Thermal-Hydraulic Analysis for

US-APWR Spent Fuel Racks

Non-Proprietary Version

March 2014

Revision History

Revision	Page	Description
0	All	Original Issue
1		The following tables and figures were revised to incorporate results of the updated thermal hydraulic analysis that was performed using the revised spent fuel racks structure.
	Page 27	• Table 7-4: Value of bounding peak local water temperature
	Page 28	• Table 7-5: Value of bounding peak local fuel cladding temperature
	Page 30	• Figure 6-1
	Page 31	• Figure 7-1
		The followings revisions were made to incorporate editorial corrections and changes to the input parameter for the heat of vaporization of water.
	Page 2	• Section 2.0: Made editorial correction to change “EPRI” to “Electric Power Research Institute (EPRI)”.
	Page 4	• Section 3.1: Made editorial correction to change “QA” to “Quality Assurance (QA).”
	Page 7	• Section 3.4: Made editorial correction to change “spent fuel pool“ to “SFP”
	Pages 22 and 26	• Table 6-3: Increased significant digits of the input parameter for the heat of vaporization of water from “1000 Btu/lb” to “970.3 Btu/lb” in order to use a more realistic value for conservative analysis. In accordance with this change, the Table 7-3 value of maximum boil-off rate of each scenario was also revised.
	Pages viii, 15, 17, 18, 28	• List of Figure, Sections 6.4, 7.5 and 8.0, Table 7-5 and Figure 7-1: Made editorial corrections to change “SFP

Revision	Page	Description
	and 31	Rack“ to “SFR”
	Pages viii, 12, 23, 27, 29 and 30	• List of Figure, Section 5.4, Tables 6-4 and 7-4 and Figures 2-1 and 6-1: Made editorial corrections to change “spent fuel rack” to “SFR”.
	Page 29	• Figure 2-1: Replaced a figure with that which is more legible. No change has been made on the figure.
	Pages v and ix	• Updated the Table of Contents and the List of Acronyms.

Mitsubishi Heavy Industries, Ltd.
16-5, Konan 2-chome, Minato-ku
Tokyo 108-8215 Japan

Abstract

This report presents the results of the thermal-hydraulic design analyses performed on the cooling portion of the US-APWR Spent Fuel Pit Cooling and Purification System (SFPCS), primarily composed of the spent fuel pit, spent fuel racks, and cooling equipment. The report aims to demonstrate that the SFPCS design is conformant to the applicable and binding thermal-hydraulic design regulations.

The report concludes that for a fully loaded spent fuel pit at all plant operating conditions: (1) the spent fuel pit maximum bulk water temperature is below the regulation limits; (2) no local boiling occurs anywhere along the hottest fuel rods; and (3) the maximum fuel cladding temperature is below the minimum saturation temperature of the spent fuel pit water—a condition that inhibits local boiling in the coincident local points.

Table of Contents

List of Tables

List of Figures

List of Acronyms

AAC	Alternate Alternating Current
ASME	American Society of Mechanical Engineers
CCW	Component Cooling Water
CFD	Computational Fluid Dynamics
CS/RHRS	Containment Spray/Residual Heat Removal System
DNB	Departure from Nucleate Boiling
EPRI	Electric Power Research Institute
EPS	Emergency Power Source
GTG	Gas Turbine Generator
LOCA	Loss-of-coolant-accident
LOOP	Loss of Offsite Power
NRC	U.S. Nuclear Regulatory Commission
ORNL	Oak Ridge National Laboratory
OT	Office of Technology
QA	Quality Assurance
RG	Regulatory Guide
SBO	Station Blackout
SFP	Spent Fuel Pit
SFPCS	Spent Fuel Pit Cooling and Purification System
SFR	Spent Fuel Rack
SRP	Standard Review Plan
URD	Utility Requirements Document

1.0 INTRODUCTION

A thermal-hydraulic analysis of the spent fuel and spent fuel racks (SFR) in the spent fuel pit (SFP) is performed to establish the integrity of the spent fuel pit cooling and purification system (SFPCS) and SFR designs for spent fuel cooling. The analysis conforms to the guidelines set in the U.S. Nuclear Regulatory Commission (NRC) Standard Review Plan (SRP) 9.1.3, “Spent Fuel Pool Cooling Review and Acceptance Criteria” [1] and the U.S. Office of Technology (OT) Position Paper for the Review and Acceptance of Spent Fuel Storage and Handling Applications [2].

The thermal evaluations performed and documented in this report are as follows:

i. Calculation of the spent fuel decay heat for the SFRs
ii. Calculation of the maximum bulk temperature in the SFP for several offload scenarios, to demonstrate that bulk temperature limits will not be exceeded.
iii. Calculation of the minimum time-to-boil after a complete loss of forced cooling coincident with the maximum SFP bulk temperatures, to demonstrate that sufficient time is available for remedial actions.
iv. Calculation of a bounding peak local water temperature in the SFR cells, to demonstrate that the local water temperature will not exceed the local saturation temperature.
v. Calculation of a bounding peak fuel cladding temperature for the hottest spent fuel assembly in the SFR cells, to demonstrate that the fuel cladding temperature will not exceed the local saturation temperature.

2.0 DESCRIPTION OF THE SPENT FUEL PIT COOLING AND PURIFICATION SYSTEM

All cooling equipment of the SFPCS of the standard US-APWR plant is designed according to the American Society of Mechanical Engineers (ASME) Boiler and Pressure Vessel Code III, Class 3 [3], seismic Category I standards [4], and to Quality Group C per US-NRC Regulatory Guide (RG) 1.13 [5] so that their cooling functions during natural phenomena events, including safe-shutdown earthquakes, are not lost. The free standing SFRs for the storage of spent fuel in the SFP are also designed to seismic Category I standards.

One US-APWR fuel core has 257 fuel assemblies. The SFP spent fuel storage capacity is designed according to the Electric Power Research Institute (EPRI) Utility Requirements Document (URD) requirements [6]. The SFP, therefore, is designed to hold a maximum of 900 spent fuel assemblies in moderate density fuel racks equivalent to ten years of previously offloaded spent fuel assemblies and one recently offloaded full core. Damaged fuel racks are also provided for 12 damaged fuel assemblies. The system is designed to accommodate two refueling modes, i.e. full core offloading and half-core offloading. A schematic of the SFRs, including the damaged fuel racks, in the SFP is shown in Figure 2-1.

There are two SFPCS trains A and B; each train branches off into the cooling loop and purification loop. Each cooling loop is composed of the SFP pump, SFP heat exchanger, piping, and valves. Each purification loop, on the other hand, is composed of the demineralizer, filter, piping, and valves. In this report, concern involves only the cooling loops, and for simplicity will be referred to as the SFPCS trains from here onwards.

Two containment spray/residual heat removal system (CS/RHRS) trains can be aligned to the SFPCS to back up the SFPCS trains in removing heat from the spent fuel during higher SFP heat loads; see Subsection 2.1 for details. Each CS/RHRS train is composed of a CS/RHR pump, CS/RHR heat exchanger, piping, and valves. These trains are only used for SFP cooling during refueling outages.

2.1 Normal Offloading Scenarios

Refueling operations occur every 24 months with either half a core or a full core being offloaded into the SFP. Normally, the entire core is temporarily loaded into the SFP and the newer half is later returned to the reactor vessel prior to plant startup. The design fuel capacity of the SFP is 10 years, i.e., 5 refueling cycles at 24 months apart, plus 1 full core.

In normal SFP cooling operations, only one SFPCS train is needed to cool the spent fuel assemblies. During refueling outages and half-core offloads, the total SFP heat load increases largely due to the decay heat of the recently offloaded half-core. Plant procedures specify that two SFPCS trains are operated during this period until the SFP heat load significantly reduces to a point where only one SFPCS train will be able to remove the decay

heat from the spent fuel assemblies. The total heat removal capacity of the SFP heat exchangers can support ten years worth of spent fuel and a recently offloaded half-core. For a full core offload, on the other hand, two CS/RHRS trains primarily composed of CS/RHRS pumps and heat exchangers are aligned to the SFP to aid the two SFPCS trains in cooling the spent fuel.

2.2 Abnormal Offloading Scenarios

Abnormal discharge modes are indicated by the loss of cooling water flow and corresponding increase in SFP water temperature when a cooling train ceases to function due to pump failures, failure of emergency power sources (EPS) supplying electrical energy to active components during loss of offsite power (LOOP) conditions, and station blackout (SBO) events. During LOOP, failure of one EPS entails the cessation of either both of SFPCS A and CS/RHRS A trains or of SFPCS B and CS/RHRS D trains, depending on which alignment has failed. During an SBO event, two non-Class 1E gas turbine generators (GTG) identified as alternate AC (AAC) power sources are placed on standby. At least one AAC GTG must be available for activation within 60 minutes after the onset of SBO so that one SFPCS cooling train resumes operation. Normal and postulated abnormal fuel discharge scenarios, including the regulation temperature and component cooling water (CCW) temperature limits, are summarized in Table 2-1. Accident conditions, e.g., loss-of-coolant-accident (LOCA) may also occur where SFP water temperatures abnormally increase due to increase of CCW temperature.

3.0 METHODOLOGY

3.1 Decay Heat Loads

The decay heat in the SFRs, including the damaged fuel racks, is generated by the spent fuel assemblies placed herein. There are three types of spent fuel stored in the SFRs inside the SFP: (1) previously offloaded fuel assemblies; (2) twice-burned fuel assemblies recently offloaded into the SFP; and (3) once-burned fuel assemblies in the SFP prior to reload. The previously offloaded fuel assemblies, having lower decay heat emission rates than the recently offloaded fuel, are conservatively assumed to have constant decay heat during the evaluation

period, i.e. from start of reactor shutdown to the end of the refueling outage. The decay heat contribution of the recently offloaded spent fuel, however, decreases rapidly with time and is treated as time-dependent. The total heat load of the SFP is then calculated as:

$$Q_{GEN}(\tau) = \sum_{n=1}^{n=5} Q_n + Q_R(\tau), \qquad (3.1)$$

where:

- $Q_{GEN}(\tau)$, is the transient decay heat generation rate in SFP, Btu/hr
- τ, is the time after reactor shutdown, hr
- Q_n, is the amount of decay heat given off by previously offloaded spent fuel assumed to remain constant at the point of shutdown to the end of refueling outage, Btu/hr
- n, is the number of refueling cycles
- $Q_R(\tau)$, is the amount of decay heat given off by a recently offloaded batch of spent fuel, Btu/hr

The decay heat calculations by Holtec utilize the Holtec Quality Assurance (QA) validated computer program DECOR [7] that incorporates the Oak Ridge National Laboratory (ORNL) ORIGEN2 computer code [8]. The high-burnup PWR fuel cross-section library was used in the code in consistency with the expected burnup of the discharged fuel assemblies. In order to ensure conservatism in the decay heat calculation results, a 2% reactor thermal power uncertainty is added.

3.2 Spent Fuel Pit Bulk Water Temperatures

The bulk temperatures of the SFP water must be low enough to constantly cool the stored spent fuel, thus preventing them from overheating and consequential radioactive materials release from potential fuel cladding damage. The transient thermal response of the SFP and the attendant SFPCS and CS/RHRS to decay heat load transients is governed by the following equation:

$$C \times \frac{\partial T}{\partial \tau} = Q_{GEN}(\tau) - Q_{HX}(T) - Q_{ENV}(T) \quad (3.2)$$

where:

- C, is the SFP water thermal capacity, Btu/°F
- T, is the SFP bulk water temperature, °F
- τ, is the time after reactor shutdown, hr
- $Q_{GEN}(\tau)$, is the transient decay heat generation rate in SFP, Btu/hr
- $Q_{HX}(T)$, is the heat rejection to the SFPCS heat exchanger and/or CS/RHRS heat exchanger, Btu/hr
- $Q_{ENV}(T)$, is the passive heat loss to the environment, Btu/hr

The second-order passive heat loss term $Q_{ENV}(T)$ can be eliminated from the equation to give the following equation:

$$C \times \frac{\partial T}{\partial \tau} = Q_{\mathrm{GEN}}(\tau) - Q_{HX}(T) \quad (3.3)$$

Heat removal from the SFP by the SFPCS and the CS/RHR is a nonlinear function of the SFP bulk water temperature and the cooling water temperature which can be written in terms of a dimensionless temperature effectiveness value are as follows:

$$Q_{HX}(T) = W_c \times c_p \times p \times (T - T_{ci}) \quad (3.4)$$

and $$p = \frac{T_{co} - T_{ci}}{T - T_{ci}} \quad (3.5)$$

where:

- $Q_{HX}(T)$, is the heat exchanger heat rejection rate, Btu/hr
- W_c, is the coolant flow rate to the heat exchanger, lb/hr
- c_p, is the specific heat capacity of water, Btu/(lb×°F)
- p, is the temperature effectiveness of the heat exchanger

T_{ci}, is the coolant water inlet temperature to the heat exchanger, °F

T_{co}, is the coolant water outlet temperature from the heat exchanger, °F

The heat exchanger temperature effectiveness, p, is a measure of the SFPCS or CS/RHR thermal performance. For a given set of heat exchanger operating conditions (primarily flow rates) p can be treated as a constant.

The Holtec QA validated computer program MULPOOLD [9] has been used to simultaneously solve equations (3.3) through (3.5).

3.3 Spent Fuel Pit Water Time-to-Boil and Boil-Off Rate

To conservatively evaluate the SFP bulk water temperature during transient conditions such as a concurrent single pump failure and LOOP, a complete loss of forced cooling is assumed without taking credit for the reduced temperature of any makeup water to the SFP. Equation (3.3) is then reduced to the following differential equation:

$$C \times \frac{\partial T}{\partial \tau} = Q_{\mathrm{GEN}}\,(\tau + \tau_0) \qquad (3.6)$$

where:

τ, is the time after loss of forced cooling, hr

τ_0, is the time between reactor shutdown and loss of forced cooling, hr

The SFP bulk water heat-up rate, i.e. $\partial T / \partial \tau$ (°F/hr) can be solved by algebraically solving Equation (3.6). The SFP water time-to-boil is then determined by multiplying the heat-up rate with the difference of the boiling temperature of water and the cooler SFP bulk water temperature at the loss of forced cooling as given in the following equation:

$$\tau_{boil} = \frac{\partial \tau}{\partial T}(212°F - T) = \frac{C}{Q_{GEN}}(212°F - T) \qquad (3.7)$$

3.4 Local Water Temperatures

The SFRs are loaded with spent fuel assemblies. There are water gaps, also called downcomers, between adjacent racks and between the peripheral racks and the walls of the SFP. The rack pedestals maintain a water gap, also called the bottom plenum, between the floor of the SFP and the rack base plate. These gaps allow water flow from the area above the rack through the downcomers, into the bottom plenum and into the bottom of the rack cells. The decay heat generated by the fuel assemblies stored in the racks induces a buoyancy-driven water flow upward through the fuel rack cells. Quantification of the coupled flow and temperature fields in the SFRs is accomplished through the use of Computational Fluid Dynamics (CFD) analyses. The CFD analysis is performed utilizing the FLUENT™ [10] fluid flow and heat transfer modeling program.

A three-dimensional model of the SFRs in the SFP is made using FLUENT. The regions in the SFP occupied by the fuel racks loaded with heat generating fuel assemblies are modeled as a [ ] [10]. Flow through the narrow fuel assembly passages is laminar and governed by Darcy's Law. The decay heat generated by the spent fuel assemblies stored in the racks is included in the models as volumetric decay heat generation in the [ ].

The Navier-Stokes equations of fluid motion are solved along with the energy conservation equation to obtain the local flow field and the steady-state temperature distribution in the SFP. Buoyancy effects and turbulence effects are included in the CFD analysis. Turbulence effects are modeled by relating time-varying "Reynolds Stresses" to the mean bulk flow quantities using the [ ] [10]. As stated in the previous paragraph, the flow through the fuel assemblies is laminar and turbulence effects are "turned off" in the [ ].

3.5 Fuel Cladding Temperatures

The fuel cladding temperature must not exceed the local saturation temperature of the surrounding liquid. If this is satisfied, there would be no possible cases of departure from nucleate boiling (DNB). The difference between the cladding surface temperature and the local water temperature (also called the cladding superheat) is conservatively calculated from

the principles of laminar flow heat transfer [11]. The flow of water through the fuel assemblies in the fuel racks is a buoyancy-driven, natural convection flow. Due to the low velocities and the small hydraulic diameter of the intersticies, the flow regime is laminar. Turbulence enhances heat transfer, so use of laminar flow correlations is conservative. A standard heat transfer reference [11] gives the following relationship for constant heat flux laminar flow:

$$Nu = h \times D_{hyd} / k_w = 4.364 \quad (3.8)$$

where:

- Nu, is the Nusselt number
- h, is the convective heat transfer coefficient, Btu/hr-ft^2-R
- D_{hyd}, is the flow path hydraulic diameter, ft
- k_w, is the fluid (water) thermal conductivity, Btu/hr-ft-R

This equation is solved for the convective heat transfer coefficient (h). A thin crud layer on the outside of the fuel rods provides an additional heat transfer resistance (Rc).

The overall heat transfer coefficient, which includes both the convective heat transfer coefficient and the crud resistance, is determined by summing resistances in series, as:

$$1/U = 1/h + R_c \quad (3.9)$$

where U is the overall heat transfer coefficient. The peak rod heat flux is divided by this quantity to obtain the fuel clad superheat. The peak rod heat flux q_{rod} is calculated from the following equation:

$$q_{rod} = \frac{F_{ax} \times Q_{rod}}{A_{surf}} \quad (3.10)$$

where:

F_{ax}, is the axial peaking factor (See Table 6-4.)

Q_{rod}, is the maximum decay heat per fuel rod

A_{surf}, is the fuel cladding surface area of the rod's active fuel region

Equation (3.10) conservatively determines the peak rod heat flux due to the radial peaking factor being taken into consideration in Q_{rod}.

The fuel clad superheat ΔT is obtained by dividing the peak rod heat flux by the overall heat transfer coefficient as given below:

$$\Delta T = \frac{q_{rod}}{U} \tag{3.11}$$

The maximum local water temperature (at the top of the active fuel region) and peak heat flux (typically near the mid-height of the active fuel region) are considered to occur coincidentally. The superposition of these two maximum values ensures that the calculated peak fuel cladding temperature bounds the fuel cladding temperature anywhere along the length of the fuel assembly.

4.0 ACCEPTANCE CRITERIA

In conformance with RG 1.13, "Spent Fuel Storage Facility Design Basis [5]," NUREG-0800 SRP 9.1.3, "Spent Fuel Pool Cooling and Cleanup System [1]," and EPRI URD [6] guidelines the following acceptance criteria are applied to the analyses:

1. During a half-core offload with two operating SFPCS trains (i.e., no single active SFPCS failure), the SFP bulk water temperature must not exceed 120°F.
2. During a half-core offload with one operating SFPCS train (i.e., a worst-case single active SFPCS failure), the SFP bulk water temperature must not exceed 140°F.
3. During a full core offload with two operating SFPCS trains and two operating CS/RHRS trains (i.e., no single active failures), the SFP bulk water temperature must not exceed 120°F.

4. During a full core offload with two operating SFPCS trains and one operating CS/RHRS train (i.e., a worst-case single active CS/RHRS failure), the SFP bulk water temperature must not exceed 140°F.
5. During a full core offload with one operating SFPCS train and two operating CS/RHRS trains (i.e., a worst-case single active SFPCS failure), the SFP bulk water temperature must not exceed 140°F.
6. During a full core offload with one operating SFPCS train and one operating CS/RHRS train (i.e., due to LOOP and one active failure), the SFP bulk water temperature must not exceed 140° F. This condition, however, is beyond that required by the NRC.
7. Accident condition and only one operating SFPCS train (due to a one available EPS), the SFP bulk water temperature must not exceed 200° F.
8. The minimum time-to-boil following a loss of forced cooling must provide sufficient time to perform remedial actions prior to the onset of bulk boiling.
9. The maximum local water temperature in the SFP must be less than the local saturation temperature of water at the depth where it occurs.
10. The bounding maximum fuel cladding temperature in the SFP must be less than the local saturation temperature of water at the depth where it occurs.

5.0 ASSUMPTIONS

Several assumptions have already been described in the discussion on the methodologies in Section 3.0. A number of additional conservative assumptions that justify the conservatism of the necessary assumptions are further described in the following subsections:

5.1 Decay Heat Loads

- The total fuel inventories stored in the SFP are based on five half-core offloads prior to the final offload (either a half-core or a full core). As the core holds an odd number of fuel assemblies, the number of assemblies is rounded up for half-core offloads. Thus, partial core offload scenarios have 774 discharged assemblies and full core offload scenarios have 902 discharged assemblies, slightly exceeding the number of maximum storage locations. This ensures that the calculated fuel decay heat loads are bounding maximum values.

5.2 Spent Fuel Pit Bulk Water Temperatures

- All passive heat losses (i.e., conduction through walls and floor, convection and thermal radiation from the water surface) are neglected in the analyses. This conservatively maximizes the net heat load, thereby maximizing the bulk temperatures.
- Prior to the start of fuel transfer, a single train of the SFPCS cools the SFP. Any additional cooling trains (SFPCS and/or CS/RHRS) are aligned to cool the SFP coincident with the beginning of fuel transfer operations. This conservatively maximizes the initial bulk temperature which will result in the largest peak bulk temperatures.

5.3 Spent Fuel Pit Water Time-to-Boil and Boil-Off Rate

- The time of the loss of forced cooling which initiates the time-to-boil calculation is assumed to coincide with the maximum bulk temperature calculated for each offload scenario. The highest initial temperature will yield the shortest time-to-boil.
- The supply of lower temperature makeup water is completely neglected. Makeup water supplied to maintain the SFP water level would be at a lower temperature than the noncooled SFP water. Neglecting the lower enthalpy of this water conservatively minimizes the time-to-boil.

5.4 Local Water Temperatures

- The hottest fuel assemblies in the SFP are assumed to be located together at the center of the rack array, conservatively maximizing the local decay heat generation rates. This is conservative as it maximizes the distance between the hottest fuel assemblies and the cooler water supply through the rack-to-wall gaps.
- The SFP model credits conservatively lower rack-to-wall gaps instead of the actual values, and no downcomer flow is assumed to exist between the rack modules. This conservatively maximizes the downcomer flow resistance and ensures that the calculations will encompass slight positional deviations in the as-installed rack configuration.

- The large flow holes in the SFR base plates are not credited. Instead, it is assumed that water can only enter the bottom of the fuel rack cells through the smaller holes associated with the pedestal cells (four semi-circular holes in the cell walls). This conservatively reduces the water flow area into the storage cells, thereby increasing the hydraulic resistance.
- The damaged fuel racks are modeled as having the same hydraulic resistance and volumetric decay heat loads as the SFRs. The effects of the additional resistance for flow through these racks and the associated damaged fuel containers is computed separately and added to the temperatures computed using the CFD model. The results reported in this report are the temperatures with the additional resistance included.
- Instead of modeling the inlet to and the outlet from the SFP (which are at approximately 21’ and 4’ from the low water level, respectively) explicitly, these features are modeled as 4” high slots just below the water surface along the south and north walls, respectively. This conservatively reduces the water injection velocity and does not direct the incoming cooled water toward the floor of the SFP. The flows in the SFP are buoyancy-dominated, so this modeling simplification should have no effect on the calculated results.
- The hydraulic resistance of every rack cell includes the inertial resistance that would result from a dropped fuel assembly lying across the top of the rack. This conservatively increases the total rack cell hydraulic resistance and bounds the thermal-hydraulic effects of a fuel assembly dropped anywhere in the spent fuel storage area.
- The calculated fuel rack hydraulic resistance parameters are worsened to ensure an analysis that bounds any small deviations in fuel assembly and rack geometry. The two calculated parameters, permeability and inertial resistance factor, are conservatively worsened by 5%.
- All passive losses (i.e., conduction through walls and slab or losses from the surface) are neglected in the local temperature analyses. This conservatively maximizes the net heat load, thereby maximizing both global and local temperatures.

5.5 Fuel Cladding Temperatures

- An additional heat transfer resistance of 0.0005 (hr×ft^2×°F)/Btu is conservatively imposed on the outside of the fuel rods, to account for any crud layer, thereby increasing the calculated fuel clad superheat.
- As already mentioned in Subsection 3.5, the maximum local water temperature (due to the buoyant movement of the heated water) at the top of the active fuel region and peak heat flux typically around the midsection of the active fuel region are considered to occur coincidentally. This assumption ensures that the calculated peak fuel cladding temperature bounds the fuel cladding temperature anywhere along the length of the fuel assembly.

6.0 INPUT DATA AND CALCULATIONS

6.1 Decay Heat Loads

The input parameters used in the decay heat load calculations for the SFP are given in Table 6-1. In calculating the spent fuel decay heat, two offload scenarios are being considered: (1) half-core offload, where one-half of the fuel assemblies in the reactor core are offloaded at the end of a normal reactor operating cycle; and (2) full core offload, where all of the fuel assemblies are offloaded at the end of a normal reactor operating cycle. The calculations were performed as described in Subsection 3.1.

6.2 Spent Fuel Pit Bulk Water Temperatures

The input parameters necessary in calculating the SFP bulk water temperatures are given in Table 6-2. There are seven SFP bulk water temperature scenarios which are defined as follows:

1. Half-Core Offload Without Single Active Failure – A half-core offload is performed with two operating SFPCS trains.
2. Half-Core Offload With Single Active Failure – A half-core offload is performed with one operating SFPCS train.

3. Full Core Offload Without Single Active Failure – A full core offload is performed with two operating SFPCS trains and two operating CS/RHRS trains.
4. Full Core Offload With Single Active CS/RHRS Failure – A full core offload is performed with two operating SFPCS trains and one operating CS/RHRS train.
5. Full Core Offload With Single Active SFPCS Failure – A full core offload is performed with one operating SFPCS train and two operating CS/RHRS trains.
6. Full Core Offload With Concurrent Failures – A full core offload is performed with one operating SFPCS train and one operating CS/RHRS train (i.e., concurrent LOOP and single failure of an EPS leading to unavailability of one operating train each for the SFPCS and CS/RHRS).
7. Accident Condition – An accident occurs during full core offload. During an accident, only one Class 1E EPS is available due to the failure or unavailability of another EPS.

The SFP bulk water temperature calculations for each scenario were performed based on the methods described in Subsection 3.2 and calculated decay heat loads described in Subsection 3.1.

6.3 Spent Fuel Pit Water Time-to-Boil and Boil-Off Rate

The input parameters for the time-to-boil and boil-off rate calculations are given in Table 6-3. Calculations were performed as described in Subsection 3.3.

6.4 Local Water Temperatures

The input parameters necessary in calculating the local SFP water temperatures are: (1) the overall SFP and rack dimensional data necessary to construct the three-dimensional CFD model; (2) the fuel rack and fuel assembly dimensional data necessary to calculate the hydraulic resistances of the loaded fuel rack cells; (3) the thermophysical properties of water used in the CFD computations such as water density, viscosity, thermal conducitivity, and specific heat capacity; and (4) the data necessary to calculate the volumetric heat generation rates for a bounding heat load in the SFRs when they are fully loaded with spent fuel assemblies and the temperature and velocity of cooled water entering the SFP from the cooler.

The above inputs are summarized along with the geometry input data necessary to construct the SFR CFD model in Table 6-4.

The following calculation steps are used to generate data for the CFD calculation model and are not governed by any acceptance criteria:

1. A three-dimensional coordinate system, including the [ ] to model the loaded SFRs, is constructed from the SFP and SFR array dimensions for use in the CFD calculation model.
2. The hydraulic resistance parameters, i.e., permeability and inertial resistance factor are calculated for the SFR cells.
3. The volumetric decay heat generation rates for the fuel assembly containing regions of the CFD models are determined along with the inlet water conditions. As described in Subsection 5.4, the hottest fuel assemblies are conservatively grouped together in the center of the SFP. The calculations are performed for the point in time where the maximum bulk water temperatures are reached.

The isometric view of the SFR model is shown in Figure 6-1. The coupled temperature and velocity profiles in the SFP are calculated using the FLUENT program. A single bounding scenario with the maximum total decay heat, the maximum half-core decay heat and the maximum bulk temperature, which bounds all evaluated offload scenarios, is evaluated for the SFP. These scenarios are solved using FLUENT, and the peak local water temperatures are determined using the FLUENT post-processing functions.

6.5 Fuel Cladding Temperatures

The fuel cladding temperature calculations were performed as described in Subsection 3.5. The bounding fuel cladding superheat is determined from fuel assembly geometry data and the bounding assembly decay heat. The calculations are performed for the point in time where the maximum bulk water temperatures are reached, which is the same point in time that the local water temperature calculations in Subsection 6.4 are performed for.

7.0 RESULTS AND DISCUSSION

7.1 Decay Heat Loads

The decay heat load calculations for previously offloaded fuel assemblies are presented in Table 7-1. The SFP decay heat load at the beginning of offload, i.e. 104 hours after shutdown, but prior to the transfer of either half-core or full core of fuel into the SFP is calculated. The same previously offloaded fuel decay heat load is obtained during either half-core or full core offload as there are the same number of previously offloaded fuel assemblies.

7.2 Spent Fuel Pit Bulk Water Temperatures

The calculations described in Subsection 6.2 for the maximum SFP bulk water temperatures for 7 scenarios are performed and the subsequent results are tabulated in Table 7-2. The coincident decay heat and times after shutdown are also included in the table. According to the results, the SFP water temperatures do not exceed the regulatory temperature limits in any of the 7 scenarios.

7.3 Spent Fuel Pit Water Time-to Boil and Boil-Off Rate

The minimum time-to-boil and the corresponding boil-off rate for the SFP bulk water for all 7 scenarios are calculated. See Table 7-3 for the results summary. Results show that there is a minimum of 2.7 hours (from the 7th scenario that bounds all of the seven scenarios) available prior to SFP water boiling when all forced cooling is lost, i.e. during an SBO event. This length of time, however, is much longer than the 60-minute limit of activation of the AAC reserved for operation during an SBO; cooling using one SFPCS train is resumed and potential SFP water boiling is precluded.

7.4 Local Water Temperatures

Local water temperatures in the SFP have been computed, as described in Subsection 6.4, at the point in time where the bulk water temperatures are at maximum. Converged temperature contours in vertical sections through the SFP are presented in Figure 7-1.
The saturation temperature of water increases with increasing pressure and, subsequently, increasing depth. The critical location for localized boiling in the fuel racks is at the top of the active fuel length. The minimum depth of water at the top of the active fuel length is approximately 29 feet which corresponds to a saturation temperature of water of approximately 245°F [12].

The calculated peak local water temperatures are well below the local saturation temperature, and Acceptance Criterion 9 from Section 4.0 is therefore satisfied. The large number of conservative assumptions incorporated into these analyses renders the calculated results quite conservative, so actual margins of safety will be higher than predicted herein.

7.5 Fuel Cladding Temperatures

The peak local cladding temperatures are calculated, as described in Subsection 6.5, at the point in time where the bulk water temperatures in the SFRs are at maximum. Results, including the cladding superheat values, are presented in Table 7-4. Results show that the calculated peak local cladding temperatures are lower than the local saturation temperature, so Acceptance Criterion 10 from Section 4.0 is therefore satisfied. The large number of conservative assumptions incorporated into these analyses renders the calculated results quite conservative, so actual margins of safety will be higher than predicted herein.

8.0 CONCLUSIONS

The following are a summary of the analyses:

- The SFP bulk water temperatures for all 7 scenarios do not exceed the regulatory limits.
- There is no local boiling occurring anywhere along the fuel rods in the SFRs.

- The peak fuel cladding temperatures for all of the stored assemblies do not exceed the local saturation temperature of water around the SFRs so that DNB is not a concern.

Since the assumptions incorporated into the analyses are highly conservative, the actual margins of safety are expected to be higher than predicted herein.

9.0 REFERENCES

[1] Standard Review Plan (SRP) 9.1.3, “Spent Fuel Pool Cooling and Cleanup System,” Revision 2.

[2] U.S. Office of Technology (OT) Position Paper for Review and Acceptance of Spent Fuel Storage and Handling Applications, 1978.

[3] American Society of Mechanical Engineers (ASME) Boiler and Pressure Vessel Code, Division 1, Section III, “Rules for Construction of Nuclear Components, Section III, 1992 Edition through the 1992 Addenda.

[4] Regulatory Guide (RG) 1.29, “System Design Classification,” Revision 4.

[5] Regulatory Guide (RG) 1.13, “Spent Fuel Storage Facility Design Basis,” Revision 2.

[6] EPRI Advanced Light Water Reactor Utility Requirements Document (URD) 1999.

[7] Holtec Report HI-971734, “QA Documentation for DECOR,” Revision 0.

[8] A.G. Croff, “ORIGEN2 - A Revised and Updated Version of the Oak Ridge Isotope Generation and Depletion Code,” ORNL-5621, Oak Ridge National Laboratory, 1980.

[9] Holtec Report HI-92834, “QA Documentation for MULPOOLD,” Revision 3.

[10] FLUENT Version 6.3.26, Fluent Inc., 2006.

[11] W.M. Rohsenow and J.P. Hartnett, “Handbook of Heat Transfer,” McGraw-Hill, First Edition, 1973.

[12] M.R.Lindeburg, “Mechanical Engineering Reference Manual,” Professional Publications Inc., Tenth Edition, 1997.

Table 2-1 Fuel offloading Scenarios

Scenario	No./type of cooling systems trains	SFP temperature limit	CCW Temperature
Half-core offload; normal	2 SFP trains	<120° F	100° F
Half-core offload; single active failure	1 SFP train	<140° F	100° F
Full core offload; normal	2 SFP trains, 2 CS/RHR trains	<120° F	100° F
Full core offload; single active CS/RHRS failure	2 SFP trains, 1 CS/RHR train	<140° F	100° F
Full core offload; single active SFPCS failure	1 SFP train 2 CS/RHR trains	<140° F	100° F
Full core offload; concurrent failures (e.g. LOOP and single failure of an EPS)	1 SFP train 1 CS/RHR train	<140° F	100° F
Accident conditions; single failure of an EPS	1 SFP train	<200° F	118.4° F

Table 6-1 Key Parameters for Decay Heat Calculations

Input Parameter	Unit	Value
Reactor thermal power	MWt	4451
Reactor thermal power uncertainty	%	2
Number of assemblies in reactor core		257
Number of refueling batches		2
Number of half-core offloads prior to final offload		5
Maximum fuel assembly burnup	MWd/MTU	62000
Time between refueling outages	months	24
Fuel assembly initial enrichment	^{235}U wt%	4.1
Fuel assembly uranium weight	kg UO_2	614
Fuel assembly total weight	kg	[ ]
Refueling outage duration	days	17

Table 6-2 Key Parameters for SFP Bulk Water Temperature Calculations

Input Parameter	Unit	Value
SFP water flow rate through each SFPCS HX	m^3/hr	818
SFP water flow rate through each CS/RHRS HX	m^3/hr	680
Cooling water flow rate through each SFPCS HX	m^3/hr	818
Cooling water flow rate through each CS/RHRS HX	m^3/hr	1000
Cooled SFP water flow rate from CS/RHRS HX	m^3/hr	600
Cooling water inlet temperature to SFPCS HX	° F	100
Cooling water inlet temperature to CS/RHRS HX	° F	100
In-Core hold time prior to start of fuel transfer	hr	104
Time to complete fuel transfer	hr	16

Note: The end of fuel transfer is assumed to complete at 120 hours after shutdown for both half-core and full core offloads to maximize the decay heat loads.

Table 6-3 Key Parameters for Time-to-Boil and Boil-Off Rate Calculations

Input Parameter	Unit	Value
SFP surface area	ft^2	1181
Minimum SFP water depth	ft	45
Minimum specific heat of water	Btu/lb-R	0.997
Minimum density of water	lb/ft^3	60.1
Heat of vaporization of water	Btu/lb	970.3

Table 6-4 Key Parameters for Local Temperature Calculations

Input Parameter	Unit	Value
Fuel rod active length	in	165.4
Total Peaking Factor		2.6
Radial Peaking Factor		1.78
Axial Peaking Factor		1.461
SFR Dimensions		
Storage cell inner dimension	in	8.8
Storage cell pitch	in	11.1
Storage cell length	in	196

Table 7-1 Decay Heat of Previously Offloaded Fuel Assemblies

Offload Scenario	Previously Offloaded Fuel Assemblies Decay Heat
1 – Half-Core Offload	5.645×10^6 Btu/hr
2 – Full Core Offload	5.645×10^6 Btu/hr

Table 7-2 SFP Decay Heat Loads and Bulk Water Temperatures

Scenario	Coincident SFP Total Heat Load [Btu/hr]	Maximum SFP Bulk Temp. [° F]	Time After Reactor Shutdown [hours]
1 – Half-Core Offload, Normal	33.45×10^6	112.0	123
2 – Half-Core Offload, Single Active SFPCS Failure	33.17×10^6	123.7	126
3 – Full Core Offload, Normal	57.35×10^6	113.2	122
4 – Full Core Offload, Single Active CS/RHR Failure	57.18×10^6	116.0	123
5 – Full Core Offload, Single Active SFPCS Failure	57.18×10^6	119.4	123
6 – Full Core Offload, Concurrent Failures	57.01×10^6	126.2	124
7 – Accident Condition	56.68×10^6	158.9	126

Table 7-3 SFP Minimum Time-to-Boil and Boil-Off Rates

Scenario	Minimum Time-to-Boil [hours]	Maximum Boil-Off Rate [gpm]
1 - Half-Core Offload, Normal	8.7	72
2 - Half-Core Offload, Single Active SFPCS Failure	7.7	71
3 - Full Core Offload, Normal	5.0	123
4 - Full Core Offload, Single Active CS/RHRS Failure	4.9	123
5 - Full Core Offload, Single Active SFPCS Failure	4.7	123
6 - Full Core Offload, Concurrent Failures	4.4	123
7 - Accident Condition	2.7	122

Table 7-4 Bounding Peak Local Water Temperature

Local Temperature Model	Bounding Peak Local Water Temperature
SFRs	187° F

Table 7-5 Peak Cladding Temperature

Parameter	SFRs
Peak cladding superheat	22° F
Bounding peak local fuel cladding temperature	209° F

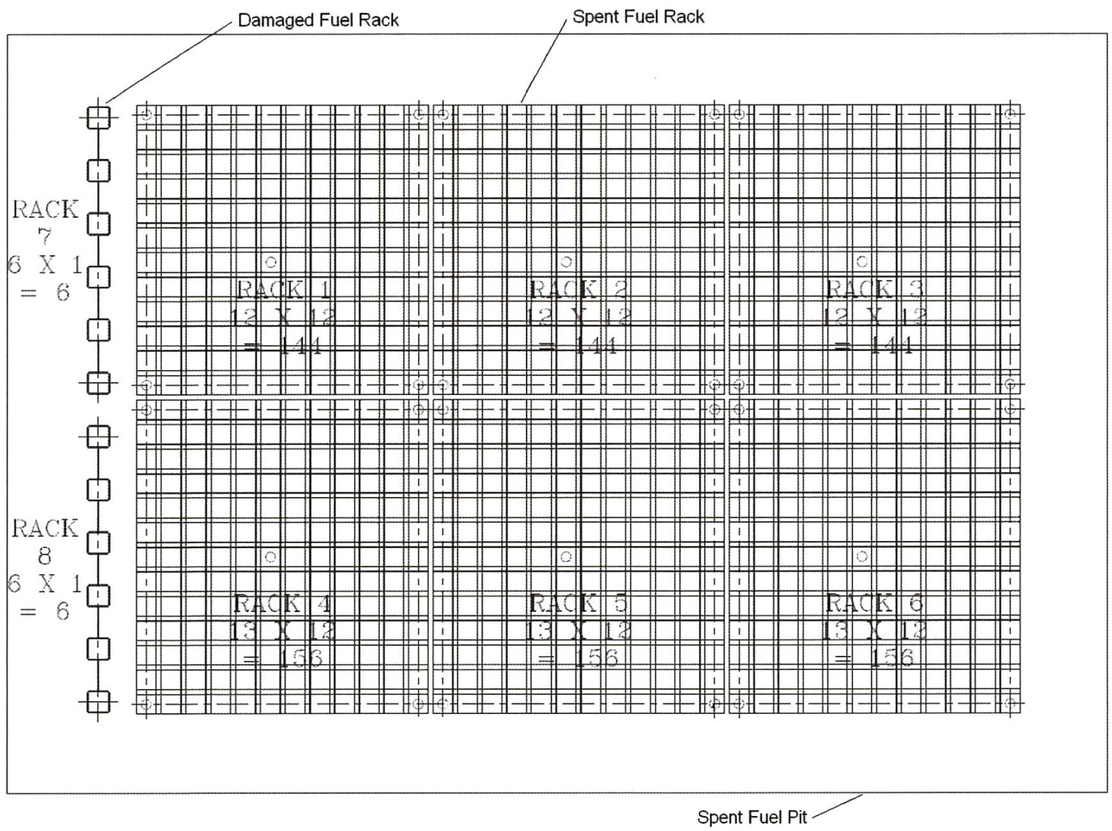

Figure 2-1 Layout of SFRs and Damaged Fuel Racks

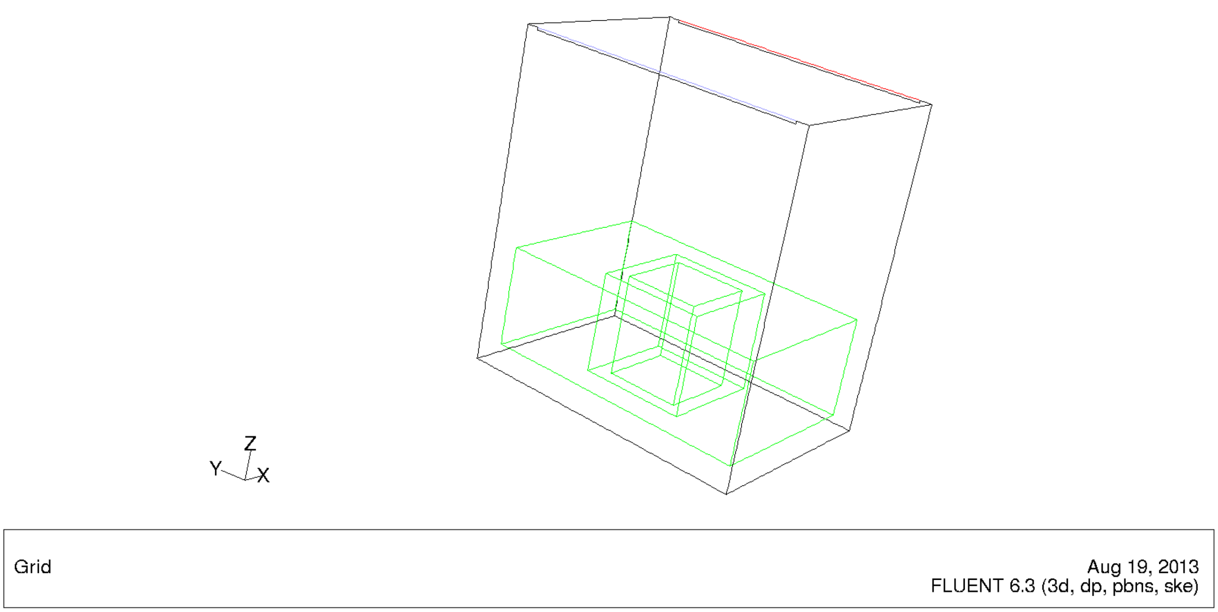

Figure 6-1 Isometric View of the SFRs for the CFD Model

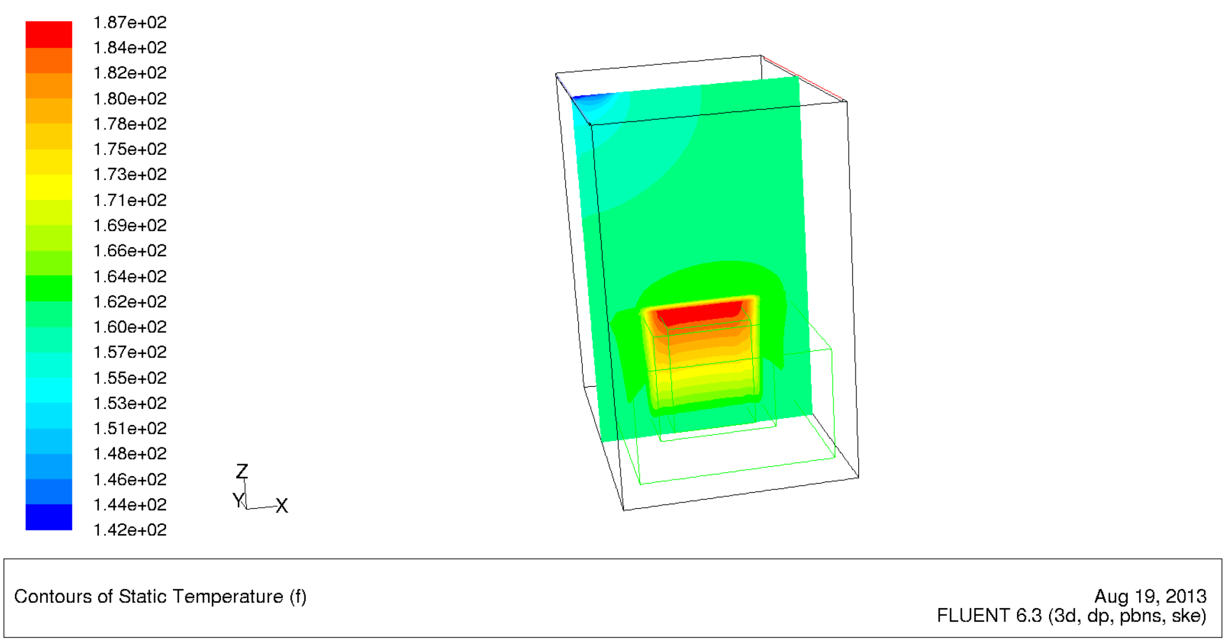

Figure 7-1 Local Water Temperature Contours from the CFD Model in the SFRs