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THERMAL-HYDRAULIC ANALYSIS OF THE D.C. COOK SPENT FUEL POOL

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D. C. COOK SPENT FUEL POOL

Prepared by

L. D. O'Dell

L. D. O'Dell, Team Leader
PWR Safety Analysis
Licensing & Safety Engineering
Fuel Engineering & Technical Services

Contributors: D. L. Mlynarczyk
D. A. Prelewicz

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1.0 INTRODUCTION AND SUMMARY

The purpose of this report is to demonstrate that the storage of fuel with 50,000 MWd/MTU exposure in up to one-half of the D. C. Cook spent fuel pool storage locations will not violate thermal limits. The current analysis for the D. C. Cook spent fuel pool high density storage racks (References 1 and 2) considered the storage of fuel with an average exposure of up to 40,000 MWd/MTU. A new type of higher enriched fuel (referred to as Type 2) is capable of burnup to 50,000 MWd/MTU, and, therefore, a higher decay heat generation rate.

This report demonstrates that the storage of fuel with a slightly higher assembly heat generation rate, potentially interspersed with lower heat generation rate and lower flow resistance fuel, is within acceptable limits. The criteria used to determine this are: (1) no local boiling following the full core offload, and (2) maintenance of adequate cooling following a loss of forced circulation cooling or partial flow blockage.

The thermal analysis consists of several portions, involving determination of the maximum heat rate per assembly, the maximum heat input to the pool, natural circulation cooling of the fuel in the pool under normal and accident conditions and the pool water heatup rate following loss of pool cooling.

Peak fuel clad temperatures were calculated for three cases: a normal cooling case, an accident case with loss of pool cooling and an accident case with partial (90%) flow blockage at the limiting assembly outlet. Results of these analyses are presented in Table 1.1. A summary of parameters used in the analysis is given in Table 3.1. and a summary of the fuel types considered is given in Table 3.2. Local boiling does not occur in the limiting assembly even under 90% flow blockage conditions. Adequate cooling is maintained even when forced circulation cooling is accidentally lost. When forced circulation cooling is lost, the minimum time to reach 212°F bulk boiling conditions is 8.6 hours.

The maximum linear heat rate calculated in this analysis increased by only 4.65%, compared to the analysis in References 1 and 2. Due to the very conservative assumption in the previous analysis that all fuel in the core was exposed at 40,000 MWd/MTU, the maximum heat rate following a full core offload calculated in the prior analysis is almost identical to that calculated in this analysis. The conservative assumption made in this analysis is that one half of the fuel is exposed to 50,000 MWd/MTU and the other one half of the fuel is exposed to 25,000 MWd/MTU prior to full core offload. This was shown to bound the case of 1/3 of the core at 50,000, 1/3 at 33,000 and 1/3 at 17,000 MWd/MTU burnup. Since there is no change in maximum heat rate, the heat removal capability of the cooling system has been shown to be adequate by the analysis presented in References 1 and 2.

Table 1.1 Summary of Results

	CASE DESCRIPTION		
	NORMAL COOLING	LOSS OF FORCED CIRCULATION	90% FLOW BLOCKAGE
Bulk Temperature	150 °F	212 °F	150 °F
Assembly Inlet Temperature	150 °F	212 °F	150 °F
Assembly Maximum Fluid Temperature	181 °F	232 °F	198 °F
Peak Fuel Clad Temperature	187 °F	236 °F	205 °F
Exit Quality	0.0	0.0	0.0
Exit Void Fraction	0.0	0.0	0.0

2.0 ANALYTICAL METHODOLOGY

The methodology described in Branch Technical Position ASB 9-2 (Ref. 3) was used to calculate the decay heat for the fuel pool loaded with fuel assemblies discharged on a normal schedule followed by a full core offload 156 hours after shutdown.

In particular, the following steps were taken to analyze the D. C. Cook spent fuel pool:

1. Determine the kw/ft per assembly for the full core offload consistent with Branch Technical Position ASB 9-2 (Ref. 3), "Residual Decay Energy for LWR's for Long-Term Cooling".

2. Determine the total power input to the pool.

3. Analyze one row of 21 assemblies and determine the flows in each assembly.

    a) Use the code XCOBRA-IIIC (Ref. 4) to generate a ΔP vs flow rate curve.

    b) Iterately solve for the total flow by balancing buoyancy and flow friction forces. Spent fuel pool loss coefficients are from Reference 2.

4. Perform a hot channel analysis using XCOBRA-IIIC to determine the maximum temperature of the coolant which will occur in the 21st assembly farthest from the pool wall.

5. Using the results from Step 4, determine the maximum clad temperature.

6. Using the heat generation rate determined in step 2, calculate the time

to reach bulk boiling following loss of forced circulation cooling for normal discharge and full core offload conditions.

Assumptions

The following major assumptions were made:

1. The 193 full core offload assemblies all come from D.C. Cook Unit 2 and are Type 2. The spent fuel pool contains 2050 fuel assembly locations and is used for both D.C. Cook units.

2. For purposes of calculating the pool heat load, 1/2 of the full core offload is assumed to have 50,000 MWd/MTU exposure, and the other 1/2 to have 25,000 MWd/MTU exposure. This exposure was compared to the case of 1/3 of the core at 50,000 MWd/MTU, 1/3 at 33,000 MWd/MTU, and 1/3 at 17,000 MWd/MTU, and the former is conservative.

3. The remaining (2050 - 193) assemblies in the spent fuel pool arrived on a schedule which assumes a 12 month cycle for Unit 1 and an 18 month cycle for Unit 2. This does not exactly fill the pool, so the oldest assemblies are assumed to be 17 from Unit 1.

4. The peak clad temperature analysis considers a limiting row of 21 assemblies. Two potentially limiting situations are analyzed: (1) all 21 assemblies 50,000 MWd/MTU exposure Type 2 fuel, and (2) alternating Type 1 and Type 2, with 11 Type 2 and 10 Type 1 assemblies. This second case results in the higher power Type 2 assembly being farthest from the wall and hence the most flow limited.

5. The Type 1 assemblies were assumed to all be 15X15, since this assembly has a lower pressure drop and hence lower flow resistance than the 17X17. This will maximize the flow through the Type 1 assemblies and hence minimize the flow through Type 2 assemblies, including the limiting

assembly at position 21.

6. A uniform axial heat flux profile was assumed. This is conservative for determining margin to boiling since it results in a high local heat flux at the channel exit where the fluid temperature is greatest. Unlike the situation in the core, PWR spent fuel axial peaking factors for decay heat are generally considerably less than 10% (Reference 5).

7. For the determination of heatup rate, conduction to the pool floor and wall, and evaporative cooling at the pool surface were neglected.

8. For the case of lost forced circulation pool cooling, the bulk temperature of the pool water was assumed to be 212°F, the saturation temperature at atmospheric pressure. While the pressure increases with pool depth, it is not possible to sustain a significant temperature gradient, i.e., temperature increase with depth, due to buoyancy forces which cause any water heated above 212°F to rapidly rise to the surface and boil.

9. The fuel rack inlet temperature for the normal cooling case was assumed to be 150°F to permit comparisons with the original analysis. The bulk temperature following a full core offload is only 130°F, so a 20°F conservatism is applied.

3.0 CALCULATIONS

Table 3-1 gives a list of parameters used for this analysis. Table 3-2 gives a list of fuel related parameters for ANF 17X17 (Type 2) and Westinghouse 15X15 (Type 1) fuel assemblies. These two fuel types will be the thermally limiting fuel. This is because they are the most recently offloaded fuel and will, consequently, have the highest decay heat rates. Further, the Type 1 fuel also has the lowest ΔP which, when taken in combination with the Type 2 fuel, will result in the lowest flow rate in the Type 2 fuel.

Following is a description of the calculations:

3.1 Linear Heat Generation Rates

ASB 9-2 was used to determine the decay heat fraction per discharge and for the full core offload of Unit 2. Unit 2 will have the worst case offload, with type 2 fuel. The linear heat generation rate was then determined for the Unit 2 (17x17) offload assemblies and for the most recent Unit 1 (15x15) discharge assemblies as follows.

a) 17 x 17 Fuel

DECAY HEAT FRACTION, P/P_0	0.003053
P_0, MW_t PER CORE (193 assy)	3411
DECAY HEAT, MW_t PER CORE	10.4137
DECAY HEAT, KW_t PER ASSEMBLY	53.957
FUEL TYPE	ANF 17 X 17
ACTIVE LENGTH, INCHES	144
LINEAR HEAT GENERATION RATE, KW_t/ft	4.50

b) 15 x 15 Fuel

DECAY HEAT FRACTION, P/P_0 (64 assy)	0.001021
P_0, MW_t PER CORE (193 assy)	3250
DECAY HEAT, KW_t PER RELOAD	3318

DECAY HEAT, KW_t PER ASSEMBLY	51.848
FUEL TYPE	W 15 X 15
ACTIVE LENGTH, INCHES	144
LINEAR HEAT GENERATION RATE, KW_t/ft	4.32

3.2 Calculations of Pressure Drop vs Flow

The linear heat generation rates determined above were used as input to XCOBRA-IIIC. An XCOBRA hot channel run was made to determine the pressure drop versus flow relationship for each of the two channel types, 15x15 and 17x17. For each fuel type three cases were run. The first case used temperatures of 150°F for normal conditions, assuming a full core offload. A 212°F case for accident conditions (both pumps unavailable) was also run, as was a case with 90% blockage at the outlet and a 150°F inlet temperature.

Results from these XCOBRA runs were used to generate two ΔP vs. flow tables from each of the three cases run. These tables were used in an iterative procedure to determine the total flow into the racks.

3.3 Solution for Total Flow

The pressure drop versus flow tables were input into a FORTRAN program written to perform an iterative procedure to determine the total flow through the spent fuel racks and through each cell of the racks. This procedure is identical to that used for the original analysis, but is implemented by a FORTRAN code. Two potentially limiting loading schemes were considered for a row of 21 assemblies. There are 41 assemblies across the pool width, so the row of 21 assemblies constitutes a limiting situation. That is, the cooling water circulates down along the pool wall and under the racks to feed the assemblies out to the farthest assembly from the wall. Two arrangements were considered: a row with all 21 assemblies 17x17, and a row with alternating 17x17 and 15x15 assemblies with a 17x17 assembly in the 21st location farthest from the wall. Since the 15x15 assemblies have a lower flow resistance, there is the possibility that the flow could be higher in a 15x15 assembly even though the linear heat generation rate is lower.

An initial guess was made for the total flow into the first cell of the rack, and the program calculates the delta-pressures and flow rates for each of the twenty-one cells. If the flow into the 21st cell does not match the total flow minus the flow inside the first 20 cells, the program tries a new total flow rate and recalculates all 21 pressures and flowrates again. This continues until the final flowrates match.

The converged flowrate through the 21st cell is then used in a final XCOBRA case which gives the temperature at 12 axial locations along the assembly. A separate calculation is performed to find the fuel cladding temperature, i.e., to account for the temperature rise from the water to the clad surface.

Flow differences for the 15x15 and 17x17 assemblies were very slight. The 17x17 case was slightly more limiting at 150°F, whereas the alternating 15x15 and 17x17 case was more limiting at 212°F. However, the differences between the cases was very small. This indicates that any mixture of 15x15 and 17x17 assemblies is acceptable from a thermal standpoint.

The mass flux used, and the resulting maximum fluid temperature, are given below for each case analyzed:

FINAL XCOBRA RUNS

MASS FLUX	FLOW (lbm/sec)	MAX. FLUID TEMP.	CASE
0.01917	1.6752	180.51 °F	150°F, normal cooling
0.02986	2.609	231.80 °F	212°F, no pool cooling
0.01218	1.0643	197.96 °F	150°F, 90% blockage

3.4 Pool Heatup Rate

Should all pool cooling by forced circulation be lost, the pool will heat up slowly due to the large thermal inertia. A very conservative estimate of the time to reach bulk boiling at 212°F can be made based on a low estimate of pool water inventory and neglecting conduction to the pool walls and evaporative heat transfer at the pool surface. The most rapid heatup to boiling will occur following a full core offload when the heat generation rate and the bulk pool temperature are at maximum values.

To reach bulk boiling at the pool surface, the initial pool temperature must be increased to 212°F. In the limiting case of a full core offload, the initial bulk pool temperature is 130°F and the required temperature increase is 82°F. The decay heat fraction for the pool, assuming the full core offload, is 0.003 based on the Branch Technical Position ASB 9-2 (Ref. 3). This produces a pool heat input of 3.493×10^7 Btu/hr which, based on a minimum pool volume, results in a pool heatup rate of 9.54°F/hr. The minimum time to raise the temperature by 82°F is therefore:

$$\text{time} = 82°\text{F}/(9.54°\text{F/hr}) = 8.6 \text{ hrs.}$$

Again, this is a very conservative estimate and corresponds to the abnormal case of a full core offload and initial bulk temperature of 130°F.

Following a normal discharge of fuel with all fuel cells filled, except the 193 spaces reserved for the full core offload, the initial bulk pool temperature is 120°F and the decay heat fraction is 0.00163 (Ref. 3). This corresponds to a pool heat input of 1.9×10^7 Btu/hr and a heatup rate of 5.19°F/hr, again assuming a minimum pool volume. For this case, the minimum time to raise the temperature to 212°F is:

$$\text{time} = (212 - 120°\text{F})/(5.19°\text{F/hr}) = 17.7 \text{ hrs.}$$

3.5 Clad Surface Temperature

The clad surface temperature will be greater than the maximum fluid temperature due to the temperature rise across the surface film. For the normal cooling case, a laminar flow film coefficient is used. The temperature rise from the fluid to the clad surface is then 6.5°F.

In the abnormal case of boiling in the assembly, a boiling heat transfer coefficient must replace the convective coefficient. This yields a ΔT of 4.0°F.

Table 3.1 Parameters Used in Analysis

PARAMETER	VALUE
Number of Assemblies in Pool	2050
Number of Assemblies in Full Core (Units 1&2)	193
Maximum Pool Temperature	120°F
Max. Pool Temperature (Full Core Offload)	130°F
Max. Pool Temperature (Full Core Offload With One Pump Out)	165°F
Full Power (Unit 2)	3411 MWT
Full Power (Unit 1)	3250 MWT
Batch Average Burnup (Type 1)	40,000 MWd/MTU
Batch Average Burnup (Type 2)	50,000 MWd/MTU
MTU/assembly (Units 1 & 2)	0.467
Cooling Time After Shutdown Before Placement in Racks (Full Core Offload)	156 hrs.
No. of Type 1 or 2 Assemblies in Spent Fuel Pool	1025/1025
Reload Schedule, Unit 1	12 months
Reload Schedule, Unit 2	18 months
Assemblies Per Discharge, Unit 1	64
Assemblies Per Discharge, Unit 2	88

Table 3.2 Assembly Parameters

PARAMETER	W 15 X 15 (TYPE 1)	ANF 17 X 17 (TYPE 2)
Clad O.D. (In.)	0.422 in.	0.360 in.
Fuel Rods Per Assembly	204	264
Top Of Heated Length To Bottom Of U.T.P.	8.40*	8.40
Top Of Heated Length To Top Of U.T.P.	11.98*	11.98
Rod Pitch	0.563 in.	0.496 in.
Flow Area Per Bundle	43.32 in.^{2}	45.30 in.^{2}
Fuel Length (Heated)	144 in.	144 in.
Bottom Of Inlet Orifice To Heated Length	3.98 in.*	3.98 in.
Top Of Inlet Orifice To Bottom Of Heated Length	3.73 in.*	3.73 in.
Instrument Tube Per Bundle	1	1
Instrument Tube O.D.	0.544 in.	0.482 in.
Wetted Perimeter Per Assembly	341.4 in.	371.3 in.
Guide Tube O.D.	0.544 in.	0.482 in.
Guide Tubes Per Assembly	21	24
Fuel Rod Heated Perimeter Per Assembly	270.5 in.	298.6 in.

* The values for the 15x15 fuel are assumed to be equal to the 17x17 fuel; not a significant parameter.

4.0 SUMMARY OF RESULTS

The peak assembly linear heat generation rate is increased by 4.65% over that used in the original spent fuel pool analysis due to extending the burnup to 50,000 MWd/MTU compared to 40,000 MWd/MTU. The previous analysis assembly linear heat generation rate was 4.3 kw/ft whereas the new value is 4.5 kw/ft. Due to a large conservatism in the prior analysis, in particular the assumption that all of the fuel in a full core offload is exposed to 40,000 MWd/MTU (a physically impossible situation), the calculated total pool heat load is essentially unchanged. A conservative assumption of 50,000 MWd/MTU for one-half of the fuel core offload and 25,000 MWd/MTU for the remaining half has been assumed for the present analysis. Since there is no calculated increase in total pool heat load, the cooling system performance, i.e., ability of the forced circulation cooling system to remove heat from the pool, is covered by prior analysis (Ref. 1 and 2).

Both a normal cooling case and a loss of forced circulation cooling case were analyzed following a full core offload 156 hours after shutdown. For the normal cooling case, the maximum fuel clad temperature is 187°F, a value well below the onset of local boiling temperature. A partial blockage (90%) at the top of the limiting fuel cell was also analyzed. In this case, the maximum fuel clad temperature was 205°F, still well below the saturation and onset of local boiling temperatures.

Should forced circulation cooling of the spent fuel pool be lost following a full core offload with the pool totally filled (2050 assemblies), it will take more that 8.6 hours for the pool water to reach a bulk boiling (212°F) condition. Even in this case, the maximum fuel clad temperature was calculated to be 236°F, a temperature well below that at which fuel integrity is challenged.

The design of the D. C. Cook fuel racks is such that no interstitial gaps exist in the spent fuel pool. Therefore, no analysis of intercell voiding was performed.

In summary, boiling will not occur in the fuel pool in the limiting case of a full core offload with the pool filled following the offload. Even if forced circulation cooling is lost, the fuel clad temperatures will not approach values which threaten clad integrity.

5.0 REFERENCES

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4. XN-NF-75-21(P)(A), Rev. 2, "XCOBRA-IIIC: A Computer Code to Determine the Distribution of Coolant During Steady State and Transient Core Operation," Exxon Nuclear Company, Inc., Richland, WA, January 1986.

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