Journal of Energy

VOLUME 65 Number 3–4 | 2016 Special Issue

journal homepage: http://journalofenergy.com/

External Reactor Vessel Cooling Evaluation for Severe Accident Mitigation in NPP Krško

Mario Mihalina
Nuklearna elektrana Krško
Vrbina 12, 8270 Krško, Slovenija
mario.mihalina@nek.si

Srđan Špalj, Bruno Glaser
Nuklearna elektrana Krško
Vrbina 12, 8270 Krško, Slovenija
srdjan.spalj@nek.si, bruno.glaser@nek.si

ABSTRACT

The In-Vessel corium Retention (IVR) through the External Reactor Vessel Cooling (ERVC) is mean for maintaining the reactor vessel integrity during a severe accident, by cooling and retaining the molten material inside the reactor vessel. By doing this, significant portion of severe accident negative phenomena connected with reactor vessel failure could be avoided.

In this paper, analysis of NPP Krško applicability for IVR strategy was performed. It includes overview of performed plant related analysis with emphasis on wet cavity modification, plant's site specific walk downs, new applicable probabilistic and deterministic analysis, evaluation of new possibilities for ERVC strategy implementation regarding plant's post-Fukushima improvements and adequacy with plant's procedures for severe accident mitigation.

Conclusion is that NPP Krško could perform in-vessel core retention by applying external reactor vessel cooling strategy with reasonable confidence in success. Per probabilistic and deterministic analysis, time window for successful ERVC strategy performance for most dominating plant damage state scenarios is 2.5 hours, when onset of core damage is observed. This action should be performed early after transition to Severe Accident Management Guidance's (SAMG). For loss of all AC power scenario, containment flooding could be initiated before onset of core damage within related emergency procedure. To perform external reactor vessel cooling, reactor water storage tank gravity drain with addition of alternate water is needed to be injected into the containment. ERVC strategy will positively interfere with other severe accident strategies. There are no negative effects due to ERVC performance. New flooding level will not threaten equipment and instrumentation needed for long term SAMGs performance and eventually diluted containment sump borated water inventory will not cause return to criticality during eventual recirculation phase due to the lost core geometry.

Keywords: *in-vessel corium retention, external reactor vessel cooling, severe accident management*

1 INTRODUCTION

If a severe accident involving core damage is not arrested, at some point relocation of molten core material into the lower plenum of reactor vessel will occur. Reactor vessel integrity can be maintained by performing external reactor vessel cooling by retaining the molten material inside the reactor vessel, therefore avoiding significant severe accident negative phenomena connected with reactor vessel failure, such as:

- evaporation of water which is in contact with molten core debris which could result in containment overpressure;
- generation of additional flammable gases, as a consequence of molten core - concrete interaction (MCCI), which could threaten the containment;
- non-condensable gaseous buildup, as a consequence of MCCI, which could result in containment overpressure;
- additional radioactive aerosol production;
- reactor cavity steam explosions;
- basement floor concrete ablation, as a consequence of MCCI, which can threaten containment integrity;
- direct containment heating as a result of high pressure melt ejection of corium; and
- other accident phenomena connected with degradation of overall plant capabilities to mitigate the post-accident site releases and to restore controllable accident condition.

In case when ERVC performance is not successful to prevent reactor pressure vessel (RPV) failure, it will slow down boil off of reactor inventory, thus delaying the time of vessel failure. Gaining time could be crucial because it may be able to restore failed equipment back to service.

2 EVALUATION OF ERVC APPLICABILITY FOR NPP KRŠKO

An evaluation of current evidence, site specific analysis, and area of improvement in equipment and guidelines for IVR as an accident management strategy for NPP Krško will be presented. Also an overview of ERVC strategy for severe accident will be made. Areas of interest are:

- evaluation of NPP Krško current possibility for external reactor vessel cooling as a mean for severe accident mitigation, and
- eventual improvement of current "wet cavity" design and overall plant capabilities during accident mitigation.

Results of performed NPP Krško reactor cavity walkdown will be discussed and incorporated into the overall findings and conclusions.

2.1 Description of external reactor vessel cooling

The external reactor vessel cooling (ERVC) goal is to cool the RPV lower head from the outside. The objective is to prevent the RPV failure. As long as this objective is met, core debris remains inside RPV and therefore limits containment loads during severe accident. The goal can be satisfied by timely submerging the RPV lower head to a height some margin above the level which the core debris will reach inside the vessel following relocation from the original core boundaries. Nucleate boiling occurring on the outside vessel wall following core melt relocation will then remove sufficient heat from the debris to prevent vessel wall melt through.

Any actions required to achieve the flooding must be performed within a time window defined by the time interval between the start of the SAMG operations (i.e., Core Exit Thermocouple (CET) temperature > 650 °C (925 K)) and the predicted time of lower support plate failure, for the severe accidents under consideration.

In the long term, it is also necessary to compensate for the steaming due to the decay heat. For successful ERVC, focusing effect is on contact of metallic pool layer with RPV wall. It is expected that RPV wall on position 90 degrees will have the highest temperature and the creep deformation will lead to wall thickness reduction with partial wall melting. It will be potentially failure position of RPV, as seen in Figure 1. The focusing effect can be much reduced if the upper face of the metal layer is cooled on top (an example is injection into the core, spraying the upper portions of RPV from outside, or hot gases circulation with partial heat transfer to steam generators).

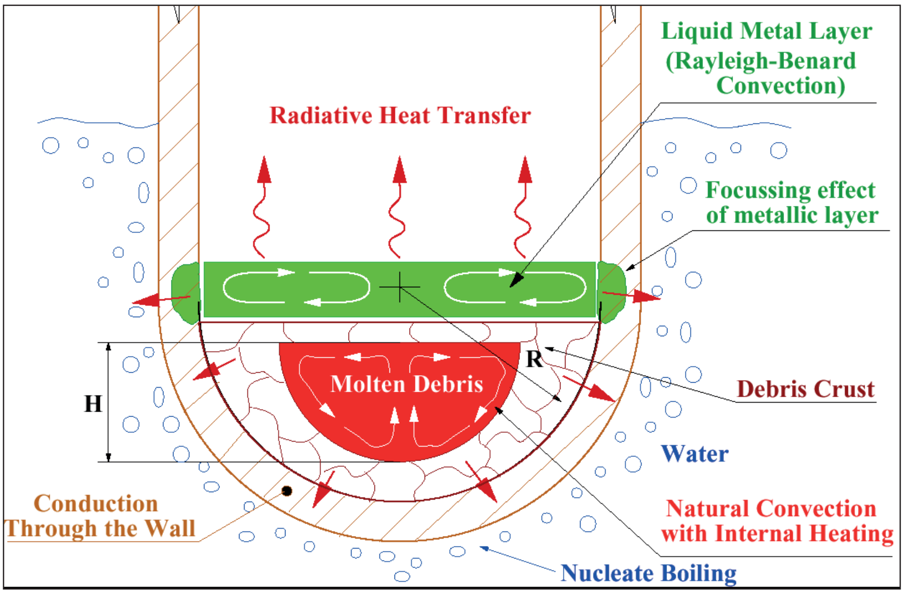

Figure 1: Basic principle and heat removal process of ERVC [1]

Once as successful ERVC strategy of vessel cooling has established IVR, heat removal from the containment stays crucial for long term severe accident mitigation.

2.2 History of ERVC development for NPP Krško

IPE Level 2

Summarized NPP Krško Individual Plant Examination (IPE) Level 2 [2] results based on the studies, experiments and analysis [3], represented that by performing ERVC strategy the heat transferred by nuclear boiling on the outer head wall surface can remove a large amount of heat, and that may be enough to prevent failure of the vessel wall due to melted corium thermal attack during the severe accident.

It was also concluded that if the reactor vessel could be timely flooded, this measure could prevent vessel failure in case of severe accident with relocated core. More practical considerations for NPP Krško included in [2] were:

- proposal of "wet cavity" modification at the plant by allowing free communication of water from the lower compartments to the RPV cavity, which will be beneficial to cool the debris if the vessel will fail, and
- with "wet cavity" design injection of total RWST volume would not flood the lower portion of the Krško vessel. Therefore, an accident management strategy to attempt to prevent vessel failure by IVR would require additional water to be injected into the containment than expected due to safeguards system operation.

In view of mounting evidences, it was recommended that NPP Krško considers vessel flooding as an ERVC severe accident strategy at a future date.

NPP Krško reactor cavity flooding evaluation

In the Reactor Cavity Flooding Evaluation Report [4] it was investigated and justified the flooding of the region below the reactor vessel as a means to mitigate a severe accident, and at the same time ensuring that such flooding will not have negative impacts on design basis accidents or on normal operations. The two main goals of RPV cavity flooding function were:

- containment floor concrete protection, and
- external RPV cooling.

An additional goal can is achieved when satisfying the main goals: scrubbing of fission product aerosols released from ex-vessel core debris.

NPP Krško wet cavity modification

Based on findings from [4], NPP Krško performed during 2001. modification 347-FD-L "Containment sump check valve removal", where wet cavity design is adopted by simple removal of check valve, as seen in Figure 2. The modification requirements included external reactor vessel cooling analysis.

The objective of performing this modification would be to mitigate the consequences of a potential severe accident by:

- ensuring the presence of water in the cavity in the event of reactor vessel failure and core debris transport to the reactor cavity, to quench and cool the core debris, and thereby prevent the occurrence of long term molten core-concrete interactions,
- flood the outside of the reactor vessel before core melt relocation to the lower head, and thereby potentially prevent the failure of the reactor vessel, and
- to ensure an overlying water layer if core debris does enter the containment, to scrub fission products released from the debris.

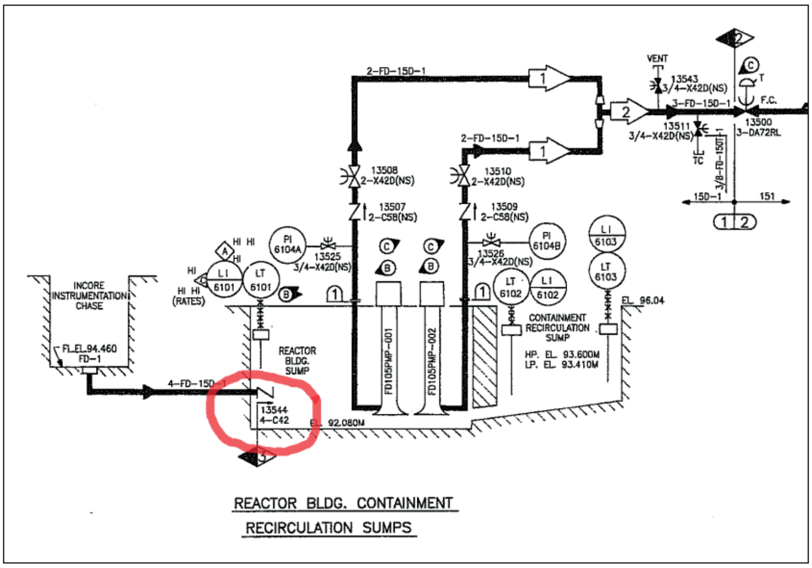

Figure 2: Containment sump check valve removal by plant modification 347-FD-L

Regarding that during wet cavity modification RWST was only source for containment injection, and analysis limitations for timely performance of ERVC strategy were applied, the RPV external cooling strategy was not implemented, despite deterministic benefits. Modification was accepted only for cavity floor concrete protection. See sections 3.8 and 3.9.

3 REQUIREMENTS AND LIMITATIONS FOR ERVC STRATEGY PERFORMANCE

3.1 Containment water level needed for IVR

The cavity water level shall be at least at the melted core level inside the RPV which is 1m above the RV Lower Head Bottom (inside RPV) plus a margin of 0.5 meter (see Figure 3).

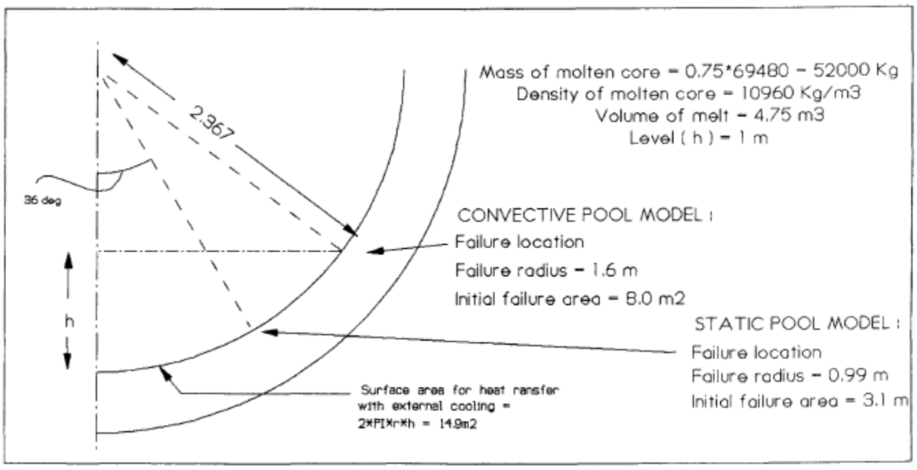

Figure 3: NPP Krško in-vessel corium pool geometry calculation [3]

This corresponds to a water height at elevation 99.2 m or approximately 152 m^3 of water in the cavity, or 1440 m^3 of water in the containment if the cavity and sump are connected.

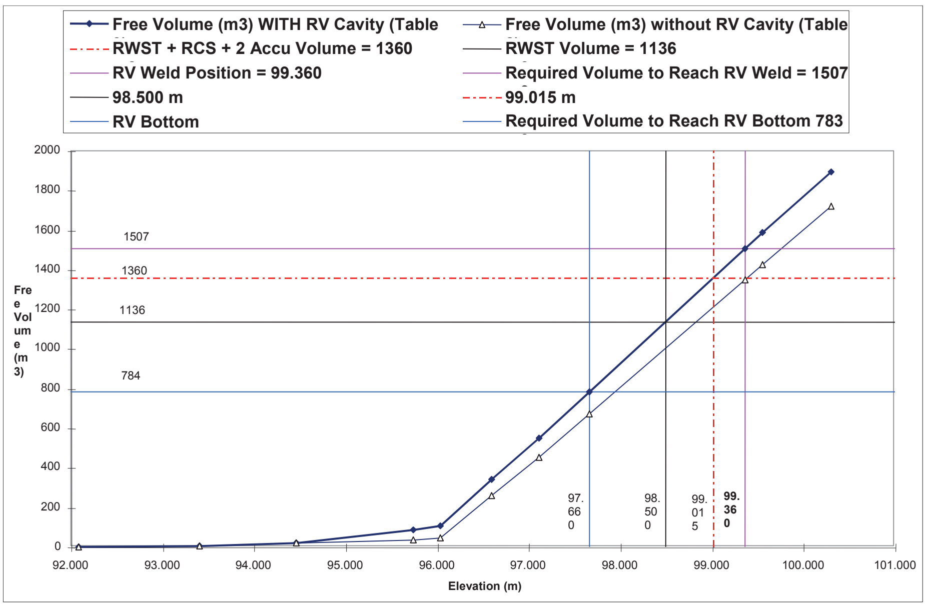

Figure 4: NPP Krško RB flooding level evaluation [4]

In Figure 4 and Table 1 are represented NPP Krško containment water volumes, elevations and plant instrumentation measured levels. Information's are collected from [4], [9], and [10].

Table 1: NPP Krško containment volumes, elevations, measured water levels

Level / RB plant elevation	Related minimum volume	LI 6102/ LI 6103	Description (sp. - setpoint)
92.080 m	-		RB sump bottom
93.410 m	-		Containment sump bottom
93.560 m	-	0 m	Containment recirculation sump level - bottom LI 6102 / LI 6102
94.460 m	-	0.9 m	Cavity floor bottom
95.500 m	75 m^3	1.94 m	Cavity concrete protection (SP – 2 m)
97.110 m	-	3.55 m*	Minimum recirc. sump operability water level *with (+) 0.3 m for EOP / SAMG sp.= 3.9 m
97.660 m	784 m^3	4.10 m	Bottom of the RPV
98.500 m	1136 m^3	4.94 m**	1. RWST useful volume 2. Flood level elevation FR-Z.2 **with (-) 0.3 m for EOP sp.= 4.6 m Ventilation opening to cavity (bottom)
99.015 m	1360 m^3	5.45 m	RWST + RCS + 2 SI ACC water volume Ventilation opening (top)
99.160 m	1440 m^3	5.60 m	RPV external cooling SP
99.360 m	1507 m^3	5.80 m	RPV weld
99.560 m	-	6 m	Containment recirculation sump level - top LI 6102 / LI 6103

3.2 RPV cavity flooding flowpath

Currently reactor cavity flooding in NPP Krško is performed through one 4 inch floor drain line (Figure 5).

Figure 5: RPV cavity floor drain opening protected with sieve (marked)

Afterwards, when containment level is sufficient high, water can enter through reactor compartment ventilation ducts (Figure 6). Therefore there are no flow limitations for timely performance of the cavity flooding strategy regarding containment to reactor cavity compartment injection.

Figure 6: Reactor compartment ventilation entry

3.3 Containment equipment flooding limitations

Regarding beyond design basis accidents and already adopted NPP Krško SAMG strategies [18], equipment flooding is predicted per SAMG [8] (see Table 2), where detailed information of potential effected equipment were made (as seen in Table 1).

Table 2: NPP Krško SAMG, SAG-8 Attachment "Loss of equipment and instrumentation", detail

Negative Impacts for Injecting Into the Containment (equipment and instrumentation location in RB below elevation 105)				
TAG NUMBER	DESCRIPTION	TYPE	ELEVATION	MEC
TE127	REGEN HX LETDN RTD	ELE	98.16	1
TE229	EXCES LETDN HX RTD	ELE	98.25	2
FE167	RCP 2 #2 SEAL ORIFICE	ELE	98.35	2
FE1008	RC DRN TANK DISC ORIF	ELE	98.63	2
FT1008	RC DRAIN TNK DISC FT	XMT	98.63	2
TE6530C	REACT SUPPORT PAD HI TEMP RTD	ELE	100.30	02B
TE6530D	REACT SUPPORT PAD HI TEMP RTD	ELE	100.30	02B
LT6102	**CNTMT RECIRC SUMP LT**	**XMT**	**100.30**	**13**

Affected instruments by additional flooding over el. 98.5 m (FR-Z.2) [21], [10] are part of reactor coolant drain tank (RCDT) flow measurement instrumentation, which are not necessary for containment sump recirculation, and are not essential for any further SAMGs strategy performance.

3.4 Pressurized Thermal Shock (PTS) issue for reactor vessel

In order to assure structural integrity of the Krško RPV for a postulated external flooding event, a stress and fracture mechanics analysis was performed (ref. [3], [4]), reflecting enveloping conditions in terms of internal pressure and temperature, and external temperature. The structural analysis focused on stability of postulated defects using fracture mechanics methods that are typically applied to demonstrate RPV integrity under PTS (Pressurized Thermal Shock) type of loading. Conclusion from [4] is that plant modifications, which allows vessel flooding to mitigate a severe accident, could not lead to PTS caused catastrophic vessel failure in case of vessel flooding during normal operation or design basis accident (DBA).

3.5 **Reactor vessel insulation water ingression**

NPP Krško IPE documentation suggests that NPP Krško reflective reactor vessel insulation would not impede the ingression of water needed for successful ERVC. The experiments referenced in plant specific IPE Level 2 [3] and EPRI [11] also show no effect of reflective insulation, with sustained nucleate boiling being maintained in cases performed with and without insulation.

Figures 7, 8 and 9, represents reactor cavity walkdown photos of NPP Krško reactor vessel bottom head insulation details.

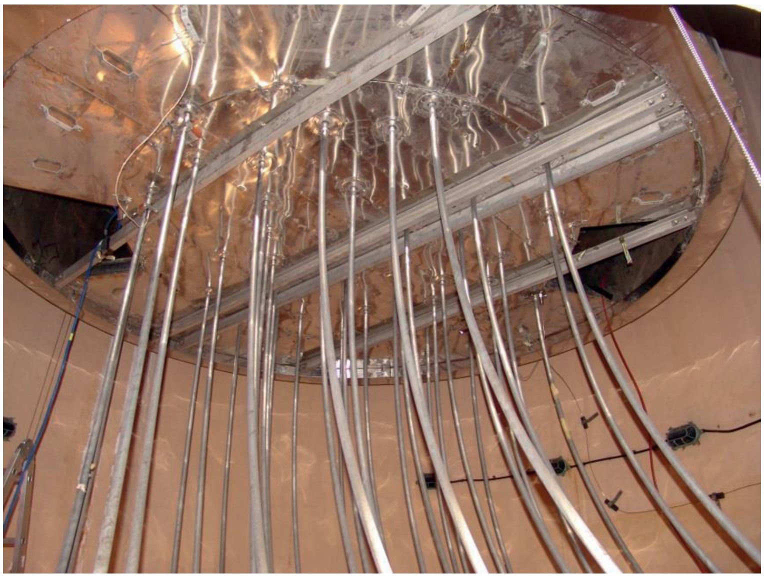

Figure 7: NPP Krško RPV insulation details (1) - inspection openings

Document Final Independent Review of NPP Krško Design Modification Package [14] reviewed plant modification 347-FD-L “Containment sump check valve removal”. The conclusions are in accordance with findings from [4]. This report as a new input defines minimum water in-flow for successful ERVC strategy performance (8 m^3/hr). According to [3], various experimental evidences exist that insulation would not impede the ingression of water because it is not watertight.

Figure 8: NPP Krško RPV insulation details (2) – incore penetrations

Figure 9: NPP Krško RPV insulation details (4) – insulation - concrete gap

Regarding plant specific IPE Level 2 analysis [2], and EPRI SAMG TBR generic documentation [11] – additional insulation openings for NPP Krško are not needed.

3.6 Steam explosions

Steam Explosions phenomena for NPP Krško are addressed in phenomenological evaluation [3], and site specific report [24]. Approaches to the issue of steam explosions which have been used in various analyses have also been reviewed.

Based on the reviews, evaluations and caluculated results, ex vessel steam explosion, as a result of eventual vessel failure into the flooded reactor cavity, will cause no additional challenges to the containment integrity since:

- for containment pressurization due to steam generation, the potential for steam explosions has no impact, and
- ex vessel steam explosion shock waves during eventual vessel failure scenarios pose neglible threat to containment integrity.

3.7 Recriticality during severe accident conditions

Partially diluted or unborated containment sump water inventory, will not cause return to criticality of molten core debris during in-vessel recirculation phase or eventual ex-vessel quenching, because of lost core geometry [7].

3.8 Time window requirements for ERVC strategy performance

For successful ERVC strategy performance, flooding must be performed within a time window defined by the time interval between the start of the SAMG operations (i.e., Core Exit Thermocouple temperature > 650 °C) and the predicted time of lower support plate failure.

The time window was identified as follows [4]:

- Severe accident sequences to be considered are identified based on Plant Damage States (PDS). Damage states participating for the most dominating Core Damage Frequency (CDF) are considered for the time window calculation.

- For most dominant damage states, where ERVC usage is reasonable, the accident sequence analysis from the level 2 study was used to determine the time window between the Core Exit Thermocouple reaching 650 °C and the predicted time of core lower support plate failure (corresponding to the time of core melt relocation to the lower head).
- The minimum time window for most dominant PDS is selected. The results of this process are summarized in Table 3.

Table 3 represents MAAP calculated NPP Krško PDS scenarios with dedicated time for ERVC. Calculated time for ERVC performance (criterion per [4]), for successfully strategy performance is 2.5 hours for TEHNNN plant damage state (PDS) scenario (58% of total CDF participation - as was used for design of passive containment filtered vent system (PCFV) [20]).

Table 3: NPP Krško most dominant PDSs applicable to ERVC, with calculated time [15]

Most dominant PDS contributors to overall CDF	Frequency for NPP Krško PDS, summ. regarding releases	Core uncovered (CET>650 C*) (sec.) (A)	Core relocation begins (sec.) (B)	RV failed, (sec.) (C)	**Minimum time for ERVC performance 1) (B) - (A) [4] hours (h)**
TEHNNN	58,18%	6463	15472	21767	**2,5 h**
TEHANN	7,46%	6463	15472	21767	2,5 h **
TEHAYN	5,45%	1920	9183	13429	2,0 h
UXXXXB	2,95%	6680	16096	20546	2,5 h
SELAYN	2,76%	15298	31205	37579	4,2 h
WUUUUB	0,90%	69529	79687	84700	2,7 h

* After core uncovers, roughly 250 to 500 seconds (depending on overall scenario length) is needed that CET rises from 370 deg. C (saturation water temperature), to 650 deg. C (SAMG entry). Assumption is based on similar results from [4].

** TEHANN scenario differs from TEHNNN regarding containment injection after vessel failure. Therefore TEHANN results for in-vessel accident progression are the same as TEHNNN.

It should be noted that first Reactor Cavity Flooding Evaluation Report [4] (with too conservative result with time window for vessel flooding of 30 minutes) took into account only PSA results for specific, worst case (fastest) PDS scenario, and this was chosen to give a judgment for adoption of ERVC strategy. Deterministic benefits from appliance of ERVC strategy were not used. Meanwhile, NEK PSA model [15] was updated with initiating events for: internal flooding, internal fires, seismic events, high energy line breaks (HELB), and other external events. Recent codes calculation of accident scenarios are using different severe accident phenomenology, where some of effects have changed the accident sequences and overall results (as hot leg creep rupture effect which happens before high pressure vessel failure, which enables safety injection accumulators to be injected into the RPV, thus postponing time of vessel failure).

For further development, if early depressurization of RCS is performed before core damage (or when it is noted that core damage is imminent), or when still in EOP procedure, for TEHNNN PDS scenario for the time from CET > 650 °C and the predicted time of lower support plate failure extends time window for ERVC performance for additional 1 hour. Also, with early EOP flooding action, ERVC successful performance time window per criteria [4] could be extended to at least 4 hours [25].

3.9 Curent plant availability for ERVC performance

For ERVC performance water inventory needed is 1440 m^3, to cover bottom of reactor vessel up to elevation 99.2 m (or 5,6 m on containment recirculation sump level indication).

Current Refueling Water Storage Tank inventory (RWST) inventory (1250 m^3), together with spilled RCS and SI ACC (226 m^3), is not sufficient for performance of IVR strategy. Nevertheless, after performing post-Fukushima short term improvement plant modifications [5], [6], NPP Krško is available to inject additional water (see Table 5) into the containment through alternate flowpaths (containment spray lines, ECCS flowpath, RCP fire protection spray lines), including mobile equipment usage.

Injecting RWST up to main control room "RWST Empty" alarm (18%) [21] will inject 1110 m^3 of water. Basis for that alarm is that RWST vortexing regarding ECCS PMP operation will be prevented (if later in the accident they will become available). Also, for core damage to occur, core should remain "dry", and it can be supposed that RCS has been spilled via PRZR safety / relief valve or through the RCS break (assuming the brake from RCS is spilled into the containment). RCS spilled total volume is roughly 226 m^3, including the accumulators. Together with RWST it would be 1360 m^3. Nevertheless by conservative assumption that RCS may spilled through IS LOCA or through SG tube rupture, this volume will not be taken into the account for ERVC purposes for flooding the containment.

NPP Krško current means for containment injection are:

- RWST gravity drain (1250 m^3) or RWST injection (1010 m^3) with ECCS or Containment Spray System to "RWST Empty" alarm (18%)

  AND
- additional 190 m^3 (430 m^3) needed to be injected by severe accident management equipment (SAME):
  - mobile AE900PMP-001/002 (FOX3) pump with capacity 96 m^3/h at 10 bar,
  - mobile AE900PMP-007 (HS450) pump with capacity 660 m^3/h at 12 bar.

It should be noted that for Extended Loss of AC Power (ELAP), containment flooding strategy by RWST gravity drain is currently performed within EOP "Loss of all AC power" procedure (before core damage). Applicable water sources are in Table 4.

Table 4: NPP Krško available water sources for inject into the containment (SAMG / EOP usage)

Source	Capacity	Water quality
RWST tank	1250 m^3	borated
BAT tank (2)	51 m^3	borated
WT tank 01	379 m^3	demineralized
WT tank 02	1000 m^3	demineralized
CY tanks (2)	879 m^3 each	demineralized
PW tanks (2)	1000 m^3 each	demineralized
FP tank	235 m^3	raw water
City water	unlimited	raw water
Condenser hotwell	not defined	raw water
CW tunnel	not defined	raw water
Sava river	unlimited	raw water

4 SEVERE ACCIDENTS MEASURES UPGRADE REGARDING ERVC PERFORMANCE

Severe accident assumes occurrence of a meltdown of the core, breaching the first barrier of the clad to release the radioactive fission products. If the accident progress further, the molten corium moves to the bottom head of the vessel. The bottom head will fail if the corium melt remains uncooled, thereby failing the second barrier to the release of radioactivity to the environment. The corium melt released to the containment may fail the containment in a short time if some energetic reactions, for example, hydrogen burn (detonation), steam explosion, or if direct containment heating occurs. If such energetic interactions do not occur, or are managed not to occur, the containment could fail later (by several hours or few days) due to the attack of the core melt on the concrete, which would release the non-condensable gases pressurizing the containment and possibility cause the melt-through of the basement. The containment structural failure represents failure of the third and the last barrier to the release of radioactivity to the environment.

Severe accident management guidelines (SAMGs) consist of actions (measures) that would prevent the failure of the barriers 1 (cladding), 2 (reactor pressure vessel) to 3 (containment). The first aim of SAMG is to prevent damage to the clad on the uranium fuel pellets.

This should be done by operator actions from severe accident control room guidance initial response, or after Technical Support Centre (TSC) becomes operable - by injecting into the secondary side, by depressurizing RCS and by injecting into the reactor vessel [8].

If that is not possible due to the inability to timely inject water to the vessel, the second barrier protection aim of SAMGs should become the prevention of the bottom head of the RPV by performing ERVC strategy. If that aim is not achieved due to either the inability of inject water to the vessel to quench and the melt pool in the lower head; the next (third) aim becomes prevention of the failure of the containment due to gaseous buildup, and/or the basement melt-through so that there is no significant release of radioactivity to the environment.

NPP Krško uses as a last mean for containment protection SAMGs severe challenge guidelines where usage of dedicated equipment is introduced from Phase 1 Safety Upgraded Project (SUP) implementation [6], [8]:

- Passive Autocatalytic Recombiners (PAR) - for mitigation of containment severe challenge due to buildup of flammable gases in containment, and
- Passive Containment Filtered Vent System (PCFV) for mitigation of containment overpressure severe challenges.

4.1 NPP Krško EOP Upgrades

Accident sequence with high contributing core damage frequency in PSA is loss of AC power initiator [20]. First procedurally containment injection action is in plant Emergency Operating Procedure (EOP) ECA-0.0 “Loss of All AC Power [21]. The basis is to establish RWST gravity flow to containment early enough to flood RPV if is evident that all attempts to establish decay heat removal by injecting into the secondary or primarily side are not successful and that core uncover is imminent. Also, benefit of that action is in the fact that containment pressure is low enough that RWST gravity drain is available. Decision for performing that action is made by Technical Support Center.

Also as a part of further SUP project there will be additional availability for early RCS depressurization with new Pressurizer PORV bypass valves [25]. Therefore, early RCS depressurization could prolong vessel failure for additional 1 hour.

So, by performing early RCS depressurization and containment flooding when there are no alternative means for beyond design basis accident mitigation, there is significant improvement in current plant chances for successful ERVC performance.

4.2 NPP Krško SAMG Upgrades

Currently, NPP Krško does not use ERVC strategy for in-vessel melt retention. Nevertheless early containment flooding strategy for reactor cavity flooding is adopted in NPP Krško SAMG's [8] for reactor cavity floor concrete protection to mitigate consequences of eventual vessel failure where MCCI could occur [4]. Means for containment flooding are usage of containment spray, injection through eventual RCS openings, or if AC power is lost - RWST gravity drain, as well as alternate mobile pumps, additional water sources with alternate containment injection flow paths for containment injection.

Regarding further development of generic SAMG's, containment flooding strategy to perform ERVC will also be used [26]. Also development of "Severe Accident Control Room Guideline - Loss of DC and Instrumentation" [24], proposes integrated RCS and containment flooding strategy for prevention of RPV failure, by application of ERVC strategy if core condition is unknown.

Main control room initial response guideline (SACRG-1)

Currently, NPP Krško SAMGs guideline SACRG-1 [8], or main control room (MCR) initial response to severe accident before technical support center (TSC) is activated, performs early containment flooding strategy to assure reactor cavity flooding up to recirculation sump level of 2 m [9]. Basis is reactor cavity basement floor protection [4]. Anyway, due to practically reasons, the operators are instructed to flood up to recirculation sump level of 3.9 m, or EOP / SAMG setpoint [10]; to establish containment sump level for strainers operability for usage of containment spray or emergency core cooling system in recirculation mode. Other actions, including attempts to inject into the RPV are followed later.

For timely performance of ERVC strategy, SACRG-1 guideline is most suitable. Although RWST gravity drain is possible during performance of Loss of All AC Power procedure (as TSC evaluated action for extended loss of AC power condition), certain containment flooding as a operators action will be performed during SAMG's SACRG-1 guideline for MCR.

Usage of alternate provisions (SAME equipment) and water sources will be needed, to fill containment with 1440 m^3. Beside 1250 m^3 of RWST inventory, additional 190 m^3 could be needed from other sources. Note that RCS and SI ACC inventory (which may or may be not spilled in sump) is not taken into the account (maximum 225 m^3 of inventory).

Therefore, if attempts to inject into the RPV had failed, or injection flow is insufficient to remove decay heat, suggestion is that SACRG-1 direct operators to establish ERVC to prevent / delay vessel failure, by injecting into the containment with alternative provisions.

Technical support centre severe accident guidelines (SAG's)

NPP Krško SAMGs guidelines [8], SAG-4 "Inject into containment" and SAG-8 "Flood the containment", performs strategy of injecting water into the containment by using all available means, as directed by technical support centre (TSC) evaluators.

The current purposes of injection into the containment are to [8]:

- prevent or mitigate the consequences associated with core-concrete interactions,
- scrub fission products released from ex-vessel core debris,
- allow ECCS recirculation (long term containment heat removal), and
- perform external cooling of RPV lower head (SAMG's generic [17]).

SAG-4 is suitable for performing ex vessel cooling strategy, even if it comes somehow late per SAMGs diagnostic flowcharts. If previous SAG-s strategies are not successful, flooding up to new level of 5.6 m will also allow more confidence for retaining core inside the vessel, even if unsufficient

RCS injection flow is established within SAG-3 "Inject into the RCS". EPRI SA TBR [7], notes that insufficient injection flow less than 29 m^3/h (SAMG setpoint [F02], CA-1, [9], could accelerate core damage from core damage states OX/BD to EX. ERVC can assure that even for insufficient water injection (etc. insufficient STORE mobile pump characteristic for RCS decay heat removal with RPV injection), possible negative effects will be mitigated. Additionally, in combination with containment spray which will cool upper sections of RCS, ERVC strategy could provide more confidence in retaining the core inside the RPV.

Regarding SAG-8 "Flood the containment", this strategy is performed when reactor vessel is already failed, so it is not suitable for ERVC strategy. SAG-8 flooding is to the elevation of [L03] (4000 m^3 of water) or [L03a] (9000 m^3 of water).

For containment flooding levels used in NEK SAMG [8], see Figure 10.

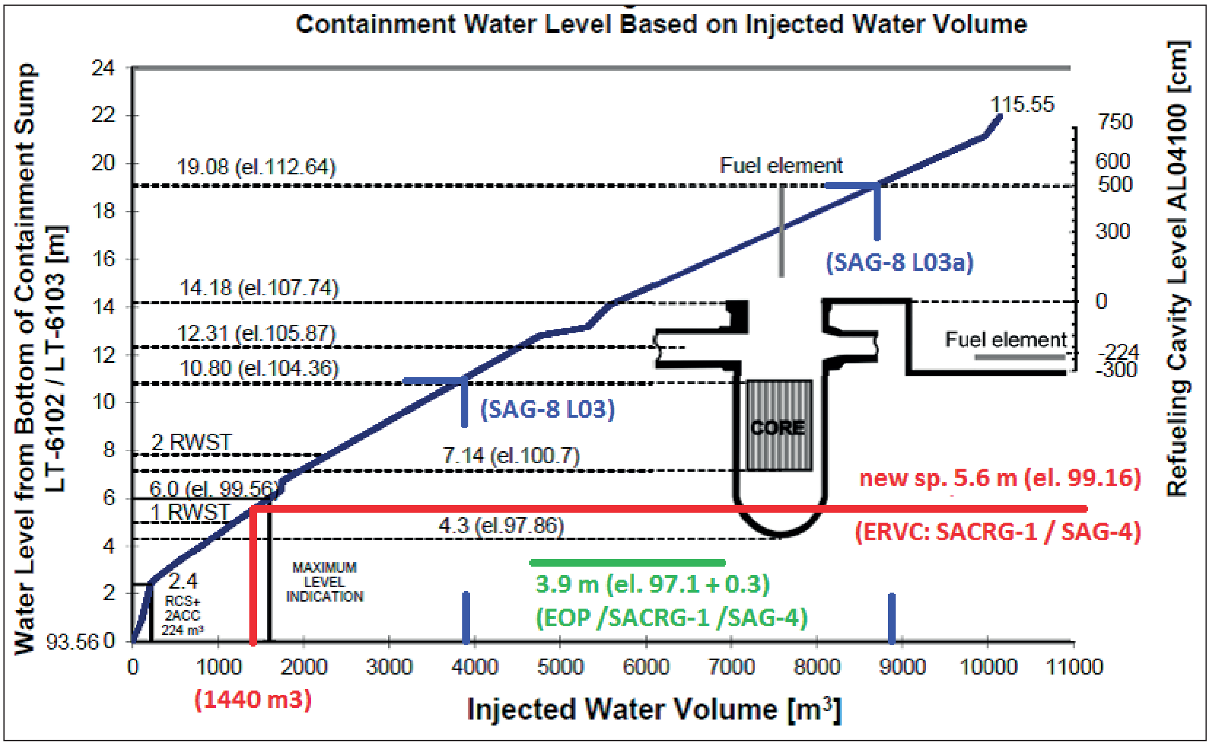

Figure 10: NPP Krško's CA-5 "Containment Water Level and Volume" sketch [8] with marked EOP and SAMG containment flooding levels [9], [10]

4.3 Furtherer plant upgrade for ERVC performance

As a part of Safety Upgrade Program (SUP) modification 1029-RH-L, alternate containment injection flowpaths for variety of mobile pump usage with ERVC applicable performances will be installed. Also there will be installed additional borated water water tank, dedicated for beyond design basis accidents (design extended conditions) [6].

5 CONCLUSION

NPP Krško could perform external reactor vessel cooling (ERVC) strategy with reasonable confidence. Total containment water inventory need for ERVC performance is 1440 m^3, to cover bottom of reactor vessel up to elevation 99.2 m (or 5.6 m measured on containment sump level indicators) [27]. Strategies for performing this action for severe accident scenarios are:

- for Loss of all AC event - RWST gravity drain (up to 1250 m^3 - depending on containment backpressure), with additional alternate water inventory needed to be injected by AE equipment, and
- for AC available events - RWST injection with ECCS (total inventory of 1010 m3) up to “RWST Empty” alarm (18%), with additional 430 m^3 of alternate water inventory needed to be simultaneously injected by ECCS, DEC or AE equipment.

If RWST gravity drain is unavailable, containment injection by alternate equipment and water sources will take a place. Eventually spilled and partially evaporated RCS and SI ACC inventory (in total 226 m^3) is not taken into account.

Per probabilistic and deterministic analysis, time window for successful ERVC strategy performance during severe accident occurrence (after observed CET > 650˚C) is 2.5 hours for TEHNNN plant damage state (PDS) scenario with 58% of total CDF participation. This action should be performed early after transition to Severe Accident Management Guidance (SAMG). During loss of all AC power scenario leading to core damage, early containment flooding is performed before CET > 650˚C condition within EOP ECA-0.0 procedure, which extends time for successful strategy implementation.

There are no negative effects due to ERVC performance. New flooding level will not threaten equipment and instrumentation needed for long term SAMGs performance or hamper the ECCS recirculation capabilities. Eventually diluted containment sump borated water inventory will not cause return to criticality during recirculation phase because of lost core geometry [7].

ERVC strategy will also positively interfere with other severe accident strategies regarding corium retention inside reactor vessel. It will supplement the effect of insufficient individual equipment performances needed for successful severe accident mitigation. Example is combining ERVC with simultaneously insufficient RCS injection and/or minor containment spraying of upper RCS sections.

Changes in current NPP Krško SAMGs regarding ERVC strategy implementation could include: SACRG-1 “Severe Accident Control Room Guideline Initial Response”, and SAG-4 “Inject into Containment”.

Regarding further development of generic SAMG’s, containment flooding strategy to perform ERVC will be used. Development of Severe Accident Control Room Guideline - Loss of DC and Instrumentation, proposes integrated RCS and containment flooding strategy for prevention of RPV failure, by early application of ERVC strategy if core condition is unknown.

As a part of NPP Krško Safety Upgrade Program (SUP) modification regarding ERVC applicability, alternate containment injection flowpaths for AE equipment and additional borated water tank, will be introduced.

REFERENCES

[1] SARnet, IRSN “Nuclear Safety in Light Water Reactors, Severe Accident Phenomenology”, Bal Ray Sehgal, Georges Vayssier, & others; SARnet, IRSN; Elsevier 2012.

[2] WENX-95/25 “Krško IPE level 2 – Summary Report”, 1995.

[3] WENX-95/24 “Containment Event Tree notebook – Part 2: Phenomenological Evaluations”, 1994.

[4] WENX-00-08 “Krško NPP Reactor Cavity Flooding Evaluation Report”, 2000.

[5] “Slovenian Post-Fukushima National Action Plan”, 2012.

[6] DCM-RP-083, Program nadogradnje varnosti NEK rev.1. 2013.

[7] EPRI Severe Accident Technical Basis Report, “Candidate High Level Actions and Their Effects” Volume 1, 2012.

[8] SAG-17.001 Rev. 6 “Severe Accident Management Guidance”, NPP Krško, 2014.

[9] NEK ESD TR-23/00 “NEK SAMG Setpoint Calculation”, Rev. 4, 2014.

[10] NEK ESD TR-11/02 “NEK EOP Setpoint Footnote Calculation”, Rev. 0, 2009.

[11] EPRI Severe Accident Technical Basis Report, “The physics of Accident Progression”, Volume 2, 2012.

[12] WENX-13-36 "Pre- and Post-Vessel Failure Strategies and Vessel Failure Detection”, PWROG PA-PSC-1081 Project, 2013.

[13] PA-PSC-0932 “PWROG SAMG Structure”, presentation, PWROG - NPP Krško meeting, 2015.

[14] IJS-DP-8339 FIER “Design modification package No. 347-FD-L, Containment sump check valve removal” L. Fabjan, L. Cizelj, M. Čepin, I. Kljenak, B. Mavko, 2001.

[15] NEK ESD-TR-09/14 “NEK Source Term Recalculation”, 2014.

[16] NEK ESD-TR-12/14 “Revision of Risk Significance Evaluation Based on the Actual Design Characteristic of PAR-s”, 2014.

[17] LTR-RRA-01-119 “WOG SAMG Addendum”, Implementation Guidance, 2001.

[18] WOG-94-083 “WOG SAMG”, 1994.

[19] ZKP 2015-1062, NPP Krško, Corrective Action Program

[20] WENX-12-05 STR-NEK-11-18 “Krško Passive Containment Filtered Pressure Relief Ventilation System Partial Design Package”, Rev.1, 2012.

[21] NEK EOP-3.5 “Emergency Operating Procedures”, Rev.18, 2014.

[22] WENX-95/24 “Krško IPE Level 2 Main Report”, 1995.

[23] WENX-13-26 “Strategies for Loss of all D.C./Instrumentation”, PWROG PA-PSC-1081 Project “SAMG Update for International Participants”, October, 2013.

[24] IJS-DP-9103 “Analysis of Influence of Steam Explosion in Flooded Reactor Cavity on Cavity Structures”, M. Leskovar, L. Cizelj, B. Končar; 2005.

[25] PORV-NEK-AR-00002 “Krsko Pressurizer PORV Bypass - Bleed and Feed in Design Extension Conditions” Rev.0, August 2015.

[26] OG-16-58, "Transmittal of PWROG-15015-P Revision 0 PWROG SAMG (PA-PSC-0932)", February 2016.

[27] NEK ESD-TR-14/15 "External Reactor Vessel Cooling Evaluation for NPP Krško - NPP Krško In-vessel Core Retention Strategy Analysis for Severe Accident Mitigation", M. Mihalina, November 2015.