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Analysis of the inherent response of nuclear spent fuel pools

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ABSTRACT

This work performs an analysis of the inherent nuclear spent fuel pool response to a loss of pool cooling accident. The influence of fuel offload times, fuel assembly arrangement, fuel assembly binning for modelling, and building compartmentalization are evaluated. These impacts are assessed through sensitivity calculations performed with the MAAP code. Results are compared in terms of selected significant safety quantities such as fuel uncovery time, hydrogen generation, building temperature, relocated mass to the floor, and integrated total radiological dose at 1 km distance from the spent fuel pool.

According to the results, the impact of the fuel assembly arrangement on the output safety quantities is more limited than initially expected. Also, the offload power (as a function of elapsed time between shutdown and removal from the reactor pressure vessel to the spent fuel pool), relevant in the pre-uncovery phase, does not present a crucial role in fuel damage progression.

Somewhat unexpectedly, user effects on the building modelling hosting the pool significantly affect its inherent response. This is due to the large influence that natural circulation currents of gas have on mitigating fuel damage as such currents significantly rely on the modelling of the building in terms of nodalization, thermodynamic imposed conditions and heat sinks configuration. Follow-on work is identified to address uncertainties in the calculation of natural convective flows and heat transfer.

1. Introduction and contents

Spent Fuel Pool (SFP) loss-of-cooling accidents feature very long times–ranging in the order of days if not weeks–before reaching degraded conditions (The National Academies of Sciences, 2016). This is the main reason why many nuclear licensees have not taken any further commitment to improve safety related to the SFP accident response. In addition, conducted probabilistic risk assessments show very low core damage frequencies based on the available time for recovery actions, but also on its high degree of versatility (as there are multiple means to provide alternative cooling in the case of an accident) and low degree of complexity (as the safety of the SFP relies on covering the FAs (fuel assemblies) with water).

Notwithstanding the above, both IAEA and WENRA have issued recommendations (IAEA, 2016; WENRA, 2013) pointing at the so-called 'practical elimination conditions' through which nuclear plants shall prevent conditions that result in large and/or early radioactive releases. These organizations have warned utilities not to solely base their arguments in low-frequency numbers but to support them with highly reliable safety response to residual-risk, high-consequence events. The emphasis placed on providing countermeasures against severe accidents has increased after the events that unfolded in Fukushima-Daiichi. A broader approach to risk is now emphasized, where events falling under residual risks (Yang, 2014) (i.e. risks assumed in the operation of the plant) is now being taken into consideration.

Such an attitude towards reducing the level of risk, no matter how low accident frequencies are, goes in line with the ALARA/ALARP (as low as reasonably achievable or practicable) approach (Melchers, 2011). This concept has been recently applied for determining the risk criteria in the management of the Fukushima-Daiichi decommissioning plans: The Nuclear Damage Compensation and Decommissioning Facilitation Corporation (NDF) has developed a comprehensive risk reduction strategy for all units at the Fukushima Daiichi site. According to the results (Cf. Figs. 3–5 in (NDF, 2016)), the risk attributed to the SFPs are ranked at the highest level. Such high value mainly derives from the hazard side of risk as the SFPs store huge amounts of radioactive nuclear material, far beyond those located within the reactor pressure vessel. As a consequence, plans have been developed to promptly take the FAs (fuel assemblies) out from the SFPs and store them in dry casks.

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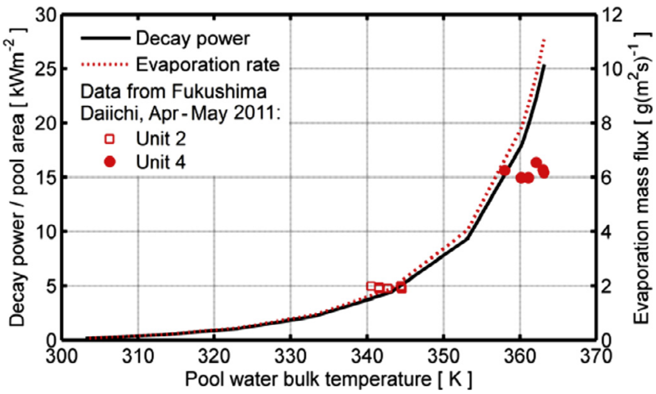

Fig. 1. Thermal equilibrium temperature vs decay power to pool area ratio and evaporation mass in Fukushima Unit 2 and 4 SFPs (taken from (The National Academies of Sciences, 2016).

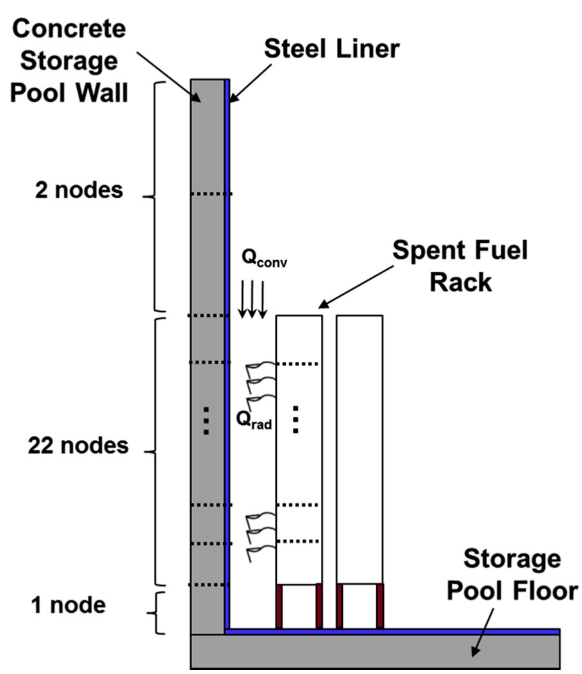

Fig. 2. MAAP SFP wall heat sinks. Elevation view.

Well before the occurrence of the Fukushima Daiichi accidents, several reports had already warned about low-frequency accidents at the SFP leading to long-term contamination consequences worse than those from the Chernobyl accident (Collins and Hubbard, 2001; Alvarez et al., 2003), some of which included recommendations to improve safety and mitigation.

The current work aims at analysing the impact that different modifications performed at an SFP or SFP building level can have on the accident response through performing sensitivity calculations with the MAAP nuclear integral system code. Within these modifications, the influence of user effects on the results has also been studied and reported hereafter.

Section 2 elaborates on the selected approach to address the issue, together with the scope of the work. The third section analyses recommendations to improve SFP safety, as well as identifies suitable indicators to measure the impact each input modification has on the SFP response. The fourth section presents the implemented model and simulation tool used to perform the simulation, whose results are first analysed in section five, and afterwards used as a first reference calculation when carrying out sensitivity simulations in section six. The last section is devoted to conclusions.

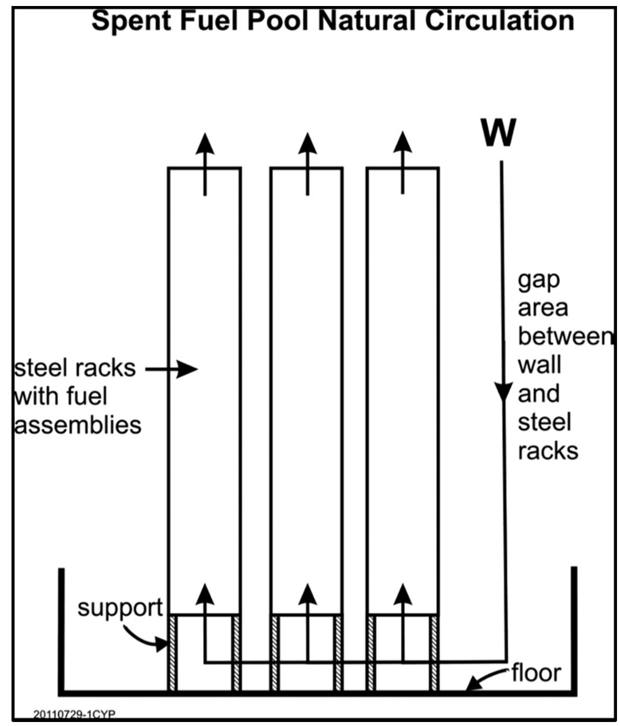

Fig. 3. MAAP SFP natural circulation flow paths. Elevation view.

2. Approach and scope

In terms of accidents occurring in the SFP, both operating experience and analysis of potential events (Nuclear Energy Agency, 2017) allow us to classify them into two main categories, namely loss-of-cooling and loss-of-coolant accidents. Each of them evolves along different time phases. The latest phase of the loss-of-cooling accidents (i.e. the fully uncovered phase where the water level has dropped below the fuel assembly inlet elevation) shares some important aspects with loss-of-coolant accidents. In particular, the importance of air natural circulation in arresting/preventing fuel damage, as later on analysed in Section 6.

Loss-of-cooling events are characterized by a slow progression evolution where water is gradually lost by boiling or evaporation. This first, pre-uncovery phase comes to an end when the water level reaches the Top of Active Fuel (TAF). The second, partial uncovery phase begins with the FA uncovery until reaching around half the height of the FAs (The National Academies of Sciences, 2016). During this first part, the water boils up–if not boiling already during the pre-uncovery phase–and cools down the FAs effectively. This cooling prevents the fuel from reaching critical temperatures for triggering degraded cladding phenomena such as ballooning and oxidation. The second part of the partial uncovery phase begins with the heating up of FAs with associated large amounts of hydrogen and radiation releases. During the heating up process, the mechanical integrity of the FAs is lost with the potential of subsequent relocation to the SFP floor. This phase continues until the water level reaches the Bottom of Active Fuel (BAF). The third, full uncovery phase is characterised by the interaction of the FAs with the surrounding air. If the accident is not arrested, it may eventually result in molten corium concrete interaction (MCCI) and subsequent non-condensable gas release.