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The Best Estimate Evaluation of Success Criteria for Spent Fuel Pool PRA in Case of Loss of Cooling

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This paper outlines the process used to develop the methodology for the determination of operator response timings using the thermal hydraulic analysis code MAAP5.[a]

The spent fuel pool is a plant system which is used to remove decay heat from irradiated assemblies and maintain the assembly cladding temperature below the point where substantial fission product release can occur. The ability to maintain this cooling capability or inventory in the spent fuel pool can be challenged due to operator error, loss of power, or natural phenomena which lead to prolonged cooling system unavailability. The key accident timings have been evaluated to define the time to boil the spent fuel pool water and the time at which the stored assemblies become uncovered for several accident sequences at various plant operating conditions.

Four sequences have been evaluated for the extended loss of the SFP cooling system with failure of active and/or passive safety mitigation systems. The first two sequences which were performed were for a loss of cooling in Case 1 before defueling the reactor and in Case 2 with newly offloaded batches. The difference between these two sequences is the decay heat load which is present in the spent fuel pool. Case 3 and 4 are initiated by a break in cooling system suction piping and discharge piping respectively. These analysis cases are selected to perform success criteria evaluations, assess operator response timings, and evaluate plant transient response.

I. INTRODUCTION

The purpose of this calculation is to document the timings and consequences for a severe accident impacting the spent fuel pool. The spent fuel pool is a plant system which is used to remove decay heat from irradiated assemblies and maintain the assembly cladding temperature below the point where substantial fission product release can occur. The spent fuel pool uses cooling systems consisting of pumps and heat exchangers to maintain the water temperature in a sub-cooled state. 10 CFR Part 72 requires that spent fuel cladding be protected during storage against degradation that leads to gross ruptures. Nuclear fuel cladding has been shown to degrade and rupture at high storage temperatures. Therefore assemblies are stored in a large pool of water until the assembly decay heat is low enough for dry storage.

MAAP5 was used as a thermal hydraulic analysis code to analyze accident scenarios to evaluate the accident timing for plant specific sequences. MAAP5 is a program which models the transient response during severe accident scenarios in the spent fuel pool. This model includes the initial fuel heat up upon loss of cooling, zirc-steam and zirc-air oxidation phenomena, fuel melting, and MCCI interaction. (Ref. 1)

A steady state transient sequence (when no accident conditions are present) was analyzed to verify the base spent fuel pool model before analyzing accident conditions. Reasonable results from these test sequences indicate that the developed SFP model can be used for plant specific sequences.

The key accident timings for plant specific sequences consist of time to start boiling in the spent fuel pool water and the time at which the stored assemblies become uncovered. The ability to maintain the cooling capability or inventory in the spent fuel pool can be challenged due to operator error, loss of power, natural phenomena which lead to prolonged cooling system unavailability, or if there is a loss of inventory with no makeup flow. Therefore, it is necessary to analyze a series of sequences in order to provide a best estimate representation of the spent fuel pool during severe accidents at different plant

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[a] MAAP is a computer code that is used for integrated severe accident analysis. The MAAP code is owned by the Electric Power Research Institute (EPRI).

operating conditions. The timings and consequences of key severe accident indicators are calculated for use in additional analysis to define necessary mitigating actions and operator response timings.

II. Thermal Hydraulic Analysis Model for spent fuel pool

The MAAP5 SFP Thermal Hydraulic Analysis Model is designed to provide a best estimate representation for severe accident analyses. The purpose is to consistently describe the physical processes associated with the integral system response to plant transient conditions, especially those that can progress to severe accident conditions. The spent fuel pool is a regional routine that calculates the spent fuel pool thermal hydraulics during a postulated loss of cooling event, including best estimate evaluations of operator procedures and success criteria during the transient.

II. A. Fuel Assemblies & Fission Product Models

The spent fuel pool model in MAAP5 uses the same core and fission product models as an in-vessel MAAP5 sequence with a few minor differences in the geometric modeling of the core. Figure II-1 shows the Axial Nodalization of Fuel Assemblies in a PWR Spent Fuel Pool.

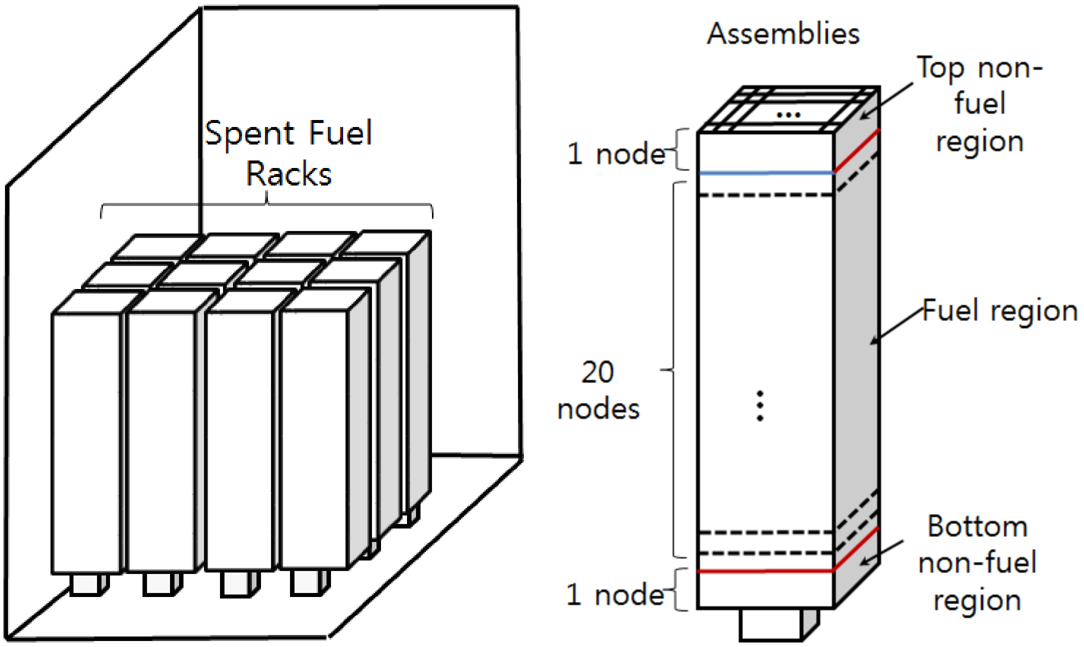

Figure II-1 Axial Nodalization of Fuel Assemblies in a PWR Spent Fuel Pool

II. B. Inventory

The base spent fuel pool model can be set up to simulate the refueling operation condition, which consists of a full core offload 100 hours after reactor shutdown with 15 previously offloaded batches. For simplicity, it is assumed in the MAAP5 model that the entire core is offloaded instantaneously at 100 hours, which is conservative since this maximizes the decay heat in the spent fuel pool.

It is assumed that there are the 241 assemblies in the APR1400 core. During a refueling outage, the maximum number of assemblies discharged (100) will occur once every third refueling outage with the remaining 141 assemblies being split (71/70) between the subsequent two refueling outages. This pattern is then repeated throughout the future plant cycles. The

MAAP5 SFP model will use the same pattern when determining the number of assemblies included in each discharged batch. MAAP5 model will model 18 fuel groups, one for each of the 15 previous batches and three for the full core offload. The full core offload is split into three groups, in MAAP5, to simulate the partial burnup included on the once and twice burned fuel.

II. C. Decay Heat

The methodology for decay heat in MAAP5 is to calculate the decay heat based on user inputs for cycle length, cooling time, burnup per cycle, enrichment, and initial uranium loading. The methodology is recommended for use when fuel has been recently discharged to the spent fuel pool, because the reduction in decay power over the sequence analysis time may have a significant impact on the event timings and results. The correlation used for decay heat calculation is that provided in ANSI/ANS-5.1.

The APR1400 spent fuel pool model is divided into 37 separate channels. It provides a table which documents the type and number of cells in each rack. It states that 10 years of storage capacity will be included in the initial construction and additional Region 2 racks will be installed to increase the storage capacity to 20 years. (15 previous batches and a full core off load)

II. D. Spent Fuel Pool Containment Model

The generalized containment and heat sink models in MAAP5 are used in the spent fuel pool model to model the pool and the fuel handling building. The MAAP5 spent fuel pool model automatically models heat sinks for radiation heat transfer between the spent fuel pool racks and the walls of the spent fuel pool.

The junctions of the containment model will ensure that the fuel handling building does not pressurize and provide a flow path for fission products to reach the environment. To model the spent fuel, pool two containment nodes were added to the model. The first containment node was added to model the spent fuel pool and surrounding fuel handling building. The second containment node was added to represent the fuel transfer canal which is connected to the spent fuel pool through the isolation gate. Figure II-2 shows the spent fuel pool containment node and Figure II-3 shows Spent Fuel Pool and Refueling Pool Layout.

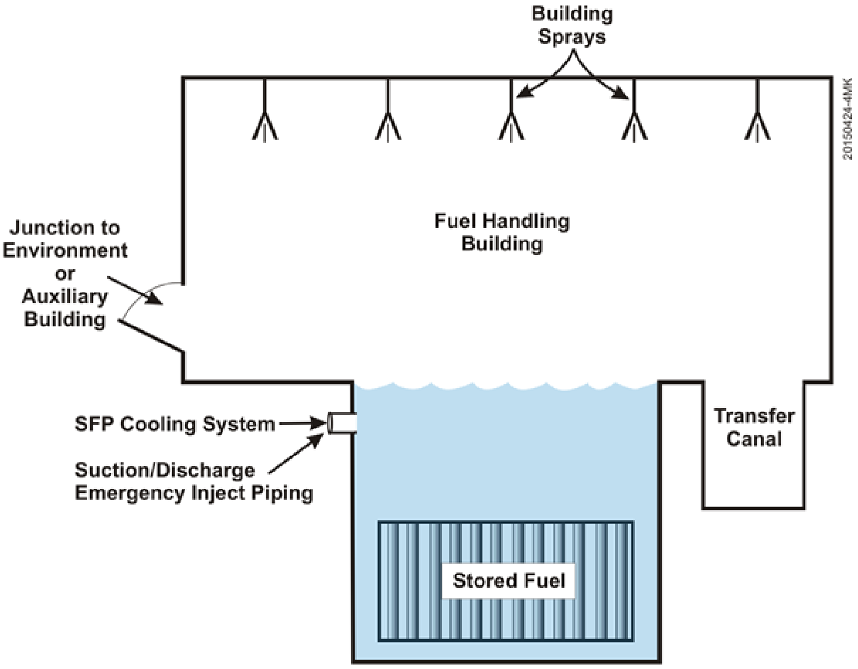

Figure II-2 Spent Fuel Pool Containment Node

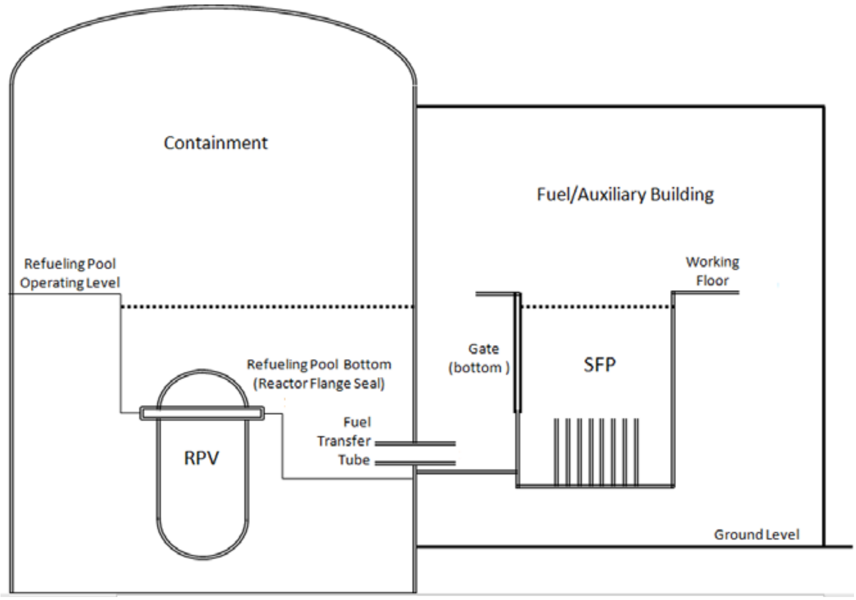

Figure II-3 Spent Fuel Pool and Refueling Pool Layout

III. Analysis Cases

III. A. Steady State

A steady state transient sequence was analyzed to demonstrate that a stable configuration is achieved when no accident conditions are present. Steady system performance is a key indicator of proper initialization and consistent model definition. Figure III-1 shows the total spent fuel pool decay heat beginning from 4 days after reactor shutdown. It can be seen that the expected exponential decay occurs over the length of the transient. Figure III-2 shows the spent fuel pool water temperature. After initialization the pool water level and temperature remain relatively constant, meaning that the spent fuel pool cooling system model is functioning as expected.

The operating cycle of the Nuclear Power Plant was discretized into six operating cycle phases (OCPs). Table III-1 shows the six OCPs that were defined in this study for the NPPs SFP. (Ref. 2)

Table III-1 Definition of Operating Cycle Phases for NPPs SFP PRA

Operating Cycle Phase	Description
OCP 1	• From power operation to hot shutdown (Tech Spec Mode 1 to 4) • Safety systems status almost identical to the power operation state as per Technical Specifications
OCP 2	Plant in cold shutdown (Tech Spec Mode 5) • Reduced RCS inventory operation performed
OCP 3	• Initial period of refueling (Tech Spec Mode 6) • Fill for refueling • RCS isolated from the spent fuel pool
OCP 4	• Plant in refueling mode (Tech Spec Mode 6) • Consists of 3 different states 1) Off-Load Fuel Movement : A full core off-loaded into the SFP in a hydraulically connected condition between the reactor side and the SFP side through fuel transfer tube 2) Defueled State: A full core loaded in the SFP with the SFP isolated from the reactor side 3) On-Load Fuel Movement: Two thirds of the full core offloaded placed back into the RPV
OCP 5	•Last period of refueling (Tech Spec Mode 6) •RCS draindown after refueling •RCS isolated from the spent fuel pool
OCP 6	•From cold shutdown to power operation (Tech Spec Mode 5 to 1)

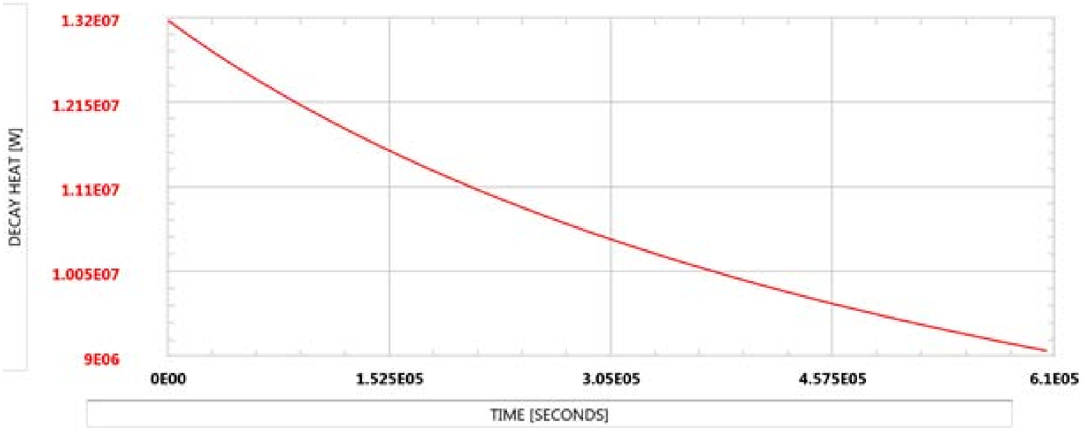

Figure III-1 Steady State SFP Decay Heat 4 Days After Shutdown

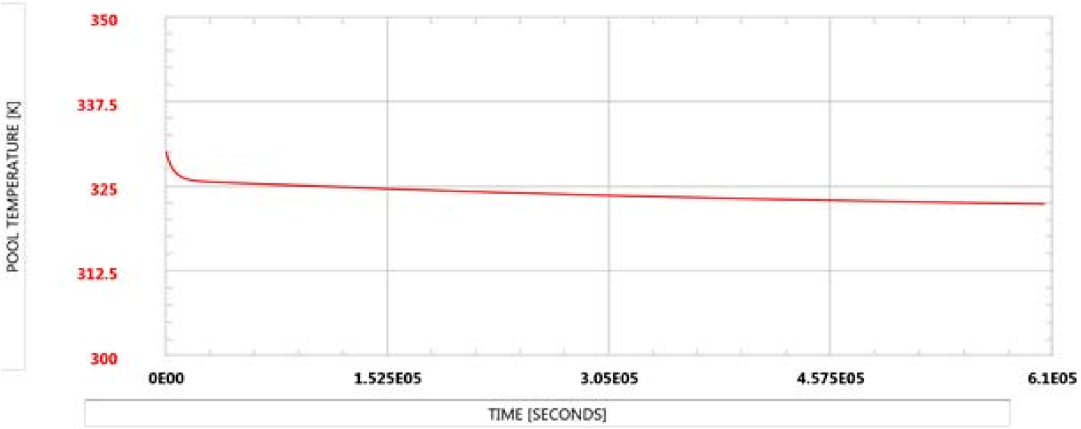

Figure III-2 Steady State SFP Water Temperature 4 Days After Shutdown

III. B. Loss of SFP Cooling

There are two major types of initiating events which can lead to a severe accident in the spent fuel pool. The first major type is an extended loss of the spent fuel pool cooling system. The extended loss of cooling can occur due to loss of electrical power to the cooling pump, loss of cooling water to the system heat exchanger, mechanical failure of the system, or unnoticed operator error. The loss of cooling accident in the spent fuel pool is characterized as a loss of decay heat removal capability. With the loss of decay heat removal the water temperature will begin to heatup and approach the saturation temperature and begin bulk boiling. If cooling cannot be restored, then the pool inventory will begin to deplete and eventually will lead to fuel uncovery and subsequent fuel heatup and melting. The following subsections will describe the specific sequences postulated for a loss of the spent fuel pool cooling system. (Ref. 3, 4)

III.B.1. Loss of SFP Cooling (Case1- OCP1)

OCP1 for the spent fuel pool analysis will be analyzed assuming the reactor has reached hot shutdown conditions following an outage after the 15th cycle. In this sequence the spent fuel pool inventory is assumed to contain only the 15 previously offloaded batches from previous cycles. The severe accident is assumed to occur at the entry into this plant operating condition (i.e. 30 days) following the last reactor shutdown. The spent fuel pool water temperature is modeled to be at an initial temperature of 120°F for normal operation.

III.B.2. Loss of SFP Cooling (Case2- OCP5)

OCP5 for the spent fuel pool analysis is analyzed assuming the entire core from cycle 16 has been removed from the reactor vessel and is being cooled in the spent fuel pool. In this sequence the spent fuel pool inventory is assumed to contain the previously offloaded 15 batches in addition to three additional batches from cycle 16. Three fuel batches are used to represent the latest core offload in order to represent the partially irradiated fuel assemblies which will be returned to the reactor vessel for future cycles. The spent fuel pool water temperature is modeled to be at an initial temperature of 140°F for refueling operation.

III. C. Loss of Inventory

The second major type of initiating events which can lead to a severe accident in the spent fuel pool is a loss of water inventory. (Ref. 3, 4) The loss of inventory accident in the spent fuel pool is characterized as a loss of spent fuel pool water to the environment. A loss of inventory can occur due to a break in the cooling system piping (possibly due to an external event such as an earthquake), seal gasket leakage, or due to failure of the anti-siphon device attached to any external hoses or pipes. The spent fuel pool cooling system is assumed to be functional until the water level drops below the suction piping elevation for the system.

OCP5 for the spent fuel pool is analyzed assuming the entire core from cycle 16 has been removed from the reactor vessel and is being cooled in the spent fuel pool. In this sequence, the spent fuel pool inventory is assumed to contain the previously offloaded 15 batches in addition to three additional batches from cycle 16. It is assumed that a loss of inventory occurs due to a break in the cooling system piping.

III.C.1. Break in Cooling System Suction Piping (Case3-OCP5)

A double ended guillotine break in the suction side of the spent fuel pool cooling system piping is characterized as gravity driven flow from both directions of the break. This occurs because water will begin to drain immediately through the suction piping. Due to a lack of NPSH the pump in the cooling system will fail and reverse flow (i.e. flow through the discharge piping) driven by the pressure in the column of water in the spent fuel pool will flow through the pump and out the second side of the break. Once the water level of the spent fuel pool drops below the suction and discharge elevation of the cooling system the flow through the break will terminate

III.C.2. Break in Cooling System Discharge Piping (Case4-OCP5)

A double ended guillotine break in the discharge side of the spent fuel pool cooling system piping is characterized as gravity driven flow and pump run out flow from the suction side of the cooling system. This occurs because water will begin to drain immediately through the discharge piping. The spent fuel pool cooling pump will maintain enough NPSH to continue operating and the flow rate will be at the pump run out flow because of the atmospheric back pressure. Once the water level of the spent fuel pool drops below the suction and discharge elevation of the cooling system the flow through the break will terminate. The flow rate driven by the pump will be modeled as a constant 4000 gpm of cooling pump capacity following a break in the discharge piping.

III. D. Severe Accident Indicators

There are several key indicators which will show the severe accident progression in the spent fuel pool. These key indicators include spent fuel pool water temperature, fuel temperature, water level, and fuel handling building environment conditions. These key indicators will be used to provide insight into the accident progressions. Table III-2 shows water level indicators and functions.

The second major indicator is the temperature of the water pool because this will indicate when the spent fuel pool water has begun boiling. The third major indicator is the fuel temperature during the sequence because this will indicate when significant oxidation and fuel damage occurs. When the oxidation reaction has reached the runaway criteria significant fission product release can be expected.

Table III-2 Water Level Indicators of SFP

Indicator	Description
SFP Cooling Suction	Loss of SFP cooling occurs when water elevation drops below this elevation
10 Feet above fuel	Typically lose radiation protection functionality
Top of Fuel	Fuel begins to uncover
2/3 of Fuel	Fuel heatup begins
1/3 of Fuel	Significant fuel heatup occurring
Fuel Fully Uncovered	Fuel complete uncovered

IV. Results

IV. A. Loss of SFP Cooling

The first two sequences which were performed were for a loss of cooling in OCP1 and in OCP5. The difference between these two sequences is the decay heat load which is present in the spent fuel pool.

OCP5 represents a significantly larger decay heat load in the spent fuel pool. Figure IV-1 provides a comparison of the differences in decay heat. It can be seen that the decay heat in OCP5 is approximately four times greater than OCP1. Table IV-1 provides timings of accident indicators such as boiling and fuel damage. Sequence 2 shows that the large decay heat in OCP5 is having a significant impact on the results as compared to sequence 1.

This causes the water level to decrease more rapidly and progress to sever accident conditions (cladding oxidation, fuel melting, and relocation) much earlier than OCP1.

Table IV-1 The timings of accident indicators for Loss of Spent Fuel Pool Cooling

No	Name	Time to Boiling [hours]	Time to Fuel Damage [hours]	Time to SFP Structure Breach [hours]	Time to Zirconium Oxidation [hours]	Time to Hydrogen Burn [hours]
1	Case1-OCP1	85.5	N/a	N/a	N/a	N/a
2	Case2-OCP5	12.4	175	N/a	172	175

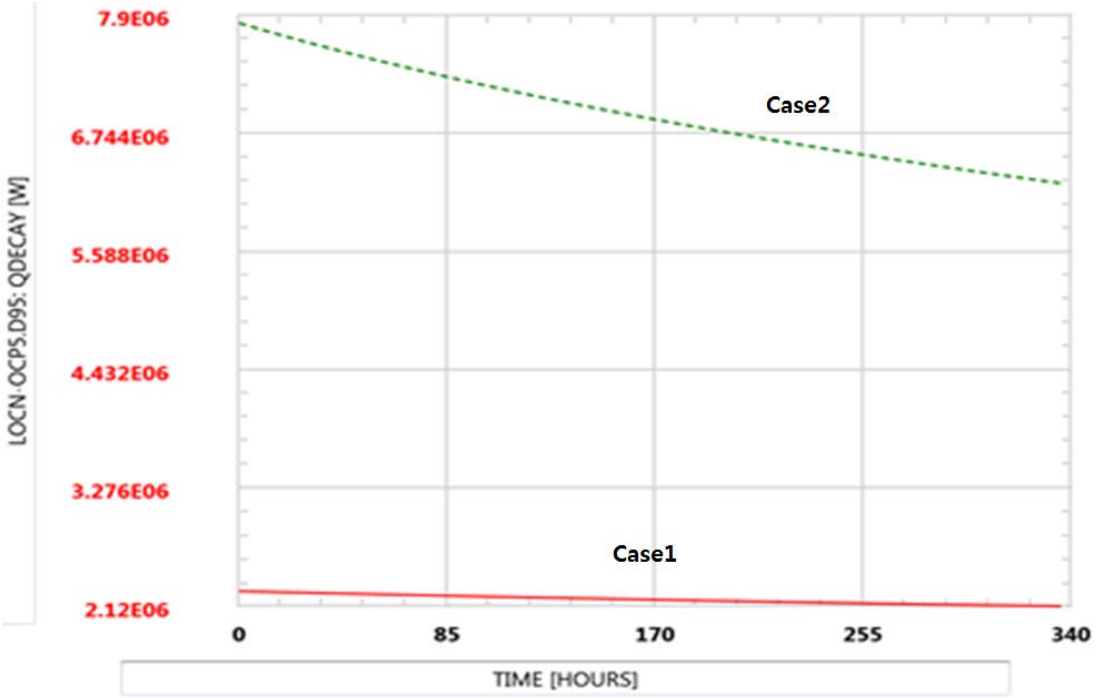

Figure IV-1 Decay Heat of Case1-OCP1 and Case2-OCP5

IV. B. Break in Cooling System Suction and Discharge Piping

IV.B.1. Break in Cooling System Suction Piping (Case3-OCP5)

Because the break occurs on the suction side, it was assumed that both the suction and discharge side of the piping would have gravity driven flow. Further, no cooling would be available once the break was initiated, and there were no other safety mitigation actions defined.

The break leads to rapid draining of the SFP pool. Once the water level reaches the level of the break, there will no longer be any draining of the SFP pool due to the break in the suction piping. After that, the only additional loss of inventory is caused by the water boiling because of the loss of cooling.

IV.B.2. Break in Cooling System Discharge Piping (Case4-OCP5)

Four cases were performed with a break in the SFP cooling discharge piping. These breaks differ from the breaks defined in Section IV.B.1 because these breaks occur on the discharge side of the SFP cooling pump and it is assumed that the pump will continue to operate. Thus, instead of two gravity driven breaks, there will be one gravity driven break and one break limited by the pump run-out flow rate.

For the discharge break, the water level will reach the elevation of the SFP cooling line slightly earlier, compared to that for the suction break. After that point, both the suction break and discharge break will progress in a similar manner. Table IV-2 provides timings of accident indicators such as boiling and fuel damage.

Table IV-2 The timings of accident indicators for Break in Cooling System Piping in OCP5

No	Name	Time to Boiling [hours]	Time to Fuel Damage [hours]	Time to SFP Structure Breach [hours]	Time to Zirconium Oxidation [hours]	Time to Hydrogen Burn [hours]
1	Case3-OCP5	8.73	125	N/a	122	126
2	Case4-OCP5	8.73	125	N/a	122	125

V. Conclusion

This paper describes the process used to develop the definition of mitigating actions and operator response timings using the MAAP5 thermal hydraulic analysis code. The analysis cases are selected for the loss of cooling due to cooling system unavailability such as failure of all active and/or passive safety mitigation systems. The loss of coolant analysis cases are selected to analyze the break in the cooling system suction piping and cooling system discharge piping.

OCP5 has considerably more decay heat than OCP1. Even without cooling available, the decay heat at OCP1 is small enough to not cause significant accident progression in a two week time frame. The break in cooling system discharge piping is slightly faster than that in cooling system suction piping. So, the break location in cooling piping does not impact the results significantly. The case with a break in cooling system piping is much faster than that without break because the break leads to rapid draining of the SFP pool.

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