13th International Conference on Probabilistic Safety Assessment and Management (PSAM 13)
2~7 October, 2016 • Sheraton Grande Walkerhill • Seoul, Korea • www.psam13.org

PROBABILISTIC SAFETY ASSESSMENT FOR SHUTDOWN STATES OF REACTORS, SPENT FUEL POOL AND RECENT R&D RESULTS

Manorma Kumar[1], Anders Olsson[1], Horst Löffler[2], Emmanuel Raimond[3]

[1] Lloyd's Register, Sweden: manorma.kumar@lr.org
[2] GRS, Germany; [3]IRSN, France

This paper is associated to the European project ASAMPSA_E Advanced Safety Assessment: Extended Probabilistic Safety Assessment (PSA) which gathers more than 30 organizations (industry, researchers, universities, technical safety organizations and regulators) from Europe, USA and Japan. This is a 3-4 years project on extending PSA (e.g. in order to better represent external hazards), which aims at identifying some meaningful practices to extend the scope and the quality of the existing PSA developed for nuclear power plants.

This paper is focused on summarizing the complementary guidance for Level 2 PSA for the shutdown states of reactors; complementary guidance for the modelling of risks associated to the spent fuel pools; and utilization of recent Research and Development (R&D) in Level 2 PSA. The summary of complementary guidance is addressing the shutdown states and spent fuel pool accidents including its influence on the nuclear safety for Level 2 PSA. The initial step suggested is to identify the most relevant items for shutdown states (different shutdown states and related accident sequences), and spent fuel pools (types of accidents) and related items, including how to better introduce recent R&D items into Level 2 PSA.

I. INTRODUCTION

The objective of this paper is to provide summary of ASAMPSA_E[1] complementary guidance [1] for Level 2 PSA for accidents in the Nuclear Power Plant (NPP) shutdown states and in spent fuel pools and comments on the importance of these accidents on the nuclear safety. It includes also information on recent R&D useful for Level 2 PSA developments. This guidance is being reviewed and the present paper does not take into account this review. The conclusions of the ASAMPSA_E end-users survey [1] which are relevant for Level 2 PSA is reflected in Ref [2] and are taken into account as much as it is possible with the current status of knowledge.

For **shutdown states** with closed Reactor Pressure Vessel (RPV), core melt accident phenomena are very similar to the sequences going on in full power mode. Therefore, the large body of guidance which is available for full power mode is largely applicable to shutdown mode with RPV closed as well. Some specifics of the containment isolation status may be an important part of the Level 2 PSA. When the RPV is open, some of the Level 2 PSA issues become irrelevant compared to full power mode, while others come into existence. The paper also covers containment issues in shutdown states and discusses the applicability of existing guidance, potential gaps and deficiencies and recommendations are made.

For **Spent Fuel Pools (SFP)** accidents in Level 2 PSA a set of issues, for example core concrete interaction for SFP accidents, fuel degradation process, hydrogen issues, heat load due to SFP melting, release paths to the environment, criticality and correlations between accident progression in SFP and in reactor system are identified and discussed in this paper. If the spent fuel pool is located inside the containment, the potential release paths to the environment are almost the same as for core melt accidents in the RPV. If the spent fuel pool is located outside the containment, the potential release paths to the environment depend very much on plant specific properties, e.g. ventilation systems, building doors, roof under thermal impact, size of rooms on the path etc. In any case the impact of very hot gas and of hydrogen has to be considered.

---

[1] ASAMPSA_E project defined extended PSA i.e. an extended PSA applies to a site of one or several NPPs and its environment. It intends to calculate the risk induced by the main sources of radioactivity (reactor core, spend fuel storages and other sources) on the site, taking into account all operating states for each main source and all possible relevant accident initiating events (both internal and external) affecting one NPP or the whole site.

The dependencies between reactor accident and SFP management appear to be an important issue for Level 2 PSA risk assessment.

The **recent R&D achievements** are focused on summary of on-going R&D activities supporting extended Level 2 PSA, including results presentation and application. In addition, a list is provided for those topics which seem to have inadequate covering in present activities.

II. LEVEL 2 PSA IN SHUTDOWN STATES

In shutdown states the correct core inventory and decay heat level, which is different from full power states, has to be taken into account according to the plant operating modes. This has implications for the accident progression and for source term calculations. The definition of shutdown states seems adequately covered in the existing guidance. For Level 2 PSA in shutdown states, two plant conditions are to be distinguished: 1) Accident sequences with RPV head closed, 2) Accident sequences with RPV head open. The status of containment should appears at the same level (close, open, connection between reactor and SFP etc.).

II.A. Accident Sequences with RPV closed

The shutdown states with closed RPV are mentioned here for completeness, but it will probably be enough to recommend proper application and adaptation (e.g. due to different decay heat Levels) of the existing Level 2 PSA guidance to these plant conditions, and to draw the attention to the possibly difficult plant conditions impacting mainly on Level 1 PSA. Special attention shall be devoted to the following issues:

- Availability or recovery of safety systems (e.g. spray pumps, high pressure emergency core cooling systems) which can be under maintenance;
- the state of the containment i.e. it is opened and questionable to be closed (an additional question may be introduced into the containment event tree reflecting this issue); and
- accident management systems.

When the RPV head is closed, core melt accident phenomena are very similar to the sequences going on in full power mode. MAAP4 [3] can be used to perform calculations; however, the assessment of open reactor cases is limited, which is discussed in next section ‘RPV open’ below. For example, heat radiation and convection above the RPV, the air inlet into the RPV cannot be assessed appropriately using MAAP4. MAAP5 can assess SFP severe accidents and it can perform assessments for open reactor cases too. MELCOR [4] has been applied by several organizations in the shutdown regime, also with open RPV head. Apart from a few cautionary warnings regarding heat radiation and convection above the RPV, MELCOR is applicable for such analyses.

II.B. Accident Sequences with RPV open

In case of a core melt accident with the RPV open, two cases can be identified. The first case is the RPV bottom closed (always the case for Pressurized Water Reactor (PWR), not always for Boiling Water Reactor (BWR) accident scenarios). In this case, core uncovery (damage) can only occur due to coolant boiling. The second case is a RPV bottom leak (e.g. at recirculation pumps in a BWR), which leaves the RPV open at top and bottom. In both cases it can be imagined that air contacts the melting core, generating different conditions and releases compared to the almost pure steam atmosphere which is present in a closed RPV. However, analyses with the current version of the codes do not indicate significant differences. This may be due to the fact that the air in the atmosphere near the RPV top and bottom is almost completely replaced by steam. This statement cannot be considered as a general rule, and pertinent analyses are recommended for such scenarios in a PSA.

For most shutdown states with open RPV head, reactor vessel and SFP are connected by a large water pool in some reactor designs. Level 1 PSA as well as Level 2 PSA for shutdown states should consider interconnection between RPV and SFP (possibility to use common safety systems, common Severe Accident Management Guidelines (SAMG) strategies, etc.).

The following issues obviously are less significant as compared to closed RPV head, which is explained in detail in [2]:

- high pressure core melt sequences with the large number of associated complications;
- retention of radionuclides inside the reactor coolant loop; and

- restoration of heat removal by normal systems.

It should be mentioned that severe accidents emanating from full power mode can also have particular issues after the RPV bottom has failed, when part of the fuel still is inside the RPV and a large leak exists somewhere higher in the reactor coolant loops. Probably, under such conditions the atmosphere in the cavity contains neither oxygen nor nitrogen so that significant effects (e.g. chemical issues, increasing releases etc.) need not be expected. However, discussions or guidance related to the accompanying effects are not available. Release fractions for closed RPV cannot be transferred to open RPV sequences. It is justified to assume that for an open RPV all fission products which are released from the degrading core will be transferred to the containment atmosphere.

II.C. Containment Issues

It is discussed in Ref [2] that it can be considered likely that hatches and airlocks are or will be closed when critical conditions in the containment begin. However, since the consequences of an open containment are very severe, a PSA should quantify the probability for an open containment. In the context of an extended PSA also internal and external hazards should be taken into account which may affect the possibility to close the containment. Some plants have a procedure to close the containment hatch before certain maintenance.

The flow path through the reactor building and auxiliary building or turbine hall or ventilation systems – whatever is applicable – to the environment has to be considered for an open containment. Hydrogen threats in the release path and deposition of fission products are the most relevant aspects in this regard. However, a detailed analysis of such buildings and flow paths and systems may be beyond the possibilities of most PSA. In that case, it seems to be acceptable to assume that severe hydrogen combustion occurs inside the buildings – such as the Fukushima experience – and that a large release path to the environment will be opened.

It is recommended that extended PSA Level 2 for sequences with open RPV carefully evaluate temperature evolutions in structures above the RPV. Heat radiation as well as convection out of the open RPV shall be considered. Typical integral accident simulation codes may be applied for this purpose; however care has to be exercised in the nodalization of the flow paths above the RPV.

III. LEVEL 2 PSA FOR SPENT FUEL POOLS

In the past, the SFP has not been considered with a high safety risk for operating plants. Studies, such as the one conducted by Idaho National Engineering Laboratory in 1996 [5], generally showed that the frequency for an accident involving the SFP was low compared to the contribution of the core to the fuel damage frequency.

Nevertheless, the anxiety during the Fukushima Dai-chi accident for the SFP # 4 was extremely high and has increased the interest of the nuclear safety community for the SFP issues.

There are some challenges in considering SFP PSA, for instance reactor-SFP interactions, radioactive and hydrogen release, shared support system between reactor and SFP, maintaining SFP cooling and human actions/responses in these scenarios. The release paths from the SFP to the environment are different depending on the location of the SFP i.e. the SFP is located inside the containment and the SFP is located outside the containment.

If the SFP is located inside the containment, the potential release paths to the environment are almost the same as for core melt accidents in the RPV. If the SFP is located outside the containment, the potential release paths to the environment depend very much on plant specific properties, e.g. ventilation systems, building doors, roof under thermal impact, size of rooms on the path etc. In any case the impact of very hot gas and of hydrogen has to be considered. The issues related to spent fuel pool are summarized as follows:

III.A. Reactor - SFP Interactions

The reactor – SFP interactions can take one of three forms: 1) SFP events impacting the reactor, 2) reactor events impacting the SFP, 3) common events impacting the reactor and SFP simultaneously. Most existing Level 2 PSAs are limited to core damage accidents, and to the related containment threats (e.g. due to hydrogen, pressurization, temperature). An important reason for this limitation is related to mission time. However, the Fukushima events demonstrated that this argument may not be convincing.

Core melt occurs only if the plant status is in severe disorder. It seems difficult to prove that the SFP systems would not be affected by such disorder. This is especially the case for external hazards. There is a satisfactory reliability of various containments for mitigating the consequences of core melt accidents but Level 2 PSA should include an assessment of the status of the SFP during the progression of a severe accident in case of core melt: as a minimum the risk of spent fuel loss of cooling shall be quantified on the long term phase of the accident. Additional loadings due to SFP steam generation and melting processes will add an additional challenge. This could be considered as a cliff-edge effect. It is conceivable that melt-through of the SFP bottom or wall could affect systems and components which are important for reactor safety, e.g. molten material from the SFP could enter the sump and damage Emergency Core Cooling System (ECCS) components.

At present, very limited literature is available which addresses simultaneous degradation in core and SFP. The practical realization of simultaneous accident progression analysis in reactor and SFP proves to be difficult because none of the available accident simulation codes is capable of simulating more than one melting fuel entity. Therefore, at present it is important to combine accident analyses from the core and from the SFP with the help of expertise. The task may become less complicated when considering that in most cases the fuel degradation in the SFP will begin much later than in the reactor core.

III.B. SFP Melt Interaction with surrounding buildings

When the SFP is located inside the containment, the events during SFP degradation will threaten the containment. Regarding core concrete interactions for SFP accidents, the melt level in the SFP can become rather thick. Such a thick melt layer would probably develop convection patterns which predominantly transfer the heat to the upper edge of the melt. In addition, a metal layer could float on top of the melt and also create local high lateral heat fluxes. On the other hand, vigorous bubbling due to fuel-concrete interaction would tend to equalize heat fluxes. In summary, it has to be taken into account that local peak heat fluxes at the upper edge of the melt pool in the SFP can exist. Lateral erosion and failure of the SFP wall may occur before bottom failure, and melt could enter adjacent rooms. Depending on the design, this can have consequences on remaining barriers and systems.

III.C. Particular Heat Transfer Mechanisms for SFP

Melting in a SFP will cause different threats - an example is the heat load from the melting pool to structures above the pool. Guidance is needed how to take these different threats into account in extended Level 2 PSA. Several analyses show that the heat load from the SFP upwards to structures above (containment dome, or roof of reactor hall) is significant. Analytical models should include thermal radiation and apply a suitable nodalization to model convection. Consequences of the high thermal load should be considered (e.g. reduction of containment pressure bearing capacity, impact of hot gas on venting system, induced fires).

III.D. SFP Melt Interaction with building atmosphere

Hydrogen generated in a SFP inside the containment is in principle covered by the arrangements foreseen for core melt accidents. If the SFP is located outside the containment in the reactor building or in specific buildings, in general no provisions for hydrogen challenge are available. Consequently, a significant risk of deflagration or even detonation exists. This may result in significant collateral damage such that mitigation equipment, sprinkler outlets, and even structural integrity of the SFP may be compromised. In addition, potential generation of Carbon Monoxide may occur which has similar deflagration characteristics as hydrogen. Hydrogen management concepts developed for hydrogen release from a degrading core (e.g. autocatalytic recombiners, igniters) need to be checked for their efficiency in SFP.

There is concern about the impact of air on the fuel degradation process and the consequences in terms of thermal energy release and fission product chemistry. Little experience is available for these issues, and related guidance may not yet be defined in the sense of good practice. Air ingress into the degrading fuel can be imagined for sequences where the water from the SFP is lost rather rapidly. For sequences with loss of heat removal, several analyses show that the previous evaporation of the large amount of water from the SFP would almost completely generate a steam atmosphere with little air having access to the degrading fuel. It is recommended to further substantiate this statement by performing additional analyses.

IV. LEVEL 2 PSA CONSIDERING RECENT R&D

Recent development and the ongoing research with relevance on extended Level 2 PSA are evaluated based on the various on-going research projects e.g. ASAMPSA_E, SARNET (Severe Accident Research Network), SARNET-2, OECD and European projects (public results only), NUGENIA roadmap and ASAMPSA2 [6]. A short synthesis of acquired knowledge and remaining gaps are provided. The knowledge gaps and future research needs to improve the Level 2 PSA quality, which are listed as follow and explained in detail in next section IV.A.:

1. Level 2 PSA guidance is missing on quantitative analyses of releases into the waters and ground and its related source term characteristics.
2. The long term resilience of containments against fuel degradation accidents are not adequately covered in existing Level 2 PSA, however it is noted that some activities are going on in this field, but the state of the art seems unfit for producing guidance.
3. Basic research has been performed in the radiochemistry (Iodine and Ruthenium chemistry) field, but the existing models are not yet suitable for routine application in Level 2 PSA. Source term R&D programmes conducted in the last two decades have shown that iodine oxide particles, gaseous organic iodides and gaseous ruthenium tetroxide may contribute significantly to the environment source term in case of venting. The filtration efficiency review and update of the filtered containment venting systems is the scope in European ongoing projects (MIRE and PASSAM). Furthermore the potential revolatization of the various deposited iodine and ruthenium species has to be further assessed for conditions representative of a severe accident. Despite the recent achievement of major experimental programs and significant advances in understanding of source term issues, additional research is still required as recently reviewed in an international workshop [7] for the consolidation of source term and radiological consequences analyses. Guidance cannot yet be provided for these issues. It is prudent to associate a high degree of uncertainty to releases of these species.
4. Hydrogen and carbon monoxide issues within the containment are routinely taken into account in PSA. However, related issues outside the containment seem to require additional attention, e.g.
   - Distribution and transport of combustible gas in containment venting systems, in particular connected to steam condensation processes.
   - Leak of combustible gases out of the containment into adjacent rooms, and related distribution of these gases.
   - Distribution and transport in ventilation systems, taking into account the disturbed plant conditions after core melt.
   - Probabilities of ignition for potentially ignitable atmosphere in different parts of the disturbed plant.

   Detailed Computational Fluid Dynamics (CFD) models or lumped containment models may in principle be available for precise evaluations, but given the multitude of potential accident sequences.
5. The uncertainty analysis in Level 2 PSA shall provide information on the possible deviation in accident progression on the NPP and impact on the accident consequences.

IV.A. Knowledge Gaps and Future Needs

Even today's advanced Level 2 PSA and the related research encounters some important knowledge gaps. The following topics belong to this group where research is needed to improve the Level 2 PSA quality according to the opinion of the authors.

IV.A.1. Releases into the waters and ground

The most of Level 2 PSA exclusively addresses releases into the atmosphere. Quantitative analyses of releases into water (river, lake, sea – see the Fukushima Dai-chi experience) were considered as missing. This is rooted in historic developments which concentrated on (immediate) health effects, and which seem to be less significant for water and ground releases. Nevertheless the consequences of such releases may be very significant. Therefore, the related source term characteristics should be explored by Level 2 PSA and the relevant research and guidance in this field is missing.

IV.A.2. Long-time effects inside plants

The long time effects – in particular related to the long term resilience of containments against fuel degradation accidents – should be addressed by Level 2 PSA. There may be some activities going on in this field, but the state of the art seems unfit for producing guidance.

IV.A.3. Iodine and Ruthenium chemistry

Level 2 PSA typically considers iodine releases to the environment in the chemical form of CsI. However, in the presence of intense radiation fields, as would be expected in severe accident conditions, complex iodine chemistry can develop over time resulting in the formation of additional gaseous molecular iodine (I2) via a number of routes, as well as stimulating other reactions with containment surfaces and aerosols that consume the gaseous iodine. In long-term accident sequences which do not develop early catastrophic source terms, the release of various iodine compounds may dominate over the CsI release.

With regard to Ruthenium, the amount of ruthenium produced by nuclear fission is important and increases with the fuel burn-up. Ruthenium has a high specific activity and high radio-toxicity compared to the other released fission products. The formation of volatile Ruthenium compounds is a significant concern. Much basic research has been done in the radiochemistry field, but the existing models are not yet suitable for routine application in Level 2 PSA. Therefore, guidance is needed how to introduce the existing information in Level 2 PSA and practically usable methods should be developed.

IV.A.4. Combustible gases outside the containment

Hydrogen and carbon monoxide issues within the containment are routinely taken into account in PSA. However, related issues outside the containment seem to require more attention. As an example, still today there is no conclusive interpretation of the combustion events in the Fukushima Dai-chi accident sequences, notably within block four. It seems that PSA need to focus more on the related issues, e.g. distribution and transport of combustible gas in containment venting systems, leak of combustible gases and probabilities of ignition for potentially ignitable atmosphere in different parts of the disturbed plant. Additional guidance seems to be needed for adequately addressing these issues.

IV.A.5. Treatment of uncertainties

Assessment of uncertainties should provide among other things a measure of the confidence that the results provided by PSA represent “real life” (what used to be called “robustness of results”). If the confidence is found to be low, the uncertainty analysis in Level 2 PSA shall provide information on the possible deviation in accident progression on the NPP and impact on the accident consequences.

The IAEA [8] provides a discussion of the sources of uncertainties (and some methodologies applied to Design Basis Accidents safety demonstrations that can be extrapolated also to severe accidents), and the USNRC [9] provides some guidance on the treatment of uncertainties for decision making. The ASAMPSA2 guidelines [6] in Vol. 2 provide discussions on this subject.

Some may actually be the biggest sources of uncertainties (Fukushima Dai-chi may be the best example in terms of modelling uncertainties and completeness). Nevertheless, advances in this area have not been forthcoming since issuance of the ASAMPSA2 guidelines; hence ASAMPSA_E needs not address or repeat what has been already discussed at length in the past in these areas.

Since the Fukushima accidents sometimes doubts are raised whether PSA truly represent the accidental risk of NPPs [10]. In this discussion it seems prudent to distinguish between Level 1 PSA issues and Level 2 PSA issues which are subject of the present document. With regard to Level 2 PSA the available experience in TMI, Chernobyl and Fukushima is not at all surprising. If Level 2 PSA had been performed based on the status of these NPPs at the onset of core damage, then it had probably provided results not far from the real experience.

V. CONCLUSIONS

The following list of Level 2 PSA conclusions and recommendations has been derived from this paper based on ASAMPSA_E guidance on Level 2 PSA [2] and PSA lessons learned from Fukushima accident [10]:

1. Since the consequences of an open containment are very severe, a PSA should quantify the probability for an open containment in shutdown states. In the context of an extended PSA; internal and external hazards should also be taken into account because they may affect the possibility to close the containment,
2. Simultaneous accidents in reactor core and SFP can be imagined, but have hardly been addressed in existing PSA. It is recommended to perform analyses considering both of these sources, including accident management actions. Development and improvements in accident simulation codes are needed before they are capable of simulating more than one melting fuel entity, e.g. simultaneous melting in core and SFP.
3. Level 2 PSA in SFP needs guidance how to define the initial loading, residual heat generation and radionuclide inventory inside the SFP.
4. Depending on the SFP design and its inventory, it may be imagined that criticality occurs during an accident sequence. Research and guidance is needed whether and how to address this issue in Level 2 PSA.
5. Level 2 PSA models should include source term assessments for the release category end states. Branches in the accident progression event tree should be defined also in light of the impact of systems, measures, or phenomena on release characteristics. Models limited to containment failure assessment should be extended as practicable.
6. Level 2 PSA models should be extended to the extent practicable to include repairs of previously failed systems or components. The longer PSA Level 2 analysis and mission times become, the more important is the consideration of such repairs. Moreover, effective modelling approaches should be developed for this issue to model appropriately the increasing chances of repair with time available.
7. Level 2 PSA models should include extended analysis times in the reliability models for systems, components and actions needed during the accident progression. Dependencies with support systems or supporting measures (like refilling water storage tanks), especially if induced by a longer mission time, should be systematically investigated and included into the Level 2 models to the extent sensible.
8. For accidents in the spent fuel pool, appropriate definitions for these Level 1 end states, e.g. “fuel damage”, should be defined. The respective end states should be part of an appropriately defined interface to the PSA Level 2. The Level 2 end states shall include the spent fuel storage status in a long term perspective.
9. Availability of key instrumentation and measurements during severe accident scenarios should be investigated using PSA methods, including scenarios coming from severe hazard impact. Failure of such instrumentation and measurements should be part of PSA Level 2 models.

ACKNOWLEDGMENTS

The authors would like to thank ASAMPSA_E partners’ organisations for their support and valuable technical contribution in development of project deliverable. The ASAMPSA_E project is funded by EU in Euratom FP7.

REFERENCES

[1] ASAMPSA_E, “Synthesis of the initial survey related to PSAs End-Users needs”, Technical report ASAMPSA_E/WP10/D10.2/2014-05, IRSN PSN-RES/SAG/2014-00193, January 2015.

[2] ASAMPSA_E, “Complement of existing ASAMPSA2 guidance for shutdown states of reactors, Spent Fuel Pool and recent R&D results”, Technical report ASAMPSA_E / WP40 / D40.6 / 2016-25, IRSN PSN/RES/SAG/2016-00170, June 2016.

[3] EPRI, “Modular Accident Analysis Program 5 (MAAP5) applications guidance”, Final report May 2015.

[4] L. Humphries, MELCOR Code Development Status, 7th meeting of the “European MELCOR User Group”, BEL V, Tractebel Engineering, Brussels, Belgium, march 17-18, 2015.

[5] N. Siu, S. Khericha, S. Conroy, S. Beck and H. Blackman, “Loss of Spent Fuel Pool Cooling: Model and Result”, INL-96/0334, October 1996.

[6] ASAMPSA2, “Best Practices guidelines for LEVEL 2 PSA development and applications, Volume 2- Best practices for the Gen II PWR, Gen II BWR LEVEL 2 PSAs. Extension to Gen III reactors”, IRSN-PSN/RES/SAG 2013-0177, April 2013.

[7] International Iodine Workshop, Marseille, March 2015, Full Proceedings, *OECD/NEA/CSNI report*, NEA/CSNI/R(2016)5, 2016

[8] IAEA SSG-4, “Development and application of Level 2 Probabilistic Safety Assessment for nuclear power plants”, Vienna, 2010.

[9] U.S. Nuclear Regulatory Commission, "Evaluation of External Hazards to Nuclear Power Plants in the United States," NUREG/CR-5042, December 1987.

[10] M. Kumar, A. Wielenberg, E. Raimond, “Post Fukushima lesson learned for Probabilistic Safety Assessment”, *Proceeding of European Safety and Reliability (ESREL) Conference*, Zurich, Switzerland, 7-10 September, 2015.