PSA of the Spent Fuel Pools at Oskarshamn 3

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Abstract: New regulations for Swedish NPP's require a PSA for Spent Fuel Pools (SFPs) during power operation. With the operational conditions being distinct from a planned outage, the existing PSA for the SFPs during a planned outage was not directly applicable. The criteria for identifying and screening initiating events required adaptation and with the introduction of the independent core cooling system (OBH) which takes water from the SFP's, system dependencies during power operation required further analysis. A deterministic and conservative model for the water temperature and subsequent boil-off rate in the SFP's was developed and some conservative bounding cases were defined. Identified initiating events were then categorised by which bounding case represented the worst-case scenario for each initiating event. The initiating events whose consequence were not directly applicable to a bounding case were instead analysed by probabilistic means. All initiating events could subsequently be screened out for the Oskarshamn 3 SFP's.

Keywords: PSA, Spent Fuel Pools, Screening.

1. INTRODUCTION

The Swedish radiation safety authority (SSM) updated in 2018, with additional amendments since, the regulations for basic provisions for licensees of ionizing radiation producers [1]. In it, they specify that:

The probabilistic safety analyses shall consider:

1. *The frequency for damage to nuclear fuel elements (Level 1), and*
2. *The frequency for release of radioactive nuclides to the environment as a consequence of damage to nuclear fuel elements (Level 2).*

This requirement consequently includes nuclear fuel outside of the core during power operation, startup and shutdown, specifically nuclear fuel in the Spent Fuel Pools (SFP). Having not been assessed previously by the PSA for Oskarshamn 3, a 1450 MWe BWR plant, hereinafter referred to as O3, it was necessary to update the PSA to also include the fuel elements in the SFP during power and low power conditions to satisfy the new regulation.

2. DEFINITIONS AND ASSUMPTIONS

As the PSA Level 1 is not only focused on fuel elements in the reactor core the additional Level 1 consequence Fuel Damage (FD) was defined. The definition of FD was conservatively chosen to be the time at which water level reaches the top of the fuel elements in the SFP's, whereas the criterion for CD considers a time-limited bounding temperature as calculated by MAAP. It is assumed that the cooling of the fuel elements will not be sufficient as soon as they are fully submerged in water level, causing a meltdown and subsequent release. Since there are no active system barriers in place to mitigate a release from the SFP, the interface between PSA Level 1 and Level 2 is immediate for the SFP's. It shall also be noted that in the concept of FD lies the aspect that the radioactive release to the environment needs to be significant to be considered. A release that exceeds 0,046% of the core inventory in O3 (focusing on CS-134 and Cs-137) is considered as an unacceptable release from a PSA Level 2 perspective and this criterion has also been applied in the SFP PSA. This means in practice that mechanical damage of fuel elements, cladding damage, etc. is not included in the concept of FD for release to the environment. For FD to be include in the release to the environment, fuel elements in the SFP's have to face thermal damage (over heating followed by melt down).

The deterministic screening time for initiating events was chosen to be 50 hours, the same as is being used in the PSA for planned outage which studies damage to fuel elements situated both in the reactor core and the SFP during outage conditions. This means that if it can be shown that the FD end state is not reached within

50 hours the initiating event can be screened out. It was recognised during the work that the amount of residual heat in the SFP's are lower during power operating conditions than during outage conditions (during which fuel elements will be transferred from the reactor core to the SFP before they are replaced to the reactor core). Despite this, the 50 hours screening time was chosen in order to be coherent with the outage PSA. An important aspect here is that the SFP PSA would utilize the same mission times as in the already existing PSA, e.g. 48 hours for PSA Level 2.

The probabilistic screening criterion for initiating events was set to $f_C = 10^{-7}$/year, i.e. if it can be shown that the frequency of the initiating event is less than the criterion the event can be screened out.

In addition to the existing Deterministic Safety Assessment for O3, potential initiating events were compiled from [2][3][4] and were assessed and screened for their relevance to the SFP's at O3.

3. OVERVIEW OF THE SFP's AND INTERFACING SYSTEMS

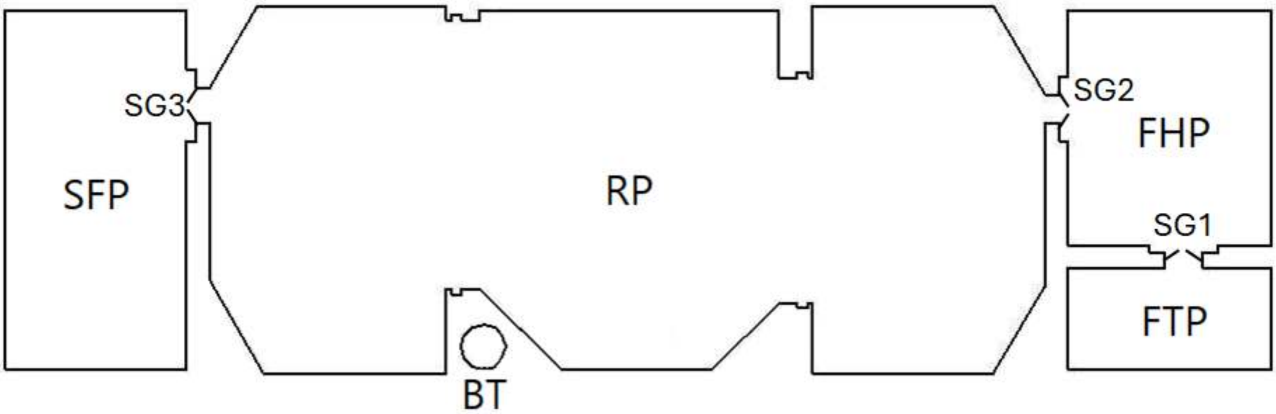

Figure 1 Overview of the spent fuel pools at Oskarshamn 3

The SFP's at O3, seen in Figure 1, consist of a reactor pool (RP), a spent fuel pool (SFP), a fuel handling pool (FHP) and a fuel transfer pool (FTP). The SFP and FHP/FTP are at opposite ends of the RP. All pools are cooled by a pool cooling system. The pools are drained from the edges in to the balancing tank (BT) connected to the pool cooling system that pumps the water through heat exchangers before it returns to the pools. If the BT is empty and the water level in the pools is below the drains, circulation and cooling ceases. The water inlet to the pools is placed below the waterline. In the case of loss of coolant from the inlets the water level in the pools can at most be reduced to the height of the inlets.

The cooling system has a diversified secondary pump and heat exchanger system in case the primary system is inoperable or insufficient. The RP has a bottom drain connected to the independent core cooling system which uses the RP as its primary source of cooling water. The FTP also has a bottom drain for maintenance purposes. To prevent water level from dropping in the SFP when water is drained from the RP or FTP, the FTP has an outwardly facing self-closing sluice gate between it and the FHP (SG1) and the RP also has outwardly facing self-closing sluice gate towards both the FHP (SG2) and SFP (SG3).

4. DEFINITION OF BOUNDING CASES

Given how the SFP's pools are designed, taking into account the construction of the SFP's and the interfacing systems, three conservative bounding cases were identified:

(i) Extended Loss of All Power (ELAP) such that recirculation and cooling ceases.
(ii) The same as (i) with the addition that an instantaneous drop of water level to the water inlet is assumed to occur simultaneously as the ELAP.
(iii) Loss of Ultimate Heatsink (LUHS), allowing for recirculation of water from all pools but no cooling of the water by the heat exchangers.

The following assumptions were made for all bounding cases:

- The sluice gate between the fuel storage pool and the central pool is assumed to be closed.
- Any heat exchange between the water in the pools and the air or any pool structure is ignored.
- Evaporation is ignored, meaning that the mass of the water is assumed to be constant before boiling.
- The residual heat is assumed to be constant and equal to the residual heat of the fuel at the end of a planned outage.

5. ANALYSIS OF BOUNDING CASES

Assuming a rectangular cuboid geometry for the SFP where the surface of the pool has constant area $\boldsymbol{A}$, the total height of the water in the SFP is defined as

$$h(t) = h_f + h_s(t), \tag{1}$$

where h_f is the height of the water up to the top of the fuel elements and $h_s(t)$ is the height of the water from the top of the fuel elements to the surface of the pool at time t, called the screen height. When $h_s(\tau) = 0$ for some time τ the definition for FD is met. The volume of the water in the pool is known and so the mass of the water is computed using the density of water ρ at the initial temperature $T(t = 0) = T_0$.

The heat added to the water can be proportionally related to the mass, specific heat capacity and temperature increase of the water as

$$dQ = mc\, dT. \tag{2}$$

Integration of the left-hand side yields the energy added to the mass which we assume is the residual heat from the fuel. The energy imparted is linearly dependent on the radiated power $\boldsymbol{P}$ and the time $\boldsymbol{t}$. The radiation and absorption of energy is assumed to be homogenous and isotropic throughout the SFP. Assuming that the specific heat capacity and mass of the water is constant with respect to temperature, the time for the pool to reach a temperature up to boiling is given by the integral

$$\tau(T) = \frac{mc}{P}\int_{T_0}^{T} dT = \frac{mc}{P}(T - T_0). \tag{3}$$

The mass of the water in the pool can be expressed in terms of the height in Eq. (1) as

$$m(t) = \rho(t)\big(Ah(t) - V_{fuel}\big)\,, \tag{4}$$

Where A is area of the surface of the pool and V_{fuel} is the volume of water displaced by the fuel and the fuel rack. Since the mass is assumed to be constant, $m(t) = m$, then by Eq.(4) we find that $\frac{d}{dt}(\rho(t)h(t)) = 0$. In other words, the height increase of the SFP exactly corresponds exactly to the thermal expansion of the SFP as the density decreases with temperature. The expanded height h_E can be expressed as a function of temperature by taking the initial height $h_0 = h(0)$ from Eq. (*1*) to define Eq. (*5*) as

$$h_E(T) = h_0 + \frac{m}{A}\left(\frac{1}{\rho(T)} - \frac{1}{\rho(T_0)}\right), \tag{5}$$

where it relates to the difference of the reciprocals of the density of the water at temperature T and the initial density of the water at temperature T_0.

Once the SFP has reached boiling temperature, all the heat added is assumed to contribute entirely to converting the mass of the water from liquid to gas, given the enthalpy of vaporization ΔH_{vap}. The mass of water from the water screen that boils off, m_b, can be expressed as a function of time in Eq. (6) as

$$m_b(t) = \frac{P}{\Delta H_{vap}} t. \tag{6}$$

This mass is subtracted from the (constant) mass function in Eq. (*4*), yielding a linear mass function with respect to time. Substituting the height function $h(t)$ in Eq. (*4*) with the expanded height $h_E(t)$ in Eq. (*5*), remembering that $h_0 = h_f + h_s$, and rearranging in terms of the time t, the time taken to boil off water to a screen height h_s is defined in Eq. (*7*) as

$$\tau(h_s) = \frac{\Delta H_{vap}}{P} A\rho\big(h_E(T = 100°\mathrm{C}) - \big(h_s + h_f\big)\big), \tag{7}$$

The sum of Eq. (3) and Eq. (7) yields the time to FD, assuming no cooling and circulation after an initiating event, and therefore represents the time for bounding case (i).

For bounding case (ii), the initial height h_0 is reduced to the height of the inlets h_I and assumed to be constant for the calculation of the time to boiling, which implies reducing the initial mass by $(h_0 - h_I)\rho A$. The constant height approximation yields a time to boil that is <2% longer than accounting for the mass flow out of the inlets due to thermal expansion[1]. For the boil off time the expanded height h_E is also reduced to the height of the inlets h_I.

Bounding case (iii) allows for the circulation of water between the pools, resulting in a larger effective mass of water, in turn leading to a longer time to heat and boil off. For this reason, bounding cases (i) and (ii) can be considered as bounding cases to (iii) and so no explicit analysis of bounding case (iii) is presented here.

For all bounding cases, the time to FD was $>$50h, i.e. greater than the deterministic screening time.

6. SCREENING OF INITIATING EVENTS AFFECTING THE POOL COOLING SYSTEM

Initiating events affecting the SFP cooling system can most conservatively either lead to complete failure of cooling and/or circulation, or a loss of coolant from the inlet with an equivalent loss of cooling and/or circulation. Bounding cases (i) and (ii) represent such cases and so since the time to FD for the bounding cases is greater than the deterministic screening time then all initiating events which primarily affect the SFP cooling system can be screened out.

7. ANALYSIS OF LOSS OF COOLANT FROM THE FTP

If there is a loss of coolant from the bottom drain of the FTP, water levels can sink in all pools, including the SFP, until there is not enough water to recirculate through the cooling system. There are 3 sluice gates separating the FTP and SFP, see Figure 1, where the bottom of the sluice gates are close to the top of the fuel elements. It is therefore assumed conservatively that FD cannot be avoided if all three sluice gates remain open at the same time as an initiating event causes the FTP to drain from the bottom.

It is sufficient for any of these sluice gates to close to maintain sufficient water levels in the SFP. The sluice gates are kept closed during power operation. During fuel transport, the two sluice gates between the SFP, RP and FHP (which will be denoted sluice gates 1 and 2 respectively) are kept open while the sluice gate between the FHP and FTP (denoted sluice gate 3) is closed. For this reason, the conditional probability that sluice gates 2 and 3 are open is conservatively assumed to be equal to 1. A CCF for the failure of automatic closing of the sluice gates is conservatively assumed. Likewise, complete dependency is conservatively assumed whenever manual closing is considered for >1 of the sluice gates. Probabilistically, the following sequence of independent events (and their associated frequencies f_i and probabilities p_i) are necessary and sufficient for FD:

- f_1: Loss of coolant from the bottom drain of the FTP due to pipe rupture
- p_2: Inadvertently open sluice gate 1
- p_3: Inadvertently open sluice gate 2&3

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[1] Instead of assuming a constant mass, a constant volume up to the inlets is assumed. By then integrating the density across the temperature increase, where density monotonically decreases with temperature in this range, the mass decreases, which can be interpreted as the mass flowing out of the inlet unrestricted. The lower mass requires less energy to reach boiling and so yields a shorter time.

- p_4: Failure of automatic closing of sluice gates 1, 2 & 3
- p_5: Failure of manual closing of sluice gates 1, 2 & 3

Plugging in conservatively estimated values for each independent event into Eq. (8) yields

$$f_1 \cdot p_2 \cdot p_3 \cdot p_4 \cdot p_5 < f_C \,. \tag{8}$$

i.e. the event is screened out by use of the probabilistic screening criterion.

If sluice gates are closed yet water levels drop such that the balancing tank's water volume is insufficient to maintain circulation, the scenario is comparable to bounding cases (i) and (ii), depending on the magnitude of the water level decrease.

All initiating events causing a loss of coolant from the FTP can be screened out.

8. ANALYSIS OF LOSS OF COOLANT FROM THE RP

The independent core cooling system (OBH) use the RP as its primary water supply. Loss of coolant due to pipe rupture within the OBH system is screened out from the full power internal events PSA for O3 since the system is in standby, and thereby isolated, during power operation. As a proxy for the frequency of activation of OBH, the frequencies for core damage due to inadequate core cooling and core damage due to inadequate residual heat removal are used[2]. The conservatively assumed frequency for an inadvertently open sluice gate is higher than the frequency of fuel transport campaigns during which sluice gate 3 is open. It is therefore more likely that an OBH activation occurs in combination with an inadvertently open sluice gate than an OBH activation occurring during a fuel transport campaign. Probabilistically, the following sequence of independent events (and their associated frequencies f_i and probabilities p_i) are necessary and sufficient for FD:

- f_1: Activation of OBH
- p_2: Inadvertently open sluice gate 3
- p_3: Failure of automatic closing of sluice gate 3
- p_4: Failure of manual closing of sluice gates 3

Plugging in conservatively estimated frequency for each independent event into Eq. (9) yields

$$f_1 \cdot p_2 \cdot p_3 \cdot p_4 < f_C, \tag{9}$$

and so the event is screened out by the probabilistic screening criterion.

Similar to the analysis for loss of coolant from the FTP, bounding cases (i) and (ii) are comparable to the scenario where the sluice gates are successfully closed but the water levels drop with consequent cessation of circulation and cooling.

All initiating events causing a loss of coolant from the RP can be screened out.

9. ANALYSIS OF LOAD DROP ACCIDENTS

Potential load drop accidents are divided in to lifting of loads with a mass less than 1000 kg and lifting of loads exceeding 1000kg.

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[2] A conservative proxy by virtue of OBH activation make up less than 20% of the sequences that lead to core damage.

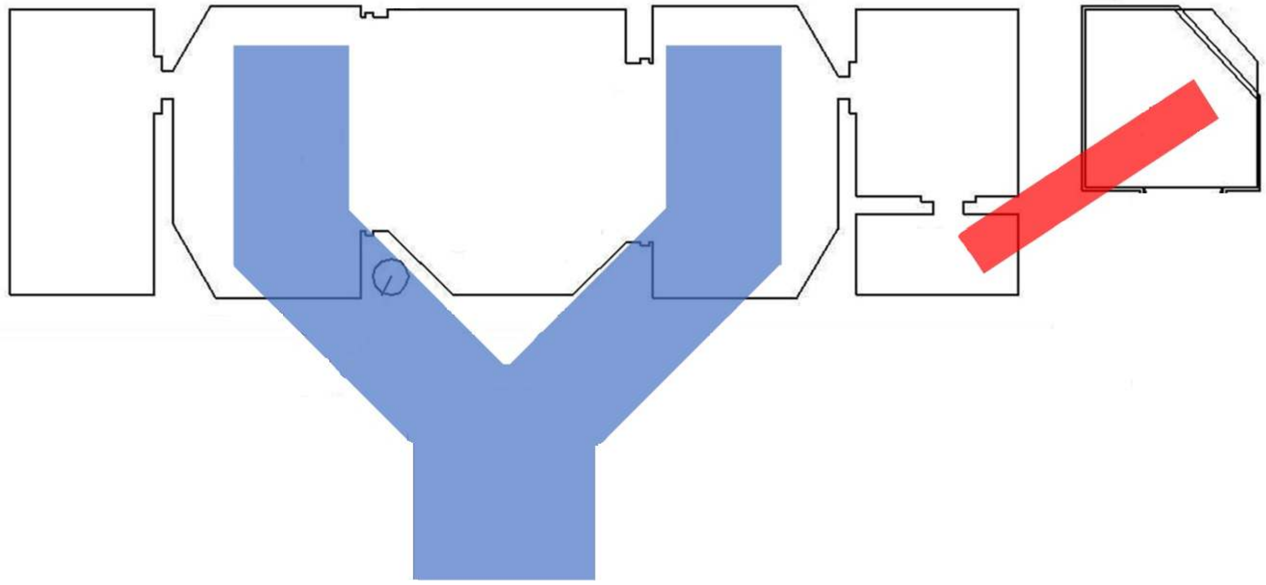

Figure 2 Lifting zones for the reactor pool bridge (shown in blue) and the fuel transport cask (shown in red).

Loads less than 1000 kg include fuel elements, control rods, tools, and other components. Mechanical damage to the pool structure is assumed to be negligible due to such loads being dropped. The fuel storage rack in which the fuel elements are placed is designed such that no significant reactivity excursions can occur from a dropped fuel element. Mechanical damage to the affected fuel elements can lead to limited releases, typically gap release from ruptured cladding, that do not satisfy the condition for FD.

Loads greater than 1000kg, called heavy load drop accidents, include the fuel transport cask and the reactor pool bridge, see their lifting zones in Figure 2. Heavy load drop accidents could lead to severe loss of coolant in the pools or damage to fuel elements and the fuel rack such that reactivity excursions cannot be excluded.

The lift of the fuel transport cask takes place between the FTP and the transport shaft adjacent to the FTP. The fuel transport cask can therefore be dropped in the FTP, causing a loss of coolant accident. Fuel elements must not be stored in the SFP when the left of the fuel transport cask takes place. If the lifting procedure is not followed and it is lifted outside of the allowed lift zone, the cask could be dropped in the FHP or even the RP. The four identified least unlikely scenarios involving the fuel transport cask that could lead to FD are:

(1a) The cask is dropped outside the allowed lift zone in the FHP while fuel is stored in the FHP and the joining sluice gate is open, causing mechanical damage to the fuel rack and a subsequently a reactivity excursion with radiological release.
(1b) The cask is dropped outside the allowed lift zone into the RP causing a loss of coolant from the RP while the sluice gate to the SFP (SG3) is open.
(1c) The lift take place within the allowed lift zone and the cask is dropped in the FTP causing a loss of coolant from the FTP while fuel is stored in the FHP and SFP.
(1d) The lift take place within the allowed lift zone and the cask is dropped in the FTP, causing a loss of coolant from the FTP. Fuel is only in the SFP.

Scenario (1a) is probabilistically analysed in Eq. (10) as the product of the independent events of dropping the fuel transport cask outside of its lift zone (f_1) and fuel remaining in the fuel service pool even though this is a violation against the lifting procedure (p_2).

$$f_1 \cdot p_2 < f_C. \qquad (10)$$

The scenario is therefore screened out in accordance with the probabilistic screening criterion.

Scenario (1b) is probabilistically analysed similar to the loss of coolant in the RP analysed in Chapter 8 Eq. (9), the difference being that the frequency for activation of OBH (f_1) is replaced with the frequency of dropping the fuel transport cask outside the lift zone. The frequency for dropping the fuel transport cask outside the lift zone is less than the frequency for activation of OBH and so the scenario is screened out.

Scenario (1c) is also probabilistically similar to the loss of coolant in the RP analysed in Chapter 8 Eq. (9), the difference being that the frequency for activation of OBH (f_1) is replaced with the frequency of dropping the fuel transport cask inside the lift zone and instead of sluice gate 3 it is sluice gate 1 (probabilistically identical). The frequency for dropping the fuel transport cask inside the lift zone is less that the frequency for activation of OBH and so the scenario is screened out.

Scenario (1d) is similar to loss of coolant from the FTP analysed in Chapter 7 Eq. (8), the difference being that the frequency for loss of coolant is replaced with the frequency of dropping the fuel transport cask inside the lift zone. The frequency for dropping the fuel transport cask inside the lift zone is less that the frequency for a pipe rupture and so the scenario is screened out.

Since the reactor pool bridge can only be dropped in the RP, the scenario is probabilistically similar to the scenario considered in Chapter 8 Eq. (9), the difference being that the frequency for the activation of OBH (f_1) is replaced with the frequency of dropping the reactor pool bridge. The frequency for dropping reactor pool bridge is less than the frequency for activation of OBH and so the scenario is screened out.

All load drop accidents are therefore screened out.

10. ANALYSIS OF EXTERNAL EVENTS

Since the bounding cases defined in Chapter 4 includes all consequences that affect the cooling system for the pool, all external events whose consequence only affects the cooling system, such as LUHS or ELAP, are screened out. Only external events which cause structural damage are considered. Of those, only weather-related events are not screened out by the probabilistic screening criterion. An important note here though is that earthquakes are generally outside of the scope for nuclear PSA's in Sweden and hence not taken into in the analysis.

Weather-related events that cause structural damage could collapse the ceiling, causing debris to displace water in the SFP, reducing the heat capacity and cooling efficiency. Assuming the debris displaces a rectangular cuboid volume of water starting at the surface of the pool, the displaced mass is subtracted from the mass in Eq.(3) to adjust the heating time. Similarly, the initial height of the water h_0 is reduced by the height of the debris in Eq.(5) and plugged back in to Eq.(7) to adjust the boil-off time. The volume of debris from the ceiling, assuming surrounding ceiling collapses into the SFP, is not sufficient to displace enough water such that the definition for FD is met within the deterministic screening time.

All external events can therefore be screened out.

11. ANALYSIS OF LOSS OF VENTILATION

The radioactive emissions from the spent fuel includes γ-emissions which contribute to the radiolysis of the water, producing hydrogen gas. If ventilation is lost, hydrogen gas concentrations would increase in the reactor hall. The time needed for a combustible concentration of hydrogen gas to accumulate throughout the reactor hall is well beyond the deterministic screening time analysed. The motivation on why hydrogen production is in focus during loss of ventilation scenarios is that the only way that loss of ventilation could cause a severe radioactive release is if an explosion would occur that would damage the integrity of the SFP's causing the fuel elements not to be submerged in water.

Local pockets of combustible concentrations of hydrogen gas could conceivably cause mechanical damage such that heavy objects being dropped in to the pools. Since all load drop accidents and falling debris from the ceiling have been considered in chapters 9 and 10 respectively, it is conceivable that the reactor hall crane could be dislodged from its railing, given the deflagration or detonation of a sufficient amount of hydrogen gas, and cause a loss of coolant.

The reactor hall crane is parked at the opposite end of the reactor hall from the SFP. The low density of the gas implies that most trapped gases will be higher up in the reactor hall, close to the ceiling. It is thermodynamically deemed unreasonable that hydrogen gas produced in the SFP will spontaneously accumulate in high concentrations close to the reactor hall crane on the opposite side of the reactor hall. Rather, during fuel transport campaigns the fuel stored in the FHP will produce hydrogen gas that could produce local pockets of high concentrations of hydrogen gas close to the reactor hall crane. The mass of hydrogen gas produced by radiolysis during this time is approximated by Eq. (11)

$$m(t) = M \frac{G}{N_A e} P_R t, \tag{11}$$

where $M\left[\frac{g}{mol}\right]$ is the molar mass of hydrogen, $G[\frac{mol}{eV}]$ is the radiation chemical yield factor (assumed to be 1 hydrogen molecule per 200 eV), $N_A\left[\frac{1}{mol}\right]$ is Avogadros constant, $e\left[\frac{J}{eV}\right]$ is the value of the elementary charge and $P_R\left[\frac{J}{s}\right]$ is the power of the γ-emissions from the spent fuel contributing to radiolysis (assumed to be 10% of the total emitted residual heat power). Only a small fraction of all the fuel stored in the spent fuel pool is transported during any given fuel transport campaign, meaning the amount of hydrogen gas produced by this fuel is a small fraction of what is produced from the fuel in the opposite end of the reactor hall in the SFP. The computed mass, given the time spent on a fuel transport campaign, is considered too small to cause significant mechanical damage to the reactor hall crane. Therefore, loss of ventilation is screened out.

12. CONCLUSION

A combination of deterministic and probabilistic analyses was used to screen initiating events for the Oskarshamn 3 SFP's. By defining bounding cases, similarities between sequences and their consequences could identified. Since the bounding cases can be screened out on deterministic grounds, all initiating events whose consequences are comparable to the bounding cases could similarly be screened out. Some remaining events, such as external events whose consequence was not similar to that of a bounding case, or loss of ventilation, were also evaluated deterministically in terms of soundness. The remaining initiating events could be probabilistically screened out, also in this case identifying similarities in sequences. Consequently, all initiating events for the Oskarshamn 3 SFP's could be screened out.

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