Proceedings of the 16th International Conference on Nuclear Engineering
ICONE16
May 11-15, 2008, Orlando, Florida, USA

ICONE16-48530

ORIENTED SPRAY COOLING SYSTEM ULTIMATE HEAT SINK FOR FUTURE NUCLEAR PLANTS

Charles F. Bowman, P. E.
Chuck Bowman Associates, Inc.
Knoxville, Tennessee
cbainc@usit.net

ABSTRACT

The reference safety-related ultimate heat sink (UHS) for the evolutionary advanced light water reactor nuclear plants that require a safety-related reactor service water system (RSWS) is a spray pond. Spray ponds offer significant advantages over mechanical draft cooling towers including superior simplicity and operability, lower preferred power requirements, and lower capital and maintenance costs. The UHS for the Columbia Generating Station (CGS), one of the last nuclear plants that was licensed during the last round of nuclear plant construction in the United States of America (USA), is the Oriented Spray Cooling System (OSCS), an evolutionary spray pond design. Unlike a conventional spray pond in which spray nozzles are arranged in a flat bed and spray upward, the OSCS nozzles are mounted on spray trees arranged in a circle and are tilted at an angle oriented towards the center of the circle. As a result, the water droplets drag air into the spray region while the warm air that is concentrated in the center of the circle rises. Both of these effects work together to increase air flow through the spray region. Increased air flow reduces the local wet-bulb temperature (LWBT) of the air in the spray pattern, promoting heat transfer and more efficient cooling. During the late 1970's while working for the Tennessee Valley Authority, the author developed a purely analytical model to predict the thermal performance of the OSCS which was successfully compared with the OSCS at the CGS in the mid 1980's. This paper describes the OSCS and the analytical model that is used to predict its performance and compares the predicted performance of the OSCS at the CGS with the full-scale field test results. The paper describes how this technology has been successfully used to design the UHS for a future nuclear plant that requires a safety-related RSWS that must not exceed a peak temperature of 95 ^{o}F.

INTRODUCTION

Spray ponds have been employed as the UHS for several nuclear plants in the USA. Spray ponds are simple, relatively inexpensive, essentially passive devices that do not require electrical power and can be seismically qualified. The pond is sized to store sufficient water for continued plant operation for up to 30 days following an accident as required by the Nuclear Regulatory Commission's Regulatory Guide (RG) 1.27[1]. Therefore, the source of makeup water is not considered safety-related. However, since spray ponds cannot be protected from tornado missiles, a diverse source of cooling water such as the main cycle cooling tower makeup might be required to be tornado-missile protected to serve as an alternative source of RSW.

Most of the existing UHS spray ponds employ the classical flat bed sprays that are oriented in the vertical direction. The thermal performance of this design has proven to be very poor[2]. The problems with this design have been the subject of extensive investigation[3]. The author supervised the development of an analytical spray pond model in the late 1970's. The application of this model to the flat bed spray pond design identified the cause of the low thermal performance. In the flat bed design with all spray nozzles oriented in the vertical direction, the bulk drag force of the water droplets which is vertically downward resists the natural buoyancy of the warm air which is of the same order of magnitude and is directed vertically upward. Since the two forces which are acting on the air oppose each other, the result is a reduced air flow rate through the spray region and a large increase in the LWBT. However, one nuclear plant, CGS employs a radically different spray pond design for their UHS that overcomes these problems. This design, known as an OSCS, was first proposed by Ecolaire Condenser Company (ECC) in the late 1970's[4].

Figure 1 shows the OSCS that was constructed, operated, and thoroughly tested by ECC at the Ingersoll-Rand pump and turbine factory in Phillipsburg, NJ. As one may readily see from Figure 1, the outstanding feature of the OSCS design is the fact that the spray nozzles are arranged in a circle and oriented at an angle from the vertical towards the center of the circle. In this design, both the bulk drag force of the water droplets on the air and the buoyant force promote ventilation of the spray region. The result is a reduction on the LWBT in the spray region and improved cooling of the droplets as they fall through the spray region to the pond surface below.

ULTIMATE HEAT SINK DESIGN BASIS

RG 1.27 requires that a nuclear plant UHS be analyzed in a conservative fashion to demonstrate that it can function adequately under the worst meteorological conditions recorded in the plant region. The RG requires that the meteorological conditions be selected with respect to the critical time periods unique to the specific design of the UHS. Sufficient conservatism is required to ensure that a 30-day supply of water is available without exceeding the design basis temperature. The analysis presented herein considers time periods of five days prior to and 30 days following the design basis accident to determine the initial and peak pond temperature (PT). The design basis meteorology for the five days prior to the accident and the 30 days following the accident consists of two-hour average meteorology for the worst day recorded at the nearest National Weather Station. On the worst day the maximum two-hour average ambient wet bulb temperature (AWBT) was 84 ^{o}F.

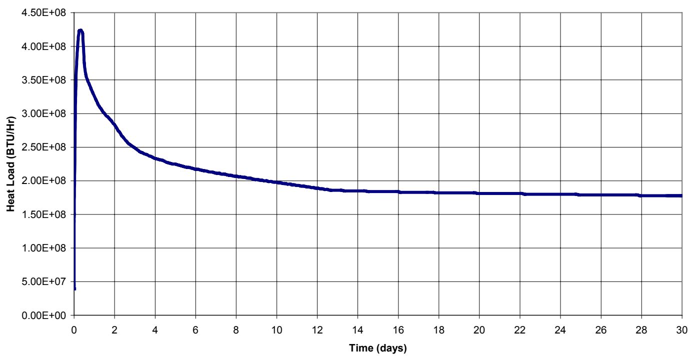
For a nuclear plan with three active safety-related RSWS divisions, the design basis accident is assumed to be a loss of coolant accident (LOCA) in one unit and the safe shutdown of the other unit and the loss of one division of RSW. Figure 2 shows the resulting total required heat load for the remaining two divisions including the decay heat and other heat loads which must be dissipated by the UHS for a typical 1,300 MWe nuclear plant. In addition, a maximum solar heat load of 825 Langleys/day that must be dissipated is modeled as a sinusoidal function during daylight hours. The RSW flow is 12,500 gal/min per division.

DESCRIPTION OF THE ULTIMATE HEAT SINK

The proposed UHS consists of a single spray pond serving both units excavated from undisturbed earth and sized for a water volume adequate for 30 days of cooling under design basis conditions. Figure 3 shows the pond with three divisionalized ring headers. Half of each ring header is dedicated to Unit 1 and the other half to Unit 2. Each half of each ring header consists of two header segments joined at a tee located on shore. The first segment provides flow to the first 10 spray trees on the spray ring header. These trees are always in service any time the RSW system is in service. The second segment contains a motor-operated butterfly valve and runs parallel to the first header for 106 degrees of the arc of the circle and then serves the remaining 7 spray trees in that half-circle. This segment terminates after the last tree and is only in service when both RSW pumps are in service. A cold weather bypass is provided to dump a portion of the RSW flow directly

Figure 1

Figure 2
Heat Load
Unit 1: LOCA, Unit 2: Safe Shutdown



into the pond such that only a minimal amount of flow is discharged from the top nozzles. There is a second set of Unit 2 headers that are a mirror image of the first that occupy the other half-circle for one division of RSW. There are 17 identical OSCS Spray trees per unit per division for a total of 102 trees. Each spray tree will pass an average of approximately 735 GPM. The physical arrangement of each spray tree is similar to those at CGS. The spray tree centerline spacing is the same as that at the CGS, and the nozzle pressures are very close to those at CGS. However, there are two more nozzles and the nozzles are larger than those at CGS, so the total spray tree flow in the proposed design is greater than that at the CGS.

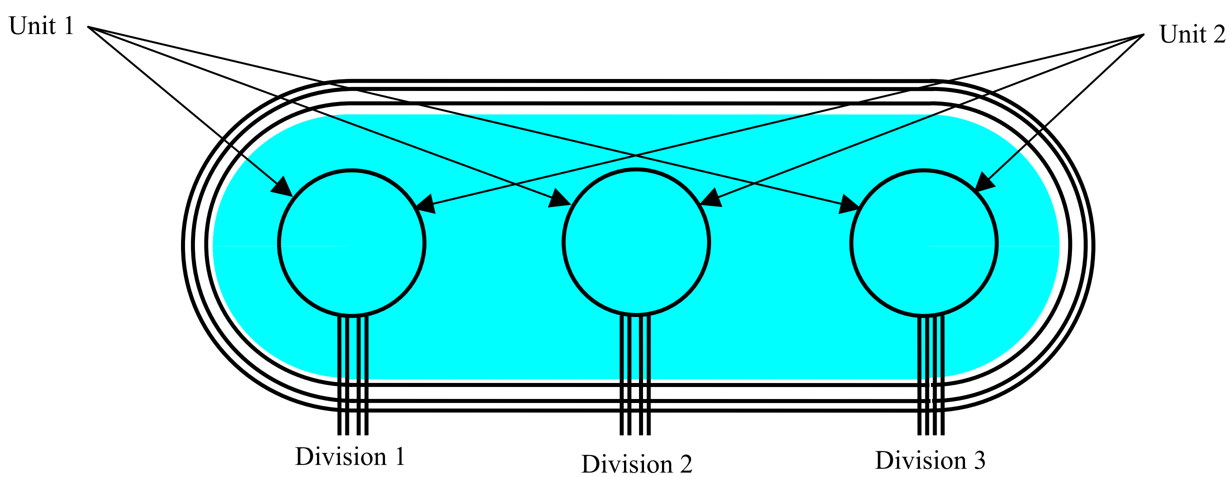
CGS OSCS THERMAL ANALYSIS

The basis for the analytical spray pond thermal model, was published in 1978[5]. The model utilizes the Ranz and Marshall correlation[6] for evaporative cooling to predict enthalpy drop and the experimentally derived drop spectrum for the particular spray nozzle. The other elements of the model are analytical, based on first principals, and do not rely upon any other experimental thermal performance data from individual spray units or from particular spray configurations. Therefore, the model is not limited in application with regard to spray pressure or nozzle spacing or orientation and is not limited by droplet size considerations. The significant assumptions employed in developing the analytical model are as follows:

- conditions are uniform across the inlet and exit area,
- air enters at known ambient psychrometric conditions,
- relative humidity within and at the exit of the control volume is 100 percent,
- the rate of heat addition to the spray system is known,
- ambient wind is neglected,
- bulk drag forces are known functions of velocity,
- drops are spherical,
- collisions and interactions between drops are neglected,
- nozzles are axi-symmetric,
- drop size distribution is known,
- air velocity and air properties are uniform across the region of interest.

Validation of the model against the results of tests conducted at the Rancho Seco Nuclear Plant for classical vertical flat bed

Figure 3
Proposed OSCS Pond Plan View



sprays was reported in Reference 5. A comparison was presented in Reference 7 between the analytical model and predictions based on the proprietary tests conducted by ECC. When CGS (formerly Washington Public Power Supply System Nuclear Project No. 2) issued the report of the tests conducted on their OSCS UHS[8], verification of the analytical model for that full-scale configuration became possible and was first published by the author in Reference 9. Figure 4 shows the results of this comparison between the CGS test results and the analytical model predictions in which the cold water temperature (CWT) measured in pans as the sprayed droplets hit the pond surface is plotted as a function of the AWBT.

Figure 4
CGS OSCS
CWT vs. AWBT

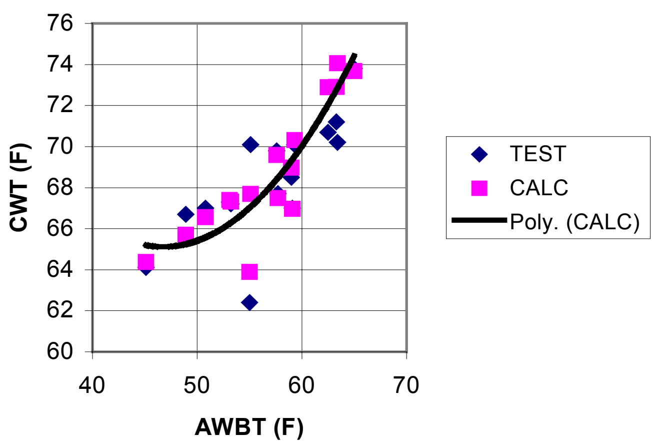


Figure 5 shows the results of this comparison with the CWT approach to the AWBT (CWT-AWBT) plotted as a function of the hot water temperature (HWT) minus the CWT, or the cooling range. Figure 6 shows the comparison presented in terms of the spray efficiency as a function of ambient wind velocity (AWV). Spray efficiency is the ratio of the cooling range divided by the cooling potential (HWT – AWBT). One may see from Figure 6 that the analytical model is increasingly conservative at higher AWV as would be expected since the analytical model assumes zero AWV. The agreement between the CGS test results and the analytical model leaves little doubt as to the validity of the author's analytical model even though it is purely analytical.

Figure 5
CGS OSCS
Approach vs. Cooling Range

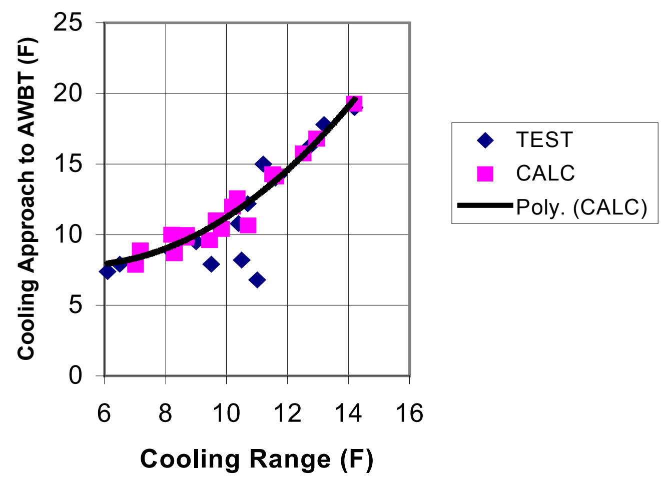
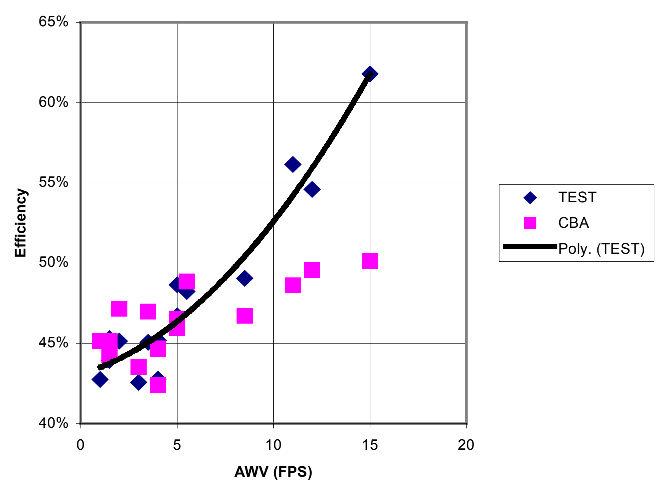


Figure 6
CGS OSCS
Efficiency vs. AWV

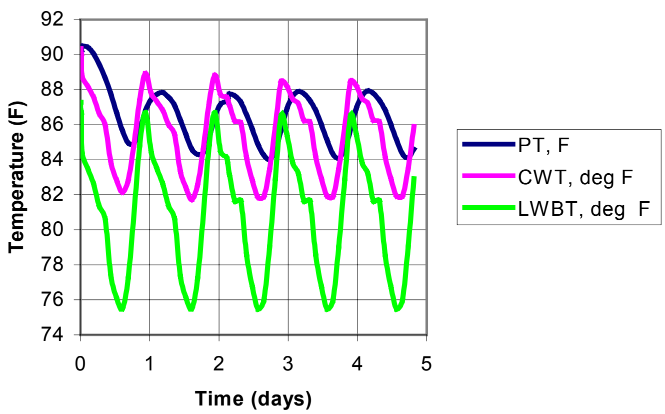


FUTURE NUCLEAR PLANT THERMAL ANALYSIS

Figure 7 shows the results of the analysis of the five days of normal operation prior to the accident. Time zero is taken as noon of the first day, and the initial pond temperature is arbitrarily selected as 90.0 °F. The LWBT shown in Figure 7 is the average of the AWBT and the exit wet-bulb temperature and is computed based on the AWBT, heat load, and air flow rate. The CWT is the weighted average temperature of the water droplets as they land on the pond surface. The CWT is seen to be quite sensitive to the LWBT. The PT is the average bulk temperature of the pond mass assuming perfect mixing occurs between the pond mass and the sprayed water. The PT responds to diurnal variations in meteorology, but not to hourly changes due to the large mass of water in the pond. The maximum PT is 88.0 °F. Based on these results, an initial PT of 90.0 °F was conservatively selected as the initial PT in calculating the PT transient following the accident.

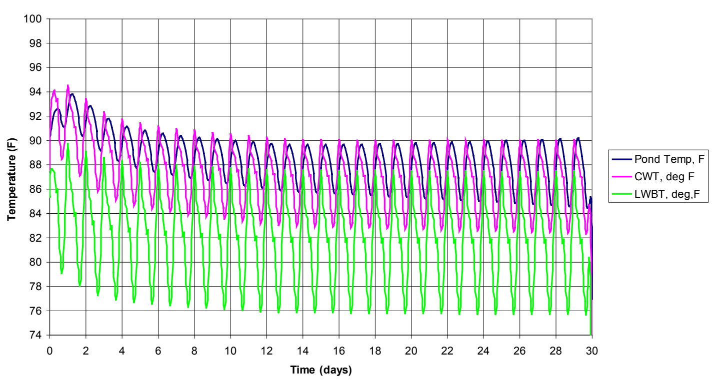
Figure 8 shows the results of the transient spray pond analysis subsequent to a LOCA. Both the CWT and the PT are seen to respond to the peak heat load that occurs within the first

Figure 7
OSCS UHS
Normal Operation Prior to LOCA



few hours, but the PT reacts more slowly due to the "thermal inertia" effect of the mass of water in the pond. The PT does not peak until after the first day following the accident. The mass of water in the pond serves to displace the peak PT, but it does not attenuate the peak PT very significantly. Both the peak CWT and the peak PT are directly affected by the initial PT. Therefore, operation of the spray pond during normal plant operation is important, since the pond would otherwise assume the solar equilibrium temperature which could be even higher than the temperature determined from Figure 7. The PT peaks

Figure 8
OSCS UHS
Unit 1:LOCA, Unit 2: Safe Shutdown



at approximately 94 ^{o}F in this analysis.

CONCLUSIONS

A spray pond is an appropriate selection for the next generation of nuclear plants that require a safety-related RSWS and UHS. Spray ponds offer advantages of improved operability, simplicity, and lower cost as compared with mechanical draft cooling towers. The OSCS is superior to the flat bed spray pond design because the nozzle orientation promotes ventilation of the spray region. The result is a design that is considerably more efficient than the flat bed spray.

REFERENCES

1. U.S. Nuclear Regulatory Commission Regulatory Guide 1.27, Ultimate Heat Sink for Nuclear Power Plants, Revision 2, 1976.

2. Shrock, V.E., Trezek, G.J., and Keilman, L.R., "Performance of a Spray Pond for Nuclear Power Plant Ultimate Heat Sink," ASME Paper 75-WAHT-41.

3. Janis, M.L., and Porter, R.W., "Heat, Mass, and Momentum Transfer from Sprays to Air in Cross Flow," IIT Waste Energy Management Technical Memorandum TM-79-2, Illinois Institute of Technology, July 1979.

4. Stoker, R. J., Water Cooling Arrangement, U. S. Patent No. 3,983,192, September 28, 1976, The United States Patent and Trademark Office. Washington, D. C.

5. Berger, M.H. and Taylor, R.E., "An Atmospheric Spray Cooling Model," In *Environmental Effects of Atmospheric Heat/Moisture Release: Cool Towers, Cool ponds and Area Sources; Proceedings of the 2nd AIAA/ASME Thermophysics and Heat Transfer Conference, Palo Alto, CA, May 24-26, 1978,* 59-64. New York: American Society of Mechanical Engineers, 1978.

6. Ranz, W.E and Marshall, W.R., Jr., "Evaporation From Drops," Chemical Engineering Progress, Volume 48, Nos. 3 and 4, March and April 1952.

7. Bowman, C.F., Smith, D.M.,and Davidson, J.S., "Application of the TVA Spray Pond Model to Steady-State and Transient Heat Dissipation Problems," Proceedings of the American Power Conference, Volume 43, 1981.

8. Conn, K.R., "1979 Ultimate Heat Sink Spray System Test Results," Washington Public Power Supply System Nuclear Project No. 2, WPPSS-EN-81-01.

9. Bowman, C.F., "Analysis of the Spray pond Ultimate Heat Sink for the Advanced Boiling Water Reactor," Proceedings of the American Power Conference, Volume 56, 1994.