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Severe Accident Management: Assessment of Time Window for Performing RCS Depressurization

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ABSTRACT

Following the Fukushima Daiichi event, a number of international assessments and studies have been initiated to extend the scope of accident simulation tools to incorporate design extension conditions (DEC). These studies have resulted in various forms of plant simulators being developed which incorporate severe accident analysis codes like MAAP or MELCOR. Among other purposes (e.g. Probabilistic Safety Analyses (PSA)), the suggested application of these severe accident simulators is training plant personnel in severe accident plant response to assist in training on severe accident management guidance (SAMG). There has also been discussion of applying severe accident analysis tools to the refinement of SAMGs.

Extending the application scope of severe accident codes requires also new considerations to ensure that simulation results are appropriately incorporated in the overall decision-making/evaluation process. New studies underline the need for extensive assessment of the modelling uncertainty on the use of severe accident code results.

For example, while prevention of RPV lower head breach remains a critical factor to evaluate effectiveness of post-core damage injection of water to the RPV, accident management evaluations also require assessment of the impact of successful Reactor Coolant System (RCS) depressurization to prevent Reactor Pressure Vessel (RPV) fail on the high system pressure.

Paper presents continued work on MAAP5.03 assessment of RCS depressurization per appropriate guideline in SAMG presented in [1] extended with simple illustration of uncertainty quantification of the most impacting input variables related to observed accident scenario.

Keywords: *Severe Accident Management, MAAP, RCS Depressurization*

1 INTRODUCTION

The RCS depressurization per typical Emergency Operating procedure (EOP) (FR-C.2, Inadequate Core Cooling) or SAMG (SAG-3, Depressurize RCS) is necessary in the case of loss of ac power (LOAC), small break loss of coolant accident (SB LOCA - when loss of inventory is not enough big to depressurize RCS) or loss of all feedwater (LOAF) Purpose of such operator action is to depressurize the primary system to either try recovering the core in-vessel (achieve in-vessel recovery (IVR)) by initiating accumulator injection and low-pressure SI injection (or any alternative method like fire water etc.), or to achieve a low-pressure vessel failure preventing potential high pressure melt ejection (HPME) ([4], phenomenology evaluation in Appendix N) or direct containment heating (DCH) ([4], Appendix S.4). As it was summarized in [3], effects and considerations are different for different conditions (for this paper purpose it was interesting to study effects on damage condition once Core Exit Temperature (CET) reaches entrance condition to transfer from EOP to SAMG (typically 650°C for PWR). These conditions are defined in [3] as OX (core significantly oxidized but intact) and BD (core significantly oxidized and not intact (core structural components have melted and are relocating downward). Based on experimental work [3], depressurization of RCS as candidate for high level accident management action could cause different positive effects (e.g. increases opportunity for injecting water into RPV/RCS from low-pressure, etc.) or negative effects (depressurization would cause flashing of the water in the lower core region increasing the steam flow through the overheated core and could increase the hydrogen production within the core region ([4], Appendix D) and potential deflagration and detonation in the containment ([4], Appendix S.3 and [10]), etc.).

The limiting time in which the depressurization must be performed for either case is considered to be determined by the accumulator injection setpoint. This pressure must be reached before reactor pressure vessel (RPV) failure. Once the accumulators inject it is considered that it would prevent the vessel failure for the time being and, thus, enable that depressurization can be completed. From Probabilistic Safety Analyses (PSA) perspective, as typically modelled in bridge event trees (BET), there can be observed the list of applicable sequences [5] at which is expected to potentially have high RCS pressure with degraded core before RPV failure. Among them there are no cases with auxiliary feedwater (AFW) success, e.g. with possibility of decay heat removal by secondary side OR actuation of high-pressure safety injection (HPSI). Since the AFW has failed, only the depressurization from primary side available (i.e. opening of pressurizer (PRZ) power operating relief valves (PORVs)). Taking into account the particular interest, due to core damage frequency (CDF) contribution, such sequences involve also failure of HPSI recirculation and, due to assumed high dependency, low pressure safety injection (LPSI) recirculation which is not credited in the BET logic. Therefore, for these sequences IVR is not credited. The role of depressurization is reduced to converting eventual high pressure (HP) RPV failure to low pressure (LP) RPV vessel failure.

The results of MAAP5.03 [6] analyses for Westinghouse 2 loop PWR ([7]) are used to illustrate presented paper concluding that the time window for performing RCS depressurization per appropriate EOP/SAMG procedure to assure accumulator injection and reduce the primary pressure bellow Emergency Core Cooling System (ECCS) LP injection pump head (with 2 of 2 PRZR PORVs) is around 30 minutes.

2 PERFORMED ANALYSES

The analyses discussed in [1] presents scenarios with SB LOCA (base case analysis assumes the RCP seal loss of coolant accident (LOCA) with initiated break area of 1.27E-4 m^2 (0.5”) on the RCS cold leg) without AFW and HPSI available are performed by MAAP5.03 to investigate time window for performing necessary RCS depressurization as discussed above. As mentioned before, since the all AC assumed be failed (including AFW and HPSI), *only the depressurization from primary side is available* (i.e. opening of pressurizer PORVs).

2.1 Assumed initial and boundary conditions

Initial conditions are assumed nominal:

- reactor power – 100%
- primary system loop flow - nominal
- hot leg temperature and cold leg temperature - nominal
- primary system pressure - nominal
- SG secondary side pressure - nominal
- SGs secondary side level - nominal
- PRZ level - nominal
- Steam flow to turbine - nominal

- FW flow – N/A

Various MAAP 5.0.3 sensitivity cases analyses were performed [1] taking into account initial conditions as listed above with initialization of SB LOCA on RCS cold leg (break area of 1.27E-4 m^2 (0.5”)) at time =0s. In all scenarios Auxiliary Feed (AF) system was not assumed operable and steam-generators (SGs) dried out at the certain time.

The few MAAP input combinations included the following scenarios:

- Without operator actions to manually open PRZR PORVs OR operator manually open 1 or 2 PRZR PORVs once when core exit thermocouples reach 650oC (exit from plant EOP to enter SAMGs),
- Operator trip the Reactor Coolant Pump (RCPs) at saturation condition in RCS OR RCPs run till loss of conditions,
- Assuming accumulators operable or not.

As discussed in [1], the specially the MAAP 5.0.3 model of core blockage (FGBYPA, min.=0 and max.=1) was tested. Nominally (for Best Estimate (BE) calculation), FGBYA is set as 1 and for sensitivity case 0. Set of 1 means that channel gas flows are diverted to the bypass channel if all of the fuel channels are blocked due to a core melt progression. Once the gas is diverted, it flows up through the bypass without re-entering the fuel channels. This mitigates the amount of hydrogen that is generated in the core due to steam up-flow. Similarly, the sensitivity runs were performed to check influence of the cut-off porosity below which the flow area and the hydraulic diameter of a collapsed core node (geometry configuration are zero, i.e. and the node is fully blocked. Nominally, (for BE calculation) EPSCUT is set 0.1 and EPSCU2 is set 0.2 while for sensitivity cases the maximal values of both variables are chosen, respectively 0.25 and 0.35.

2.2 Analysis results

Time sequences of main events for all analysed cases (base cases and sensitivity cases) were presented and discussed in [1].

For better understanding of this paper, thereafter is given description related only to base case run (SBLC_000) [1] where small break LOCA was run without operator actions to manually open PRZR PORVs once when core exit thermocouples reach 650^{o}C (exit from plant EOP to enter SAMGs). The analysis assumed that operator successfully trip RCP on saturation conditions in RCS. From base case run (SBLC_000) [1] it can be concluded that successfully trip off RCP prolonged time for core uncover what is reasonable taking into account that RCP contribute with almost 6MWth heating the RCS water.

After initiation of SB LOCA at time 0.0s, the reactor scram on low steam-generator level happened at 27.2s. Steam-generators (SGs) PORVs are opened and maintain pressure and temperatures in both SGs and RCS. SGs dried out around 1250s and RCS water temperature starts to increase. Saturation condition in RCS reaches set-point at 1390.14s and operator switch-off both RCPs. Without secondary cooling and primary make-up core is uncovered at 3497.98s (around 1h). Core heats up and core melt starts at 6155.41s (1.7h). The core relocation to RPV lower plenum starts at 10860.21s (3.06h). Finally, RPV fails at 12139.27s (3.37h).

Base case scenario with operator actions to manually open 1 of 2 PRZR PORVs once when core exit thermocouples reach 650^{o}C is SBLC_001. Timing of all events are similar as SBLC_000 till core uncover (around 1h from beginning). At time before core melt 6092.9s (1.69h), operator recognizes the conditions for entrance in EOP function restoration procedures and FR-C.1 where RCS depressurization is required. SG PORVs depressurization is not assumed and operator open 1 of 2 PRZR PORVs.

Base case scenario with operator actions to manually open 2 of 2 PRZR PORVs once when core exit thermocouples reach 650°C is SBLC_001A. Timing of all events are similar as SBLC_001 till core uncover (around 1h from beginning). At time just before core melt 6044.66s (1.68h), operator recognizes the conditions for entrance in EOP function restoration procedures (or SAMG) where RCS depressurization is required. SG PORVs depressurization is not assumed and operator open 2 of 2 PRZR PORVs.

In all sequences where RCS is not properly depressurized, accumulators injected after RPV fails. There are 2 cases, SBLC-001B and 001D where depressurization is assumed but accumulator isolation valves were closed (no accumulators injection even that RCS pressure is decreased bellow accumulator head pressure).

The most important parameters from performed analyses are presented in [1] only for SBLC-001M case. SBLC-001M presents scenario with SB LOCA with RCS depressurization with 1 of 2 PRZR PORV taking into account that operator does not stop RCP on saturation conditions, core blockage model assumed). Analysis resulted with successful depressurization of RCS bellow ECCS accumulator setpoint but RCS pressure remains close to LPI pumps heads and injection is not enough to prevent corium relocation.

Additionally, to discussion of all analyses and results presented in [1], this paper presents the simplified uncertainty quantification distributions of major sequence consequences. Sensitivity analysis is usually performed along with or before uncertainty quantification in order to evaluate the uncertain input parameters. The objective of the sensitivity analysis is to identify the sensitive input parameters that have a significant impact on the Figures of Merit (FOMs). The sensitivity runs can either change only one input parameter at a time or change multiple input parameters a time. For this paper, we adopted the approach to change one input parameter a time. The parameter's value is different in each case as these values are sampled according to the parameter's range and distribution. All variation of sensitive MAAP5 input variables were not analysed as deep as it was given in [8] except recommended changes for FGYPA and EPSCU2.The most impact variable ISIDRL (used to enable/disable sideward relocation within the core) was always selected to not bypass sideward relocation calculation. Also, VFCRCO (porosity of a collapsed core region) was chosen 0.35 for all performed calculations as recommended by MAAP5 user [6] and [5].

Taking into account that 2 values per each parameter (e.g. FGYPA and EPSCU2) were chosen, the necessary number of calculations without combination of parameters were n=2 x p+1=5.

Simplified approach was taken for characterizing the uncertainty, just for illustration purposes. The shortest calculated value for observed time of occurrence of accident sequence event (e.g. core uncover, core melt, core relocation, RPV failure and time to perform RCS depressurization) was interpreted as 5th percentile (or Lower Boundary Value) and longest calculated value as 95th percentile (or Upper Boundary Value) of an assumed underlying lognormal distribution.

Table 1 summarizes the calculated values from MAAP5 runs, documented in [1] and parameters of the associated indicative lognormal distribution, from the observed accident sequence event timeline.

Table 1: Calculated Values from MAAP5 Runs Used for Uncertainty Quantification Illustration

Observed Accident Sequence Event Analyses Results	Core uncover (s)	Core melt (s)	Core Relocation (s)	RPV failure (s)	Time window to perform RCS depressurization (min)
Average Value	3194.73	5784.10	9257.84	10241.93	40.84
Upper Boundary Value (95th percentile)	3497.98	6155.41	10860.21	12139.27	44.29
Lower Boundary Value (5th percentile)	3104.02	4892.65	8073.30	8949.80	30.34

2.3 Analyses Conclusions

Analyses results [1] provide the several observations. Main conclusion was that blockage model with FGBYA=1 (blockage model is on) and maximal values of EPSCUT and EPSCU2 resulted with sooner core melt, core relocation and finally reactor pressure vessel (RPV) failure if RCS depressurization with PRZR PORVs are not successful. Blockage model slightly decreases the hydrogen production in the core if accumulator and LPSI is successfully injected.

Based on presented analyses in [1], it was concluded that the shortest time window for performing RCS depressurization bellow ECCS LP injection pump head (with 2 of 2 PRZR PORVs) is 30 minutes taking into account:

- Time window between start of core melt and core relocation: 8073.2s - 5561s = 2512s;
- Time needed to depressurize: 700s;
- Hence: time margin = 2512s - 700s = 1812s, or approximately 30 minutes.

Also, it was clearly obtained that the number of pressurizers PORVs to be successfully opened for performing RCS depressurization to established successful ECCS LP injection is 2 of 2, or 1 of 1 new installed bypass PORV which has capability as 2 designed pressurized PORVs.

Reference [1] evidenced that the time window for initiating the LP injection following the successful accumulator injection measures in a number of hours; the mentioned run indicates a time window longer than 7 hours. Additionally, it was obtained that, time window between RVF and Accumulator injection is assessed at 32936 - 6000 = 26936s or 7.4h what was considered to be a bounding case as compared to the case with successful injection from RWST until reaching the level of 31%; RWST would reach this level only after 2h hours as discussed above. During this time decay heat level would reduce considerable.

Altogether, for HRA purposes a time window (for establishing the recirculation) can be considered at the order of several hours.

Illustrative cumulative distribution functions of four FOMs representing observed accident sequence event occurrences (core melt, core relocation, RPV failure and time to perform RCS depressurization) are presented in Attachment 1.

3 CONCLUSION

Presented plant specific analyses by MAAP5.03 code for typical Westinghouse PWR underline the importance role of timely RCS depressurization as candidate for high level actions in SAMGs in the high-pressure severe accident scenarios (LOAC, SBLOCA, LOAF, etc.) in accordance with generic post Fukushima Daiichi accident studies ([3], [4]). Also, illustrated plant specific analyses results clearly proved clearly the study's conclusions ([2]) that proper phenomenological uncertainty parameters should be carefully chosen and assessed. Continuous and extensive assessment of the modelling uncertainty based on full scale experimental work should ensure in the future that simulation results are appropriately incorporated in the overall decision-making/evaluation process. Particularly, usage of MAAP5.03 blockage model and maximal values cut-off porosity (below which the flow area and the hydraulic diameter of a collapsed core node become zero) resulted with sooner core melt, core relocation and finally reactor pressure vessel (RPV) failure if RCS depressurization with PRZR PORVs is not successful.

Paper presents continued work on MAAP5.03 assessment of RCS depressurization per appropriate guideline in SAMG presented in [1] extended with simple illustration of uncertainty quantification of the most impacting input variables related to observed accident scenario.

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Attachment 1: Uncertainty Quantification Illustration Through Lognormal Cumulative Distribution Function