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7. Abstract PWR Core II fuel pool chiller-off test was conducted because it appeared possible that acceptable pool-water temperatures could be maintained without operating the chillers, thus saving hundreds of thousands of dollars in maintenance and replacement costs. Test results showed that the water-cooling capability is no longer needed to maintain pool temperature below 38 °C (100 °F)		
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Evaluation of Storing Shippingport Core II Spent Blanket Fuel Assemblies in the T Plant PWR Core II Fuel Pool Without Active Cooling

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October 1994

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MASTER

Summary

Pacific Northwest Laboratory (PNL) developed the test requirements for and evaluated the results of turning off chillers that maintain pool-water temperature in the 190-m³ (50,000 gallon) pressurized-water reactor (PWR) Core II fuel pool at Hanford's T Plant in Richland, Washington, where 72 spent Shippingport Core II blanket fuel assemblies are stored. The requirements were developed for Westinghouse Hanford Company, which conducted the test for the U.S. Department of Energy. Test results showed that the water-cooling capability is no longer needed. This report describes the test results and provides recommendations for future operation without the chillers.

Before storage of the Shippingport fuel, water chillers (large heat exchangers) were installed at the T Plant to maintain the pool-water temperature at 6 to 12°C (45 to 54°F) to prevent the fuel assemblies from overheating and to comply with industry's then-current standards and practices for fuel-storage pool operation. However, because of their modest burnup and long decay time, each assembly now produces approximately 100 watts of decay heat (7.2 kW total). Furthermore, since the Shippingport assemblies were placed in storage in 1978/1979, industry has raised its recommended fuel-storage, pool-water temperature to 32 to 38°C (90 to 100°F). PNL's preliminary calculations indicated that the temperature in the PWR Core II fuel pool would remain below this range. The chiller-off test was conducted because it appeared possible that acceptable pool-water temperatures could be maintained without operating the chillers, thus saving hundreds of thousands of dollars in maintenance and replacement costs.

The following operating procedures are recommended for pool operations without active cooling:

- Monitor water temperatures to verify storage at less than 38°C (100°F). Statistical scatter and possible bias in thermocouple readings should be accounted for in setting operating limits.
- Sample water quality twice per month to verify that water quality is within limits. In addition, monitor the content of phosphate and nitrate in the pool water; each should be less than 2 ppm. Water quality superior to current limits would be desirable. Consider improving the current cleanup and water turnover rate relative to the industry standard.
- Monitor the water turbidity and algae growth twice monthly by periodic inspection of a visual reference point in the pool and occasional swiping of pool surfaces.
- Do not add chemicals in response to an indication of algae formation without a thorough review of the benefits and potential for new problems.

The water-cooling capability is no longer needed for the PWR fuel-storage pool as long as no additional heat loads or unreviewed fuel types are added to the pool, the water quality is maintained or improved, and the water quality, radioisotope concentration, and temperatures continue to be monitored. A change to continuous operation of the recirculating pump would be a significant added heat load.

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1.0 Introduction

Seventy two spent Shippingport Core II blanket fuel assemblies are stored in racks in the 190-m³ (50,000 gallon) pressurized-water reactor (PWR) Core II fuel pool, in Cell 4, at the T Plant in the 200-West Area of the Hanford Site^(a) in Richland, Washington. The assemblies contain thin UO₂ wafers clad in Zircaloy-4 metal plates. These assemblies were discharged in February 1974 with an average uranium burnup of 1.8 at% (16,000 MWd/MTU) and have been stored at the T Plant since 1978/1979. Water chillers (large heat exchangers) were installed before storage to maintain the pool-water temperature at 6 to 12°C (45 to 54°F), thereby preventing the fuel assemblies from overheating, precluding algae growth, and complying with then-current industry standards and practices for fuel-storage pool operation (Hanson and Jackson 1978; Johnson 1977).

However, because of their modest burnup and long decay time, each assembly now produces only approximately 100 watts of decay heat (7.2 kW total). Also, industry has raised its recommended fuel-storage, pool-water temperature to 32 to 38°C (90 to 100°F) [American Nuclear Society (ANS) 1988]. In 1992, Westinghouse Hanford Company (WHC) decided to conduct an extended, instrumented test to evaluate the results of turning off the PWR Core II fuel-pool chillers, which would save hundreds of thousands of dollars in operation, maintenance, and replacement costs. WHC commissioned Pacific Northwest Laboratory (PNL)^(b) to develop the test requirements and evaluate the results.

Before the test, which was conducted from May 17 through September 1, 1994, WHC cleaned the pool, installed additional water thermocouples, and intensified water-sampling and analysis procedures. During the test, water temperatures in four locations were continuously recorded on a data acquisition system, and the water was sampled and analyzed twice weekly for conductivity, pH, chloride and fluoride content, and radioisotope concentration (e.g., ¹³⁷Cs and ⁶⁰Co activity). High ambient air temperatures within the canyon [up to 30°C (86°F)] during the test were expected to maximize the equilibrium water temperatures.

Maximum equilibrium water temperatures were less than 31°C (88°F), which is below accepted limits for reactor fuel-storage pools with Zircaloy and stainless-steel-clad oxide fuels.^(c) The measured water quality and radioisotope concentration remained within established limits and, in fact, did not significantly change within the 3.5-month test period. There

(a) The Hanford Site is operated for the U.S. Department of Energy by Westinghouse Hanford Company.

(b) PNL is operated for the U.S. Department of Energy by Battelle Memorial Institute.

(c) Hanford T Plant Engineering. 1994. "Pressurized Water Reactor (PWR) Chiller Off Test Final Report." Letter No. 87430-94-LTB-004, Hanford T Plant Engineering to D. C. Hedengren (WHC) August 26, 1994, Westinghouse Hanford Company, Richland, Washington.

was no evidence of algae growth. Thus the water-cooling capability is no longer needed for the PWR fuel-storage pool as long as additional heat loads or unreviewed fuel types are not added to the pool, the water quality is maintained or improved, and the water quality, radioisotope concentration, and temperatures continue to be monitored.

A description of the PWR pool, its auxiliary equipment, and the Shippingport fuel assemblies are presented in Section 2.0. The test procedures and results are described in Section 3.0 and discussed in Section 4.0. Conclusions and recommendations are given in Section 5.0, and the references are listed in Section 6.0. The assumptions and procedures used for pretest water-temperature predictions are presented in the appendix.

2.0 PWR Core II Fuel Pool

The features of the Cell 4 PWR Core II fuel pool, the features of the PWR Core II blanket fuel assemblies, and the conditions of normal fuel operation are described in this section.

2.1 Description of the Pool

The Cell 4 PWR Core II fuel pool is an unlined, concrete water pool with inner dimensions of 4.0 x 8.4 x 8.5 meters (13 ft wide by 27.67 ft long and 28 ft deep). The typical water depth is 5.79 ± 0.06 meters (19 ± 0.2 ft). The concrete sides vary in thickness from 2.1 to 3.3 meters (7 to ~11 ft), as shown in Figure 2.1. The bottom side, which is ~2 meters (6 ft) thick, rests on a sand liner in contact with earth, but the four walls are partially in contact with ambient air, as shown in Figure 2.2.

The water was cooled by two 37-kW (126,000 Btu/hr) heat exchanger systems (one active, one on standby). Simple evaporation from the pool surface constitutes a passive heat-removal mechanism. At the nominal cooled pool temperatures, the evaporation rate is about 0.014 mL/m² per second (0.03 gallon per square foot per day), which corresponds to a heat removal rate of 1.5 kW. This passive evaporation-related heat removal rate increases by a factor of 5 as the pool-water temperature approaches 38°C (100°F). At elevated pool temperatures there is also heat loss through the concrete walls into the environment, which approaches 5 kW as the water temperatures approach 38°C. The convective heat transfer with the air above the pool is negligible.

The heat loads on the pool include the decay heat from the fuel (7.2 kW) and the heat added by the support systems pumps.^(a) The pump for the ion exchange unit now runs continuously and adds approximately 0.3 kW to the heat load. A recirculation pump in the filtration system is run intermittently and, while running, adds about 2 kW.

2.2 Description of the Fuel Assemblies

The fuel assemblies come from the blanket region of Core II of the Shippingport PWR. A complete assembly consists of a bottom extension region, the fuel cluster region, and the top extension region, as shown in Figure 2.3. The overall length is 3.6 meters (142 in.);

(a) D. C. Hedengren. 1994. "Meeting Minutes--PWR Core II Chiller-Off Test (7-25-94)." Memo from D.C. Hedengren to Distribution July 28, 1994, Westinghouse Hanford Company, Richland, Washington.

Figure 2.1. Schematic Drawing of the T Plant PWR Core II Fuel-Storage Pool (plan views)

however, the fueled length is only 2.45 meters (96.5 in.). The assemblies are constructed as two subassemblies welded side by side. Each subassembly contains 30 fuel plates and two side plates. Each Zircaloy-4 clad fuel plate in turn contains a large number of depleted sintered uranium dioxide fuel wafers, as indicated in Figure 2.3. Further dimensions and other details on the plate fuel are given in Table 2.1. Predicted assembly decay heat is shown as a function of time in Figure 2.4. The majority of the heat is generated in the uranium oxide fuel. The fuel wafers within each fuel plate are pneumatically interconnected, such that fuel oxidation from a leak in a plate could propagate. Also while the plate cladding is made of corrosion-resistant Zircaloy-4, the extension pieces are made of stainless steel, which could be somewhat sensitized to degradation by chloride

Figure 2.2. Schematic Drawing of the T Plant PWR Core II Fuel-Storage Pool (relative layout)

contamination, especially in transition weld areas. This means that maintenance of low chloride concentration in the storage-pool water is desirable.

2.3 Normal Pool Operation

In normal operation, the pool height reduces from 5.79 meters (19.0 ft) by 0.09 meters (0.3 ft) every 2 to 3 months due to evaporation.^(a) At that point, sufficient deionized water is injected into the pool to bring the pool depth up to the 5.79-meter (19.0 foot) nominal value. The normal operation of the PWR fuel pool also includes the following activities:

- Maintain water temperature at 6 to 12°C.

(a) As discussed in Section 4.0, the water-loss rates both before and during the test are consistent with expected evaporation rates.

Figure 2.3. Shippingport Core II Blanket Fuel-Assembly Layout

Table 2.1. Characteristics of Shippingport Core II Blanket Assemblies Stored in the T Plant PWR Fuel Pool

Parameter and units	Values
Number of fuel assemblies	72
Average uranium burnup, MWd/MTU	16,000
Decay time (2/4/94), years	20.0
Decay heat, W/assembly (as calculated from ORIGEN2)	
20 years decay	104
30 years decay	89
Assembly length, meters (inches)	3.61 (142.3)
Active length, meters (inches)	2.369 (93.25)
Assembly width (square) mm (inches)	187 (7.376)
Plate width, mm (inches) (this is active/fueled width)	92.8 (3.653)
Plate thickness, mm (inches)	3.56 (0.140)
Cladding wall, mm (inches)	0.508 (0.020)
Water channel, mm (inches)	2.3 (0.091)

- Maintain the following permitted water quality limits (by continuous operation of a 0.63-L/s (10 gpm) ion exchange filtration system):
 - conductivity <29 μ mho/cm (normal range <26)
 - pH in the range 4.5 to 9.6 (normal range is 6 to 8)-chloride concentration <5 ppm (normal <2)
 - fluoride concentration (not specifically limited) (normally <2 ppm)

Figure 2.4. ORIGEN2 Calculations (Morford 1988) of Shippingport Core II Blanket Assembly Decay Heat vs. Cooling Time [heat generation rate in uranium (UO_2), stainless steel, and Zircaloy-4] (time after discharge on February 4, 1974)

- ^{60}Co activity plus ^{137}Cs activity $< 1 \times 10^{-3} \mu\text{Ci/mL}$ (normal is $< 1.5 \times 10^{-4} \mu\text{Ci/mL}$, $> 99\%$ Cobalt activity).

- Verify water quality: bi-weekly samples and analysis.

The water quality standards are compared to those for the General Electric (GE) fuel pool located in Morris, Illinois, in Table 2.2. The latter is the basis for the industry standard for fuel-pool operation [American Nuclear Society (ANS) 1988]. As can be seen, the PWR Core II fuel-pool standards are less stringent than those for GE's Morris pool. Thus, the acceptability of operating at elevated temperatures in the PWR core II fuel pool could not be judged by simple reference to the excellent experience at Morris. The results of the chiller-off test were needed to confirm the calculated equilibrium pool temperatures. These results were also needed to determine the effect of combined higher water temperatures and less stringent water quality limits on the pool and fuel condition.

Table 2.2. Comparison of PWR Core II Fuel Pool-Water Limits and Test Conditions to ANSI/ANS Standards (based on GE's Morris pool limits)

Parameter and Units	Current PWR Core II Fuel Pool Limits	ANS Standard, Based on GE's Morris Pool Conditions
Maximum water temperature, °F	< 100 (in test) 45 to 54 (normal operation)	90 in normal operation, < 110 more than 5% of time during 4 warmest months
pH	4.5 to 9.6	5.8 to 6
Conductivity, $\mu\text{mho/cm}$	< 29	< 1
Impurity levels, ppm	< 5 Cl	< 1, all impurities
$^{134}\text{Cs}/^{137}\text{Cs}$ activity, $\mu\text{Ci/mL}$	*	1×10^{-3}
^{60}Co activity, $\mu\text{Ci/mL}$	*	1×10^{-3}

* The limit for the sum of all radionuclides is $1. \times 10^{-3} \mu\text{Ci/mL}$.

3.0 Chiller-Off Test Procedures and Results

In 1993, before the chiller-off test, the accessible surfaces within the fuel pool were mechanically cleaned. Three Type J thermocouples were installed, in addition to the one (near-surface) thermocouple already in use, for monitoring water temperatures. All four thermocouples were connected to a data-logging device with the following correlation between approximate location and channel number designations:

Channel 3 - previous probe installed (near surface, at side, away from fuel racks)

Channel 4 - near surface (above fuel)

Channel 5 - just above fuel storage racks

Channel 6 - pool bottom (very near bottom surface), near fuel storage racks.

These thermocouple locations are indicated in the sketch in Figure 3.1.

The water sampling locations remained unchanged (a dip sample from the pool near the surface and one near the side and a stream sample from the line coming from the ion exchanger). However, the sampling frequency was increased from twice per month to twice per week. In addition, a water sample was taken from just above the fuel racks and sent to PNL for detailed analyses, including an ICP analysis for trace cations and a survey for all common anions, including tritium. A water sample taken at the end of the test provided data for comparison with results from samples taken earlier before and during the test.

3.1 Temperature Measurements

The chillers were turned off on May 17, 1994, and have remained off. The official time period of the chiller-off test is defined as May 17 to September 1, 1994. As predicted by pretest thermal calculations,^(a) the water temperatures rose slowly over the 3.5-month test period and reached an equilibrium level of less than 31°C (88°F). The thermocouple readings were tabulated every 4 hours during the test.

The maximum measured temperatures came from the Channel 5 thermocouple, located just above the fuel racks. The data from this thermocouple together with the range of the pretest

(a) E. R. Gilbert and D. D. Lanning. 1992. "Interim Report on T Plant Chiller Option Task." Letter from E. R. Gilbert (PNL) to D. C. Hedengren (WHC) December 7, 1992, Pacific Northwest Laboratory, Richland, Washington.

predictions are shown in Figure 3.2. The measured temperatures were near the upper bound of the predicted temperatures. These pretest predictions did not include the heat load from the filtration system pump (0.3 kW) and contained an underestimate of the summertime air temperature on the outside of the concrete pool walls. Corrections for these deficiencies bring even closer agreement between measured and predicted temperatures, as discussed in Section 4.0.

A small temperature increase from the bottom to the top of the fuel racks was expected, because of natural convection-current cooling flow within the fuel assemblies. The expected temperature difference is a function of the velocity (unknown) of the natural circulation. Estimating this velocity leads to temperature differences of approximately 1 to 3°C (2 to 6°F). The measured temperature difference between the top and the bottom of the fuel racks is found by comparing Channel 6 data to that from channel 5, as shown in Figure 3.3. The large oscillations in the Channel 6 (pool bottom) temperatures indicated in Figure 3.3 are correlated with intermittent operation of the recirculation pump. It is suspected that recirculation currents may have caused thermocouple contact with the pool floor, leading to spuriously low readings. The smaller oscillations in these temperatures, with periods of approximately one day, have not been fully explained. The maximum difference recorded was about 6°F, but this was reduced after August 10. This reduction was a consequence of moving the cleanup system pump from the mid pool position to the bottom of the pool, which occurred on August 10, plus its almost constant operation thereafter; the pump action disturbed the weak natural circulation current.

The pool near-surface temperatures (from the thermocouples connected to Channels 3 and 4) are plotted vs. time in Figure 3.4. These surface temperatures rose with time during the test but showed less variability (less sensitivity to pump operations) than the temperatures measured deeper in the pool. The fuel temperature variations are presented in Section 4.0.

The concentrations of anions, cations, and tritium found in detailed pre-test and post-test water analyses are compared in Table 3.1. Within detection and analysis limitations, no change in these concentrations or in water conductivity were found as a result of the chiller-off operation. Note that sodium (at a very low concentration) was the only cation found in the pre-test sample, although approximately 50 common elements were scanned by ICP, with detection limits at 0.01 to 0.05 ppm typically. Cations were not analyzed in the post-test sample.

3.2 Water-Quality Parameters and Radioactivity

Even though the temperatures rose significantly during the testing period, there was little change in the water-quality parameters. This is demonstrated by the following plots of measured parameter values vs. time after start of test: conductivity (Figure 3.5), pH (Figure 3.6), and chloride concentration (Figure 3.7). These parameters did not vary systematically or significantly during the test period.

Figure 3.1. Location of Thermocouples in the PWR Core II Fuel-Storage Pool

Figure 3.2. Channel 5 (Top-of-Fuel Rack) Temperatures vs. Time, Compared to Pre-Test Predicted Values for Pool-Water Temperature (Prediction Range Indicated by the Curves Labelled "Max. Temp." and "Min. Temp.")

Figure 3.3. Channel 5 and Channel 6 Temperatures vs. Time (top of rack compared to bottom of rack)

The concentrations of the two reported radioactive isotopes (^{137}Cs and ^{60}Co) are plotted vs. time in Figures 3.8 and 3.9, respectively. There is no systematic or significant variation to the ^{137}Cs activity. The rise in ^{60}Co activity near the end of the test may have resulted from the movement of the filtration system pump to the bottom of the pool on August 10 and a consequent change in the water flow pattern. The cleaning performed before the chiller-off test raised the ^{60}Co activity by an order of magnitude relative to pre-cleaning values (see Figure 3.10). This was presumed to be due to disturbance of activity-bearing deposits built up over years of fuel storage. The surface of the fuel plates is expected to contain some activity-bearing, ionic "crud" deposits that over extended time could, in limited terms, migrate by physical and chemical processes to other surfaces within the pool. The total activity in the water, however, still remains well below the limit of $1 \times 10^{-3} \mu\text{Ci/mL}$.

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Figure 3.4. Pool Surface Temperatures vs. Time (Channels 3 and 4)

No direct analytical assessment of bacteria or algae growth was made on the water samples taken during the test. However, due to lack of nutrient and limited lighting, no such growth was expected. As judged by visual references within the pool, water turbidity did not increase and surface slime did not develop within the testing period.

The behavior of the water quality parameters and radioactivity is presented in Section 4.0.

Table 3.1. Comparison of Pre- and Post-Test Detailed Water Analyses

Element	Pre-Test Concentration, ppm ^(a)	Post-Test Concentration, ppm ^(b)
Cl	1.6	1.6
F	< 0.25	< 1.6
PO ₄	< 0.5	< 1.5
NO ₃	< 0.5	< 1.8
SO ₄	< 0.5	< 1.8
NO ₂	< 0.5	NA
Br	< 0.25	NA
Na	5	NA
³ H	20 to 70 picoCi/mL	< 5.2 picoCi/mL

(a) Performed at the PNL Analytical Chemistry Laboratories, 300 Area.

(b) Performed at the WHC 222-S Laboratory, 200-W Area.

3.3 Water-Level Measurements

Water level (depth) in Channel 1 of the recorder was recorded continuously during the test. These data are shown vs. time in Figure 3.11. The sharp rises in water levels around July 26 and August 26 are due to deliberate water additions to maintain the pool at the nominal 5.8-m (19-ft) depth. The water-level decrease is due to evaporation. The rate of depth decrease increased in response to the water temperature rise during the test, as predicted. The magnitude of that rate increase, and its current equilibrium value, is consistent with the equations used for evaporation rate, as discussed in Section 4.0.

34080605.SPW 08/13/94

Figure 3.5. Water Conductivity vs. Time

SH020015PV 08/13/94

Figure 3.6. Water pH vs. Time

9408003.5PV 08/13/94

Figure 3.7. Water Chloride Concentration vs. Time

94050025PV 08-1994

Figure 3.8. Activity of ^{137}Cs in Water vs. Time During the Test

9408001.SPV 08/13/94

Figure 3.9. Activity of ^{60}Co in Water vs. Time During the Test

94091402 SPW 09/14/94

Figure 3.10. Activity of ^{60}Co in Pool Water vs. Time, from September 1991 to September 1994; Showing the Effect of Pool Cleaning in 1993

94080202 SPW 05/12/94

Figure 3.11. Water Level vs. Time During the Test

4.0 Discussion of Results

The behavior of the pool-water temperatures during the test and the general behavior of the water quality parameters are discussed in this section. The derivations of the thermal models used in pretest temperature predictions are located in the appendix.

4.1 Water-Temperature Behavior

When the pool water was chilled, the heat exchangers may have actually been removing ground heat as well as fuel decay heat, since typical ground (earth) temperatures at the depth of the pool bottom are around 10°C (50°F). With the chillers turned off, the two passive heat removal pathways are conduction through the sides and bottom of the pool and evaporation of water from the top. In this mode, the pool resembles a solar-heated natural pond; semi-empirical equations for the evaporative heat loss for such ponds were used to estimate that term (see the Appendix). The conduction heat losses from the sides were calculated using nominal values for concrete thermal conductivity and estimates for ambient air and ground temperatures (see also the Appendix). The initial equations used to estimate the equilibrium temperatures that the pool would reach are summarized as follows:

$$\begin{aligned} \text{Conduction heat loss (kW)} &= 0.110 \cdot (T-55) \text{ for pool temperature (T) } > 55^\circ\text{F} \\ &= 0.0 \text{ if } T < 55 \end{aligned} \quad (4.1)$$

when T is pool temperature in °F.

$$\text{Evaporation heat loss (kW)} = [A/(TK)^{0.5}] \cdot \exp[-13.11 \cdot (373-TK)/TK] \quad (4.2)$$

where TK = pool temperature in Kelvin

A = constant, determined from measured evaporation rates as determined from historical pool refill data.

The constant "A" was given upper and lower bounding values based on the amount of time the PWR fuel-pool operators allowed for pool refills under normal operation. They reported that the pool level fell 0.3 ft every "2 to 3 months." The dimensions for the pool and the latent heat of evaporation for water result in upper/lower values of "A" of 1745/1163 kW-K^{0.5}.

Figure 4.1. Estimated Pool Heat Losses, Heat Loads, and Range for Equilibrium (chiller-off) Water Temperatures

The estimated range of stabilized temperatures was determined graphically and numerically by matching total heat losses to the assumed 7.2-kW heat load, as shown in Figure 4.1. These heat-loss functions were also used in a numerical solution to the lumped-parameter differential equation for pool-water temperatures to generate the predicted temperatures vs. time. The lumped-parameter equation is simply

$$dcV dTK/dt = \text{heat load} - \text{heat loss rate} \quad (4.3)$$

where d = water density (1.0 g/cm^3)

c = water specific heat ($4.186 \text{ Joules/gram/K}$)

V = water volume ($190 \text{ m}^3 = 1.9 \times 10^8 \text{ cm}^3$)

TK = pool-water temperature in K

t = time in seconds

heat load = $7.2 \text{ kW} = 7200 \text{ watts}$

heat-loss rate = sum of equations (1) and (2), converted to watts.

The original solution used a heat load of 7.2 kW (corresponding to the estimated decay heat generation of the fuel assemblies). A revised solution using 7.5 kW ($7.2 + 0.3 \text{ kW}$ mechanical pump heat addition), together with the Channel 5 (top-of-fuel rack) water temperature data is shown in Figure 4.2. This revised calculation, which includes summertime ambient air temperatures up to 21°C (70°F), is more consistent with the measured data. Equation (4.1) can also be used to estimate the evaporation rate and, hence, the reduction in pool heating rate. This can then be compared to the measured rate, which is indicated in Figure 3.11. The calculated equilibrium value for this rate is 5.5 mm/day , which compares well with the 5.75 mm/day rate derived from the data of Figure 3.11. Because both the equilibrium temperatures and the equilibrium evaporation rate are predicted well by Equations (4.1) through (4.3), it is probable that the estimated partition of heat loss between evaporation rate and conduction is approximately correct, at least at the equilibrium condition. Because of this agreement, the test results provide an approximate consistency check of radionuclide decay heating rate calculations with the ORIGEN2 Code (Morford 1988).

4.2 Behavior of Water-Quality Parameters

The most significant change in water-quality parameters related to the test actually occurred before the test. That was the order-of-magnitude rise and persisting higher values for the ^{60}Co activity, corresponding with the mechanical cleaning of pool surfaces. This occurrence was probably due to the re-dissolution (rather than simple resuspension) of cobalt-bearing ionic complexes from the fuel element surfaces and from other pool surfaces, caused by other re-dissolution/resuspension occurrences related to the cleaning activities. The pH of the pool shifted slightly upward during the cleaning period (see Figure 4.3); this shift may have been sufficient to alter the bonding balance (the Zeta potential) of the activity-bearing species on its respective surfaces. Such occurrences have been documented in PWR coolant systems that experience pH shifts.

During the test, all the measured water-quality parameters remained unchanged. The slight upward shift in the ^{60}Co activity following the movement of the filtration system pump to the pool bottom on August 12, 1994, is considered to be possibly related, which may have changed circulation pattern and resuspended activity-bearing contamination on the pool bottom.

Spent-fuel operating experience with GE's Morris pool has shown negligible algae growth under the pool-water limits shown in Table 2.2. Because this experience did not provide direct guidance for algae growth under the pool-water impurity and conductivity level limits shown in Table 2.2 for the PWR Core II pool test, the result of negligible algae growth during this test has provided information needed to support continued operation of the Cell 4 pool at or below these limits without active cooling.

Key factors that are important to prevent algae growth in the PWR Core II pool are to limit algae nutrients by continued maintenance of pool-water impurity and conductivity levels below the limits shown in Table 2.2 and to limit the photon energy below that required to support photosynthesis by continued maintenance of low levels of integrated illumination in the pool.

Experience has shown that adding chemicals in response to algae problems can cause other problems with storage facilities. Chemicals should not be added in response to an indication algae formation without a thorough review of the benefits and potential for new problems. Similarly unreviewed fuel types should not be stored in the PWR Core II fuel pool without further evaluation.

Figure 4.2. Revised Predicted Range for Pool Water Temperatures (with heat load increased to 7.5 kW), Compared to Channel 5 Temperatures

Figure 4.3. The Pool-Water pH vs. Time, from September 1991 to September, 1994

5.0 Conclusions and Recommendations

The key conclusion is that the test confirmed predictions that water temperature will be maintained at a level acceptable for pool storage of commercial spent nuclear fuel without the operation of the chillers. A test of the feasibility of maintaining acceptable storage temperatures with the 72 Shippingport Core II spent blanket fuel assemblies in the PWR Core II fuel storage pool, without active cooling, was performed for approximately 100 days and culminated during an unseasonable hot period in August 1994. To support test feasibility, the peak equilibrium temperatures were estimated by calculating transfer rates from the fuel and equipment heat sources to water evaporation and surrounding pool structure before the test was initiated. The water temperatures measured during the test were within the limits accepted by industry standards and were in good agreement with water temperatures estimated before test initiation. Because of this agreement, the test results also provide an approximate consistency check of radionuclide decay heating rate calculations with the ORIGEN2 Code (Morford 1988).

Relevant experience in commercial spent fuel storage installations at the water conductivity and impurity levels for the PWR Core II fuel pool was not determined for the temperatures expected without active cooling. Experience in commercial spent fuel storage installations indicated that the radionuclides and impurities in the pool water should not increase as a result of pool operation without active cooling. The test results were in agreement with this experience. There were no significant changes in either the pool radionuclides or impurity levels.

Negligible algae growth was observed during the test. These observations support continued operation of the Cell 4 pool at or below the current limits of water conductivity and impurity levels without active cooling.

Key factors that are important to prevent algae growth in the PWR Core II fuel pool are to limit algae nutrients by continued maintenance of pool-water impurity and conductivity levels below the limits shown in Table 2.2 and to limit the photon energy below that required to support photosynthesis by continued maintenance of low levels of integrated illumination in the pool.

The following operating procedures are recommended for pool operations without active cooling:

- Monitor water temperatures to verify storage at less than 38°C (100°F). Statistical scatter and possible bias in thermocouple readings should be accounted for in setting operating limits.

- Sample water quality twice per month to verify that water quality is within limits. In addition, monitor the content of phosphate and nitrate in the pool water; each should be less than 2 ppm.^(a) Water quality superior to current limits would be desirable. Consider improving the current cleanup and water turnover rate relative to the industry standard.
- Monitor the water turbidity and algae growth twice monthly by periodic inspection of a visual reference point in the pool and occasional swiping of pool surfaces.
- Do not add chemicals in response to an indication of algae formation without a thorough review of the benefits and potential for new problems. Do not store additional fuel in the pool without further evaluation.

The water cooling capability is no longer needed for the PWR Core II fuel-storage pool as long as no additional heat loads or additional fuel are added to the pool, the water quality is maintained or improved, and the water quality, radioisotope concentration, and temperatures continue to be monitored. A change to continuous operation of the recirculating pump would be a significant added heat load.

(a) The basis for this recommendation is that phosphates and nitrates provide nutrients for algae. General Electric Company's experience at Morris shows that maintenance of low nutrient levels, such as those recommended here, inhibit algae growth even in lighted and heated pool conditions.

6.0 References

American Nuclear Society. 1988. *Design Criteria for an Independent Spent Fuel Storage Installation (Water Pool Type)*. ANSI/ANS-57.7, American Nuclear Society, LaGrange Park, Illinois.

Hanson, G. L., and R. R. Jackson. 1978. *Safety Assessment Document - PWR Core 2 Project*. RHO-CD-356, Rockwell Hanford Company, Richland, Washington.

Johnson, A. B., Jr. 1977. *Behavior of Spent Nuclear Fuel in Water Pool Storage*. BNWL-2256, Pacific Northwest Laboratory, Richland, Washington.

Morford, R. J., L. L. Carter, R. A. Schwarz, W. P. Stinson, and W. L. Bunch. 1988. *Radiation Source in the Shippingport Pressure Vessel Package*. WHC-SP-0408, Westinghouse Hanford Company, Richland, Washington.

Appendix

Pool-Heating Calculation Worksheets

Prepared By:

R. Williams RWH Date: 8/12/92

Project:

ED 3240

Title/Subject:

POND EVAPORATION RATES

~50 000 gal pool

~7 kW heat generation within pool

Water temperature range = 45-70 °F

Air flow = 70 000 cfm / bldg,

5 cells / bldg = 14 000 cfm / cell -

Assume: cell = pool

air volume over pool = $27.5^2 \times 13$ ft³

Then: Air exchange time = Vol / Cflow

$$= \frac{27.5^2 \times 13}{14000} = .7 \text{ min} = 42 \text{ sec.}$$

Rough Estimates

1. 7.102 25. Shaw Intro to Colloid and Surface Chemistry
Butterworths Publ 1985

"Annual loss of water from hot country lakes and reservoirs due to evaporation is usually about 3 m per year" - Now convert this to gal/day

for the above pool: 1 gal = 3785.4 cm³

Pool area = 332,128.37 cm²

1 gal over pool surface has depth of $\frac{3785.4}{332128} = .0114 \text{ cm}$

$$\text{So, } 3 \text{ m/yr} \rightarrow \frac{30 \text{ cm/yr}}{.0114 \text{ cm/gal}} = 2632 \text{ gal/yr} = 7.21 \text{ gal/day}$$

or: Approx 14.4 gal/day Summer
0 gal/day winter

ENGINEERING WORKSHEET

Prepared By: RECURRO RWN Date: 11/10/92 Project: E03240
Title/Subject:

Observed loss rate from refill data ≈ 13 gal/day -

So the pool is comparable to a pond in summer.

2. Pg 62 AW Adams, Physical Chemistry of Surfaces, Wiley Publ. 1990

From gas kinetic theory, number of moles striking 1cm^2 of

surface per second is $Z = P / \sqrt{2\pi MRT}$ For vapor

saturated with respect to liquid water at room temperature

$Z \approx 0.02 \text{ mol/cm}^2\text{sec} \approx 1.2 \times 10^{22} \text{ molecules/cm}^2\text{sec}$ At

equilibrium, evaporation rate = condensation rate, differing

by a factor α (evaporation coefficient), which varies

by 3 orders of magnitude (10^{-3} to 1.0) (see pg 152 Adams).

Assuming saturated air above pool, then at 70°F , evaporation

rate is $\approx \frac{0.02 \text{ mol}}{\text{cm}^2\text{sec}} \frac{1\text{cm}^3}{\text{mol}} \frac{1 \text{ gal}}{3785\text{cm}^3} \frac{332.1 \times 10^3 \text{ cm}^3}{\text{hr}} \frac{3600 \text{ sec}}{\text{hr}} \frac{24 \text{ hr}}{\text{day}}$

$= 151,629 \text{ gal/day}$

This large value requires an evaporation coefficient $\alpha = 10^{-4}$

to be reasonable. It is apparent that gas kinetic

theory applied to this problem can be subject to

some serious uncertainties. It is therefore advisable

to work with relative rates to study the temperature

dependence of pool evaporation.

ENGINEERING WORKSHEET

Prepared By:

RE Williams RSW

Date:

11/10/92

Project:

203240

Title/Subject:

Relative Rates of Evaporation

From I.N. Levine, Physical Chemistry, McGraw-Hill 1988,
page 154, the rate of escape (gas effusion rate)

$$\text{is } \frac{dN}{dt} = - \frac{P N_A A_{\text{hole}}}{\sqrt{2\pi MRT}} \quad \text{where}$$

A_{hole} = area of "hole" in surface film through which
molecules pass

N_A = Avogadro's number

P = vapor pressure above liquid (equilibrium)

Now from page 200-202 of Levine, the vapor pressure

is given by the Clausius Clapeyron Eqn

$$\frac{d \ln P}{dT} = \frac{\Delta \bar{H}}{RT^2} \quad \text{assuming } \Delta \bar{H} \text{ does not change much with temperature.}$$

this last assumption means that we don't want to get too
far from the boiling temperature $T_b = 373^\circ K = 100^\circ C$.

With $\Delta \bar{H}_{\text{vap}} = 40.66 \text{ kJ/mol}$ for water (page 200),

we have $\frac{P}{P^*} = \exp \left[- \frac{\Delta \bar{H}}{R} \frac{T_b - T}{T_b T} \right]$ and $P^* = 1 \text{ atm}$.

$$\text{so } P = \exp \left[- 4890 \frac{373 - T}{373 \cdot T} \right] \quad T = ^\circ K$$

$$\text{Now: } \left. \frac{dN}{dt} \right|_T = E_T = \text{constant} \cdot \frac{\exp \left[- 4890 \left(\frac{373 - T}{373 \cdot T} \right) \right]}{\sqrt{T}}$$

ENGINEERING WORKSHEET

Prepared By: R. WILLIAMS RSN Date: 11/10/92 Project: E03240
Title/Subject:

The evaporation rate ratio for 45°F and 70°F is

$$\frac{E_{70}}{E_{45}} = \frac{\exp\left[-\frac{4890}{373.294} \left(\frac{373 - 294}{373.294}\right)\right]}{\exp\left[-\frac{4890}{373.250} \left(\frac{373 - 280}{373.250}\right)\right]} \times \sqrt{\frac{280}{294}}$$

$$= \frac{\exp[-3.5227]}{\exp[-4.3544]} \cdot \sqrt{.9524} = 2.2971 \cdot .9759 = 2.24$$

For 45°F and 100°F, we have

$$\frac{E_{100}}{E_{45}} = \frac{.0733}{.0129} \cdot .9489 = 5.41$$

Refinement

Since we are significantly departed from the boiling temperature, we apply Trouton's rule, which is especially important for polar liquids such as water

$$\Delta S_{\text{vap}, n.b.p} \approx 4.5 R + R \ln(T_{b.p})$$

where $n.b.p$ = normal boiling point = 373°K, so

$$\Delta S_{\text{vap}, n.b.p} = 4.5(8.314) + 8.314 \ln(373)$$

$$= 86.64 \text{ J/mol}^\circ\text{K}$$

Now for the Clausius-Clapeyron equation

$$\frac{dP}{dT} = \frac{\Delta S}{\Delta V} \approx \frac{\Delta S}{V^{\text{gas}}}, \text{ and } V^{\text{gas}} = \frac{RT}{P}$$

ENGINEERING WORKSHEET

Prepared By: RE WILLIAMS Date: 10/10/92 Project: E03240
Title/Subject:

$$\frac{dP}{dT} = \frac{\Delta S}{RT} P \quad \text{so} \quad \frac{dP}{P} = \frac{\Delta S}{R} \frac{dT}{T}$$

$$\ln \left(\frac{P}{P_0} \right) = \frac{\Delta S}{R} \ln \left(\frac{T}{T_{0p}} \right) \quad T_{0p} = 373^\circ K, P_0 = 1 \text{ atm}$$

$$P = \left(\frac{T}{T_{0p}} \right)^{10.42}$$

$$\frac{E_{70}}{E_{45}} = \left(\frac{294}{280} \right)^{10.42} \sqrt{\frac{280}{294}} = 1.61$$

$$\frac{E_{100}}{E_{45}} = \left(\frac{311}{280} \right)^{10.42} (.95) = 2.82$$

These numbers are substantially below previous estimates, so do a final check against data. Page 202 of Levine contains a plot that gives $\frac{\Delta H_v}{R} \approx 5122$, as opposed to the 4820 used before. With this value, we get

$$\frac{E_{70}}{E_{45}} = \frac{.0249}{.0104} (.97) = 2.32$$

$$\frac{E_{100}}{E_{45}} = \frac{.0617}{.0104} (.95) = 5.91$$

In summary, it appears that the Trouton correction is erroneous, and evaporation rates will vary by up to a factor of about six as the pool water temperature rises to $100^\circ F$. Note that this analysis ignores the non-equilibrium effect of air circulation above the pool, and the air temperature/humidity factors. These factors

ENGINEERING WORKSHEET

Prepared By: RE WILSON Date: 11/10/92 Project: 23240
Title/Subject: _____

may increase the above evaporation rate ratios via
non-equilibrium effects.

Pacific Northwest Laboratories

ENGINEERING WORKSHEET

Page 1 of 1

Prepared By:

DD Lanning

Date:

12/3/92

Project:

T-Plant Chiller Test

Title/Subject:

Quantifying Evaporation Rate and Heat Loss Rate (Range) vs. Pool Water Temperature.

Data / Assumptions

1. "Every two to three months" according to T-plant cell pool operators, the water level drops 0.3 feet ~~and~~ due to evaporation, and makeup water is then injected to restore pool depth to ~19 feet.
2. The pool surface area is 27.5 feet x 13 feet; Temp = 45°F
3. Assume energy for conversion of water to water vapor at ~50 to 100°F is 540 cal/gram, density = 1.0 g/cm³

I - Quantification of Evaporation Rate

$$\text{Evap. Rate} = \frac{0.3' \times 13' \times 27.5'}{60 \text{ to } 90 \text{ days}} = 1.2 \text{ to } 1.8 \text{ cu. ft. / day}$$

$$* 2.48 \text{ gal / cu. ft.} = 9.0 \text{ to } 13.5 \text{ gal / day}$$

II - Heat Loss vs. Pool Water Temperature

$$\begin{aligned} & 9.0 \text{ to } 13.5 \text{ gal / day} * \frac{3785 \text{ cm}^3}{\text{gal}} * 1.0 \text{ g / cm}^3 * \frac{540 \text{ cal}}{\text{gram}} * \frac{4.186 \text{ J}}{\text{cal}} \\ & * [24 * 3600] \frac{\text{sec}}{\text{day}} * \frac{1}{1000} \frac{\text{KW}}{\text{W}} \\ & = 1.34 \text{ to } 0.89 \text{ KW at } 45^\circ\text{F} = 280 \text{ K} = T_K \end{aligned}$$

$$1.34 \text{ to } 0.89 = \frac{A}{\sqrt{T_K}} * \exp\left[\frac{-4890 (373 - T_K)}{373 * T_K}\right] \quad (\text{From Attach. \#1})$$

$$= 0.00768 * A$$

$$A = 1163 \text{ to } 1745 \text{ for heat loss in KW}$$

Prepared By: DD Lanning Date: 12/3/92 Project: T-Plant Chiller Test (Cell 4 Pool)
 Title/Subject: Est. Heat Loss by Conduction through Sides and Bottom of Pool

Data / Assumptions

1. Concrete thermal conductivity = $0.1 \text{ Btu/hr/ft}^2/\text{inch}/^\circ\text{F} = 0.0208 \text{ W/cm}^\circ\text{C}$
2. White cement cond. = same as above
3. Concrete Thickness on long side = 7 feet; short side = 11 feet
 Bottom = 3 feet (est.)
4. Ambient ground temp = Avg. air temp (now) = 55°F
5. Surface heat flux = $-K[\Delta T/\Delta X]$ ΔX = thickness, K = therm. cond.

I: Surface Areas

$$(2) \text{ Sides Long} = 27.5 \times 19' \times 144 \times 2.54^2 \times 2 = 9.7 \times 10^6 \text{ cm}^2$$

$$(2) \text{ Short} = 13 \times 19' \times 144 \times 2.54^2 \times 2 = 4.6 \times 10^5 \text{ cm}^2$$

$$\text{Bottom} = 13 \times 27.5 \times 144 \times 2.54^2 = 3.3 \times 10^5 \text{ cm}^2$$

II Heat Flow per 1°F Above Ambient

$$\text{Heat flow} = \frac{0.0208}{\Delta X (\text{cm})} \times \text{Area} (\text{cm}^2) \times \frac{1}{1.8} (^\circ\text{C}/^\circ\text{F})$$

$$= \frac{0.0208}{1.8} \left[\frac{9.7 \times 10^6}{7 \times 12 \times 2.54} + \frac{4.6 \times 10^5}{11 \times 12 \times 2.54} + \frac{3.3 \times 10^5}{3 \times 12 \times 2.54} \right]$$

$$= \frac{0.0208}{1.8} [0.45 \times 10^4 + 0.14 \times 10^4 + 0.36 \times 10^4]$$

$$= \frac{1440 \text{ W}}{1.8}$$

$$= 110 \frac{\text{W}}{^\circ\text{F}} = 0.110 \text{ kW}/^\circ\text{F}$$

$$\text{So Heat loss (kW)} = 0.110 \times (T_{\text{pool}} - 55), T_{\text{pool}} \text{ in } ^\circ\text{F}$$

Prepared By: DD Lanning Date: 11/30/77 Project: T-Plant Cell #4
 Title/Subject: Connection Between Morris Operation Evaporation/Makeup
Data and RE Willford's Evap. Rate Estimated and T-Plant Evap. Data

Data/Assumptions:

1. T-plant evap. rate at $\approx 45^\circ\text{F}$ water temp and varying air temp is 0.3 feet per 2^{1/2} months; Pool area is $13 \times 27.5'$
2. Morris evap. rate is 100,000 gal per year at est avg. water temp. of 90°F and avg. air temp of $\approx 68^\circ\text{F}$. Area = 2800 sq. ft.
3. Willford's est. of evap. rate vs. temp (of water) is

$$E_T = \frac{A}{\sqrt{T_K}} \times \exp \left[\frac{-4890}{373 \cdot T_K} \right], \quad T_K = \text{temp in } ^\circ\text{K}$$

$A = \text{constant}$

T-Plant Evap. Rate

$$0.3 \text{ ft} \times 27.5' \times 13' = 10725 \text{ Cu. Ft.} = 822 \text{ gallons}$$

$$\div 60 \text{ to } 90 \text{ days} = 13.4 \text{ to } 8.9 \text{ gal/day, } \div (27.5 \times 13) = 0.037 \text{ to } 0.025 \text{ gal/sq. ft./day}$$

Solving for "A", $T_K = 280$

$$0.037 \text{ to } 0.025 = 0.000768 \times A; \quad A = 48 \text{ to } 32 \text{ gal/sq. ft./day}$$

Morris Evap. Rate

$$\text{Rate at } 90^\circ\text{F} = \frac{100,000 \text{ gal/year}}{2800 \text{ sq. ft.} \times 365 \text{ day/year}} = 0.098 \text{ gal/sq. ft./day}$$

Solving for "A" $T_K = 305$

$$0.098 = A \times 0.00308; \quad A = 32 \text{ gal/sq. ft./day}$$

Conclusion: The Morris and T-plant data are mutually consistent with Willford's function, within uncertainty.

Table 25. High-density Concretes for Shielding

Concrete type	Weight, lb/ft ³	Material cost, dollars/ft ³	Compressive strength, psi	Cement, lb/ft ³	Heavy aggregate, lbs. lb/ft ³ coarse, lb/ft ³ fine	Admixture	Mix water, lb/ft ³	Water content, lb/ft ³		Gross type	Place-ment
								Min	Max		
A	410	25.40	3,000 (3)	16.8	410 shot 63; punchings 324	I.A.	5.9	2.5	5.9	S-270	Puddled
B	346	18.40	3,000 (3)	20.6	Magnetite 44; punchings 270	I.A.	11.3	3.5	11.8	M-170	Prepacked
C	300	15.40	4,700 (3)	20.6	Ferrophosphorus 107; 161	I.A.	12.7	3.5	15.0	Conv.	Conv.
D	300	12.95	3,870 (4)	24.1	Ferrophosphorus 92; 171	I.A.	10.9	3.6	12.7	M-170	Pre.
E	300	11.90	3,000 (3)	19.8	Magnetite 42; magnetite + punchings 67 + 140	I.A.	12.7	4.1	12.0	M-170	Pre.
F	263	11.20	9,000 (3)	22.2	Magnetite/ 26; limonite + punchings 80 + 140	Plast.	13.5	13.0	21.9	L-146	Conv.
G	262	11.50	9,000 (3)	24.0	Limonite 65; shot No. 330 + 1320; 49 + 100	I.A.	12.8	12.5	20.9	Mortar	Conv.
H	262	7.75	3,530 (4)	23.7	Limonite 65; shot No. 330 + 1320; 49 + 100	I.A.	10.9	4.7	12.6	M-170	Pre.
I	262	7.75	3,530 (4)	19.4	Ferrophosphorus + barite 70 + 35; 70 + 30	I.A.	9.7	4.8	11.9	M-170	Pre.
J	244	2.55	4,800 (3)	17.5	Magnetite 42; magnetite + punchings 122 + 67	I.A.	11.5	5.7	13.5	Conv.	Conv.
K	232	2.30	4,800 (3)	24.3	Magnetite 64; 110	I.A.	10.5	2.9	10.5	B-155	Conv.
L	232	3.05	4,800 (3)	19.3	Magnetite 29; 168	Plast.	12.0	9.2	17.5	Conv.	Conv.
M	222	2.10	4,800 (3)	24.9	Barite 86; 105	Plast.	12.5	10.9	20.0	L-146	Conv.
N	215	2.73	3,800 (3)	31.3	Hydrous iron ore 82; 100	Plast.	15.4	17.1	27.3	Conv.	Conv.
O	154	0.59	3,800 (1)	31.3	Limonite 29; limonite + magnetite 28 + 122	Plast.	11.5	4.7	11.5	Conv.	Conv.
P	154	0.59	3,800 (1)	31.3	Limonite 62; 76	Plast.	11.5	4.7	11.5	Conv.	Conv.
Q	154	0.59	3,800 (1)	31.3	Local sand 30; 61	Plast.	11.5	4.7	11.5	Conv.	Conv.

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* Tested after number of months indicated in parentheses.

* When only one material is given, it is used for both fine and coarse aggregate.

* Inclusion Aid, 1.5 per cent by weight of the portland cement, is added where shown. I.A. (Inclusion Aid) is a special grout admixture designed and used by Plast-Concrete Co., Cleveland, Ohio. Plast. (Plastiment) is a concrete densifier manufactured by Sila Chemical Corp., Passaic, N.J.

* Minimum water content in water retained by the hardened cement paste of mix water added is water of crystallization held by aggregate. The difference between minimum water content

and maximum water content and amount of mix water added is water of crystallization held by aggregate.

* This concrete is made using magnesium-oxychloride cement, made of 12.1 lb/ft³ of MgO powder and 19.8 lb of MgCl₂ solution.* This concrete is made using magnesium-oxychloride cement, made of 12.1 lb/ft³ of MgO powder and 19.8 lb of MgCl₂ solution.* This concrete is made using magnesium-oxychloride cement, made of 12.1 lb/ft³ of MgO powder and 19.8 lb of MgCl₂ solution.* This concrete is made using magnesium-oxychloride cement, made of 12.1 lb/ft³ of MgO powder and 19.8 lb of MgCl₂ solution.* This concrete is made using magnesium-oxychloride cement, made of 12.1 lb/ft³ of MgO powder and 19.8 lb of MgCl₂ solution.* This concrete is made using magnesium-oxychloride cement, made of 12.1 lb/ft³ of MgO powder and 19.8 lb of MgCl₂ solution.* This concrete is made using magnesium-oxychloride cement, made of 12.1 lb/ft³ of MgO powder and 19.8 lb of MgCl₂ solution.* This concrete is made using magnesium-oxychloride cement, made of 12.1 lb/ft³ of MgO powder and 19.8 lb of MgCl₂ solution.* This 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SEC. 7-3] NUCLEAR RADIATION SHIELDING

Table 26. Physical Properties of Concretes

Concrete	Lb/ft ³	Bags/yd ³	Compressive strength, psi	Rupture modulus, psi	Elast. modulus (X 10 ⁻⁹)	Ult. bond strength, psi	Shrinkage, %	Expansion, in./in. (°F)	Specific heat, Btu/(lb)(°F)	Conductivity, Btu/(hr)(ft ²)(°F)	Diffusivity, ft ² /hr
Conv. (15)	153	~5.0	4,960	630	4.6	.....	0.041	5.5	0.23	1.50	0.042
Q (16)	154	9.0	8,870	1,005	5.9	900	0.012	.....	.....	.....	.....
P (16)	165	9.0	5,865	700	4.4	970	0.021	.....	.....	.....	.....
O (17)	210	6.55	4,640	516	5.0	1,396	0.023	5.6	0.20	1.20	0.030
M (15)	226	5.1	6,130	445	4.3	.....	0.029	10	0.157	0.004	0.025
L (15)	230	5.0	3,340	630	3.7	.....	0.029	10	0.146	0.067	0.026
K' (17)	224	7.0	5,780	464	4.3	1,423	0.018	5.7	0.21	1.68	0.034
F (17)	273	6.55	3,180	406	5.4	1,266	0.013	5.9	0.18	2.75	0.056

* Concrete composition is similar to that given in table of concretes, except for K', which has 46-lb limonite and 0.6-lb steel water per cubic foot. Conv. is Grand Coulee concrete. Placement method is given in Table 25. The limonite used was from Michigan; the barite was from Nevada; specific gravity of magnetite was 4.4.

† Strength values are for moist cured specimens, 28 days old.

source: H. S. Davis, *Nucleonics*, Ref. 33.

Table 27. Concrete Shield Costs

Concrete	Type	Cost, dollars/yd ³		Total cost/lb, cents
		Forma	Concrete	
Ordinary structural	.....	45	25	1.7
Ordinary	Q	60	40	2.4
High density	K or N	100	120	3.7
High density	O	300	250	9.5
High density	F	600	300	15.5

source: H. S. Davis, *Nucleonics*, Ref. 33.

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A.10

6/16/93

To Dave Hedengren

From: DD *DDY* Lanning

Subject: Estimated Temperature vs. Time for T-Plant Pool Heatup

Reference: Letter, ER Gilbert/DDL to Hedengren, 12/7/92: "Interim Report on T-Plant Chiller Option Task"

In the reference, equations were given for evaporation and conduction heat loss from the T-Plant PWR fuel pool, as functions pool temperature. These equations were used to graphically solve for the estimated "stabilized" temperature range. Within this range (82 to 88 °F) heat losses from the uncooled pool are projected to balance the assumed residual heat production by the Shippingport fuel elements.

These same heat loss expressions could be used in the lumped parameter differential equation for pool temperature vs. time, i.e.:

$$dCV \, dT/dt = \text{heat production} - \text{heat loss},$$

where: d = water density
C = water specific heat
V = water volume
T = water temperature
t = time

This equation could then be solved (i.e., integrated) analytically or numerically, to obtain the pool temperature as function of time. The analytical solution is too complex for me to solve (since the evaporation heat loss is a complex function of temperature). However, I have obtained a sensible numerical solution, which is plotted and tabulated on the attached sheets. Note that the solution asymptotically approaches the limits of the stabilized range found earlier in the reference.

This solution is being transmitted to you simply for information, and to confirm our previous estimates that up to two months might be required to achieve stabilized pool temperatures, following the shutdown of the pool water cooling system. You may wish to pass this along to T-Plant personnel. Anyway, it's a freebie.

Estimated Heatup of T-Plant PWR Fuel Pool

Estimated Heatup Rate of T-Plant PWR Fuel Pool

Estimate of Temp Rise vs. Time in T-Plant
PWR Fuel Storage Pool

Time, Days	Min. Temp. Deg. F	Min. Temp., Kelvins	Conduct. Ht.Loss (or gain kW	Max. Evap. Ht.Loss kW	Max. Total Ht. Loss Rate kW	Min Avg. Temp. Rise Rate Dg.F/day	Time, Days
A	B	C	C	E	F	G	H
0	45.0	280	-1.10	1.34	0.24	1.32	0
5	51.6	284	-0.38	1.69	1.31	1.11	5
10	57.1	287	0.24	2.02	2.26	0.93	10
15	61.8	290	0.75	2.35	3.09	0.78	15
20	65.7	292	1.18	2.65	3.82	0.64	20
25	68.9	293	1.53	2.92	4.45	0.52	25
30	71.5	295	1.81	3.16	4.97	0.42	30
35	73.6	296	2.04	3.37	5.41	0.34	35
40	75.3	297	2.23	3.54	5.77	0.27	40
45	76.6	298	2.38	3.69	6.07	0.21	45
50	77.7	298	2.50	3.81	6.30	0.17	50
55	78.5	299	2.59	3.90	6.49	0.13	55
60	79.2	299	2.66	3.98	6.64	0.11	60
65	79.7	300	2.72	4.04	6.76	0.08	65
70	80.1	300	2.77	4.09	6.86	0.06	70
75	80.5	300	2.80	4.13	6.93	0.05	75
80	80.7	300	2.83	4.16	6.99	0.04	80
85	80.9	300	2.85	4.19	7.04	0.03	85
90	81.1	300	2.87	4.21	7.07	0.02	90
95	81.2	300	2.88	4.22	7.10	0.02	95
100	81.3	300	2.89	4.23	7.12	0.01	100
105	81.4	300	2.90	4.24	7.14	0.01	105

Max. Temp. dg. F	Max Temp. Kelvin	Cond. Ht.Loss kW	Min. Evap. Ht.Loss kW	Min Total Hea Loss kW	Max Avg. Temp. Rise Rate dg. F/day
I	J	K	L	M	N
45.0	280	-1.10	0.91	-0.19	1.40
52.0	284	-0.33	1.14	0.81	1.21
58.0	287	0.33	1.39	1.72	1.04
63.2	290	0.90	1.63	2.54	0.88
67.6	293	1.39	1.87	3.26	0.74
71.3	295	1.80	2.10	3.89	0.62
74.5	297	2.14	2.30	4.45	0.52
77.1	298	2.43	2.49	4.92	0.43
79.2	299	2.66	2.65	5.32	0.36
81.0	300	2.86	2.80	5.66	0.29
82.5	301	3.02	2.92	5.94	0.24
83.6	302	3.15	3.02	6.17	0.19
84.6	302	3.26	3.11	6.36	0.16
85.4	303	3.35	3.18	6.52	0.13
86.0	303	3.42	3.24	6.65	0.10
86.6	303	3.47	3.29	6.76	0.08
87.0	304	3.52	3.32	6.84	0.07
87.3	304	3.56	3.36	6.91	0.05
87.6	304	3.59	3.38	6.97	0.04
87.8	304	3.61	3.40	7.01	0.04
88.0	304	3.63	3.42	7.05	0.03
88.1	304	3.64	3.44	7.08	0.02

C8: 'CELL FORMULAS FOR POOL TEMPERATURE ESTIMATES

A10: 0
 B10: (F1) 45
 C10: (F0) 280
 D10: (F2) $0.11 * (B10 - 55)$
 E10: (F2) $(1745 / @SQRT(C10)) * @EXP(-13.11 * (373 - C10) / C10)$
 F10: (F2) $+D10 + E10$
 G10: (F2) $(7.2 - D10 - E10) * 0.105 * 1.8$
 H10: 0
 I10: (F1) 45
 J10: (F0) $(I10 - 32) / 1.8 + 273$
 K10: (F2) $(I10 - 55) * 0.11$
 L10: (F2) $(1163 / @SQRT(J10)) * @EXP(-13.11 * (373 - J10) / J10)$
 M10: (F2) $+K10 + L10$
 N10: (F2) $(7.2 - K10 - L10) * 0.105 * 1.8$
 A11: 5
 B11: (F1) $+B10 + 5 * G10$
 C11: (F0) $(B11 - 32) / 1.8 + 273$
 D11: (F2) $0.11 * (B11 - 55)$
 E11: (F2) $(1745 / @SQRT(C11)) * @EXP(-13.11 * (373 - C11) / C11)$
 F11: (F2) $+D11 + E11$
 G11: (F2) $(7.2 - D11 - E11) * 0.105 * 1.8$
 H11: 5
 I11: (F1) $+I10 + 5 * N10$
 J11: (F0) $(I11 - 32) / 1.8 + 273$
 K11: (F2) $(I11 - 55) * 0.11$
 L11: (F2) $(1163 / @SQRT(J11)) * @EXP(-13.11 * (373 - J11) / J11)$
 M11: (F2) $+K11 + L11$
 N11: (F2) $(7.2 - K11 - L11) * 0.105 * 1.8$