference 25] it was decided to use a coordinate frame aligned with the discharge diffuser.

Results of the CFD modeling for the chronic mixing zone are summarized in the table below:

	Scenario 1	Scenario 2
River Flow	438 cfs 7Q10 Critical Flow	438 cfs 7Q10 Critical Flow
River Temperature	88.2°F	88.2°F
Discharge Flow	18.3 cfs	18.3 cfs
Discharge Temperature	**95°F**	**91°F**
CHRONIC MIXING ZONE (5:1 dilution, equivalent to 20% concentration)		
- **Volume**	0.345 acre-ft 15,039 ft^3	0.543 acre-ft 23,656 ft^3
- **Surface area**	0.120 acre 5,211 ft^2	0.149 acre 6,509 ft^2
- **Cross-Sectional area**	781 ft^2 4.8% of forebay x-area	922 ft^2 5.7% of forebay x-area
- **Average Depth/Thickness**	2.4 ft	2.5 ft
- **Maximum Depth/Thickness**	11.5 ft	12.0 ft
- **Maximum Width**	75 ft	62 ft
- **Maximum Length**	177 ft	276 ft

There were noted differences in the lateral extent of mixing zones output by the CFD model for the two scenarios considered (Figures 23 and 24). This was the result of changes in density/buoyancy attributable to the two different discharge temperatures modeled. In establishing the mixing zone size for the WET Mixing Zone request, worst case maximum dimensions for length and width were used from each of the scenarios modeled.

As determined from the CFD models, the worst case maximum dimensions of the chronic mixing zone are 75 ft (23 m) in width and 276 ft (84 m) in length (7% and 27% of the river width respectively).

As for the thermal mixing zone described previously, it is also important to consider the vertical profile of the mixing zone as the lateral dimensions of maximum length and width perhaps overstate the potential impact on aquatic organisms that might be exposed to acute and chronic conditions. Although the maximum depth of the chronic mixing zone (extending from the surface downward) is 12.0 ft, only a small proportion of the mixing zone is at that depth. Specifically, 87 percent of the mixing zone volume is found at 5 ft depth or less for Scenario 1. The same was found for Scenario 2. The average depth/thickness of the chronic mixing zone is just 2.4 ft for Scenario 1 and 2.5 ft to Scenario 2.

The relative profile of the mixing zones is further demonstrated by considering cross-section area, which for the chronic mixing zone is just 4.8 and 5.7 percent of the total forebay cross-sectional area for Scenarios 1 and 2, respectively.

Thus, given the relatively small lateral dimensions and cross-sectional profile of the mixing zone modeled under very conservative conditions, there is limited potential exposure to acute and chronic conditions for free-swimming fish or benthic organisms and their passive life stages.

As presented earlier (Section 3.4), EPA guidance provides that the area extent and concentration isopleths of a mixing zone must be such that the 1-hour average exposure of organisms passing through the mixing zone is less than the acute criteria [Reference 23]. Based on this guidance, the potential lethality to passive organisms from acute exposure within the chronic mixing zone was determined.

The average velocity in the steady-state plume was obtained from the CFD model and divided into the maximum length of the mixing zone to estimate potential travel time through the zone for a passive organism. For Scenario 1 (95°F discharge), the average velocity was estimated at 0.24 ft/s. As such, travel time through the plume's length of 177 ft was determined to be approximately 12 minutes. For Scenario 2 (91°F), the average velocity was 0.17 ft/s. The length of the plume is 276 ft so travel time is 27 minutes. Thus, no passive organisms/life stages will remain in the mixing zone for extended periods of time and certainly not an hour.

Again, determination of velocities throughout the plume is a complex exercise given the dynamic conditions in the forebay. However, the analysis is believed to be conservative in that the conditions considered (i.e., flow velocities) have been determined for the steady state condition of the plume under rare pulsed-flow conditions. Under typical continuous operation of the Ninety-Nine Islands hydroelectric facility turbines, ambient and turbine-induced flows would be expected to substantially reduce travel time for passive organisms through the mixing zone.

Further, as previously stated, including the enhanced mixing properties afforded by the high-velocity multi-port diffuser not fully considered by the current CFD model (see Section 3.3) will further diminish the size of the mixing zones reported herein and lessen exposure for passive organisms.

4.3 Whole Effluent Toxicity Parameters

Duke Energy is requesting a WET mixing zone be authorized for the Lee Nuclear Station discharge to the Broad River and has completed the SCDHEC-provided WET Mixing Zone Request Form. Information requested on the SCDHEC form is repeated here with supporting narrative.

What is the proposed ZID size (in meters)? *N/A*

Please refer to the site-specific definition of mixing zone given in Section 4.2 of this report.

What is the proposed acute WET test concentration? *N/A*

Please refer to the site-specific definition of mixing zone given in Section 4.2 of this report.

What is the proposed mixing zone size (in meters)? *Length 84 m x Width 23 m*

This proposed mixing zone size is deemed necessary to allow for adequate mixing of the discharge to the edge of the mixing zone defined distance between the end of the discharge diffuser and the turbine intake, and was conservatively determined based on the CFD model output.

What is the proposed chronic WET test concentration? *20.0 percent*

A representative value for minimum dilution at the distance between the end of the discharge diffuser and the turbine intake was calculated as 5, corresponding to a WET test concentration of 20%.

4.4 WET Mixing Zone Request

In addition to the completed SCDHEC WET Mixing Zone Request Form, this document constitutes Duke Energy's formal request to SCDHEC to authorize a WET mixing zone for the Lee Nuclear Station discharge to the Broad River. The technical information presented herein fully addresses South Carolina Regulation 61-68 Water Classifications and Standards as they relate to mixing zones for surface waters (Section C.10.); specifically:

- The size of the requested mixing zone has been reasonably minimized based on the proportion of the discharge flow to receiving waterbody critical 7Q10 flow (i.e., approximately 4 percent).

- The size of the requested mixing zone has been further minimized through the use of a submerged, multi-port discharge diffuser that provides rapid mixing of the discharge in the receiving waterbody.

- Initial analysis showed that the spatial dimensions of the acute mixing zone (based on a maximum width of 10% of the width of the river and a maximum length of 33% of the width of the river) almost entirely contained the discharge plume due to the turning of the flow towards the turbine. Thus the turbine intake was defined as the maximum extent in this case for the chronic mixing zone, while no definition or dimensions were given for the acute mixing zone.

- The spatial dimensions of the chronic mixing zone fall well within SCDHEC's specified spatial boundaries for such mixing zones of no more than one-third (33.3 percent) the width of the river (width) and a length downstream of twice (200 percent) the width of the river [Reference 22]. For the Lee Nuclear Station discharge, the width and length of the chronic mixing zone represent approximately 7 percent and 27 percent respectively of the width of the Broad River at the forebay of the dam.

- The cross-sectional areas of the mixing zones modeled relative to the total forebay cross-sectional area were small, ranging from 4.8 to 5.7 percent. As such, there is limited potential exposure to chronic conditions for free-swimming fish and their passive life stages.

- The maximum travel time through the chronic mixing zone considering both discharge scenarios was determined to be approximately 27 minutes. Thus, no passive organisms/life stages will be exposed remain in the chronic mixing zone for extended periods of time (well less than an hour).

- Given the small size of the discharge area and requested mixing zone relative to the receiving waterbody, there is no reasonable expectation that the Lee Nuclear Station discharge would "*result in undesirable aquatic organisms or a dominance of nuisance species outside of the mixing zone.*"

- Given there are no federally-listed endangered or threatened aquatic species or habitats in the Broad River in the vicinity of the discharge [Reference 1], there is no reasonable expectation that the requested mixing zone "*would adversely affect a federally-listed endangered or threatened aquatic species, its habitat, or a proposed or designated critical habitat.*"

- Based on the small proportion of the discharge flow to receiving waterbody critical 7Q10 flow (i.e., approximately 4 percent), minimization of the mixing zone to meet SCDHEC spatial requirements for mixing zones, and limited travel time through the plume for passive organisms, the requested mixing zone will allow for safe passage of aquatic organisms, and allow for the protection and propagation of a balanced indigenous aquatic community in and on the Broad River.

- The requested mixing zone will not endanger public health and welfare.

Based on the above evidence, Duke Energy requests that SCDHEC authorize a WET mixing zone as defined in this request for outfall 001. The WET limit for outfall 001 is requested to be for chronic testing only at a Chronic Test Concentration of 20%.

5. REFERENCES

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FIGURES