Journal of Energy

VOLUME 68 Number 2-3 | 2019 | Special Issue

journal homepage: http://journalofenergy.com/

Potential Impact of Reactor Core Damage on Severe Accident Management Actions in Vicinity of Spent Fuel Pool

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ABSTRACT

Fukushima Daiichi NPP accident showed that plant technical support center (TSC) in an extreme and rare external event (design extended condition (DEC)) can have a problem in the case of coincident loss of decay heat removal from the core (possibly resulting in significant core damage) and loss of decay heat removal from spent fuel pool. From the point of view of prioritizing severe accident management strategies it looks like the priority mitigation action should be to reestablish the emergency core cooling in the reactor pressure vessel. The reason is the longer time window available before the water inventory in the spent fuel pool would be evaporated and spent fuel exposed to overheating. However, if such actions would not be successful and reactor core would, consequently, be damaged, potential design basis leakage (or even greater leakage) from the containment to the fuel handling building (FHB) can affect already established TSC measures or operator accessibility to FHB, or it can jeopardize functioning of the systems, structures and components due to radioactive releases and presence of hydrogen (independently of the fact that containment atmosphere can be inerted by steam or that containment may be equipped with passive autolytic recombiners (PARs)). Paper describes an engineering evaluation of possible hydrogen presence in the containment annulus, its flammability and leakages through the penetrations toward FHB in the case of long term station blackout (SBO) without successful restoration of the core cooling in the reactor pressure vessel. SBO accident sequence progression and amount of produced hydrogen is evaluated by MAAP code.

Keywords: *core damage, SFP, SAMG, containment leakage, MAAP*

1 INTRODUCTION

One noteworthy feature of typical Westinghouse designed PWRs is that the SFP is located in close proximity to the containment in building named Fuel Handling Building (FHB). According to [1], the investigation of severe accidents for the PWR SFP-Reactor PSA should include the assessment of possible postulated initiating events (PIEs) introducing a challenge to the SFP fuel cooling.

Very generally, the interface dependencies (illustrated by Figure 1) may arise due to the following:

1. Simultaneous failures related to the initiating event (e.g., loss of offsite power, design extension condition (DEC) seismic events, etc.)
2. Reactor severe accident conditions that result in adverse conditions affecting the FHB/SFP structure or SFP cooling/make-up equipment.

Resulting adverse conditions may include the following:

- Hydrogen release that could result in deflagration events that fail structures or electrical/mechanical equipment;
- Containment failures that cause similar effects;
- Fission product releases that inhibit or preclude access to the areas needed for local alignments;
- Failure of all installed equipment may force the TSC staff to decide where to prioritize the use of any remaining portable equipment. Staging for use in one application (e.g., reactor accident mitigation) may preclude its subsequent realignment to the SFP due to local environmental conditions.

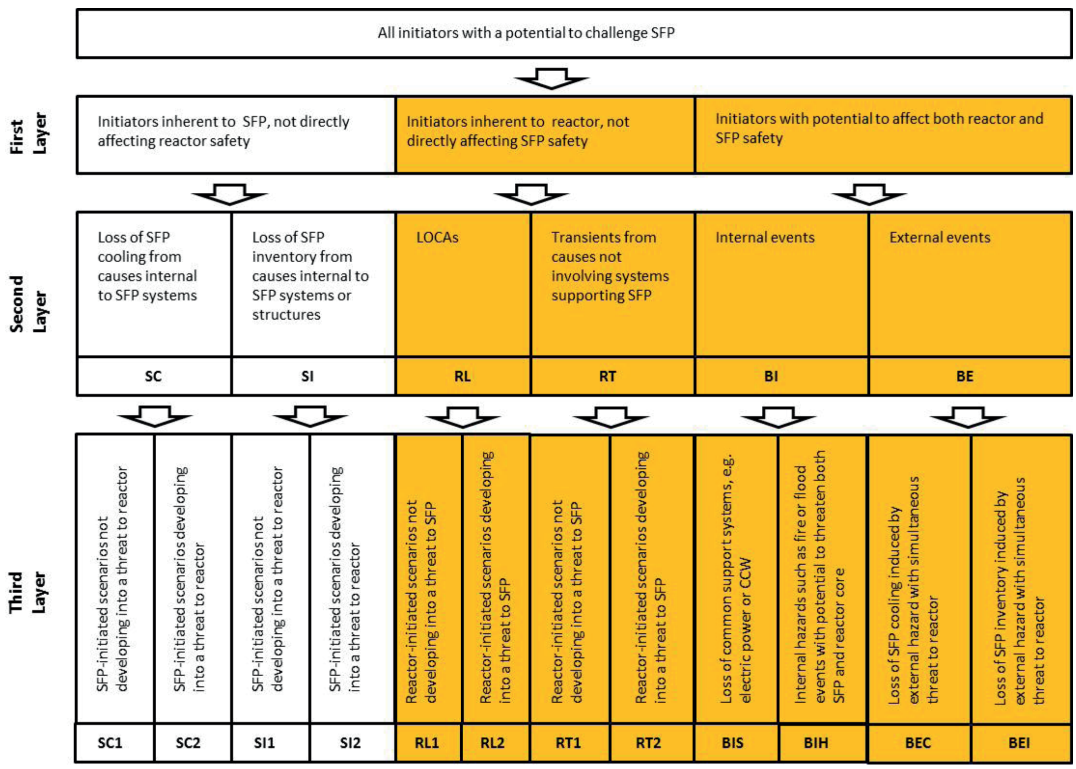

Figure 1: All initiators with potential to challenge SFP

Paper does not intend to discuss the assessment of the full PSA interface study. It describes a simplified engineering evaluation of possible hydrogen presence in the containment annulus, its flammability and leakages through the penetrations toward FHB.

2 CONTAINMENT LEAKAGES

Figure 2 presents the typical analytical scheme for leakage paths from the containment (where RB is for Reactor Building (containment); AB is for Auxiliary Building; IB is for Intermediate Building; and FHB is for Fuel Handling Building)). Plant Updated Safety Analysis Report (USAR) analyses of radiological consequences usually take into account the limited total leakage from the containment corresponding to the design leakage rate from the containment (e.g. 0.2% by weight of the containment air per 24 hours, at $P_a = 3.15$ kp/cm^2 - [5], LCO 3.6.1.2). From Figure 2 it can be reasonably concluded that a definition of distribution of leakages to the various adjacent buildings, rooms and spaces can introduce rather large uncertainties. Due to this reason, for simplification of assessment and practical usage, assumption will be used that the total design leakage is always applied to only one possible path. On the other hand, such approach generates problems because assuming that hydrogen or radioactive influents are released only to one particular area gives their unrealistic concentrations in the considered area.

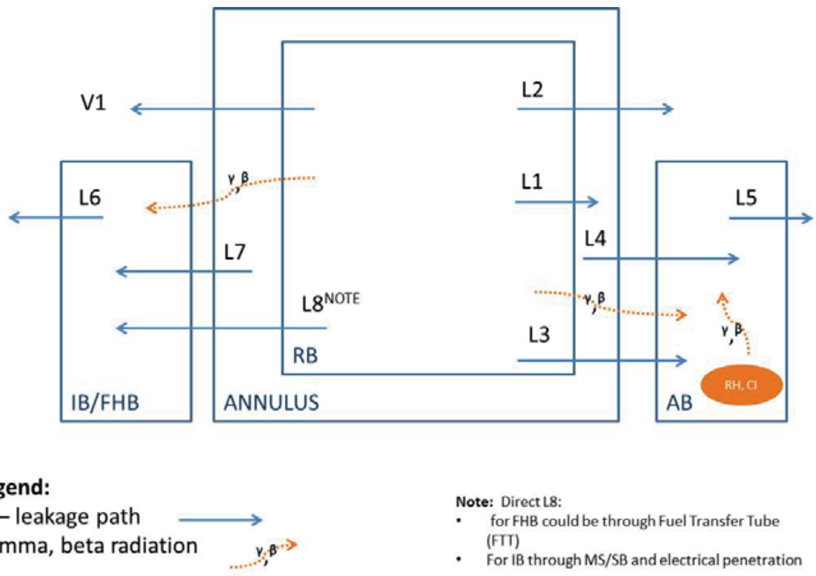

Figure 2: Containment Leakage Scheme

Path L8 on scheme shown in Figure 2 could represent the Fuel Transfer Tube (FTT), used during an outage for direct connection between FHB (fuel Transfer Canal (TC)) and the containment reactor cavity - Figure 3. FTT is isolated during normal operation by a blind flange and a valve.

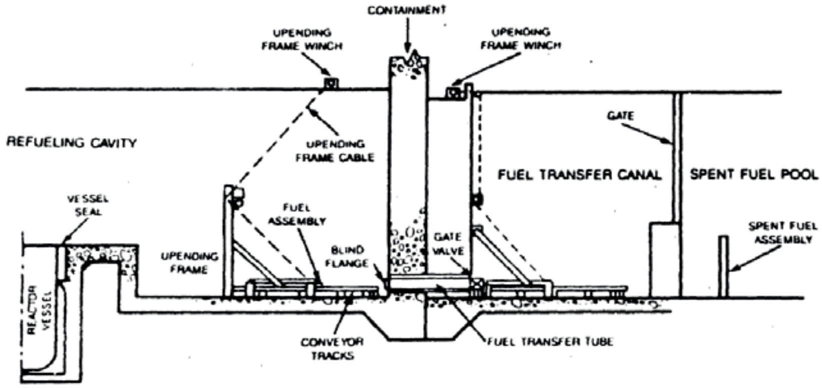

Figure 3: Fuel Transfer System, [7]

3 HYDROGEN PRODUCTION AND DISTRIBUTION

In the original Krško NPP Level 2 PSA studies (1995), the production of hydrogen by fuel cladding zirconium oxidation and its distribution in the containment were discussed and evaluated on the basis of principles presented in [8]. Deterministic analyses were performed for the chosen accident scenarios (Station Blackout (SBO), Large Break Loss of Coolant Accident (LLOCA) and Small Break LOCA (SLOCA)) by integral best estimate severe accident code MAAP 3.0B. NPP Krško repeated these analyses by upgraded MAAP 4.0.5 model in the light of the IAEA RAMP (Review of Accident Management Program) mission recommendations. Results were discussed in [4] and are summarized in Table 1 below. From the compared results it can be concluded that the evaluation by the new version of the code resulted with the increased amount of hydrogen released from corium to the containment. Krško NPP is currently preparing the new revision of [8] which will be supported with newer research information on hydrogen production/behavior in the containment, upgraded plant model and improved version of the code (MAAP5.0.3). Distribution of hydrogen in containment for observed scenarios was additionally evaluated by GOTHIC 3D code and documented in [9]. Conclusion was that hydrogen is uniformly distributed around the containment and there is no concentration which would reach the flammability limit within 24h. More recent Krško NPP's analyses (either by MELCOR 1.8.6 or/and MAAP 4.0.7) which assumed an installation and usage of containment passive autocatalytic recombiners (PARs) and Passive Containment Filter Vent (PCFV) were not taken into account in this rough evaluation. PARs recombine the hydrogen as long as all the oxygen in the containment is not consumed (so-called "starvation strategy"). The maximum allowable equivalent hydrogen mass (taking into account in and ex-vessel produced hydrogen and carbon monoxide (CO) produced by molten core concrete interaction (MCCI)) that can burn by deflagration without exceeding 6 bar abs (5% failure probability, as used in SAMG) is ~408 kg per section 20 of [10]. Therefore, the sizing criterion has been chosen to ensure that PARs reduce the oxygen content such that any combustion is oxygen limited, regardless of CO or hydrogen concentrations. Once when all oxygen is consumed the concentration of hydrogen (and explosive carbon monoxide (CO)) in containment can be potentially increased by MCCI without efficient recombination if there is no mitigative action from the TSC staff with flooding of the reactor containment cavity.

Table 1: Comparison of Hydrogen Production Mass Generated in SBO, LLOCA and SLOCA Accidents

Run ID	MAAP 3B H2 mass generated in the core at end of the transient (kg)	MAAP4.0.5 H2 mass generated in the core at end of the transient (kg)
SBO (HSBO1)	255	266
LB LOCA (LLOCA3)	103	185
Small LOCA (SLOCA2)	280	320

To simplify the discussion about influence of assumed scenario and timing of hydrogen releases from reactor vessel to containment, for illustration of the methodology described below, it will be assumed that 100% of zircaloy from fuel cladding (11860kg) is oxidized producing 525kg of hydrogen within time frame of 24h and that additional 1000kg of equivalent hydrogen is produced by MCCI. (This also takes into account a production of carbon monoxide. The hydrogen and carbon monoxide (CO) as a mixture have similar flammability limits to the gases considered alone, when expressed as a volume fraction. In addition, hydrogen and CO have similar molar heats of combustion. Thus, on a molar basis, CO and hydrogen may be considered as "equivalent".)

4 SIMPLIFIED DETERMINATION OF CONCENTRATION OF HYDROGEN IN THE CONTAINMENT ANNULUS OR/AND FUEL HANDING BUILDING (FHB)

Basic assumptions:

- The mass of hydrogen in the inner rooms of the containment is conservatively assumed at maximum. The work of passive catalytic hydrogen recombines (PARs) is not considered.
- The assessment is applied in the range of containment pressures below passive containment filter vent (PCFV) opening setpoint. (The passive actuation of the system will occur once the containment pressure exceeds the rupture disk burst pressure of 5 bar differential).
- Due to inability to determine the exact locations of leakages from the containment, the complete free volume of containment annulus or FHB is assumed for calculation. At the same time it is assumed that the environment in the annulus space between the inner metallic liner and outer containment shell is perfectly mixed. Same is valid for the FHB environment.
- Conservatively, it is assumed that only the hydrogen leaks from the containment atmosphere to annulus or FHB. In reality mixture of steam, air, hydrogen and radioactive effluents would leak from the containment to the adjacent buildings and areas as shown in Figure 2 above.
- The maximum containment design leakage from the containment is assumed (0.2% volume).
- Leakages from the annulus space to the adjacent buildings and the surrounding atmosphere are not taken into account. It is always assumed that the total amount of leakage flows to only one area/volume.

Initial data:

- Containment annulus free volume is 11220 m^3.
- Fuel Handling Building (FHB) free volume is 26220 m^3.
- Design leakage from the containment is 0.2% by weight of the containment air per 24 hours, at $P_a = 3.15$ kp/cm^2 ([5], LCO 3.6.1.2).
- Containment annulus and FHB initial pressure is atmospheric, 101325P_a.
- Containment annulus and FHB initial temperature $T_{a.s.} = 313$K.
- The mass of hydrogen in containment could be based on MAAP calculation or conservatively assumed as shown in para 4 above.

Calculation:

It is necessary to determine the volumetric hydrogen concentration in the annulus space between the liner and outer containment shells, $x_{a.s.,H_2}$.

a) Volumetric hydrogen concentration can be determined by equation (1):

$$x_{a.s.,H_2} = 1 - \frac{P_{a.s.,0}}{P_{a.s.}} \qquad (1)$$

where:

$P_{a.s.,0}$ represents the initial air pressure in the annulus;

$P_{a.s.}$ represents the pressure of the mixture (air / hydrogen) in the annulus.

b) The pressure of the mixture in the annulus space can be determined by equation (2):

$$P_{a.s.} = \frac{R \cdot T_{a.s.}}{V_{a.s.}} \left(\frac{M_{a.s.,air}}{\mu_{air}} + \frac{M_{a.s.,H_2}}{\mu_{H_2}} \right) \qquad (2)$$

where:

$M_{a.s.,air}$ represents the initial mass of air in the annulus space;

μ_{air} represents the molecular mass of air (29);

$M_{a.s.,H_2}$ represents hydrogen mass released from containment to annulus;

μ_{H_2} represents the molecular mass of hydrogen (2);

$V_{a.s.}$ represents free volume of annulus;

R represents ideal gas constant (8314kJ/mol-K).

c) The initial mass of air in the annulus space is determined by equation (3):

$$M_{a.s.,air} = \frac{P_{a.s.,0} \cdot V_{a.s.}}{R \cdot T_{a.s}} \cdot \mu_{air} \qquad (3)$$

Results of simplified evaluation:

The results of simplified evaluations taking into account maximal concentration of hydrogen without MCCI (525kg) and with MCCI (1500kg) are shown in Table 2. The determined maximum volume concentrations of hydrogen in the annulus and FHB for various initial conditions do not reach flammability limit of 4% in the observed area.

The same method is used to determine at which containment leakages the hydrogen concentration can reach flammable limit (4% for observed area) in annulus and FHB. The summarized results are shown in Table 3. The simplified evaluation shows that 7% volume/day leakage to annulus and 16.5% volume/day leakage would increase hydrogen concentration to flammable limit without MCCI but much smaller leakage is needed for it in the cases with MCCI.

Table 2: Summarized Results: Maximum Concentration of Hydrogen in Observed Area

	Calculated volumetric hydrogen concentration	
Case description	**Annulus**	**FHB**
Design Leakage (0.2%volume/day) no MCCI	0.12%	0.05%
Design Leakage (0.2%volume/day) with MCCI	0.35%	0.15%
DEC leakage (2 x design leakage), no MCCI	0.24%	0.10%
DEC leakage (2 x design leakage), with MCCI	0.69%	0.30%

Table 3: Summarized Results: Minimum Containment Leakage Needed for Flammable Limit (4%) in Adjacent Areas

Location	**without MCCI**	**with MCCI**	
Annulus	7%	2.39%	in-leakage/day
FHB	16.50%	5.60%	in-leakage/day

5 CONCLUSION

Presented simplified engineering assessment shows that hydrogen leakage from containment to annulus and/or FHB should not be safety concern from flammability (4% of hydrogen in volume) point of view if we are talking about the normal design basis leakage (or even its double value, in the light of potentially increased containment pressure during design extension condition (DEC) before passive containment filter vent (PCFV) would be actuated). However, evaluation of minimum containment leakage needed to reach flammable limit show that partial or full loss of containment tightness can cause flammable environment in the FHB and the annulus. The annulus is of particular concern because the fire or detonation can jeopardize containments liner from the outside which cannot be mitigated easily by any kind of TSC mitigative action.

Presented assessment demonstrates how important it can be to adequately address the candidates for a high level action (CHLA) related to ventilation of the auxiliary buildings (3.2.19, [2] and [3]) in the plant specific SAMGs, because it is not possible to completely eliminate the potential for a breach in the containment at the outset of the accident (postulated DEC) or as a consequence of the harsh conditions that develop inside the containment. This is also important from the point of view that presence of flammable concentrations in annulus or FHB is not monitored by the MCR.

As it is recommended by mentioned CHLA, if normal building ventilation is not available or is ineffective at mitigating the buildup of flammable concentrations in the auxiliary buildings, including the FHB and the annulus, alternate strategies must be implemented to control the building ambient conditions before entering (accessing) these areas for any other implementation strategy (e.g. makeup of SFP by portable means, see Figure 4 in Attachment 1). Examples of alternative methods to reestablish building ventilation can include the following:

- Using alternative power supplies to reestablish power to a minimal but critical set of ventilation system components;
- Using portable power, exhaust, and recirculation equipment;
- Introducing natural circulation pathways through buildings by opening doors, windows, and other barriers at multiple levels of the building;
- Introducing natural circulation flow using a chimney effect by creating openings at the lower and upper levels of the building.

One point of consideration for future work in this area would be to evaluate possible correlations between core damage and plant damage accident sequences with SFP accident sequences, as described in [1]. Also, best estimate deterministic analyses would be needed to evaluate more realistically containment leakages distribution with upgraded MAAP model, including more detailed connections between FHB / SFP and containment, as well as more detailed model of adjacent buildings to decrease all postulated conservatisms described in section 4.

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Attachment 1:

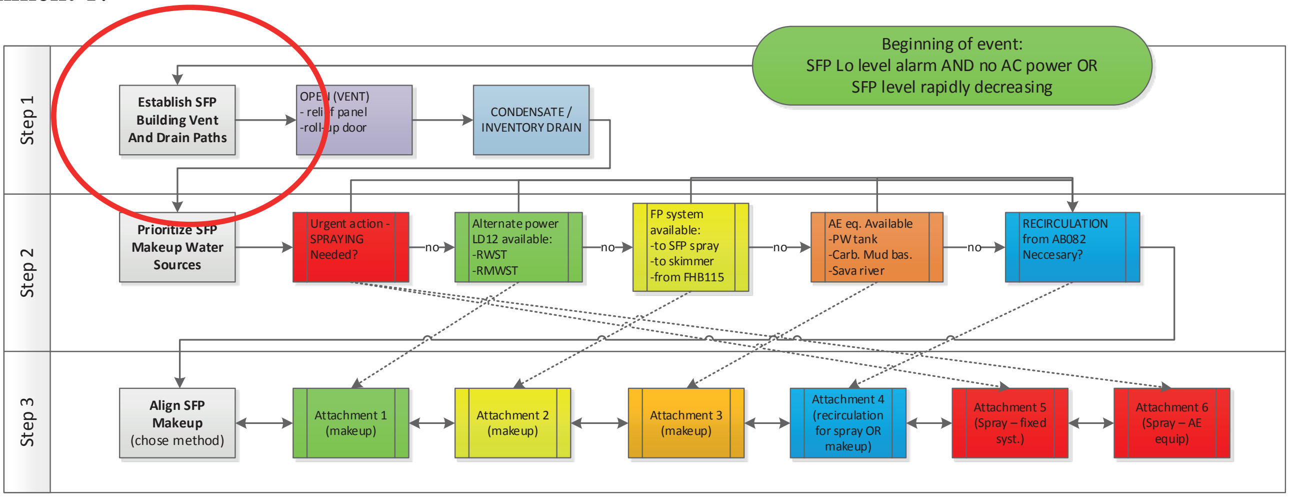

Figure 4: Example for Functional Support Guideline (FSG)