Technical Evaluation Report Related to the Exelon Generation Company, LLC, License Amendment Request to LaSalle County Station, Units 1 and 2, Technical Specification 3.7.3, “Ultimate Heat Sink.”
Docket Nos. 50-373 and 50-374

Prepared for:

U.S. Nuclear Regulatory Commission
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1 BACKGROUND

On July 12, 2012, Exelon Generating Company, LLC (the licensee) requested a change to the Technical Specification of Facility Operating License Nos. NPF–11 and NPF–18 for the LaSalle County Station, Units 1 and 2, to allow a higher temperature limit of 107 °F for water supplied from the Ultimate Heat Sink (UHS). Water from the UHS would be provided by a cooling pond that is integral to the main cooling reservoir and would retain water upon loss of integrity.

The licensee provided a technical justification based on computer models, using heat rejected to the pond, flow rates, and meteorological data, to calculate highest temperature being returned from the pond, as well as, water use for a minimum of 30 days.

This technical evaluation report (TER) provides a review of the licensee's analysis, including the July 12, 2012, license amendment request (LAR, Exelon Generating Company, 2012), and their responses to several rounds of requests for additional information (RAIs). The Southwest Research Institute® (SwRI®) staff carried out an audit-type review and focused primarily on the determination of peak return water temperature from the UHS pond, as it is our judgment the licensee's analyses of the 30-day water supply have established its adequacy (Exelon Generating Company, 2013, ML14066A234, Attachment H). Furthermore, SwRI relied on the accuracy of much of the information supplied by the licensee, including heat rejection and flow rates to the pond, the dimensions of the pond, including water level and sedimentation, meteorological data, and the acceptability of the stated temperature limit for water returned from the pond.

2 SUMMARY OF LICENSEE'S LAR AND SUPPORTING ANALYSES

The licensee calculated temperature returning from the UHS pond using a one-dimensional computer model, LAKET-PC (Nevill and Szymiczek, 2013). The pond was modeled as a series of segments of equal surface area and volume. Flow rate through the pond was initially 65.3 CFS for the first 16 hours and then 86 CFS. Heat load from both units was provided hourly. The UHS pond has a surface area of about 81 acres and a maximum volume of about 340 acre-ft. However, the pond volume and depth depended on the assumption of how much sediment had accumulated. The licensee assumed a minimum of 6 inches to a maximum of 18 inches of sediment uniformly spread over the pond.

Meteorological information was compiled from limited onsite data and mostly offsite data from stations in Peoria and Springfield, Illinois, approximately 70 and 110 miles from the site, respectively. Onsite data consisted of wind speed, wind direction, and dry bulb temperature. Offsite data were used to provide other needed meteorological parameters, namely dew point temperature, short-wave solar radiation, and cloud cover. The licensee adjusted data for the model calculations in order to account for errors and missing periods. Additionally, dew point temperature, which was collected offsite, was adjusted where necessary so it did not exceed the dry bulb temperature collected at the LaSalle site.

The data set used in the licensee's latest analysis for peak return temperature covered the 15+ year period from January 1995 to September 2010, and was compiled only from the LaSalle site and Peoria data. The licensee also provided meteorological data from Peoria and Springfield from 1948 to 1996, which had been used for the current Technical Specification (Exelon Generating Company, 2012, Page 8), and also were used by the licensee for the current calculation of 30-day evaporative water loss. The licensee screened the 1948-1996 weather data for peak return temperature, but found the later data set to be more limiting.

The licensee's LAKET-PC model used the Ryan and Harleman heat transfer relationships (Ryan and Harleman, 1973), with a correction for "natural temperature," described later in Section 4.

The licensee also developed a three-dimensional computational fluid dynamics (CFD) model to adjust volume and surface area of the UHS pond to account for sub-optimal flow conditions not captured in their one-dimensional model. They used the CFD results to adjust the effective surface and volume downward to 57.9 and 63.4 percent of their initial values, respectively, for LAKET-PC. The CFD model was developed with the assumption the pond would be unstratified based on their calculations in Attachment N of ML14066A234 (Ludovisi and Kut, 2013). To account for possible uncertainty in the CFD model, SwRI conducted sensitivity experiments on the effect of reduced UHS pond surface area and volume on peak temperature. These results are discussed in Section 4.

Heat load for Revision 8 of their calculations is based on a Loss of Coolant Accident (LOCA) in one unit and a reactor SCRAM for the other unit, coincident with a loss of circulating water for condenser cooling. The LOCA unit has both residual heat removal (RHR) heat exchangers, while the other unit has one RHR heat exchanger in suppression pool cooling mode and later shutdown cooling mode. The second non-LOCA unit RHR heat exchanger is in fuel pool cooling assist mode.

Weather Screening

The licensee screened the available meteorological data set to produce numerous sub-sets of data they expected to produce the peak return water temperature to the plant, and also the maximum 30-day evaporation rate. Screening used the LAKET-PC computer code in "open mode" (i.e., starting with a fixed water temperature entering the pond, no recirculation back to the plant) and a flow rate equal to a 3-hour recirculation time through the pond. Temperature was calculated using the 15+ years of processed weather data from the site and Peoria. The licensee determined the highest temperature that would occur with water at a fixed starting temperature of either 110°F or 120°F and travel times of 24, 33, 39, 42, and 45 hours based on a flow rate of 86 CFS. A "rolling average" temperature over a 24-hour period was calculated from the 3-hour results of LAKET-PC in order to define the "worst day" for peak temperature as a function of starting time of the design basis accident (DBA) [Attachment M, page M4/17 (Nevill, 2012)].

Weather scenarios considered were:

- Sedimentation displacing pond water being 0, 6, 12, or 18 inches deep (affects travel time of water though the pond)
- The DBA starting at 12 AM, 3 AM, 6 AM, 9 AM, 12 PM, 3 PM, 6 PM, or 9 PM
- Combining the worst time period from the screening followed by the worst 24 hour period
- Periods shorter than the circulation time of the pond (i.e., 9 or 12 hours)
- Sensitivity cases for the effect of reduction of wind speed as a function of height and time of day

They derived the maximum allowable starting temperature in the pond so the peak return temperature would not exceed 107 °F at any time during the 30-day period after the accident event. This calculation also included a 0.75 °F allowance in the starting temperature of their computer runs to account for measurement uncertainty in temperature instruments.

At the request of the U.S. Nuclear Regulatory Commission (NRC) staff, the licensee also performed several additional computational analyses:

- Determine the effect of mixing in the entrance location of the pond – In RAI 32, NRC staff expressed concern that mixing near the discharge into the pond would diminish the water temperature, and thereby environmental heat transfer, possibly leading to an increase in the calculated peak return water temperature. The licensee developed a modified calculation that includes as the first segment a well-mixed region of uniform temperature of either 10 percent or 20 percent of the pond volume to account for mixing caused by the high-velocity discharge. This had the effect of reducing the average temperature of the first segment, thereby reducing surface heat transfer. However, mixing with cooler pond water counteracted the loss of cooling, with the result being the same or lower peak return water temperature.

- Effect of land surface and structures on wind speed over the pond surface – In RAIs 12 and 37, NRC staff expressed concern about the estimation of wind speed at the pond surface being affected by the land surface, embankments, and structures. In response, the licensee commissioned a wind tunnel/scale model study to determine the influence of lower water levels, structures, and embankments on wind speed over the water surface (CPP, 2013). The results were used in the analysis to adjust wind speeds to the required two-meter elevation above the water surface for the LAKET-PC model. SwRI conducted sensitivity experiments to determine the effect of the wind speed correction factor on peak return temperature, presented later.

- Evaluation of Potential for Thermal Stratification – Stratification could result mainly from the discharge of heated water into the cooler and denser pond water, potentially enhancing flow along the surface and reduce the travel time through the pond. A necessary condition for use of the LAKET-PC model and SwRI's model is that no stratification is present. The licensee defends its conclusion the pond would not be stratified on the basis of a theoretical model for the behavior of a distinct two-layer system representing water density variation (i.e., hot water sitting on top of cool water), and no interfacial mixing except in the entrance region (Octavio, et al., 1979). This procedure is generally known as the "pond number" approach (Helfrich, et al., 1982). SwRI conducted sensitivity experiments to determine the effect of thermal stratification on peak return temperature, presented later.

On the basis of their calculations, the licensee developed a revised Technical Specification 3.7.3, which allows a higher return water temperature of 107 °F, and specifies a maximum allowable starting pond temperature that varies according to the time of day the Design Basis Accident occurs. This is shown in Table 1 [Table O4-1, (Exelon Generating Company 2013, ML14066A234)].

The table shows the actual LAKET-PC runs started at the temperatures in the third column, and were adjusted downward by 0.75 °F (in the second column) to account for the potential instrument uncertainty.

3 REGULATORY BASIS FOR SWRI'S REVIEW

This review follows General Design Criterion 2 (GDC 2), Standard Review Plan (NUREG–0800) Section 9.2.5, Regulatory Guide (RG) 1.27, Revision 2, and NUREG–0693 (NRC, 1980). The regulatory basis is stated in RG 1.27, Regulatory Position 1, which for this review can be summarized as follows:

- *"Sufficient conservatism should be provided to ensure that a 30-day cooling supply is available and that design basis temperatures of safety-related equipment are not exceeded…"*
- *"The meteorological conditions resulting in minimum water cooling should be the worst combination of controlling parameters, including diurnal variations where appropriate, for the critical time period(s) unique to the specific design of the sink…"*
- *"…Select the most severe combination of controlling parameters, including diurnal variations where appropriate, for the total of the critical time period(s), based on examination of regional climatology measurements that are demonstrated to be representative of the site…"*

Table 1. Licensee's Proposed Technical Specification (TS) 3.7.3 (Table O4-1, Exelon Generating Company 2013, ML14066A234)

Event Start Time	Proposed TS Limit	Proposed TS Limit Plus Uncertainty (0.75 °F)
0:00	103.78 °F	104.53 °F
3:00	101.97 °F	102.72 °F
6:00	101.25 °F	102.00 °F
9:00	102.44 °F	103.19 °F
12:00	104.00 °F	104.75 °F
15:00	104.00 °F	104.75 °F
18:00	104.00 °F	104.75 °F
21:00	104.00 °F	104.75 °F

4 SWRI'S TECHNICAL EVALUATION

4.1 Introduction

This section presents SwRI's independent evaluation of the licensee's results. The licensee provided the following information discussed in Section 2:

- Dimensions of the UHS pond, including depth and sedimentation thickness
- Raw meteorological data collected at the LaSalle site, Peoria and Springfield Illinois
- Processed data that combined and adjusted raw meteorological data
- Wind-speed reduction factors to account for terrain and structures near the pond
- Flow rate through the pond versus time
- Heat load to the pond versus time
- Results of the CFD study
- Results of a surveillance of the pond in 2010 to measure sediment deposition

The details of SwRI's independent confirmatory analyses are presented in Appendix A.

4.2 SwRI's Computational Model

SwRI developed a computer model, LAPLUG, derived from the original model UHS3 from NUREG–0693. The new computer program addressed only the plug-flow type analysis and was updated to use new data formats not available in the original UHS3 program, as well as, the meteorological and other data files supplied by the licensee. It also was updated to use the Ryan-Harleman heat transfer formulation (Ryan and Harleman, 1973), with the option to substitute the more-conservative Brady wind function (Brady, et al., 1969). The model was similar to SwRI staff's understanding of the LAKET-PC model, but with several distinctions:

- The licensee's model used only the Ryan-Harleman formulation.

- The licensee's model accounted for reflection of long wave and short wave radiation from the water surface, whereas the SwRI model conservatively ignored reflection.

- The licensee's model conservatively included a provision that reduced surface heat transfer to the environment when the pond temperature was less than 2.5 °F above the "natural temperature." The natural temperature was defined as the temperature that would be attained by an infinitesimal volume of water under the influence only of environmental factors, with no additional heat. The SwRI model did not include this provision, but concludes that, while it is conservative, it also is not physically realistic.

- The licensee's model treats the pond as a succession of segments of equal surface area and volume. They were not able to treat entrance mixing directly within the LAKET-PC code. However, they simulated mixing zones of 10 percent and 20 percent of the pond volume using an external procedure [Section O6.9.2, Calculation no L-002457, Revision No. 8, ML14066A234 (Exelon Generating Company, 2013)]. SwRI's model accounts for different depth and surface areas in each segment.

- Except for the first segment, the licensee's model uses a strictly plug-flow formulation that treats the movement of hot water discharged from the plant through the pond with no mixing or longitudinal dispersion. While plug flow enhances heat transfer between the water and the atmosphere, it tends to enhance the peak temperature by not accounting for mixing of hot discharged water with cooler ambient pond water. The SwRI model treats the segments as a series of well-mixed tanks, accounting for mixing of the hot water with cooler ambient pond water. We believe this to be a more realistic approach that accounts for dispersion processes encountered in real water bodies. We base our belief on the fact that the SwRI model replicates the licensee's CFD analyses (Ludovisi and Kut, 2013) more closely than strictly the plug flow model would.

4.3 SwRI's Confirmatory Evaluation of LaSalle UHS Performance

SwRI staff's analysis of the licensee's performance results can be described by the following steps:

- Determine the adequacy of using a one-dimensional cooling pond model to evaluate a complex pond.

- Determine the adequacy of using meteorological data collected at the site and from distant weather stations.

- Determine the maximum return temperature using the available meteorological record and SwRI's models and formulas.

- Determine the sensitivity of calculated maximum return temperature to model and data assumptions.

4.3.1 Adequacy of Licensee's Use of a One-Dimensional Cooling Pond Model

SwRI staff evaluated the licensee's calculations to determine whether the pond would become stratified. Although the pond number approach has been shown to be useful in the analysis of cooling reservoirs, SwRI staff felt it may not give an accurate portrayal of actual UHS pond performance, mainly because the latter is highly transient and the model does not account for interfacial transport.

Neither of these reasons is necessarily nonconservative and empirical evidence on shallow ponds shows they are frequently vertically well mixed. The high-velocity discharge of heated water into the pond should lead to considerable vertical and horizontal mixing over a significant portion of the pond, as shown by the Licensee's CFD model results. Furthermore, stratification, if it were present, would have the beneficial effect of maintaining a high surface temperature with correspondingly higher heat transfer to the atmosphere, and also promote circulation of hot water into dead-end spaces in the pond.

SwRI staff has made several sensitivity calculations postulating stratification existed in the pond and concluded stratification would not result in a return water temperature greater than that calculated by the nonstratified assumption. Results are presented in Table 2.

4.3.2 Adequacy of the Licensee's Use of Meteorological Data Collected From Distant Weather Stations

SwRI staff compared raw meteorological data on wind speed and dry bulb temperature from the LaSalle site to those data from Peoria for the years 2001 and 2010. They found the data were similar, but the Peoria data were slightly more conservative from the standpoint of pond cooling; i.e., wind speeds were on average lower and dry bulb temperatures were higher at Peoria.

The licensee used wind speed and dry bulb temperature from the LaSalle site and other data from Peoria, with the stipulation dew point temperature could not exceed the dry bulb temperature. SwRI staff concludes the final data set has been appropriately synthesized from the two sites.

4.3.3 Evaluation of Maximum Return Temperature

SwRI Staff calculated the peak return water temperature using the LAPLUG model with the licensee's primary inputs for meteorology, heat load, and flow rates. The base case refers to the benchmark run using SwRI staff's best estimate of physical pond parameters and heat transfer relationships. The calculations assumed there was 18 inches of sediment in the pond (the worst-case value), and the initial pond temperature was always 104 °F. Results of the licensee's surveillance in 2010 indicated minimal sediment deposition (less than 0.4 ft) over

Table 2. Results of Base Case and Sensitivity Runs With LAPLUG–LaSalle Meteorological Data Unless Stated Otherwise	
Description of Model Run	**Peak T, °F**
Base case, Ryan wind function	105.04
Base case, Brady wind function	106.10
Ryan wind function, Peoria met data	105.33
Brady wind function, Peoria met data	105.82
Ryan wind function, effect of 2 ft stratified layer	104.70
Brady wind function, effect of 2 ft stratified layer	105.70
Ryan wind function, Model A, 30 equal segments	105.58
Ryan wind function, 12.5 percent volume and area for segment 1	105.04
Brady wind function, 12.5 percent volume and area for segment 1	105.73
Ryan wind function, 25 percent reduction of wind speed from base run	105.28
Brady wind function, 25 percent reduction of wind speed from base run	107.10
Ryan wind function, 10 percent reduction in surface area and volume	105.04
Brady wind function, 10 percent reduction in surface area and volume	107.43
Ryan wind function, 25 percent reduction in surface area and volume	105.04
Brady wind function, 25 percent reduction in surface area and volume	108.96
Ryan wind function, add 2 °F to dry bulb, 1.6 °F to dew point	105.25
Brady wind function, add 2 °F to dry bulb, 1.6 °F to dew point	106.74
Ryan wind function, increase heat load by 50 percent	105.04
Brady wind function, increase heat load by 50 percent	108.97
Ryan wind function, add 0.75 °F to starting pond temperature	105.68
Brady wind function, add 0.75 °F to starting pond temperature	106.39
Ryan wind function, add 5 °F to dry bulb, 4° F to dew point, 0.75 °F to starting pond temperature	106.19
Ryan wind function, as above, but wind-speed reduction factor = 0.43	106.61

most of the pond, with the exception of localized areas such as the pond outfall structure and along the sloping embankment areas of the pond (Exelon Generating Company, 2012, Page 7/21). SwRI staff therefore concluded the assumption of 18 inches of sediment throughout the pond is conservative.

Calculations started on 3-hour intervals from May through September (the hottest months) from 1995 through 2010, tabulating the peak return temperature for each run. Peak temperature from SwRI staff's base case model was 105.04 °F, occurring at approximately 2:00 PM on July 26, 2001, about 7 hours after the start of the accident event. This temperature does not include the uncertainty factor of 0.75 °F added to the initial pond temperature by the licensee to account for uncertainty in temperature measurement, but this factor is included in a sensitivity case presented in Table 2.

This result shows that for SwRI staff's best estimate, the peak return temperature does not depend on the introduction of heated water from the plant, but is purely a result of heat transfer into the pond from the environment.

4.3.4 Evaluation of Sensitivity of Calculated Maximum Return Water Temperature to Model and Data Assumptions

4.3.4.1 Sensitivity Cases

Given there is uncertainty in the models, data, and heat-transfer relationships used, SwRI staff executed a number of runs to test the sensitivity of peak return water temperature to various assumptions about data, heat-exchange relationships, and model parameters. The following sensitivity runs (i.e., what-if analyses) were made:

- Alternative heat transfer relationships—Replace the Ryan wind function with the more-conservative Brady wind function to examine the importance of decreased environmental heat transfer.

- Alternative meteorological data set—Use the 1948–1996 Peoria and Springfield data set used for the previous technical specifications for returned temperature to expand the length of the data record used in the present analyses.

- Effects of stratification—Assume a 2-ft thick thermal layer on top of ambient pond water to determine if stratification would lead to a more-adverse condition.

- Effect of pond configuration in model—Assume licensee’s configuration of equal volume and surface area for each of 30 pond segments to determine the importance of taking varying depth of the pond into account.

- Size of first segment—Assume 12.5 percent of volume and area for first segment as opposed to 25 percent in base case run to determine the importance of near-field mixing.

- Effective volume and surface area of pond—Reduce the effective surface area and volume by either 10 percent or 25 percent of the licensee’s assumptions to account for uncertainties in the CFD analyses.

- Higher heat load—increase design UHS heat load by 50 percent.

- The effect of a higher starting temperature of 104.75 °F at the beginning of the run to account for uncertainty in temperature measurements.

- More adverse meteorology from global climate change (GCC) during plant lifetime—Add 2.0 °F to dry bulb temperature and 1.6 °F to dew point temperature based on an approximation of climate projections over the remaining lifetime of the plants (GLISA, 2014). SwRI staff also performed an additional, more severe case that added 5.0 °F to dry bulb temperature, 4.0 °F to dew point, and 0.75 °F to the starting temperature.

- Wind speed attenuation—SwRI staff assumed a wind-speed reduction factor (from the 10 meter to 2 meter elevation level) of 0.8, based on the licensee’s study (CPP, 2013). The licensee’s own analysis used a more-conservative wind speed reduction factor of 0.62. This sensitivity analysis assumes that a 2-meter wind speed factor is 25 percent smaller than the base case value, which is a slightly more conservative than the licensee’s factor, to determine the importance of wind to environmental heat transfer. SwRI staff also performed an additional run using a wind speed reduction factor of 0.43, based on a worst-case correlation of wind speeds from the onsite meteorological tower. This run also included the higher starting temperature of 104.75 °F and the GCC corrections of 5 °F and 4 °F to the dry bulb and dew point temperatures, respectively.

Results from these sensitivity runs and the base case are given in Table 2. Except for the last four entries, the peak temperatures do not account for the 0.75 °F temperature measurement uncertainty. These sensitivity runs include both the Ryan and Brady wind functions.

4.3.4.2 Discussion of Sensitivity Results

These runs predict the peak return water temperature would not exceed 107 °F with the preferred Ryan wind function model. Raising the starting temperature of the pond from 104 °F to 104.75 °F would result in increasing the Ryan results by approximately 0.64 °F. Note this is less than the 0.75 °F correction used by the licensee; therefore, their correction is conservative. All of the results with the Ryan wind function predicted the peak would result from environmental heat transfer only and not from the hot water addition to the pond.

The results with the more-conservative Brady wind function predict higher peak return water temperatures, in some cases exceeding 107 °F. Raising the starting temperature from 104 °F to 104.75 °F would add approximately 0.29 °F to the Brady results. Furthermore, the lower heat transfer implied by the Brady wind function results in the peak return water temperature resulting from the coincidence of environmental heating and the arrival of the thermal pulse from hot water discharged to the UHS pond. This result is not seen with the Ryan wind function cases.

Although some of the sensitivity results exceeded 107 °F, we believe this is a consequence of the over-conservatism of the Brady wind function model. The Ryan wind function sometimes overestimates cooling, but we believe it is has been shown to be the most reliable formula over a wide assortment of heated ponds and cooling reservoirs. The biggest factor in the superior performance of the Ryan wind function is it takes into account the increase in convection caused by buoyancy of hot, humid air, and therefore, increases heat transfer from evaporation and thermal convection with increased heat loads. By contrast, the Brady wind function has a fixed value for the effect of convection, which does not increase with increasing water temperature. The Brady formulation frequently underestimates cooling, often by a large margin, and even for Brady's own data (Ryan and Harleman, 1973).

The licensee's model predicts peak return temperatures considerably higher than SwRI staff's model, even though both models use the Ryan wind function, and SwRI staff's model conservatively ignores surface reflection of short and long wave radiation. On the basis of calculations using models similar to the licensee's plug-flow and natural temperature assumptions, SwRI staff believes there are two primary reasons for the difference between SwRI and licensee results:

- The licensee's use of "natural temperature" in its model to switch between two wind functions—the Ryan and Lake Hefner wind functions (Ryan and Harleman, 1973)—considerably reduces heat transfer to the atmosphere under certain conditions.

- Except for the first pond segment, where they apply a correction for mixing, the licensee used a strict plug flow approach for movement of hot water through the pond. We believe this approach does not properly account for mixing, dispersion, and multiple paths in the balance of the pond, causing the peak temperatures to be accentuated.

SwRI staff believes the use of natural temperature and strict plug flow, while conservative, is not realistic.

5 SWRI'S CONCLUSIONS

SwRI staff has carefully examined the licensee's analyses of the peak return water temperature from the UHS pond at the LaSalle site, and performed an independent confirmatory analysis based on its best understanding of the data and phenomena involved. We conclude the licensee's calculations of peak return water temperature are conservative, and the revised Technical Specification 3.7.3 is acceptable. We base this conclusion on the following factors:

- We evaluated the meteorological data used by the licensee and determined it was appropriate for use in the pond performance models.

- We examined the licensee's performance models and determined they were appropriate and conservative, even for the worst conditions of pond sedimentation and adverse meteorology.

- We performed our own confirmatory analyses that include sensitivity of peak return water temperatures to alternative assumptions about data, models, and parameters. Since our peak temperature results were uniformly more favorable (i.e., lower) than the licensee's, we conclude the licensee's results are conservative.

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APPENDIX A

Confirmatory Analysis for the Review of the Exelon Generation Company, LLC, License Amendment Request to LaSalle County Station, Units 1 and 2, Technical Specification 3.7.3, “Ultimate Heat Sink,” Docket Nos. 50-373 and 50-374

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Executive Summary

Southwest Research Institute® (SwRI®) performed an independent review and evaluation of the Ultimate Heat (UHS) pond for the LaSalle County plants. Our evaluation focused on determining the peak temperature of water returned from the pond under the influence of rejected heat from the plant and severe meteorological conditions. We also restricted our analyses to a worst-case scenario based on a high sediment load of 18 inches in the bottom of the pond.

We evaluated the licensee's use of limited meteorology collected at the LaSalle site and from distant weather stations at Peoria and Springfield, Illinois. We concluded the meteorological data were synthesized adequately to produce data sets that could be used to evaluate the cooling performance.

The SwRI model was developed from the U.S. Nuclear Regulatory Commission (NRC) cooling pond code UHS3 in NUREG–0693 (NRC, 1980). Major modifications to the UHS3 code were necessary because of different data formats available for the LaSalle evaluation and improved atmospheric heat transfer models. Key sections were extracted from the UHS3 code to develop a site-specific version suitable for the LaSalle evaluation called LAPLUG. The LAPLUG model received limited validation using data from cooling pond experiments published in NUREG–0858 (NRC, 1982).

There were significant differences between the licensee's computer codes LAKET-PC and LAPLUG. In particular, the licensee's code uses a no-dispersion model that assumes the movement of parcels of water in plug flow through the pond, with no mixing into cooler ambient pond water. In addition, the licensee's model uses a different form of the atmospheric heat transfer formulas that can significantly underestimate heat transfer from natural convection ("natural temperature" approach). Both factors potentially lead to higher return water temperature. The SwRI model allows mixing of heated water with ambient pond water and does not artificially restrict natural convection. We believe there is ample evidence for mixing and dispersion in the pond, and that artificial restriction on natural convection is overly conservative.

We also tested our results with sensitivity analyses that looked at the effect of a wide variety of factors on peak return temperature. These included alternative meteorological data; different heat transfer formulas; effects of entrance mixing, smaller volume and surface area, higher heat load, lower wind speed, and higher starting pond temperature.

We concluded that with the specified heat loads and other pond parameters, and using the preferred Ryan and Harleman (1973) atmospheric heat transfer relationships, peak return temperature is independent of heat rejected from the plant. Through model experimentation, we concluded that differences between the licensee's predictions and our own can be attributed to their use of the no-dispersion model and the natural temperature approach for atmospheric heat transfer. Since our results were uniformly less severe than the licensee's, we conclude their analysis is conservative and acceptable.

A1 INTRODUCTION

In accordance with the provisions of Contract NRC–HQ–50–14–E–0001, Task Order No. NRC–HQ–20–14–T–0014, the Center for Nuclear Waste Regulatory Analyses (CNWRA®) of Southwest Research Institute® (SwRI®) performed an evaluation of each License Amendment Request (LAR). As part of the evaluation, SwRI, in parallel with the U.S. Nuclear Regulatory Commission (NRC) staff, reviewed the licensee documents and the licensee's response to NRC's Requests for Additional Information (RAIs). SwRI staff prepared additional RAIs and reviewed the licensee's response as part of the review process. Using the data provided by the licensee in response to the new RAIs, SwRI conducted confirmatory analyses to determine if the peak return temperature would exceed 107 °F at any time during the 30-day period after an accident event. This appendix provides further details on the summary of findings presented in the main part of this Technical Evaluation Report (TER).

SwRI review was restricted to determining the maximum return water temperature under conditions of cooling reservoir failure, extreme meteorology, and other factors, such as sediment deposition within the UHS pond. We base this restriction on our judgment that the licensee has demonstrated to our satisfaction an adequate quantity of water would be available.

SwRI review of the licensee's model and data, and our independent confirmatory analysis using the NUREG–0693 approach focused on the following areas to determine:

- The adequacy of the licensee's use of meteorological data collected at the site and from distant weather stations

- The adequacy of the licensee's one-dimensional plug-flow cooling pond model

- The adequacy of the licensee's environmental heat transfer formulas

- The sensitivity of calculated maximum return temperature to model and data assumptions

Section A2 presents the computer software used and programs developed. Section A3 documents the confirmatory analyses and the review results. Section A4 documents differences between the licensee and SwRI results and their probable explanations. Section A5 presents the conclusions from SwRI's confirmatory analyses. The appendix presents an analysis of the probability of high return temperatures.

A2 SOFTWARE TOOLS

For confirmatory analysis, we used the following commercial and open-source computer software.

- Lahey FORTRAN 95 compiler, and the FORCE 2.0 FORTRAN compiler and editor were used in the preparation and execution of the FORTRAN codes

- Microsoft® Excel 2007 was used for manipulation of data and results

- R Version 2.8, JMP Version 5, and DPLOT Version 2.2.5.5 were used in sensitivity studies and general plotting of results

- FORTRAN programs (final versions) developed were LAPLUG.f for temperature calculations, MET3.f, METLA3.f, and METLA4.f for meteorological data comparisons, PLUGTEST.f to demonstrate dispersion in the one-dimensional codes, LANATURAL.f to calculate the “natural temperature,” and a version of LAPLUG.f to demonstrate how natural temperature and plug flow affect peak return temperature

- A Python Version 2.7 code was developed to extract temperature and wind speed data from the raw-data files from the licensee [National Oceanic and Atmospheric Administration’s (NOAA)’s Peoria weather station data)]

A3 ANALYSES BY LICENSEE AND SWRI STAFF

This section covers the analyses made by the licensee and SwRI staff in their respective analyses, including meteorological data and model adequacy.

A3.1 Adequacy of Meteorological Data

Calculations with the licensee and SwRI models were performed using the licensee’s prepared data set PIALSL9510.txt, based on over 15 years of data from the site and Peoria Illinois, about 70 miles southwest of the site. In addition, SwRI used the licensee’s data set PS489661.txt, prepared from meteorological data collected at Peoria and Springfield, Illinois (about 110 miles southwest) from 1948 to 1996. The licensee’s primary meteorological data set (PIALSL9510.txt) was prepared by using wind speed and dry bulb temperature from the LaSalle site and all other measurements from the Peoria site. These data are referred to in this report as the “LaSalle data set.” For thermodynamic consistency, the licensee adjusted the dew point temperature from Peoria so it could not exceed dry bulb temperature from LaSalle. We performed calculations of temperature running through the entire two data sets for the months May through September starting at 3-hour intervals.

Since the other weather stations were distant from the site, we compared offsite data to available onsite data to determine the validity of the licensee’s use of those distant data for performance evaluations. These comparisons were limited because only wind speed and dry bulb temperature were available from the LaSalle site. A statistical sensitivity study of peak pond temperature calculated with our performance model indicated the order of importance of meteorological parameters was (i) dew point temperature, (ii) solar radiation, (iii) cloud cover, and (iv) wind speed. Dry bulb temperature did not show a strong effect on peak temperature. However, this is likely to be just an artifact caused by the strong correlation (shown below in Figure A1) between dry bulb temperature and dew point temperature. Since the peak generally occurred with our model on the order of 5 to 9 hours after the event, the statistics were based on a 5-hour average of the preceding meteorological data as a better representation of cumulative effect than instantaneous values.

<u>Temperature Comparison.</u> Although no dew point data were available (in general) onsite, it is important to evaluate the similarities and differences between the LaSalle and Peoria site data because dew point and dry bulb temperatures are highly correlated. Figure A1 shows this correlation for 2010 data. The 2001 data showed similar correlation.

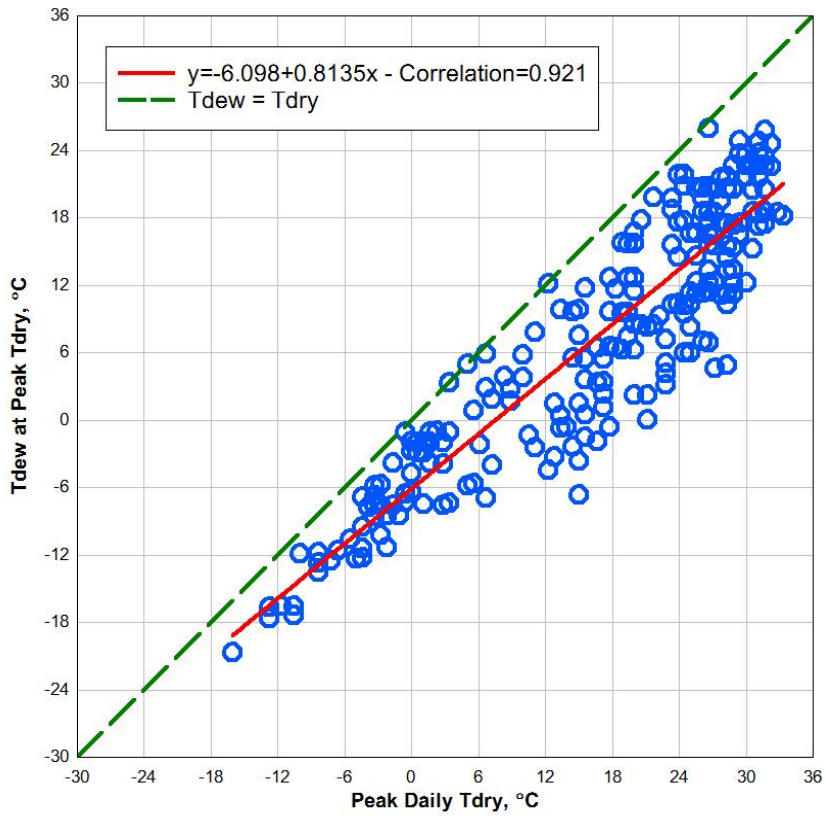

Figure A1. Correlation of Dry Bulb and Dew Point Temperatures for Year 2010, LaSalle Data Set

Comparison of the daily peak dry bulb temperatures from the LaSalle to the Peoria site for the year 2001 is shown in Figure A2.

Figure A2 shows that on average, Peoria has higher air temperatures than LaSalle, especially in the hotter summer months.

Figure A3 compares dry bulb temperature versus dew point temperature from the raw Peoria and LaSalle data set. This figure shows the two data sources are comparable, but in some cases, dew point has been adjusted downward by the licensee to be equal to dry bulb temperature for thermodynamic consistency (i.e., the relative humidity cannot be greater than 100 percent).

Wind Speed Comparison. Wind speed was one of the weaker factors for peak return water temperature, as determined from our statistical analysis of model results. Higher wind speed leads to greater heat transfer from the pond, particularly from evaporation. However, natural convection is an important part of evaporative and convective heat transfer irrespective of wind speed, as will be discussed later. Figure A4 shows the comparison of daily average wind speeds for the LaSalle and Peoria sites for 2001.

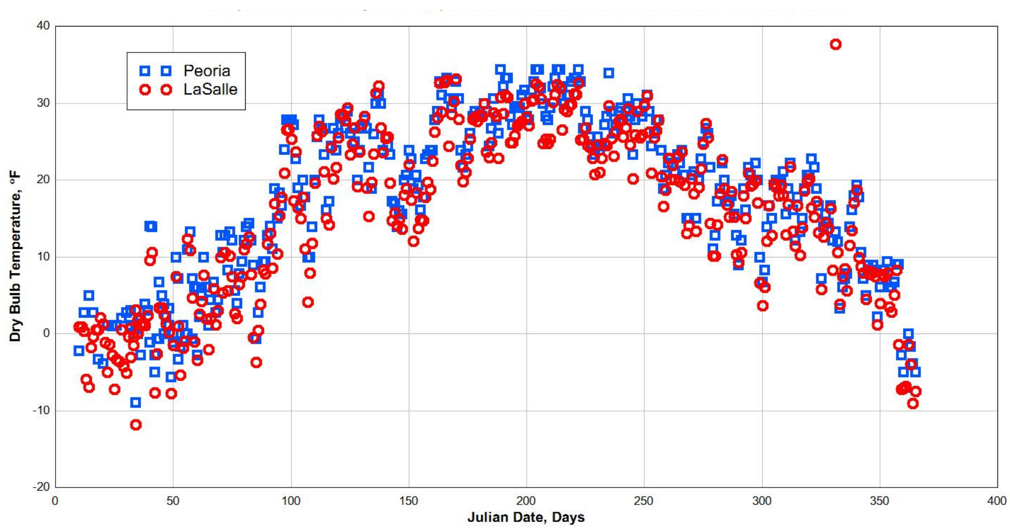

Figure A2. Daily Peak Dry Bulb Temperatures for LaSalle and Peoria Sites, Year 2001

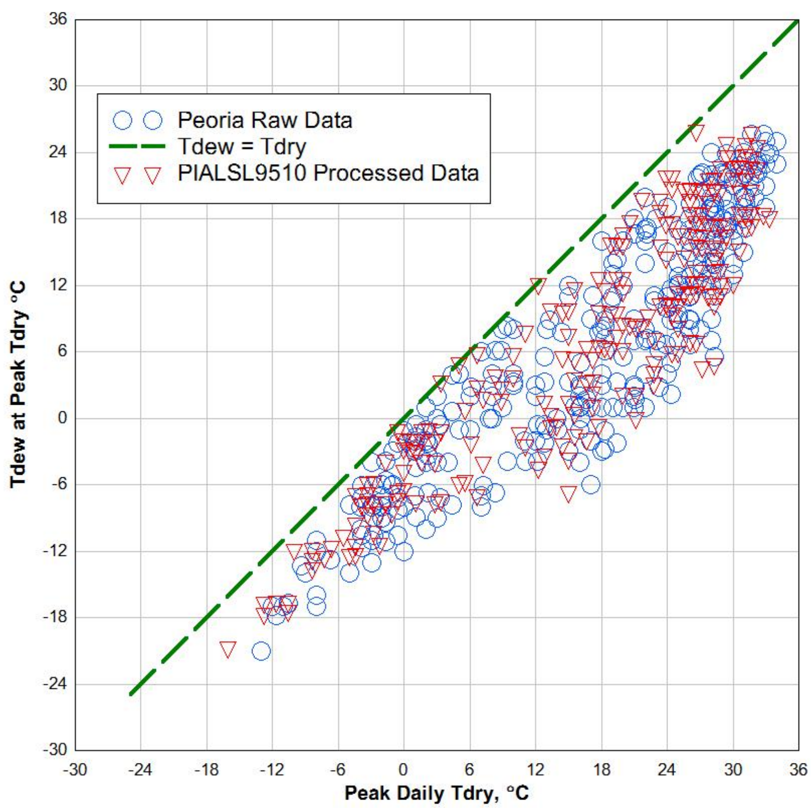

Figure A3. Dew Point Temperature Versus Dry Bulb Temperature for Peoria and LaSalle Data Sets

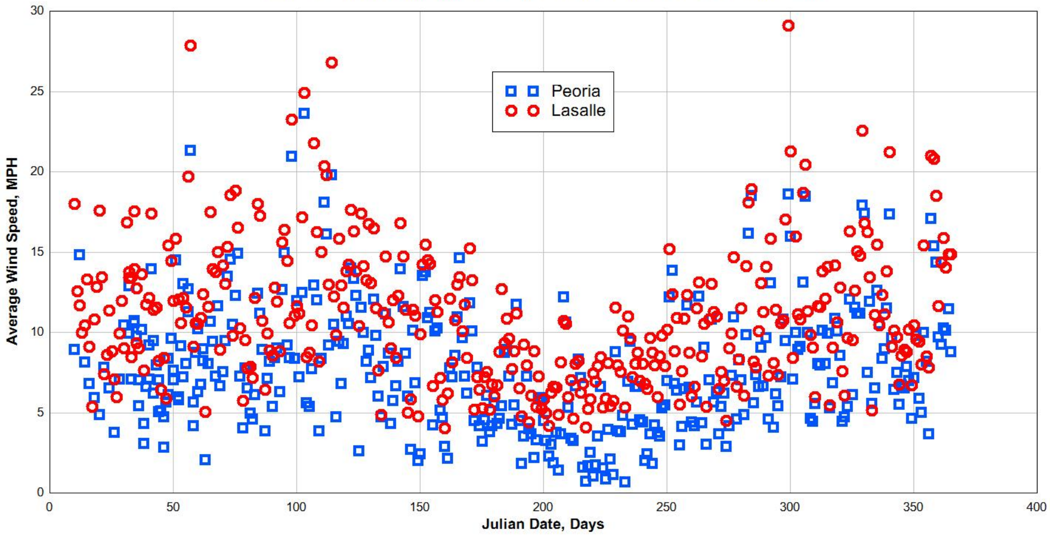

Figure A4. Comparison of Daily Average Wind Speeds at LaSalle and Peoria Sites, Year 2001

As this figure shows, the wind speeds at the LaSalle site are on average higher than Peoria; therefore, using Peoria wind speed data should produce more conservative peak temperature estimates.

Temperature and wind data also were compared for 2010 with similar results.

Other SwRI Staff Observations on Licensee's Meteorological Data. Our general observation is the licensee's use of offsite data is reasonable and essential to the calculation of UHS performance. The licensee's adjustment of dew point temperature from Peoria for use in the LaSalle data set is reasonable but not necessarily conservative because it tends to reduce the average value of that parameter. However, the amount of adjustment is slight and only affects a relatively small number of data points.

The licensee's data set included information, such as partial pressure of water at the dew point and long-wave solar radiation, that were calculated internally in the SwRI model; therefore, these redundant data were not used in the SwRI analyses. Staff verified those tabulated values were close to the ones calculated in the SwRI model.

The conclusion that Peoria data are more conservative on the basis of lower wind speed and higher dry bulb temperature is demonstrated by sensitivity experiments presented in Section A3.5.

A3.2 Descriptions of Licensee and SwRI Staff Analytical Models

Under the initial assumptions that heat rejected to the UHS pond would be responsible for the peak return temperature, we analyzed the assumptions implicit in the LAKET-PC model, which are similar in many respects to NRC's UHS models described in NUREG–0693 (NRC, 1980) and other NRC documents (Codell, 1985a,b).

Although similar, there also are several important distinctions between the licensee's LAKET-PC model and our own model LAPLUG. The most important differences are the way in which heated water flows through the modeled pond and the form of the environmental heat transfer equations. Furthermore, the analyses of the licensee consider pre-screening of meteorological data, whereas the SwRI analysis ran the model through all data at 3-hour starting intervals.

SwRI staff's model was based on the analyses presented in NUREG–0693 (NRC, 1980) and NUREG–0733 (NRC, 1981), particularly the UHS3 code. However, there were extensive changes necessary for the UHS3 code to accommodate new data formats, additional data not available when the code was developed in the late 1970's, and better heat transfer relationships. Therefore, we made a decision to excise only the parts of the UHS3 code that would be useful in the analysis of the LaSalle UHS pond. The new model, called LAPLUG, is being documented and has received extensive checking to assure it performs the same functions as the original UHS3 model.

Although we did not have direct access to the licensee's main model, LAKET-PC, we were able to discern differences from our own model LAPLUG. The following subsections describe the licensee and SwRI models used for the LaSalle analyses and the apparent differences between them. Further conclusions on the comparison of the respective model and results are presented in Section A4.

A3.2.1 Pond Hydraulic Models

A3.2.1.1 Licensee's Model LAKET-PC

LAKET-PC appears to make the assumption of an idealized rectangular channel with width and depth constant for all segments (Calculation No. L-002457, Rev. 8, Attachment N, Page N9). We had no detailed information of the licensee's model parameters, such as the number of segments, volumes, or surface areas, but it did not appear the licensee took varying depth into account.

LAKET-PC appears to assume hot water entering the pond moves from the discharge location to the intake location in discrete parcels, with no mixing into other pond water. This approach is known in the field of chemical engineering as "plug flow" (Levenspiel, 1999) and is an idealization of actual water movement through a vessel or water body. Although the "plug flow" concept is usually associated with chemical reaction processes, it is easily extended to the cooling rate of water in a pond. In some cases, plug flow is an efficient process because it keeps the hot water and cooler initial pond water from mixing, thereby maximizing the heat transfer from the water to the atmosphere. However, it also can be highly unrealistic for an irregularly shaped pond, which would have mixing processes and multiple pathways with different travel times between the discharge and intake. These processes would lead to the spreading out of the heat pulse and dilution of the hot water with the cooler pond water, which would reduce the peak temperature.

A3.2.1.2 SwRI Model LAPLUG

LAPLUG is not a strictly plug flow model, but assumes the pond consists of a series of well-mixed volumes; (i.e., in chemical engineering parlance, "mixed-tanks in series") (Levenspiel, 1999). Differences between plug flow and mixed flow are illustrated in Figures A5 and A6. Except in certain circumstances (i.e., the time period of the calculation is exactly the time to fill each tank with flowing water, and all tanks are of equal size), the mixed tank model is more dispersive and leads to mixing of the hot water with initially cooler pond water in the tank. This will ultimately lead to diminishing the strength of the peak temperature from the plug-flow model.

A3.2.2 Mixing and Dispersion in UHS Ponds

Dispersive processes in a real body of water include the spread of pathways and differences in travel time from the pond discharge to the intake, mixing caused by bottom friction, and mixing in the near field caused by jet turbulence. These processes would tend to diminish the heat pulse entering the pond, and thereby reduce the peak temperature. The plug-flow assumed in the licensee's model does not allow such mixing.

To illustrate this difference in temperature results to dispersion and mixing, we constructed a simplified example loosely based on the LaSalle pond. The no-dispersion case is represented by a plug-flow model, and the alternative dispersion and mixing case is represented by the mixed tanks in series model. The pond consists of 30 equal-size segments, has a heat addition rate based on a curve fit of the actual LaSalle heat rate, a constant flow rate through the pond, and constant meteorology[1]. The intent here is to illustrate the effect of dispersion and mixing on peak temperature, isolated from confounding effects of a varying meteorology and varying flow rate. Parameters of the model are given in Table A1.

Figure A7 shows the return temperature as a function of time for the two models. Both models approximately show the effect of the arriving heat, but the mixed tank in series model shows the effect of hot water mixing with the cooler water initially present in the tanks. This effect can be significant, demonstrating dispersion and mixing in the pond have a strong effect on the maximum return water temperature.

A3.2.3 Licensee's Computational Fluid Dynamics Model (Ludovisi, et al., 2013)

One of the best pieces of information on actual pond hydrodynamics available was the Computational Fluid Dynamics (CFD) model performed by the licensee. The CFD model was highly detailed (over a million nodes) with the intention of demonstrating the effective hydrodynamics of the pond. The primary purpose of this analysis was to predict a diminished effective surface area and volume for use by the licensee's one dimensional plug flow model (Our LAPLUG model runs also take this reduced surface area and volume into account.) The model considered two fluids: (i) water in the pond prior to discharge of heated water and (ii) heated water discharged to the pond. However, the model assumed identical physical properties for the two fluids; (i.e., it did not take into account the possibility of stratification because of density differences, but assumed, based on the pond number calculation, the pond would not be stratified.)

[1] Note that the size of the segments was developed manually from the pond measurements for the intake canal, transition area to the canal, and main body of the active pond area. The initial number of segments was kept approximately the same as the 30 equal-sized segments used in Model A (described in Section A3.5) (what we believe was the approximate number used in the licensee's analysis), with the additional constraint that residence time V/q (volume/flow rate) of each segment was less than the 0.2 hour integration time step for numerical stability considerations. In addition, the first segment is considerably larger to take into account mixing in the entrance region of the pond.

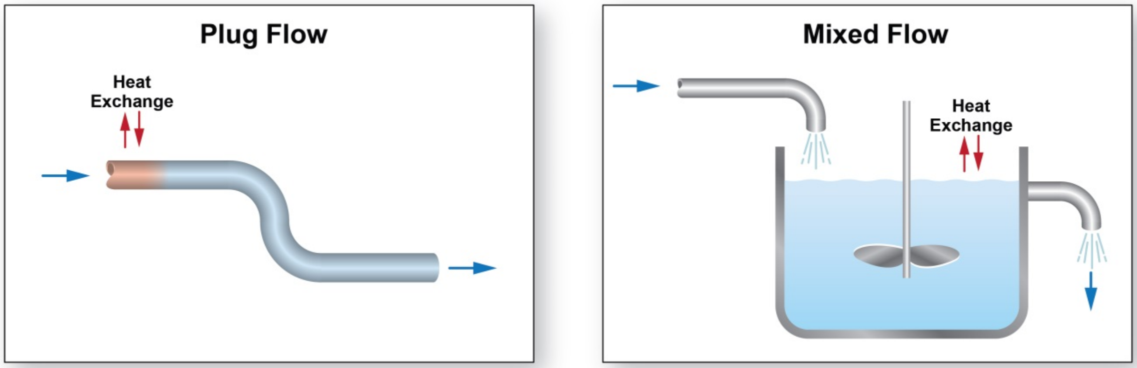

Figure A5. Difference Between Plug Flow and Mixed Tank Models (Based on Levenspiel, 1999). In Plug Flow, Fluid Passes Through Without the Mixing of Fluid Entering Earlier and Later and Later Fluid Does not Overtake Earlier Fluid. Mixed Flow Refers to Uniform Mixing of the Fluid in the Tank.

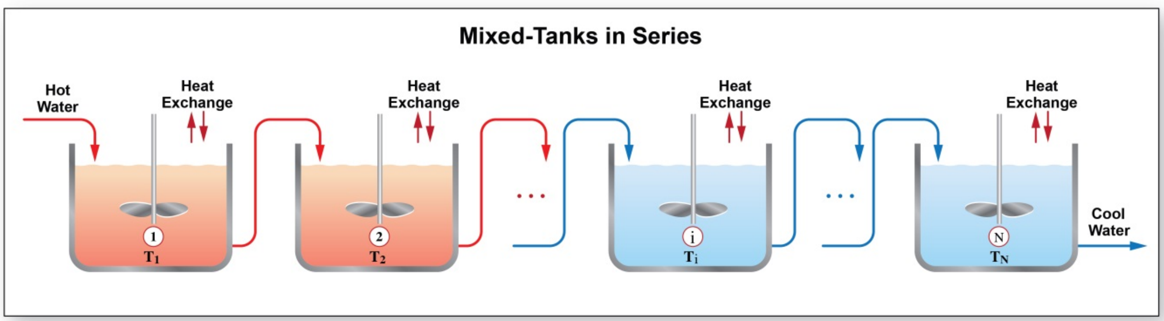

Figure A6. Mixed-Tank Reactor Representation for SwRI LAPLUG Model

Table A1. Parameters of Study Demonstrating the Effect of Dispersion and Mixing in Pond		
Number of segments or tanks	=	30
Flow rate	=	86 CFS
Dry bulb temperature	=	100 °F
Solar radiation	=	20 BTU/Ft^2/hr
Area of each segment	=	68333.33 Ft^2
Heat rate to pond, BTU/Hr	=	$10^{8.634-0.1872 \log(t)}$, where log is base 10, and t is in hours
Initial Pond Temperature	=	100 °F
Wind speed	=	2 knots
Dew point temperature	=	80 °F
Cloud cover	=	0.1
Volume of each segment	=	312,000 Ft^3

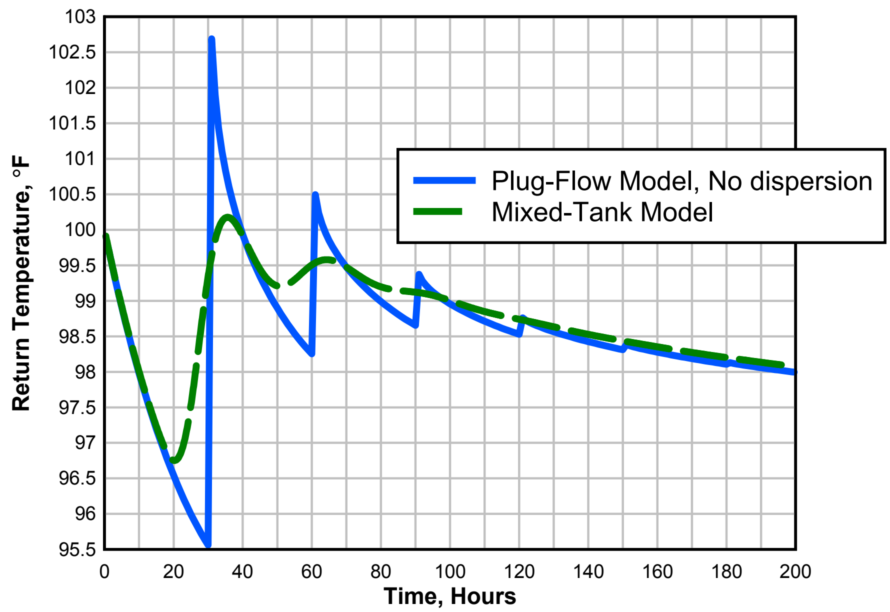

Figure A7. Effect of Mixing and Dispersion on Peak Return Temperature

Unfortunately, this analysis was not as useful as it might have been from the standpoint of our review because an assumption of different densities of the two fluids would have addressed questions that remain about stratification. Furthermore, the licensee did not give sufficient information on how the CFD model was qualified for these calculations, such as sensitivity of results to mesh refinement and turbulence closure models. Nevertheless, the CFD model proved useful for demonstrating some three-dimensional phenomena that are not displayed in a one-dimensional model. Tentative conclusions drawn from the CFD model results (i.e., effective surface area and volume, mixing in the near field) are tested later in this report with sensitivity studies.

A3.2.3.1 Mixing in the Discharge Region

The CFD model illustrates the jet formed in the lower left quadrant of the pond, extending out into the center of the pond, as shown in Figure A8. The high-velocity jet induces considerable recirculation, resulting in mixing and considerable entrainment of cooler pond water that diminishes the possibility of strong stratification in the pond. On this basis, the licensee assumed the first segment of their LAKET-PC model would be well-mixed and have a uniform temperature. We agree with this assessment, and include a large (25 percent) mixing zone in our base case analysis as well.

A3.2.3.2 Arrival Time Distribution

The licensee's CFD model also shows the travel time heated water leaving the plant arrives at the intake structure is a distribution rather than a constant, as would be the case in true plug flow. Figure A9 (J-14 in the licensee's CFD model report, Ludovisi, et al., 2013) shows some heated water would arrive at the intake faster than plug flow would predict. The distributed nature of the arrival time is a consequence of mixing in the discharge region of the

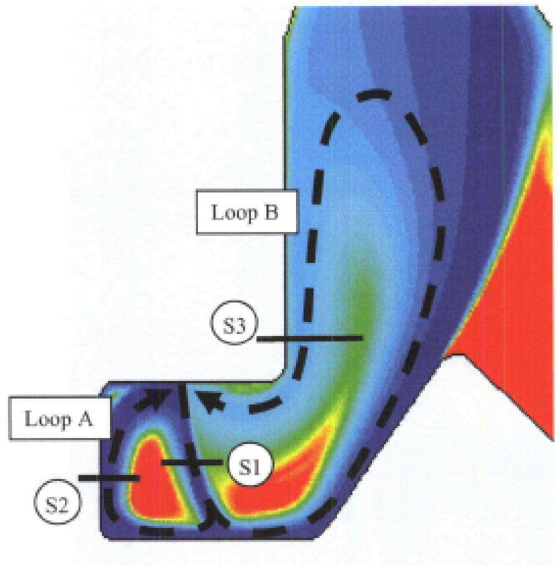

Figure A8. Result of CFD Model Near Discharge Location (Figure J8.6-10, Exelon Generation Company, 2013, ML14066A234, 2014)

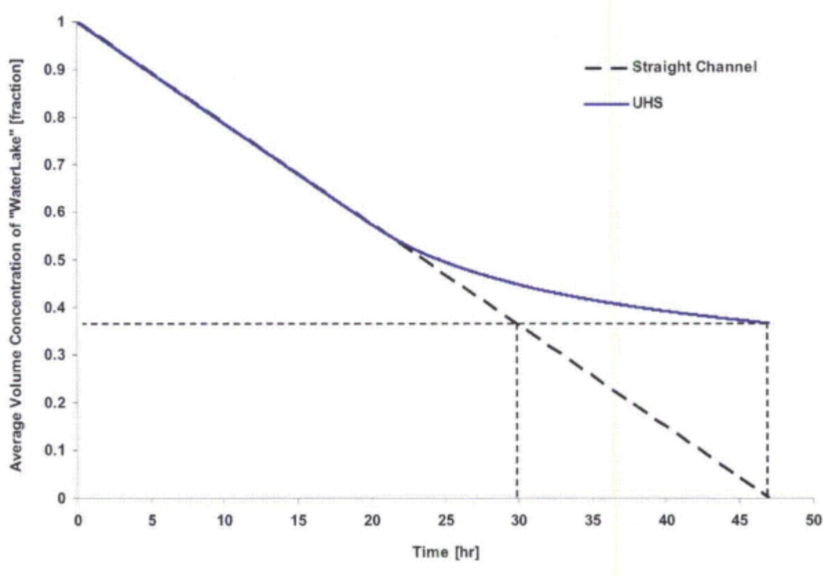

Figure A9. Arrival Time Distribution From Licensee's CFD Analysis (Figure J-14, Ludovisi, 2013)

pond, the different lengths of the pathways the water parcels traveling from the discharge to intake, and the different velocities along the pathways.

The SwRI model also predicts there is a spread in arrival times rather than a single arrival time. PLUGTEST, a version of the LAPLUG model, which was modified to look only at the transport of heated water, was used to demonstrate the effect of mixing and dispersion. This example uses Model B (38 segments, variable volume and surface area, developed in Section A3.2.1.2) for a steady flow rate of 86 CFS, heat rejection rate of 4×10^8 BTU/hr, an initial temperature of 104 °F, and no atmospheric cooling. Therefore, the calculation shows only the effect of transport through the pond, as it is represented by the LAPLUG mixed tanks in series model. *Note this is a demonstration of the effects of dispersion only, not a calculation of actual peak return flow temperature.*

Figure A10 shows the return water temperature versus time, along with lines representing the theoretical temperature of the water for the first pass through the pond (124.84 °F) and the theoretical plug-flow arrival time (31.7 hours). This figure indicates some hot water arrives at the intake before the theoretical plug-flow arrival time, and the water temperature does not reach its theoretical temperature until after the theoretical arrival time. If there were no dispersion (i.e., perfect plug-flow behavior), temperature would remain at 104 °F and jump to 124.84 °F at exactly 31.7 hours.

The first arrival of discharged hot water for the CFD and SwRI staff models are approximately the same. This spread of arrival times is the consequence of the representation of the pond by a series of mixed tanks; (i.e., the temperature in each of the tanks or segments, representing a length of the pathway, is uniform). In this case, the behavior of the model mimics the actual behavior of the three-dimensional pond. In fact, Segment 1 was specified to occupy 25 percent of the pond volume in order to account for jet mixing from the discharge structure. In response to RAI 32, the licensee performed external calculations to adjust their model results to simulate the first segment occupying 20 percent of the pond volume and surface area. This modification resulted in a lower peak return temperature.

A3.2.4 Heat Transfer Models

The rate of change in pond temperature is determined by the heat added from the plant and the gains and losses of heat exchanged with the environment (i.e., atmosphere and sky). The environmental heat exchange terms are solar or short-wave radiation, long-wave or infrared radiation from the atmosphere and clouds, back radiation of infrared heat from the water to the atmosphere and sky, convection of air in contact with the water surface, and evaporation or latent heat exchange. These terms are shown graphically in Figure A11.

The most significant apparent difference between the licensee and SwRI heat transfer models was the use of an important term known as Wind Function, which appears in the heat transfer terms for evaporation, H_E, and convection, H_C , and defines how heat is carried away from the water surface as a result of wind and thermally induced convection. Both the LAKET-PC and LAPLUG models used the standard formulation from Ryan and Harleman (1973):

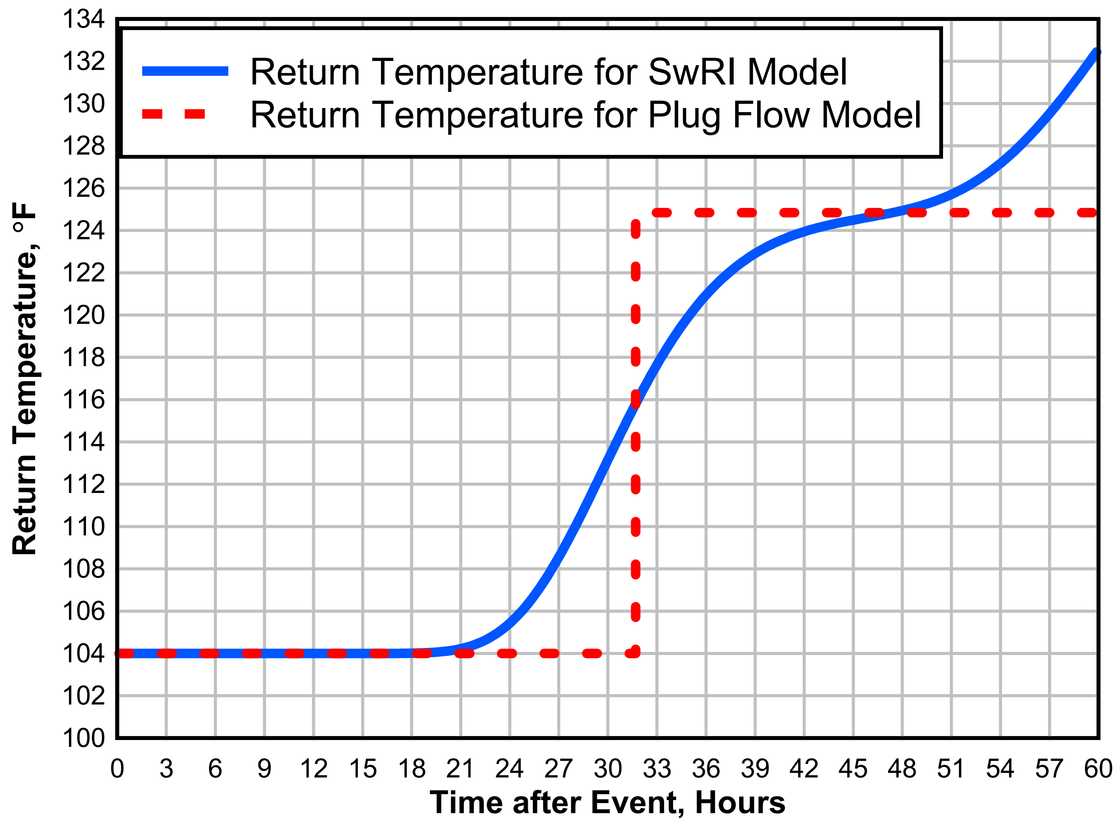

Figure A10. Demonstration of Transport of Hot Water Through the Pond With SwRI Staff's Variable Depth Model B, Steady Flow, Steady Heat Rejection, No Cooling (Note: not an Actual Temperature Result).

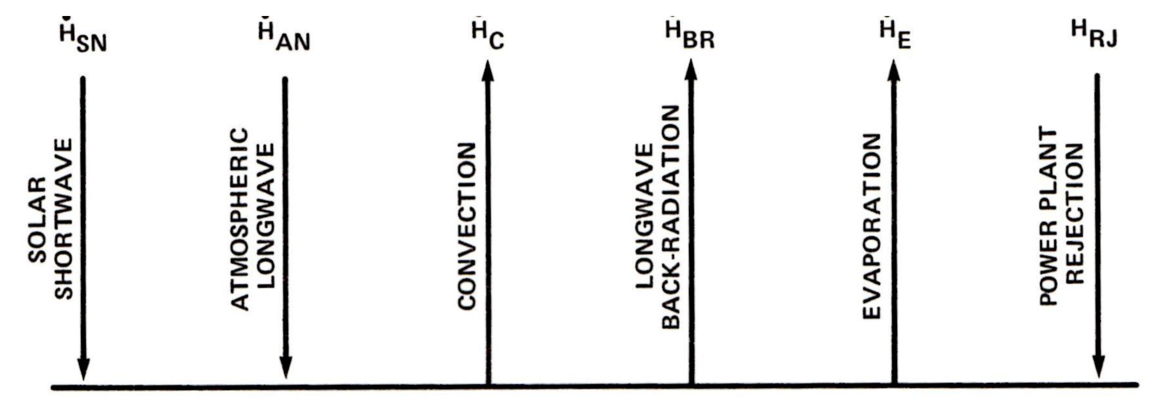

Figure A11. Heat Entering and Leaving Water in Segments

$$F_R(w) = 22.4\left[\left(\frac{T_S + 460}{1-\frac{0.378e_s}{P}}\right) - \left(\frac{T_A + 460}{1-\frac{0.378e_a}{P}}\right)\right]^{1/3} + 14W_2$$

where

$F_R(w)$ = Ryan wind function (BTU/ft^2 day/mmHg)
P = atmospheric pressure (mmHg)
W_2 = wind speed measured 2 meters above the water surface (mph) (A1)

T_s = water surface temperature, °F
T_A= air temperature, °F
e_s = water vapor pressure at the surface temperature, mm Hg
e_a = water vapor pressure at the dew point temperature, mm Hg

The term in large brackets describes the forcing function of thermal convection resulting from the lower density of air caused by temperature rise and water vapor density. The second term, $14W_2$, describes convection of heat by the wind.

SwRI staff's LAPLUG model also has the option to use the Brady wind function, which accounts for thermal convection, but is strictly empirical and not a function of surface temperature or humidity:

$$F_R(w) = 70 + 0.7\ W_{10}^2 \qquad \text{(BTU/ft}^2\text{/day/mmHg)} \qquad \text{(A2)}$$

where W_{10} is the wind speed measured at the 10 ft level (Brady, et al., 1969). Ryan and Harleman (1973) adjusts the formula for 2 meter wind height to the following:

$$F_R(w) = 70 + W_2^2 \qquad \text{(BTU/ft}^2\text{/day/mmHg)} \qquad \text{(A3)}$$

We used the more-conservative Brady formula for sensitivity calculations discussed in Section A3.5 of this report.

The licensee's heat-transfer model has an important difference in that they use the "natural temperature", defined as "…the instantaneous water temperature in response to the meteorological parameters" (Attachment N, Page N10, Revision 8 to Calculation No. L-002457). The natural temperature is not directly related to water temperature in the pond, but is the potential water temperature of an infinitesimal volume of water responding to the meteorological parameters. The licensee uses the natural temperature as an indicator to switch between two wind functions: (i) the Ryan wind function for heated water bodies and (ii) an alternative "Lake Hefner" wind function for unheated water bodies that is dependent only on wind speed:

$$F_{LH}(w) = 17W_2 \qquad \text{(A4)}$$

The licensee states "Specifically, LAKET-PC utilizes the Ryan wind function when surface temperature is 2.5 °F higher than the natural temperature of the lake" (Attachment N, Page N13, Revision 8 to Calculation No. L-002457).

SwRI staff experimented with the use of natural temperature, but was unsure exactly how the licensee calculated it. We assumed, however, it is the temperature at which the sum of all natural heat terms (illustrated in Figure A11) would be zero using the Lake Hefner wind function and no added heat from the plant. The licensee's model would have predicted a lower rate of cooling over part of the time period. This partially accounts for the differences in resulting peak temperatures and “worst meteorology” periods between the licensee and SwRI staff models. Specifically, SwRI staff’s results show the temperature peak occurs early and is a function only of ambient environmental conditions. The licensee’s results indicate the highest peak return temperature occurs later, with the arrival of the heated water. Additionally, SwRI staff predicts lower peak temperature than the licensee for equivalent conditions. Results for the licensee’s model are discussed further in Section 4.0.

We can find no justification for the licensee’s use of natural temperature to switch the form of the wind function. The extensive review of wind functions by Ryan and Harleman (1973) and Helfrich, et al. (1982) shows superior performance of the Ryan function over other approaches for a wide variety of conditions of heated and unheated bodies of water. The licensee’s use of the alternative wind function, which does not include thermal convection by buoyancy, might be especially adverse for cases where wind speed is small or zero, leading to the unlikely prediction of no evaporation at all. Since evaporation has usually been shown to be the largest heat transfer term, this is especially inappropriate. However, we also recognize the licensee is free to use a more conservative formulation in its own models. It is not inappropriate to take into account a factor of safety in the models to account for deviation from ideal predictions and the scatter in experimental data used to formulate the heat transfer relationships used in the models. SwRI staff did revert to the more conservative Brady, et al. (1969) wind function for sensitivity analyses shown in Section A3.5.

Another relatively small difference between the licensee and SwRI staff models is the former accounts for reflection of incoming short-wave (6 percent) and long-wave (3 percent) radiation from the water’s surface, thereby reducing the heat input to the pond. SwRI staff’s model conservatively ignores this reflection.

A3.3 Validation of SwRI LAPLUG Model

The LAPLUG model and its predecessor, UHS3, have received limited validation, mainly with regard to the relationships for heat transfer to the environment. A series of experiments were carried out on small ponds at a site in Idaho in the summer and fall of 1978 in order to verify NRC’s cooling pond and spray pond models (NRC, 1982). The Raft River cooling pond was filled with geothermally heated water and allowed to cool naturally. Figure A12 shows the results of cooling from one of the tests “Idaho Hot 4,” which is typical of all tests performed without spray-cooling enhancement.

Measured data were compared to a mathematical model that used either the heat-transfer relationships of Ryan and Harleman (1973), or a model based on the Brady wind function (Brady, et al., 1969). Figure A12 shows the Ryan-Harleman formulation is a better predictor of temperature, but somewhat overestimates cooling in this particular case. This was the same conclusion for all experiments at the Raft River site.

A possible explanation for this over-prediction of cooling is the Ryan-Harleman formulas were derived in part from empirical evidence collected at a variety of sites, including large cooling lakes and reservoirs, on the order of thousands of acres of surface area, small experimental ponds, and laboratory flumes. The Raft River pond had a surface area of less than one acre. The LaSalle UHS pond is modeled as having an effective surface area of 47 acres, larger than Raft River but smaller than large cooling lakes. It is possible that phenomena, such as thermal convection, are more important in large heated water bodies than very small water bodies, like the Raft River pond. We therefore made additional sensitivity runs, presented later in Section A3.5, using the more-conservative Brady wind function to determine the effect of lower

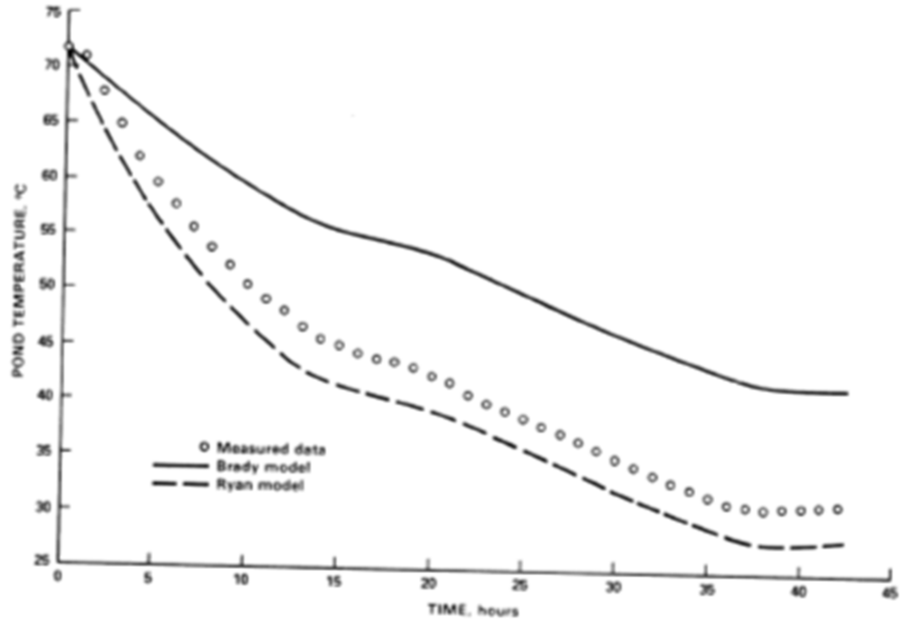

Figure A12. Cooling Pond Experiment "Idaho Hot 4" and Its Original Comparison (NRC, 1982)

environmental heat transfer from convection and evaporation. We should point out the Ryan-Harleman formulation has been shown to be among the most accurate for a wide variety of pond and reservoir data. By contrast, the Brady formulation regularly underestimates cooling, even for Brady's own experimental data (Ryan and Harleman, 1973).

For the current analyses of the LaSalle UHS pond, the validation was repeated using a version of LAPLUG configured to accept the data format available from the Idaho experiments and having five equally sized pond segments. The LAPLUG code uses a slightly different form of the Brady wind function to account for wind speed corrected to the 2-meter elevation above water surface by changing the factor in front of the wind speed term from 0.7 to 1.0.

This change slightly increases the heat transfer for the Brady model. As with the original validation, there is no flow through the pond and no addition of heat once the pond was filled with hot water. The revised comparison of the model to the field data for IdahoHot4 is shown in Figure A13.

Figure A14 shows the rate of heat loss versus time. This analysis shows more clearly the slight temperature anomaly that occurs in the first 1 or 2 hours, is most likely the result of the time it took to initially fill the pond with hot water. This figure shows the anomaly for the first hour, and the good agreement thereafter.

A3.4 Effects of Stratification

Thermal stratification in the pond could be a key issue in the present analysis. The phenomenon of stratification would result from two causes: (i) discharge in the lower left

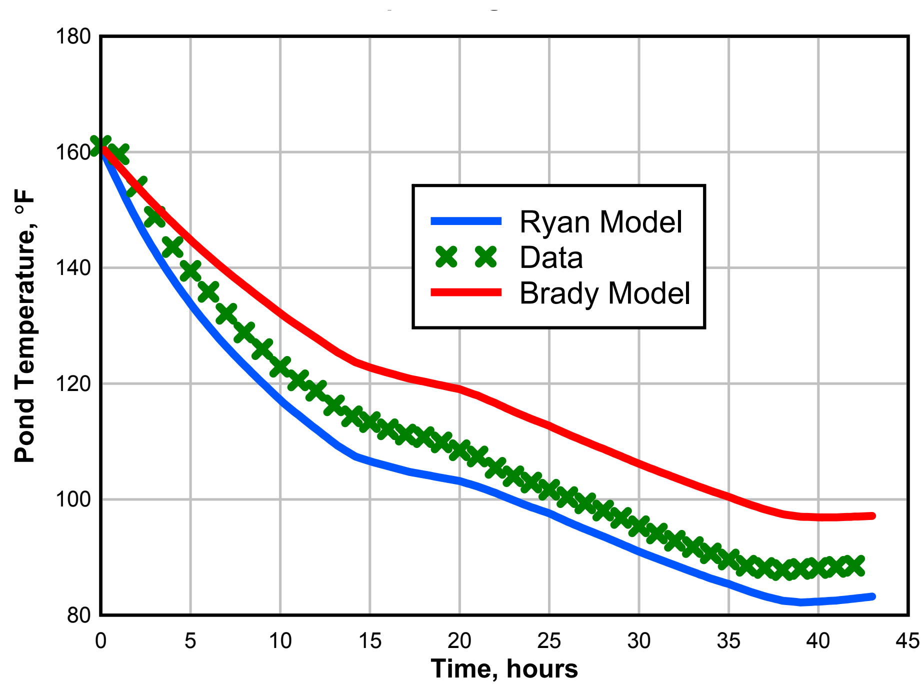

Figure A13. Partial Validation of LAPLUG Model With IdahoHot4 Data

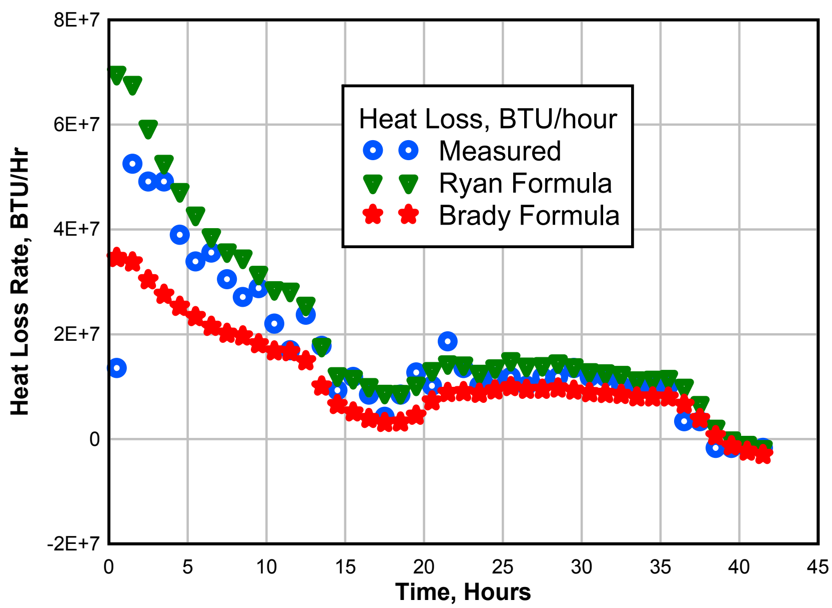

Figure A14. Heat Loss Rate for IdahoHot4 Model Validation

quadrant of the pond of highly heated, and therefore less dense, water into cooler and denser water and (ii) heat transfer between the pond surface and the atmosphere. In the first case, the release of less dense hot water into the pond would cause an enhanced flow along the surface from the discharge to the intake. Stratification caused by the first phenomenon could potentially reduce the travel time for hot water to reach the plant water intake. A necessary condition for use of one-dimensional models is no stratification being present.

The licensee defends its conclusion that the pond would not be stratified on the basis of a theoretical model for the behavior of a distinct two-layer system representing water density variation (i.e., hot water sitting on top of cool water), and no interfacial mixing except in the entrance region (Octavio, et al., 1979). This procedure is known as the "pond number" approach (Helfrich, et al., 1982). The thickness of the thermal layer, h_u, is described by the licensee with the following equation (Eq. N2-1, Attachment N, Page N4, Calculation No. L-002457, Rev. 8):

$$h_u = \left[\frac{f_i Q^2 D_s^3 L}{4 g \beta \Delta T B^2} \right]^{1/4} \qquad \text{(A5)}$$

where f_i = interfacial friction term, Q = flow rate through the pond, D_s = volumetric dilution produced by vertical entrance mixing, L = pond length, g = gravitational acceleration, β = thermal expansion coefficient, ΔT = condenser temperature rise, and B = pond width.

The "pond number" approach seeks to find the ratio of the heated surface layer to the total pond depth. The thickness of the hot water layer is determined by a balance of interfacial friction between the two layers and a pressure gradient caused by the density difference between the layers, and assumes there is a linear horizontal temperature gradient in the surface flow, with return flow in the lower layer of negligible velocity (Helfrich, et al., 1982). If the calculated thickness of the hot layer is a large fraction of the total pond depth, then the pond is considered to be unstratified.

Although the pond number approach has been shown to be useful in cooling pond design and analysis, there are several reasons it may not give an accurate portrayal of actual UHS pond performance (this is not necessarily an inadequacy of the analysis, as long as it is a conservative result):

- The release of hot water into the pond results in a highly transient condition, rather than a steady state movement of established, separate water layers.
- There is significant and rapid cooling of the hot water as it moves toward the plant intake. Therefore, the density difference between the layers diminishes with distance.
- The two-layer flow assumption conservatively ignores transfer of heat and water between the two layers, except in the entrance region. The water layers are not immiscible and such transfer would occur, thereby lowering the temperature difference between layers and reducing stratification.

The licensee's analysis (Nevill and Szymiczek, 2013) accounts for dilution of the plant water in the vicinity of the high-velocity discharge into the pond. Dilution would increase the thickness of the top layer and therefore tend toward nonstratified conditions. While the empirical analysis of near-field mixing is not in our opinion well documented, the licensee's computational fluid mechanics model, described in Section A3.2.3, shows there is likely to be significant mixing in the near field.

The pond number approach therefore may not be entirely appropriate for this situation. A definitive answer to the issue of stratification would require a complicated three-dimensional model. We did not carry out three-dimensional model analyses, but we believe there is sufficient justification to assume the pond would not be significantly stratified from the effects of heated discharge, nor would stratification necessarily lead to an adverse condition. This hypothesis also was tested with model runs that assume stratification does exist, as demonstrated in Section A3.5.

One additional factor SwRI staff did not consider with regard to possible stratification caused by hot water release would be that it could benefit the cooling efficiency of the pond. Thermal stratification under the right circumstances causes higher heat transfer to the environment, and circulation into "dead end" portions of a water body would not have much circulation under normal circumstances (Brocard, et al., 1977).

It is entirely likely there will be some stratification in the UHS pond, caused primarily by heat transfer with the environment resulting mostly from incoming short-wave and long-wave radiation. Solar and long-wave radiation to the pond surface would be absorbed into the water column, depending on conditions of light transmissivity, reflection from the water surface, turbidity, and albedo. Turbid water is known to absorb radiation faster than clear water (e.g., Butler, 1962), and it is likely that water in the UHS pond would be turbid because of sediment present and disruption caused by the failure of the cooling reservoir. Turbid water would be preferentially heated closer to the surface.

Figure A15 shows stratification caused by solar heating in shallow ponds for conditions of turbidity (Butler, 1962).

Stratification caused by solar heating is fundamentally different from that caused by release of hot water, in that the former does not provide a mechanism for significant transport in the direction of the plant intake. Water movement in the deep intake canal would move at the same velocity, regardless of any stratification that does not provide a hydraulic gradient to change the flow. We believe that even if there is such a stratification caused by solar heating, water would become mixed at the intake structure and sump (providing there are no baffles that preferentially withdraw water from the top or bottom). Therefore, SwRI staff believes stratification caused by absorption of solar and long-wave radiation can be ignored in the present calculations.

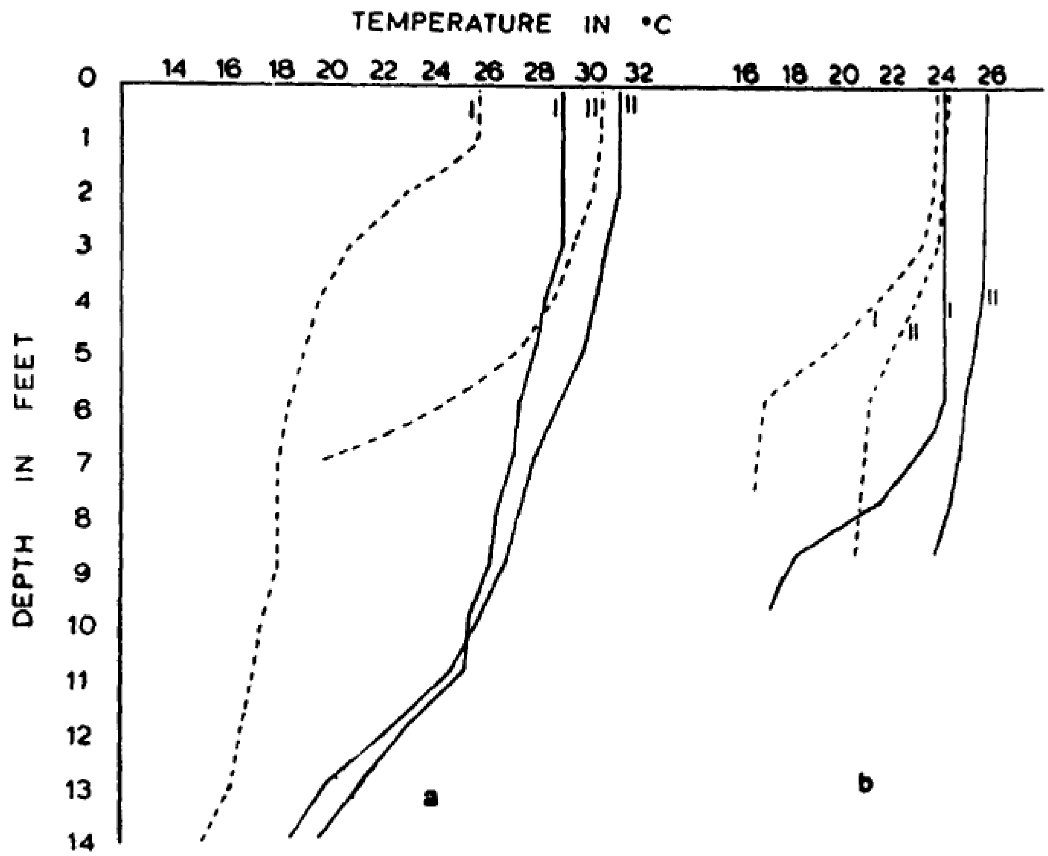

Figure A15. Thermal Stratification in Shallow Ponds as a Function of Turbidity (Butler, 1962) (With Copyrights Permission)

A3.5 Analysis with SwRI Model

We performed our determination of peak return water temperature using the LAPLUG model.[2] The model is one-dimensional and very fast running. The procedure was to start each model run at 3-hour intervals beginning May 1 and ending September 30, for the entire weather record, and calculate the peak return temperature for each run. The following salient points about the model are significant to our analysis:

- The modeling case chosen was for maximum sedimentation of 18 inches, which reduces the available water supply in the pond to its smallest level. The licensee's analysis

[2] Several variations of the computer code and parameter inputs were used for specific purposes such as variable pond geometry and alternative heat-transfer models.

included a range of sedimentation from 0 to 18 inches, but we did not repeat all cases because we judged the 18-inch level to be the worst case.

- The first pond configuration (Model A) had 30 segments, but Segment 1 had a volume and area 25 percent of the total to account for mixing in the discharge embayment, and Segments 2–30 had the remaining volume and area in total. The segment sizes were approximately chosen to allow 86 CFS of discharge in 1 hour, if all segments were of equal size. Note the flow rate through the pond is 65.3 CFS for the first 16 hours and 86 CFS thereafter. Pond depth (volume divided by area) was 4.57 ft.

- The second pond configuration (Model B) had 38 segments. This model configuration was an attempt to account for the large differences in the depth in various parts of the pond. For example, most of the pond, as modeled, has a depth of 3.5 ft, but the intake canal and a transition area between the shallow pond and the canal have a depth up to 10 ft. Since we believe environmental heat transfer may be the most important factor in determining peak return temperature, shallow areas of the pond will be affected differently from deeper areas.

- Wind speed at 2-meter elevation was necessary for the Ryan heat transfer formulas in the LAPLUG code, but the meteorological data file gives wind speeds measured at 10 meters. The wind speed was reduced by a factor of 0.8, based on an empirical formula for the atmospheric boundary layer from the licensee's wind-tunnel tests (Eq. O6-1, Calculation Document, ML14066A23)

$$\frac{v_2}{v_1} = \left(\frac{z_2}{z_1}\right)^{\alpha}$$

Where:
v_1 = wind velocity at LAKET evaluation height (knots)
v_2 = wind velocity at anemometer height (knots)
z_1 = LAKET evaluation height (2 meters = 6.562 feet)
z_2 = Anemometer height (ft)
α = Power law exponent (A6)

We used the suggested average value of the exponent α = 0.135. The performance of the UHS pond was calculated with smaller wind reduction factors in Section A3.5, "Sensitivity Analyses."

- The starting temperature of pond water was generally 104 °F, chosen to be able to make a direct comparison with the licensee's calculations. For setting the technical specifications, further runs could be made with different starting temperatures or estimated by assuming heat transfer is linearly proportional to pond temperature. These extra steps were not considered to be necessary for the present exercise.

<u>Results for Model A</u>

Figure A16 shows a run with Model A, demonstrating the lack of sensitivity of peak temperature to plant heat load. Figure A17 similarly demonstrates the lack of sensitivity of the peak temperature to flow rate[3]. Since travel time through the pond is greater than 30 hours, no heat from the plant can reach the intake canal before the environmentally induced peak occurs approximately 6 hours after the event (approximately 1:00 PM). Since there is little heat transfer between segments (except by numerical dispersion, which is an artifact of the calculation), peak temperature also is insensitive to a lower flow rate for the first 16 hours.

Although it may seem counter-intuitive the peak return temperature is insensitive to plant heat load, Figure A18 shows the relative strength of the environmental heat terms for the last model segment (BTU/ft^2/day) calculated within LAPLUG based on the Ryan and Harleman (1973) heat transfer formulas. Heat transfer terms are short-wave solar irradiation, H_{SN}, long-wave solar irradiation, H_{AN}, back-radiation, H_{BR}, conduction and convection, H_C, and evaporation, H_E. Also shown is the plant heat load, $H_{RJ,}$ averaged over the entire surface area of the model, illustrating the relatively large influence of the environmental heat transfer. This plot is for the last segment of the pond model and environmental heat transfer would be higher for hotter segments closer to the thermal discharge into the pond.

Peak temperature calculated from this modeling exercise occurs for conditions when cloud cover is small and evaporation is low because of high humidity and high air temperature. Figure A19 shows the effect of relative humidity (not used in calculations directly but a reflection of low evaporative heat transfer) on return temperature for the highest peaks (ΔT above starting temperature).

Model A results show a maximum return temperature of 105.58 °F, which occurs 6.2 hours after the event, at 1:00 PM.

<u>SwRI Staff's Model B Analysis</u>

Model B of SwRI staff's analysis attempts to take the varying depth of the pond into account, rather than make the apparent assumption of equal depth in all segments chosen for the licensee's LAKET-PC model.

We developed a 38 segment model based on approximate dimensions for the pond taken manually from Figures 2.5-50, 2.5-53, and 2.5-59 of the Updated FSAR (Lasalle UFSARBinder.pdf). We believe Model B is a more accurate representation of a nonstratified pond because for conditions of environmental heating, the deeper intake canal and transition area would receive relatively less solar and long-wave radiation than shallower sections of the pond. Transit time through the canal alone would be approximately 11 hours, well before the peak return temperature would occur.

[3] Figures A16 and A17 are for illustration only to demonstrate the lack of response of peak temperature to rejected plant heat and varying flow rate. These runs used a different wind reduction factor of 0.75 instead of 0.80. The different starting temperature of 100 °F for Figure A17 does not change the conclusion drawn.

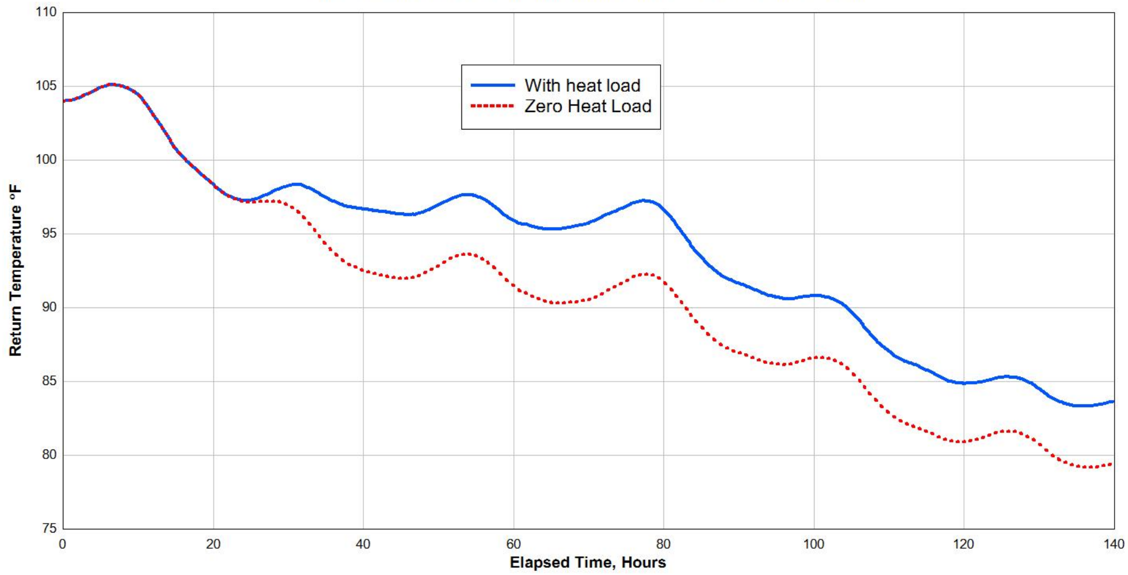

Figure A16. Effect of Heat Load on Peak temperature–Model A–104 °F Starting Temperature, Wind Reduction Factor = 0.75 (Demonstration Only, Not Final Result)

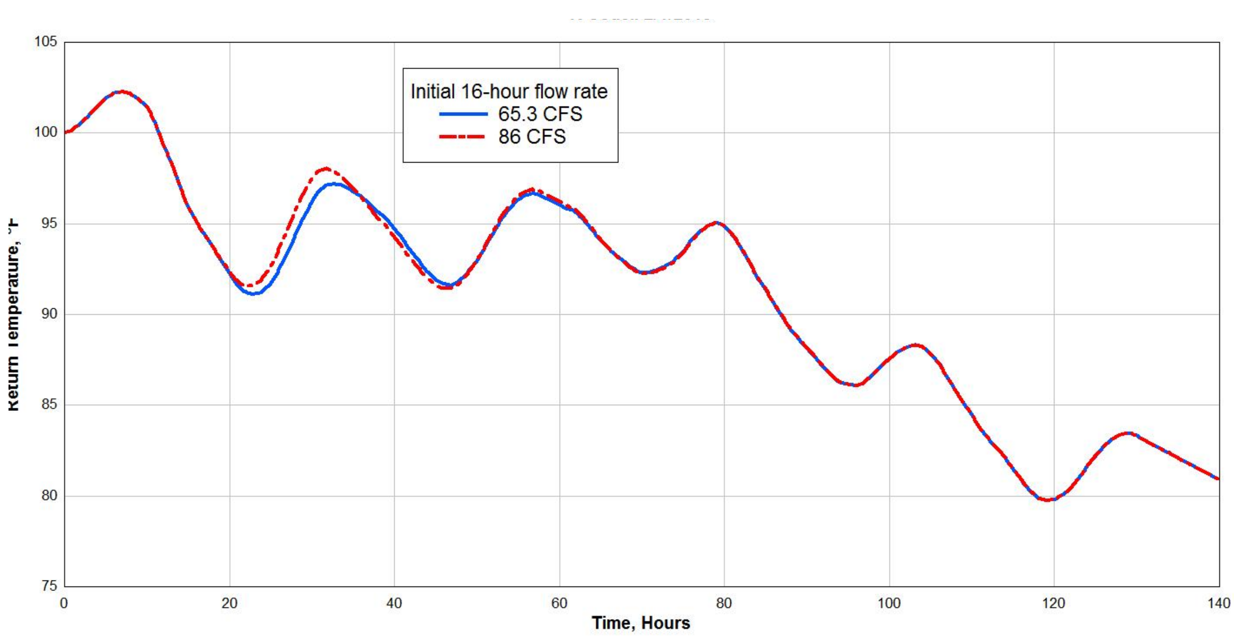

Figure A17. Effect of Flow Rate on Peak Temperature–Model A–100 °F Starting Temperature, Wind Reduction Factor = 0.75 (Demonstration Only, not Final Result)

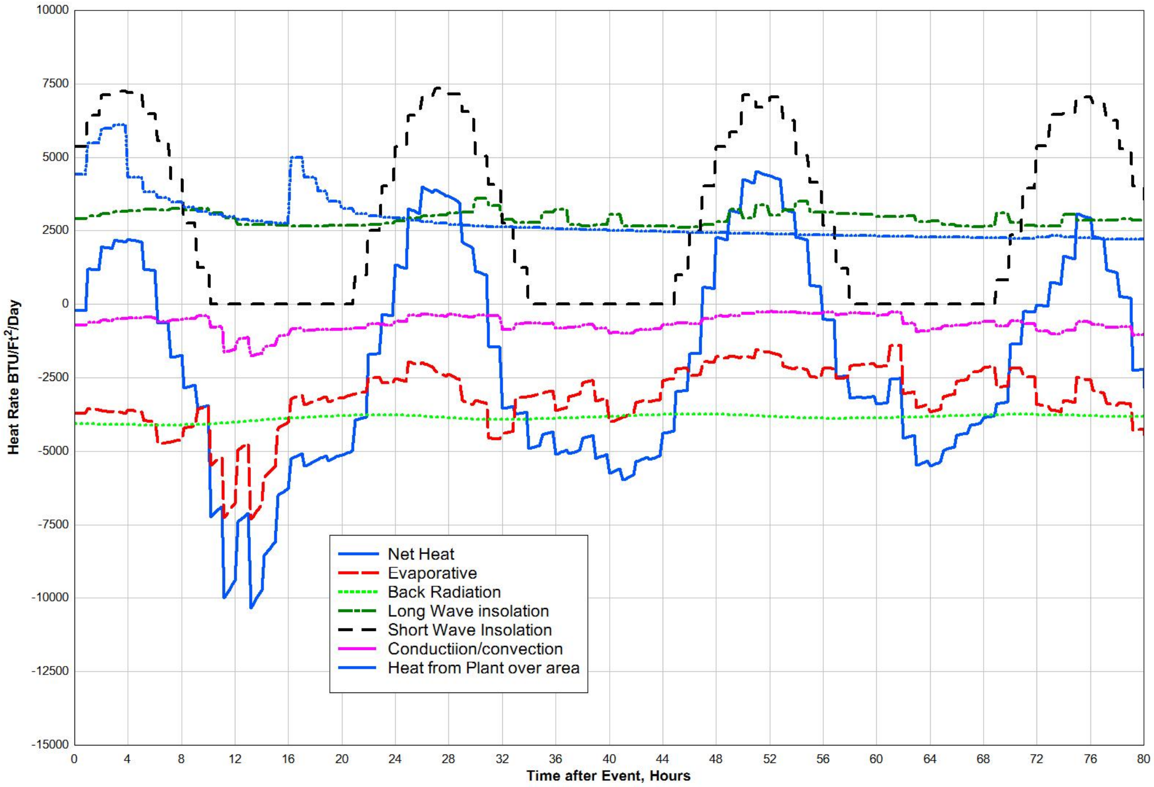

Figure A18. Environmental Heat Transfer Terms for Last Segment, Model A, and Area-Averaged Plant Heat Load Shown for Comparison (Demonstration Only, not Final Result)

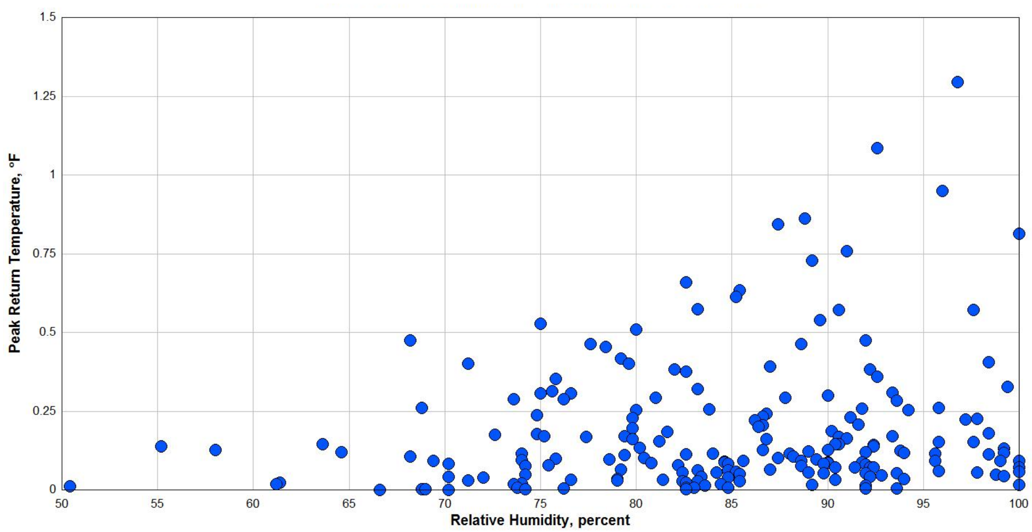

Figure A19. Effect of Relative Humidity on Peak Return Temperature Above 104 °F Starting Value (ΔT)–Model A (Demonstration Only, not Final Result)

For Model B, peak return temperature of 105.04 °F occurs at approximately 1400 (2:00 PM), 7 hours after the start of the event. This is slightly cooler than the Model A result. Figure A20 shows the peak return temperature for Model B with and without the heat load and the return water temperature for the 30 day period following the peak. We should note that starting pond temperature is 104°F, which is significantly higher than the temperature the pond would be under unheated conditions. This reflects the mode of operation under which the UHS pond is being evaluated; (i.e., pond water is at a temperature determined by conditions of normal operation of the plant just prior to the failure of the embankment for the main cooling reservoir).

Figure A21 shows the peak return temperatures for the Ryan base case as a function of time of day the peak occurs for all runs in the LaSalle meteorological data set starting at 3-hour intervals. Most of the runs did not produce a peak temperature above the 104 °F starting value of the pond. The lining up of the peaks is a function of the way meteorological data are used in the program; (i.e., each meteorological parameter is held constant for 1 hour rather than being smoothly interpolated between data points).

Results using Model B, the Ryan-Harleman heat transfer relationships, and the licensee's LaSalle data set, are SwRI staff's best estimate of pond performance and serve as the base case for comparison to the sensitivity experiments covered in the next section.

A3.6 Sensitivity Experiments

SwRI staff performed a series of model experiments to determine sensitivity of the peak return temperature to parameter values and various model assumptions (i.e., "what if?" calculations). Since the models and data have a great deal of uncertainty, these experiments help SwRI staff to determine the degree to which the peak temperatures are sensitive to these uncertainties. The following sections describe each sensitivity experiment and what it hopes to show. The base case is defined by the parameters presented in Table A2. Results for the base case and alternatives are tabulated in Table A3.

A3.6.1 Sensitivity to Alternative Heat Transfer Relationship

This sensitivity experiment repeats the base case run with the more conservative Brady wind function replacing the Ryan wind function. The peak return temperature calculated was 106.1 °F, about 1 °F higher than the base case, occurring June 26, 2009 at 4:00 PM. A major difference with this result is the peak occurred 36 hours after the event, approximately coincident with the arrival of the thermal pulse resulting from hot water release to the pond. The lower environmental heat transfer of the Brady model results in less cooling of the hot water released into the pond, causing the peak to coincide with both the arrival of heated water and heating from the environment. This is similar to the results presented by the licensee from their LAKET-PC model, which uses a more conservative heat transfer model based on "natural temperature."

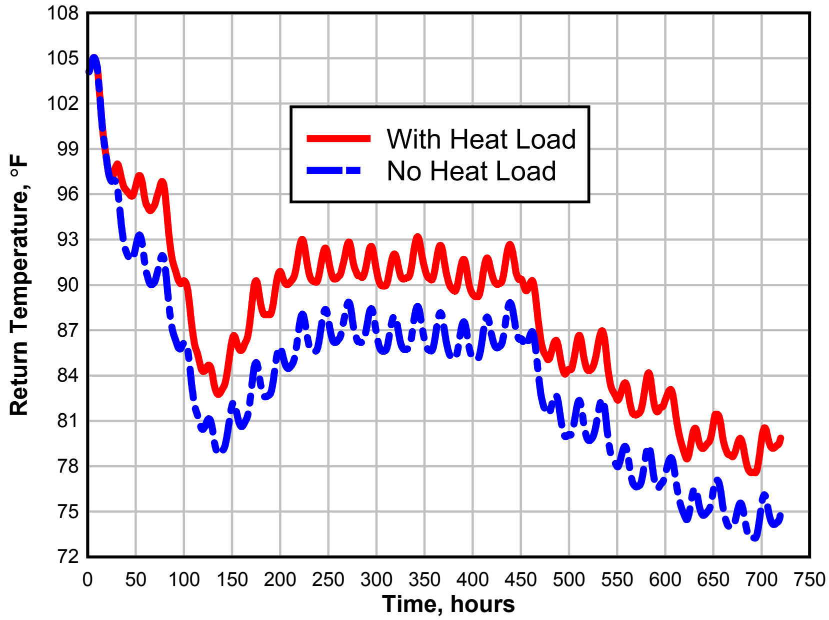

Figure A20. Temperature of Return Water With and Without Heat Load for Ryan Base Case Run Starting Temperature 104 °F

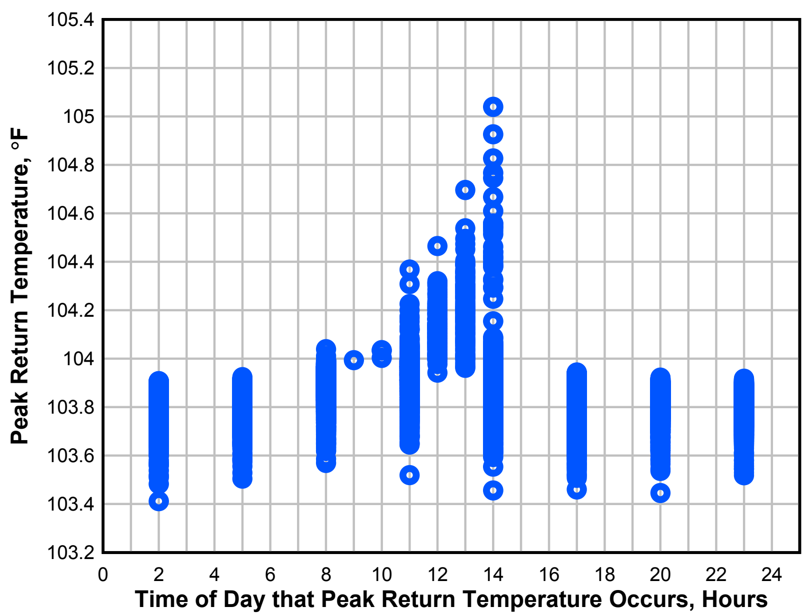

Figure A21. Peak Return Temperatures for Model B as Function of Time of Day, Ryan Base Case Model

Table A2. Parameters for Base Case	
File name	RyanBaseLasalle.in
Meteorological data file	pialsl9510.txt (licensee-supplied)
Heat load table	Lasalle_UHS_Heat_Load.csv (licensee-supplied); 38 segments; Variable volume and surface area
Pond initial temperature	104 °F
Wind speed reduction factor	0.8
Wind factor	Ryan and Harleman (1973)
Flow rate	65.3 CFS for hours 1-16 ; 86 CFS after 16 hours

Table A3. Results of Base Case and Sensitivity Runs With LAPLUG–LaSalle Meteorological Data Unless Stated Otherwise

File Name	Description of Model Run	Peak T, °F
RyanBaseLaSalle.in	Base case, Ryan wind function	105.04
BradyBaseLaSalle.in	Base case, Brady wind function	106.10
RyanBasePeoria.in	Ryan wind function, Peoria met data	105.33
BradyBasePeoria.in	Brady wind function, Peoria met data	105.82
StratRyan.in	Ryan wind function, effect of 2 ft stratified layer	104.7
StratBrady.in	Brady wind function, effect of 2 ft stratified layer	105.7
RyanModelA.in	Ryan wind function, Model A, 30 equal segments	105.58
RyanSmallSeg1.in	Ryan wind function, 12.5 percent volume and area for segment 1	105.04
BradySmallSeg1.in	Brady wind function, 12.5 percent volume and area for segment 1	105.73
WRFRyan25.in	Ryan wind function, 25 percent reduction of wind speed from base run	105.28
WRFBrady25.in	Brady wind function, 25 percent reduction of wind speed from base run	107.10
AreaVolRyan10.in	Ryan wind function, 10 percent reduction in surface area and volume	105.04
AreaVolBrady10.in	Brady wind function, 10 percent reduction in surface area and volume	107.43
AreaVolRyan25.in	Ryan wind function, 25 percent reduction in surface area and volume	105.04
AreaVolBrady25.in	Brady wind function, 25 percent reduction in surface area and volume	108.96
RyanGCC.in	Ryan wind function, add 2 °F to dry bulb, 1.6 °F to dew point	105.25
BradyGCC.in	Brady wind function, add 2 °F to dry bulb, 1.6 °F to dew point	106.74
Ryan10475.in	Ryan wind function, add 0.75 °F to starting pond temperature	105.68
Brady10475.in	Brady wind function, add 0.75 °F to starting pond temperature	106.39
Ryan150p.in	Ryan wind function, 150 percent of heat load	105.04
Brady150p.in	Brady wind function, 150 percent of heat load	108.97
Ryan10475gcc.in	Ryan wind function, add 5°F to dry bulb, 4°F to dew point	106.19
Ryan10475gccwrf.in	Same as above, but wind speed reduction factor = 0.43	106.61

A3.6.2 Sensitivity to Alternative Meteorological Data Set

This sensitivity experiment repeats the base case runs for the Ryan and Brady models with the licensee's alternative meteorological data set from Peoria (PS489661.txt). This data set was considered to be slightly more conservative than the LaSalle data set and is about three times as long. SwRI staff's preparation of the Peoria data set was limited to removing erroneous data so it would work with the LAPLUG model. This did not involve as careful scrutiny of the data set and substitution of missing data, so it is possible the Peoria data are not as reliable as the licensee's LaSalle data set.

Peak return water temperatures for the Peoria data set were 105.33 °F for the Ryan model and 105.82 °F for the Brady model. These results are close to those peaks SwRI staff predicted with the LaSalle data set for the same models and strengthen the conclusion the LaSalle meteorological data were appropriate for predicting the highest return temperature.

A3.6.3 Sensitivity to the Effects of Stratification

Although we believe the licensee has reasonably demonstrated there would be no significant stratification in the pond caused by release of highly heated water, we have performed a sensitivity run in order to estimate the potential effect of strong stratification. The assumption for this calculation is that a strong stratified layer exists and moves over the cooler pond water at a fixed thickness toward the plant intake. The hot water would move more quickly than the flow in the unstratified case because it is traveling in a thinner layer, but is still cooled by environmental heat transfer. Upon entering the intake sump, the hot layer would be mixed with cool pond water, therefore reducing its ultimate temperature. Calculations were performed using Model B (varying depth).

In this case, the pond was assumed to be stratified with the upper layer 2 ft thick and the lower layer ranging from 1.5 to 8 ft thick. For the stratified model, the transit time for discharged hot water to reach the intake is considerably smaller than the approximately 30 hours for the unstratified model, but still much longer than the peak caused by environmental heat transfer alone. Water temperature of the hot layer entering the sump is hotter (107.3 °F) than the unstratified case. However, the hot layer would mix in the sump with 8 ft of cooler (104 °F) pond water, for a resulting temperature peak of 104.7°F, which is cooler than predicted by the unstratified model. The same case was run with the Brady model and the peak temperature was calculated to be 105.7 °F. These temperatures are lower than their respective base cases, in part because the higher surface temperature leads to greater heat transfer to the environment.

A3.6.4 Sensitivity to Alternative Model Configuration

In Section A3.0.2.4, we developed two versions of the physical configuration for the plug flow model. Model A has 30 segments with equal volume and surface area. Model B has 38 segments, with varying volume and surface area estimated from depth measurements in the pond. Model B also has the first segment accounting for 25 percent of the surface area and volume in order to simulate mixing by the high-velocity jet discharge into the pond.

Model A predicts a peak return temperature of 105.6 °F, slightly higher than the base result, occurring at 1:00 PM, 6.2 hours after the event.

A3.6.5 Sensitivity to Size of Mixing Zone

The reference model configuration has the first segment accounting for 25 percent of the total volume and area. The sensitivity experiment reduces the first segment to only 10 percent of the volume and area. Peak return temperatures for this sensitivity case were 105.04 °F for the Ryan model, nearly identical to the base case, and 105.7 °F for the Brady model, slightly lower than the base Brady result.

A3.6.6 Sensitivity to Wind Speed Attenuation

In RAI 12, NRC staff expressed concern that wind speeds would be attenuated at the site because of structures and topographic features, especially related to the water surface of the UHS pond being up to 20 ft below grade upon cooling lake failure. The licensee responded to this RAI by commissioning a wind tunnel study, which developed wind-speed reduction factors for a scale model of the site. The licensee and we used the recommended wind-speed reduction factors in our model. We also used more conservative wind-speed reduction factors to determine the sensitivity of the peak return temperature results to this factor.

This sensitivity experiment shows the effect of reducing the wind speed at the surface of the pond to 75 percent of its base value, which had already been reduced to 80 percent of the 10 meter wind speed. Peak return temperature was predicted by these experiments to be 105.28 °F for the Ryan model and 107.1 °F for the Brady model. The Ryan model is less affected by wind speed reduction than the Brady model. This difference in sensitivity to wind speed can be explained by the fact the Ryan wind function has a term for heat removal by thermal convection that is a function of pond surface temperature, whereas the convection term in the Brady model is a constant, insensitive to pond surface temperature. Therefore, reducing wind speed in the Ryan model case causes an increase in heat removal by natural convection, which is not true with the Brady model. This sensitivity analysis demonstrates the importance of thermal convection and reduces the significance of the uncertainty in the wind speed at the pond surface.

<u>Wind Speed Reduction Factor and the Power Law Exponent</u>

A power law formula was used in both the licensee and SwRI models to reduce wind speed measured at onsite and offsite meteorological towers to the 2 meter height necessary for the Ryan and Brady heat transfer formulas from Section A.3.5:

$$\frac{v_2}{v_1} = \left(\frac{z_2}{z_1}\right)^{\alpha}$$

Where:

v_1 = wind velocity at LAKET evaluation height (knots)

v_2 = wind velocity at anemometer height (knots)

z_1 = LAKET evaluation height (2 meters = 6.562 feet)

z_2 = Anemometer height (ft)

α = Power law exponent (A7)

The licensee used a wind factor exponent α of 0.3 and indicated that value to be conservative because its CPP wind tunnel study (CPP, 2013) found exponents with an average value of 0.135 when used to reduce wind speed from the 375 ft level to the 33 ft level (Attachment K of the licensee's calculation document L-002457). Our base case runs used a wind speed reduction (WSR) factor of 0.8, based approximately on the use of the average CPP value, to adjust the wind speed from the 10 meter to the 2 meter level. Our sensitivity study used a WSR of 0.6, which is more conservative than predicted by the exponent of 0.3.

In the licensee's wind study (CPP, 2013), the licensee cites peer-reviewed models with an exponent (0.17 in section 2.2), similar to what the licensee has measured. Furthermore, the licensee's exponents are for stable atmospheric conditions, whereas CPP estimates atmospheric conditions close to the hot water surface will be unstable, leading to a conclusion that measured exponents will be conservative.

SwRI carried out analyses to understand the impact of the difference in the height and concluded the exponent from CPP report, although determined for wind speeds at 375 ft, should be applicable to adjusting wind speeds from any two levels. Therefore, there is no conflict between their use of 375 ft wind speeds and our use of 33 ft wind speed to determine 2-meter wind speeds for the Ryan formulas.

SwRI's original calculations did not take into account the base of the meteorological tower at the site is higher than the surface of the UHS pond by about 8.9 meters, so the 10 meter tower measurement in reality is 18.9 meters above the water surface. This fact needed to be factored into the estimates of 2 meter wind speed.

We used available data on wind speed measured at the 33, 200, and 375 ft levels of the onsite meteorological tower to determine the exponent empirically. Since the peak pond temperature for our model occurred July 25, 2001, we analyzed only meteorological data from 2001. Figure A22 shows the correlation between the hourly wind speeds measured at the 375 and 33 ft levels for the whole year. This figure also shows a straight-line regression of the data: y = 1.52 + 0.5186 x, where y is the wind speed at 33 ft and x is wind speed at 375 ft.

Ignoring the intercept, the regression predicts the wind speed ratio (33/375 ft) is R = 0.5186. The exponent α can then be calculated from the relationship:

$$\alpha = \frac{\mathrm{R}}{\ln\frac{33}{375}} \qquad \text{(A8)}$$

Therefore, α = 0.2702.

Using only the data from the hottest months, June, July, and August 2001, give somewhat different results. Figures A23 and A24 show the regressions for the 33/200 ft levels and the 33/375 ft levels for June through August 2001.

For the 33/375 ft levels, α = 0.372. For the 33/200 ft levels, α = 0.3236.

Using these estimates of the exponent α to calculate a wind speed 2 meters above the water's surface from a height of 18.9 meters gives a wind speed reduction factor of 0.5451, 0.4738, and

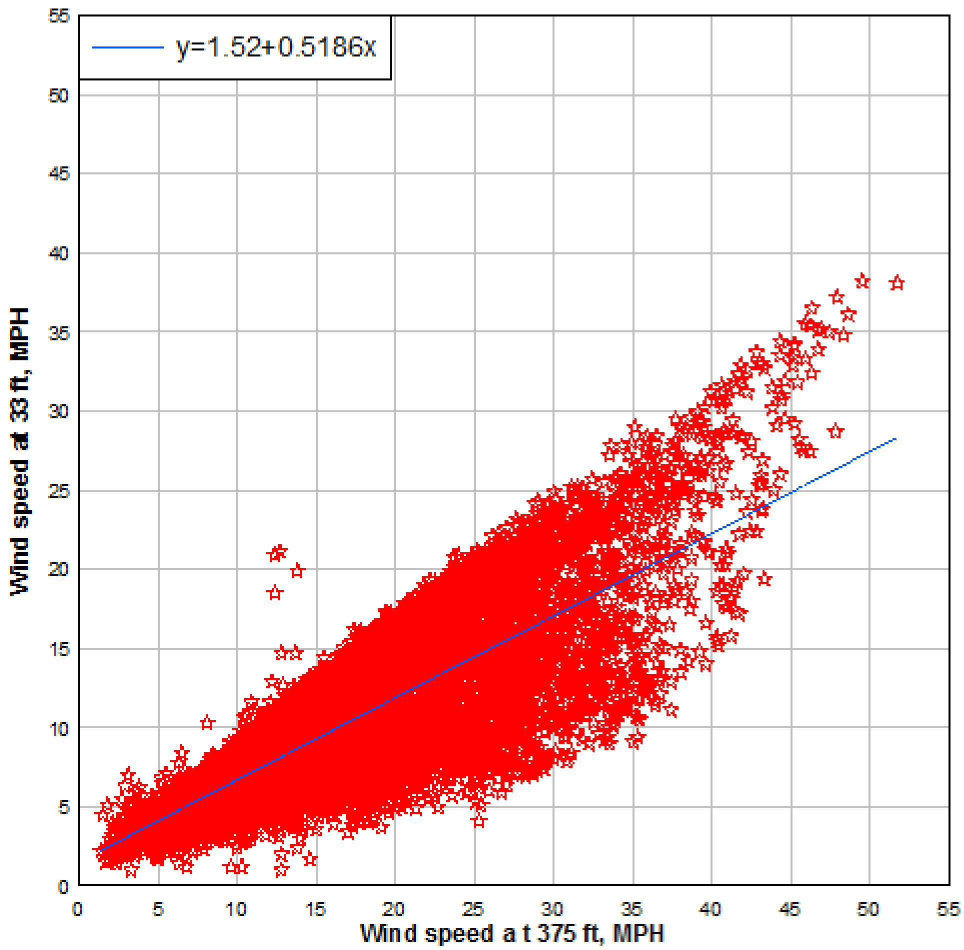

Figure A22. 2001 Correlation, Entire Year, 33 and 375 ft Levels

0.4337 from Figures A22, A23 and A24, respectively. Using the average α from the CPP report of 0.135 would give a wind speed reduction factor of 0.7384.

In order to test the sensitivity of the peak temperature calculated with the SwRI model to the worst case wind speed reduction factor of 0.43, we repeated a recent calculation using the Ryan formula with the global climate change (GCC) correction of 5 °F and 4°F for dry bulb and dew point, 104.75°F starting temperature, and a wind speed reduction factor of 0.8. The original run gave a peak return temperature of 106.19°F (Section 3.6.8 below). The repeated run with the wind speed reduction factor of 0.43 gave a peak return temperature of 106.61°F, about 0.43°F higher but still below 107°F.

Therefore, we draw the following observations from the above re-analysis of the wind speed reduction factor used in our models for the LaSalle UHS pond:

- Correlations of wind speeds at the three levels of the LaSalle tower for the year 2001 give higher (more conservative) exponents than the conclusions from the CPP report.

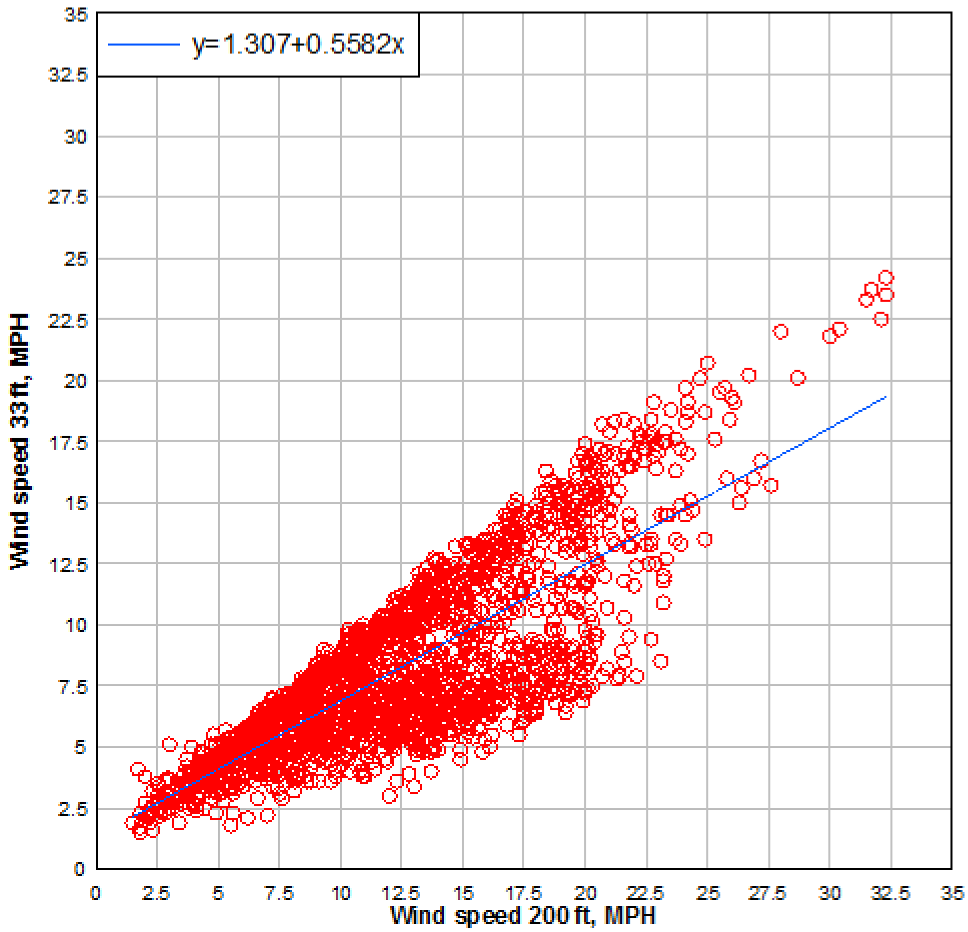

Figure A23. Correlation for June-August 2001, 33 and 200 ft Levels

- The exponent is higher when data are restricted to the hottest months, June, July, and August.
- The CPP report produces exponents that are smaller (less conservative), but more in line with peer-reviewed models.
- Wind speed reduction factors need to take into account the meteorological tower is 8.9 meters above the nominal surface of the UHS pond after failure of the dam.
- Using the worst result for the exponent from the correlations of onsite data, $\alpha = 0.43$, produces a peak return temperature of 106.61°F, 0.43°F higher than the result for $\alpha = 0.8$, but still below 107°F for one of the worst case sensitivity runs.

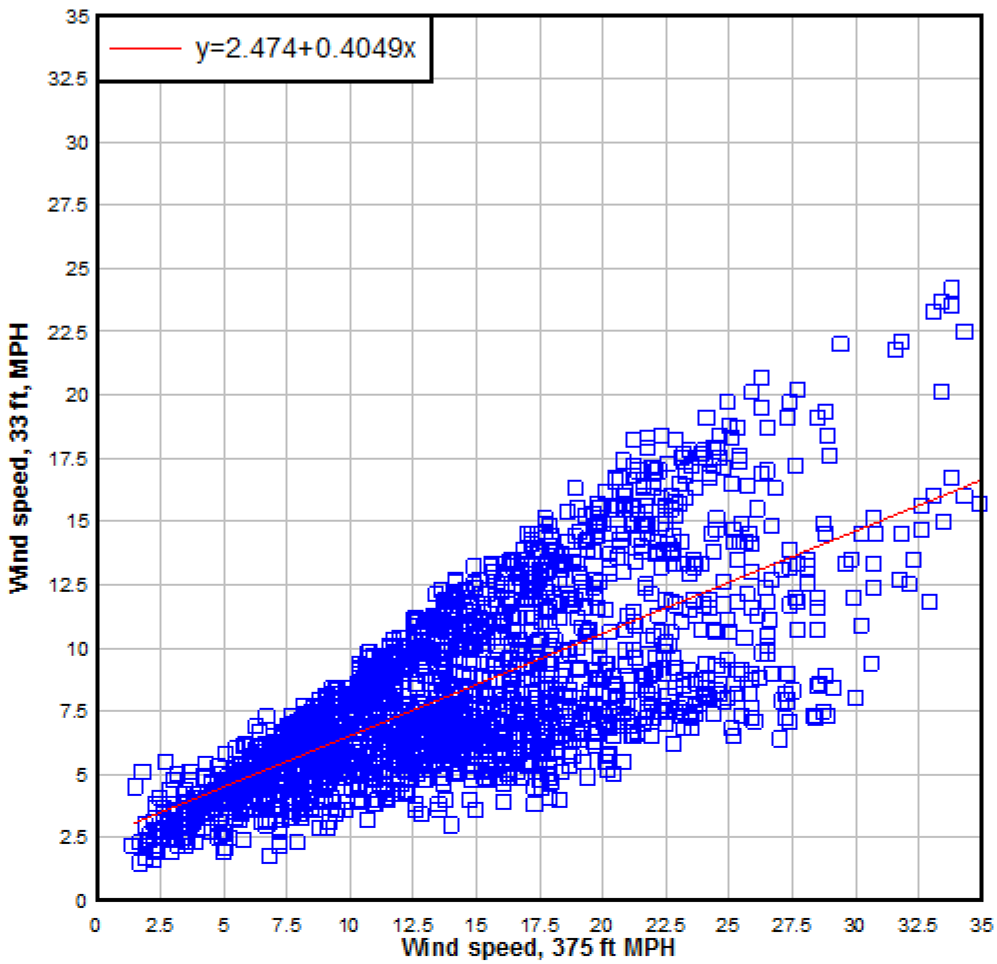

Figure A24. Correlation for June-August 2001, 33 and 375 ft Levels

A3.6.7 Sensitivity to Reduced Volume and Surface Area

The licensee used the CFD model to estimate an effective surface area percent and volume of the pond that accounts for the flow patterns in the irregularly shaped UHS pond (Ludovisi, et al., 2013). We also used more conservative values of surface area and volume reduction factors to determine the sensitivity of peak return temperature results to these factors. Reducing the surface area and volume of the model segments by 10 percent resulted in a peak return temperature of 105.04 °F for the Ryan model and 107.43°F for the Brady model. Reducing surface area and volume by 25 percent resulted in a peak return temperature peak of 105.04 °F for the Ryan model and 108.96 °F for the Brady model.

As expected, the change in peak temperatures is essentially unchanged from the base case for the Ryan model because the peak return temperature is caused by environmental heating only. The change in peak return temperature is larger for the more conservative Brady model, which is influenced by the discharge of heated water to the pond and has less ability to compensate for heat transfer caused by higher surface temperature.

This sensitivity experiment therefore demonstrates a reduced effective surface area and volume has little effect on the peak return temperature if caused only by environmental heat transfer, but would be more important if the arrival of the thermal pulse was the cause of the peak temperature (i.e., if environmental heat transfer was diminished).

A3.6.8 More Severe Meteorological Conditions Resulting From Global Climate Change

The report "Synthesis of the Third National Climate Assessment for the Great Lakes" (GLISA, 2014) states:

> *The temperatures in the Great Lakes, along with a majority of the United States, have been rising over the past several decades... The average temperature in northern portions of the region has warmed by more than 1.5°F during the period from 1991-2012 when compared to the period from 1901-1960. The most recent decade from 2000-2010 and including 2011 and 2012 has warmed faster in than any decade since 1900. The Midwest region (which includes much of the Great Lakes) has experienced an increasing pace of warming since 1900…. The observed increases in temperature also exhibit a diurnal and seasonal component with winter and nighttime temperatures warming faster than other seasons or daytime temperatures.*

Figure A25 shows the projected increase in average temperature over current conditions for 2041–2070, under the assumption of "… continuing growth in global emissions of heat trapping gases…" The LaSalle site would appear to fall in the light-brown area of the map, with an estimated increase of 4.5 to 5.0 °F.

Given the great uncertainty about future climates and the remaining lifetime of the LaSalle plants, we performed a sensitivity experiment that added a uniform 2.0 °F to the dry bulb temperature and 1.6 °F to the dew point temperature in the LaSalle meteorological data set. We estimated the dew point temperature increase from the correlation to dry bulb temperature shown in Figure A1. The peak return temperature increased to 105.25 °F for the Ryan model and 106.74 °F for the Brady model.

We also performed a sensitivity-case calculation using a 5.0 °F dry bulb temperature increase and a proportional 4.0 °F dew point increase. This increase was in response to an NRC question regarding climate conditions possible at the end of the life span for the LaSalle plants. Using a starting pond temperature of 104.75°F to account for instrument error, the resulting peak return temperature with the SwRI model would be 106.19°F. Coupling this analysis with a more severe wind speed reduction factor results in a peak return temperature of 106.61°F.

A3.6.9 Effect of Higher Initial Pond Temperature

In the LAR, the licensee takes into account a 0.75°F higher starting temperature for the pond in order to take into account potential instrument error. This sensitivity analysis considers the effect of raising the starting temperature from 104 °F to 104.75 °F. The change resulting in an increased peak return water temperature of 0.64 °F for the Ryan model and 0.29 °F for the Brady model.

We also re-ran the calculation using a finer 1-hour starting interval. We found the worst peak return temperature of 105.68°F (the same as with the 3-hour interval) occurred for a run with a design basis accident (DBA) starting at 8 AM on July 24, 2001. The peak occurred 6.2 hours after the DBA, confirming there are no higher results for this case.

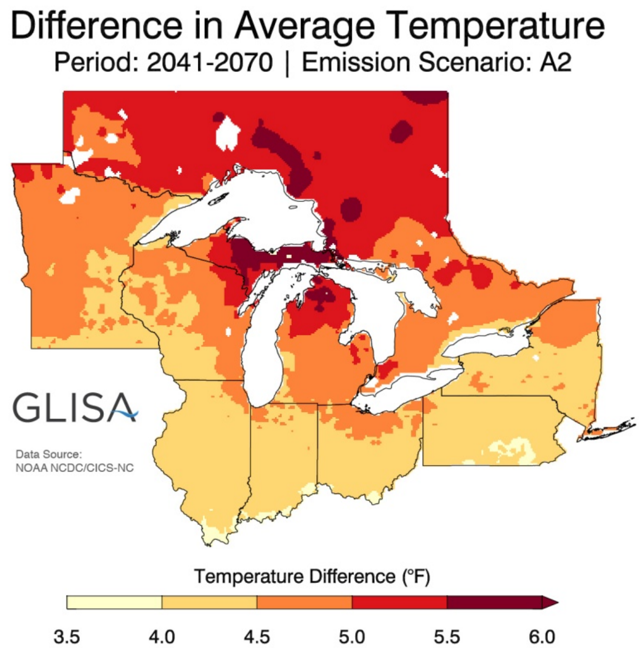

Figure A25. Projections of Average Temperature Increase for Great Lakes Region (GLISA, 2015)

A3.6.10 Effect of Higher Heat Load

This sensitivity analysis evaluates the effect of an increase in the heat load by a factor of 50 percent. There is no effect shown for the Ryan model and an increase to 108.97 °F for the Brady model. The Ryan model showed no effect since the peak occurred before the arrival of the heated water. The Brady model showed an increase because the peak was coincident with the arrival of the heated water.

A4 DISCREPANCY BETWEEN SWRI AND LICENSEE'S MODEL RESULTS

The licensee and SwRI models have some significant differences. The most important of these are:

- The licensee model has essentially no dispersion, which emphasizes the peak temperatures because it does not allow mixing of the hot water with cooler pond water. The SwRI model uses the mixed tank approach, which allows mixing and dispersion.

- The licensee's model uses the "natural temperature" to switch between two forms of the wind function, an important term that affects heat transfer by natural convection and conduction. The SwRI model uses only the Ryan wind function, and is not switched.

Both of these factors cause the licensee's model to conservatively predict a higher peak return temperature that coincides with the arrival of the heated water at the pond intake. Neither factor alone causes the peak temperatures to coincide with the arrival of the hot discharged water when using the Ryan model.

Peak temperature also occurs during a period when "natural temperature" is high, causing the model to switch to the more pessimistic Lake Hefner wind factor that does not account for natural convection.

There is ample reason to believe there will be considerable dispersion in the pond caused by a combination of jet mixing where the hot water enters the pond, the irregular shape of the pond that leads to multiple pathways and travel times of water from the discharge to the inlet, and dispersion caused by bottom friction. Furthermore, we find no reason to switch between two forms of the wind function in the heat transfer relationships based on the natural temperature.

Figure A26 show the results of a model run with our best understanding of how the licensee calculated natural temperature, which we then used to determine which wind function to use; (i.e., if pond temperature exceeds natural temperature by greater than 2.5°F, then the Ryan wind function, Eq. A1, is used). Otherwise, the Lake Hefner wind function, Eq. A4, is used. The model also employed the "no dispersion" approach, which preserves the steepness of the temperature peaks. The model used also had a fixed flow rate of 86 CFS, which was necessary in order to keep the calculations simple for the no-dispersion algorithm.

The peak return temperature for this run is 109.23 °F and occurs coincident with the arrival of the discharged hot water at 33 hours after the event. Note also in Figure A26 the first peak (107.95 °F) occurs 7 hours after the event, well before the arrival of the heated water, and is nearly as high as the maximum. We believe this result is close to what the licensee would have predicted for similar inputs. Turning off the natural temperature feature results in a peak temperature of 105.55 °F, which occurs 6 hours after the event, well before the arrival of the discharged hot water. We should also note the meteorological periods preceding the peak temperatures are different. The natural temperature result was for the event starting at 8:00 AM on June 22, 2009, whereas the no-natural temperature case was for the event starting at 8:00 AM on July 22, 2001. These times are slightly skewed by the use of a constant flow rate of 86 CFS rather than the initial flow rate of 65.3 CFS for the first 16 hours.

A5 CONCLUSIONS FROM SWRI'S ANALYSES

SwRI's confirmatory analysis, as a part of the review of the licensee's analysis, leads to the following conclusions:

- Independent confirmatory analyses predict similar or smaller temperature rise than those of the licensee for runs starting at 104 °F.
- The use of offsite data from Peoria and Springfield is reasonable and justified based on partial correlations of onsite and offsite air temperature and wind speed.
- The licensee's adjustment of dew point temperatures from Peoria so they cannot exceed dry bulb temperatures from LaSalle is appropriate.

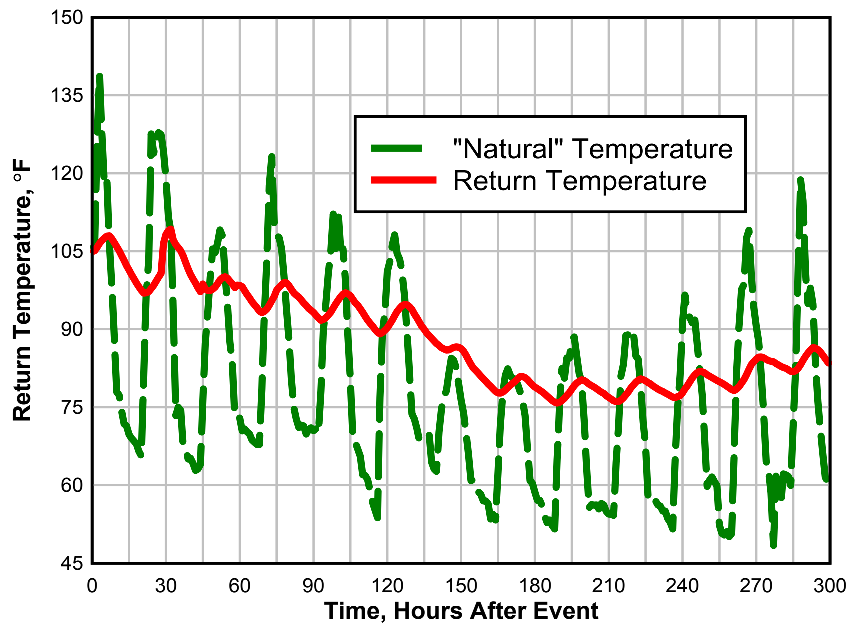

Figure A26. Return and Natural Temperatures for the SwRI Model That has no Dispersion and Uses Natural Temperature to Switch Forms of the Wind Function.

- The licensee is justified in assuming the pond is unstratified from the effects of hot water addition. Pond may become stratified as a result of environmental heating enhanced by turbidity, but this would not affect the peak return water temperature significantly. The assumption of no stratification also conservatively neglects the additional heat transfer caused by higher surface temperature and through thermally induced circulation into dead-end spaces in the pond.

- For the Ryan wind function model, the discharge of heated water to the pond does not affect the highest peak return water temperature.

- The Ryan and Harleman heat transfer relationships are the preferred heat transfer model for estimating peak return water temperature, even though this approach has been shown to overestimate cooling in some cases. Use of a more conservative model, such as Brady heat transfer model, can underestimate cooling by a large margin.

- The licensee's model approach to the wind factor (i.e., use of "natural temperature"), and a no dispersion or mixing also would lead to an increased peak return water temperature. However, we find no justification for using these approaches other than they add conservatism to the temperature calculations.

- SwRI staff's sensitivity experiments for a strongly stratified pond do not result in an increased peak return temperature.

- SwRI staff's sensitivity experiments with decreased surface area and volume for the pond demonstrate essentially no increase in return water temperature when using the preferred Ryan model. Use of the Brady model predicts higher return water temperatures, but we believe the Ryan result is more accurate.

- SwRI staff's sensitivity experiments with a decreased wind speed reduction factor of 0.6, which is 25 percent less than the base case, demonstrates only a small increased return water temperature for the preferred Ryan model. Return water temperature with the Brady model is higher, but we believe the Ryan result is more accurate. Results with even more severe wind speed reduction factor of 0.43 were still below 107 °F.

- SwRI staff's sensitivity experiments that increased heat load by 50 percent resulted in no increase in peak return temperature.

- The higher values of the licensee's predictions of peak return water temperature can be explained by the licensee's use of a no-dispersion model and natural temperature to switch between two forms of the wind function. However, we believe our results are more realistic and accurate.

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ATTACHMENT AA

PROBABILITY OF HIGH RETURN WATER TEMPERATURES

INTRODUCTION

The analysis of ultimate heat sink (UHS) performance relies on calculations that combine improbable events, such as failure of the main reservoir, with worst-case conditions, such as deep sedimentation in the UHS pond and severe meteorology. There is generally no consideration given to the probability of the worst performance. The following example estimates the probability a temperature will be exceeded based on the model parameters and base case meteorology used in the main report; (i.e., 18 inches of sediment, Brady wind function, LaSalle data set, 104 °F starting temperature).

EXAMPLE CALCULATION OF PROBABILITY

SwRI staff's analyses with our best estimates for models and parameters did not result in any cases where return water temperature exceeded 107 °F. Use of the Ryan and Harleman (1973) wind function resulted in a peak temperature that occurred well before the arrival of any water heated by discharged hot water and was the result of only heating from environmental factors. Figure AA1 shows the peak temperatures above the starting temperature of 104 °F using the more-conservative Brady, et al. (1969) wind function. The first set of peaks in this figure are from environmental heating only, as with the Ryan wind function, but the second set of peaks is due to the arrival of hot water coincident with high environmental heating. Highest peaks are still below 107 °F.

Figure AA2 is a histogram of peak temperatures for the Brady wind function case, showing the peak temperatures resulting from discharged hot water are infrequent.

Although none of the peak return water temperatures from the Brady model runs exceeded 107 °F, we calculated the probability of exceeding lower reference temperatures as a demonstration of the low probability the peak temperature events. It is first necessary to demonstrate the sampling frequency for starting time of once per 3 hours adequately results in truly worst peak temperatures; (e.g., would a 1-hour sampling frequency for start times yield a higher worst-case, or would it change the probability estimate?) While it is possible a shorter sampling time would give a somewhat higher worst case peak, it must be recognized the peak temperature record calculated in an "autocorrelated" time series (i.e., peaks for two closely-related starting times) will be more alike than for peaks with starting times further apart.

This property is shown in Figure AA3, which gives the autocorrelation factor as a function of lag between starting times (Function ACF, R version 2.8). Each lag in this figure is 3 hours. By convention, zero lag time has a correlation of 1.0. The figure shows a high correlation for 3-hour lag times (0.68), and also a correlation for larger lags that is attributed to the fact the peaks generally occurred during periods of high solar radiation and thus depended on the time of day.

The autocorrelation of peak temperatures suggests the calculation of probability of peak temperatures exceeding a reference value would reasonably be predicted for the 3-hour starting

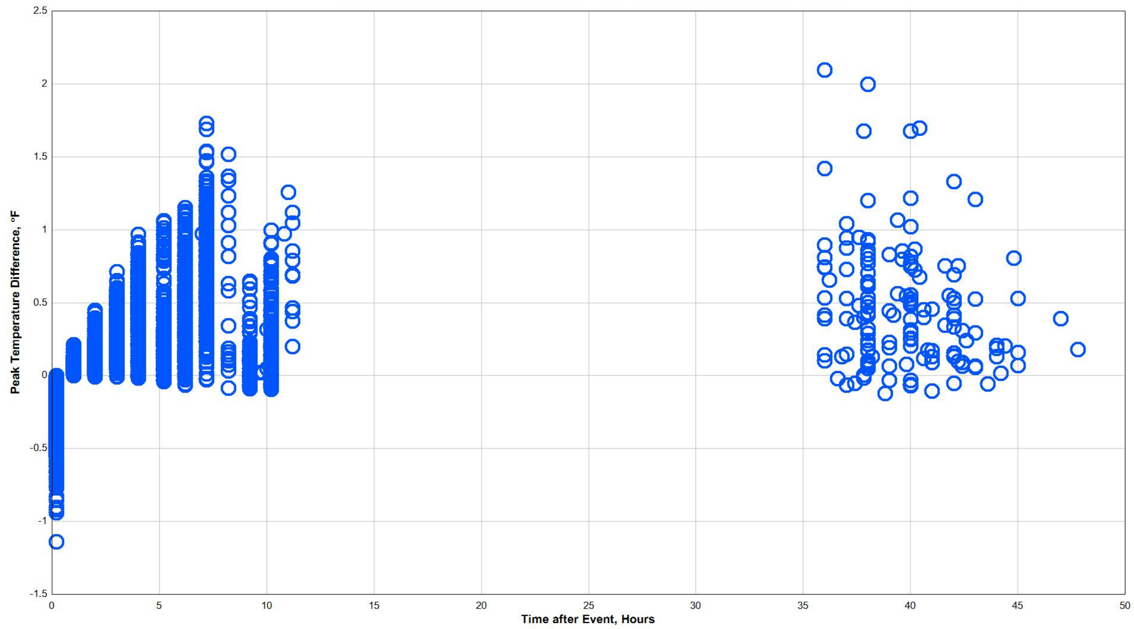

Figure AA1. Peak ΔT Above 104 °F for Brady Base Case Model

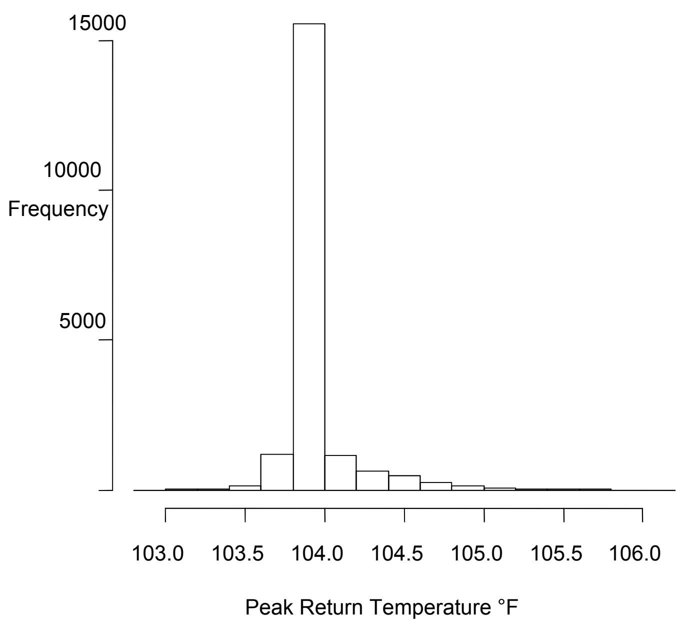

Figure AA2. Histogram of Peak Return Temperature for Base Case, Brady Model

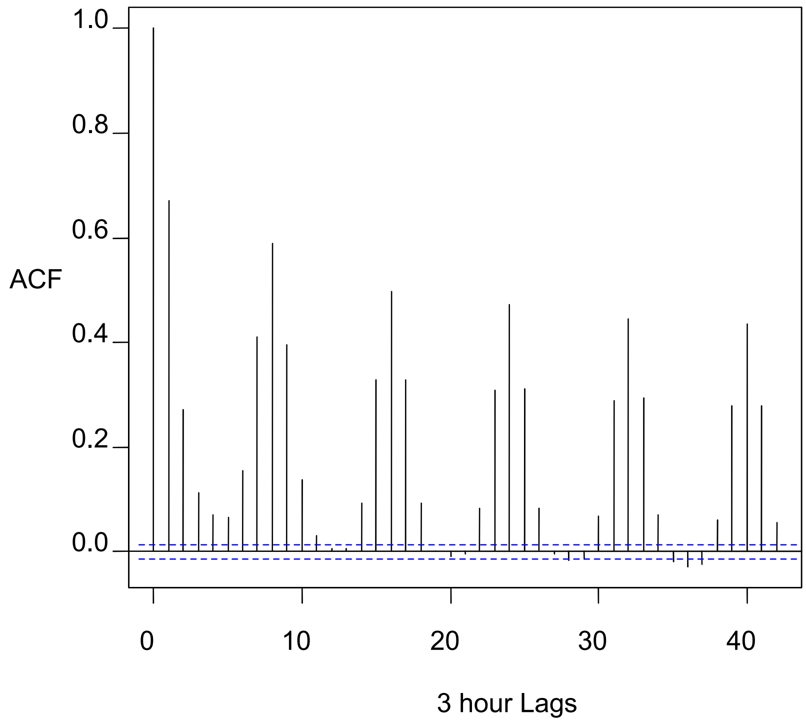

Figure AA3. Autocorrelation Function (ACF) of Peak Temperatures for 3-Hour Calculation Intervals Conclusions

interval. Table AA1 shows the calculated probability of exceeding the reference temperatures for the conservative Brady wind function model. This raw probability is calculated as the number of peaks exceeding the reference temperature divided by the number of 3-hour intervals in the 15+ year record (46020).

Table AA1 shows estimated probabilities for peak temperature from the Brady wind function model. Note that peak temperatures for each run were calculated only for starting times May through September, under the assumption this period would capture the highest peaks. However the entire length of the record was used in the probability calculations. Results of this analysis demonstrate that peak temperatures, even for those below 107 °F, are very unlikely events. Such probability estimates could be combined with other rare events (e.g., failure of the cooling lake) to make a risk-informed case regarding UHS performance.

Table AA1. Exceedance Probability for Peak Return Temperatures, Brady Wind Function Model		
Reference Temperature, °F	**Number of Peaks Exceeding**	**Estimated Probability Per Year**
106	1	2.17×10^{-5}
105.5	11	2.39×10^{-4}
105	94	0.00204
104.5	684	0.0149

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