Feasibility Assessment of Structural and Component Enhancements at Generation II Pressurized Water Reactors for Implementing External Reactor Vessel Cooling (ERVC) in Severe Accident Mitigation

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ABSTRACT

This study evaluates the feasibility of external reactor vessel cooling (ERVC) improvement as a severe accident mitigation strategy at Generation II pressurized water reactor (PWR's) not originally designed for in-vessel corium retention (IVR). To obtain more realistic results, the assessment is based on the design of NPP Krško, which has already demonstrated the feasibility of ERVC implementation with reasonable confidence in success. The assessment integrates theoretical and numerical analyses, plant specific probabilistic and deterministic (MAAP 5.03 code) simulations, and a review of existing accident management procedures, including recent scientific and industry insights related to ERVC improvement. Key factors including reactor cavity geometry, critical time windows for dominant plant damage states, thermal power characteristics, and the impact of reflective insulation are examined to determine ERVC performance limits and potential enhancement pathways.

The study identifies general measures which might improve ERVC capabilities, such as improvements to cavity flooding, the applicability of additional ex-vessel cooling features, thermal insulation upgrades, and the influence and compatibility of other concurrent mitigation strategies, together with accident management procedural enhancements. Findings indicate that with targeted structural and procedural upgrades, ERVC can be upgraded to a more viable and robust component of severe accident management, strengthening containment integrity and overall defence in depth against extreme external events in PWR's not originally designed for IVR. The study also identifies the need for further research to quantify such enhancements by defining performance indicators for ERVC in terms of reducing the probability of radioactive material release into the environment and the associated radiological consequences.

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

1 INTRODUCTION

Severe-accident management for nuclear power plants has evolved significantly over recent decades, driven by increased regulatory emphasis on enhancing defence-in-depth and resilience against beyond design basis events. In-vessel retention with external reactor vessel cooling

(IVR-ERVC) is a strategy designed to prevent lower-head failure during core-melt accidents by removing decay heat through subcooled boiling on the external reactor pressure vessel (RPV) surface. While IVR-ERVC has been adopted in many Generation III and III+ designs, its retrofitting to older Generation II reactors remains a subject of ongoing international research.

As a case study, NPP Krško, a 1994 MWt Westinghouse PWR, was originally designed without provisions for IVR. Nevertheless, plant upgrades such as adoption of “wet cavity design” and safety modernization programs, have increased interest in additional severe-accident management features. Implementing an enhanced ERVC system could potentially mitigate key accident sequences identified in probabilistic Level 1 and Level 2 analyses. This study also investigates whether targeted structural improvements and procedural upgrades could allow ERVC to become a practical and reliable mitigation measure at Generation II PWR’s with similar designs as NPP Krško. A brief evaluation of current evidence, site specific analysis, and area of improvement in equipment and guidelines for IVR as an accident management strategy will be presented. This article will cover:

- general requirements for ERVC application,
- overview of plant-specific possibility for external reactor vessel cooling at NPP Krško,
- requirements and limitations regarding current Generation II PWR’s plant designs with discussions regarding NPP Krško plant-specifics features,
- feasibility assessment of structural and component enhancements for general ERVC implementation, and
- defining further methods for quantification of ERVC improvement benefits in terms of reducing radiological consequences of severe accidents.

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

2 GENERAL REQUIREMENTS FOR ERVC APPLICATIONS

In a typical pressurized water reactor (PWR) plant, three key physical barriers are designed to prevent the release of fission products into the environment:

- 1st fuel cladding,
- 2nd reactor pressure vessel (RPV) / reactor coolant system (RCS) / steam generator (SG), and
- 3rd leak-tight containment structure – which serves as the final barrier, preventing any fission products that escape from the RPV/RCS from reaching the external environment.

Maintaining the integrity of each of these barriers under all accident conditions is fundamental to the defense-in-depth strategy widely adopted in nuclear safety and emergency planning to mitigate radioactive releases. During a severe accident, which includes core meltdown, the first barrier (the fuel cladding) by definition fails (oxidise / melts), resulting in the release of a portion of fission products (in both gaseous and aerosol forms) into the RCS. This places increased importance on the integrity of the SG U-tubes, RCS piping’s and particularly RPV (including melted fuel - corium), as well as the last barrier of pressure-retaining capability of the containment structure.

In the context of severe accident progression, the most notable 2nd fission product barrier is RPV which is subjected to melted core which slumps into their bottom head. In-vessel retention (IVR) is a severe accident mitigation strategy to stabilize the core melt relocated to the lower head of the RPV by flooding the reactor cavity and submerging the reactor vessel by providing the external reactor vessel cooling (ERVC) [1]. It aims to contain the molten core debris inside the reactor vessel by cooling its external surface via the natural circulation of cooling water, as illustrated in Figure 1. In the context of severe accident mitigation, if the RPV remains intact and the containment structure is not breached, the expected accident outcome is that impact on the population and environment would be lowered - assuming no other pathways for radioactive release exist (example is SG releases by bypassing containment).

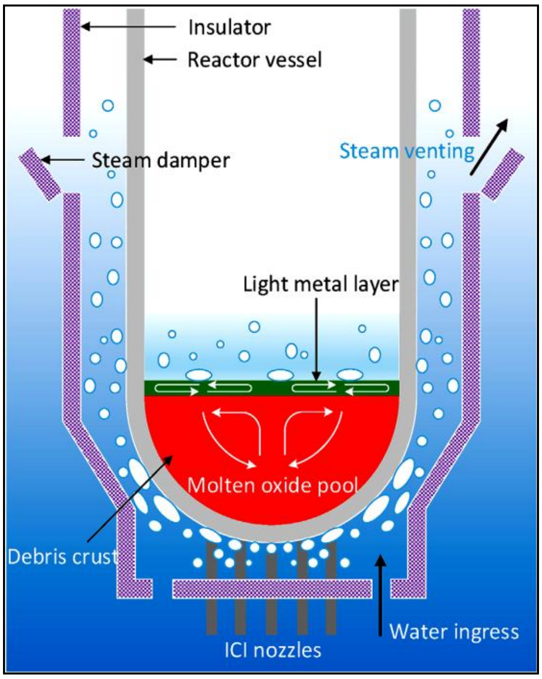

Figure 1: ERVC concept design for IVR [2]

2.1 Benefits

By sustaining RPV integrity, ERVC enables in-vessel retention of molten core material and prevents several key severe accident phenomena associated with vessel failure. These include high-pressure melt ejection (HPME) and direct containment heating, steam explosions and rapid containment pressurization due to corium–water interaction, and molten core–concrete interaction (MCCI), which generates flammable and non-condensable gases, radioactive aerosols, and leads to RPV cavity basement ablation. By avoiding these mechanisms, ERVC reduces dynamic loads and over-pressurization of the containment, preserves structural integrity, and enhances the plant's ability to control accident progression and mitigate radioactive releases [2].

2.2 Limitations

2.2.1 Critical Heat Flux

A key limitation in assessing ERVC feasibility is the uncertainty associated with critical heat flux (CHF) under the highly restricted flow and boiling conditions around the reactor pressure vessel (RPV). Experimental programs relevant to IVR for reactors in the 1500–3000 MWt range report CHF values typically between 1.0 and 1.5 MW/m² for downward-facing hemispherical surfaces and up to 1.5–2.0 MW/m² for upper side-wall regions where natural convection is more effective [2]. For a 2000 MWt-class reactor such as NPP Krško, such values represent the approximate threshold above which stable subcooled boiling cannot be maintained on the vessel exterior. These limits must be compared to MAAP-predicted external heat fluxes, which can reach 1.5–2.5 MW/m² in stratified corium pools. MAAP 5.03 *does* predict external vessel heat fluxes, but it does *not* calculate CHF.

The outcome is illustrated by comparing the probability distributions of q_w and CHF, as shown in Figure 2. In Figure 2(a), the probability of q_w exceeding CHF is low, indicating a successful IVR case. In contrast, Figure 2(b) shows a higher probability of q_w surpassing CHF, representing an unsuccessful scenario. [2]

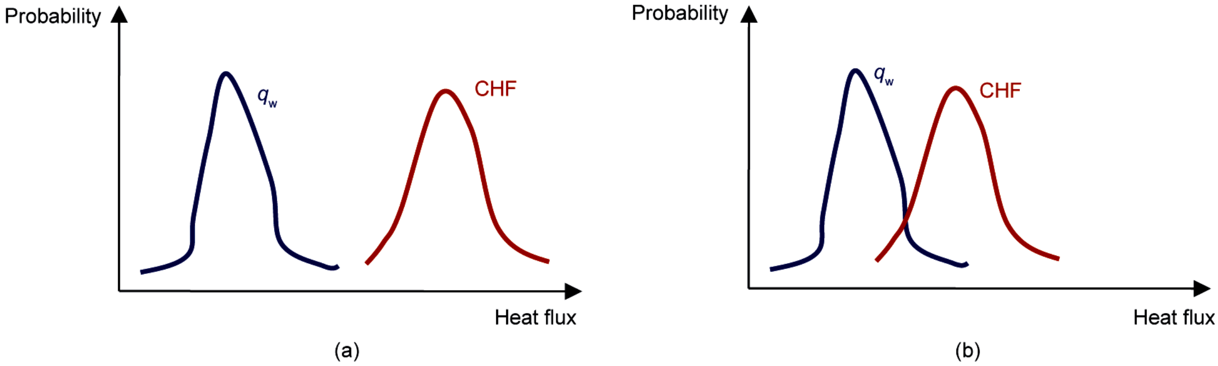

Figure 2. Heat flux distribution functions for: (a) Successful case; (b) unsuccessful case. [2]

2.2.2 RPV and Reactor cavity geometry

An additional challenge arises from the specific RPV and cavity geometry: the narrow annular clearances, the intricate configuration of reflective insulation panels, and the limited steam-venting pathways collectively hinder coolant circulation and reduce local boiling effectiveness, thereby lowering the attainable CHF and increasing the likelihood of dryout, which ultimately diminishes the thermal margin available for successful ERVC performance [1].

2.2.3 Water cooling capabilities

In the long term, the steaming generated by decay heat must be continuously compensated to maintain effective external cooling. Also there must be enough water inventory to cover all portions of RPV related to ERVC, more specifically the portion of the RPV with focusing effect, which occurs when lighter melted metallic layer of a stratified corium pool contacts the reactor pressure vessel (RPV) wall, on their top. In such cases, the RPV wall near the mid-elevation region (around the 90-degree circumferential position) is expected to experience the highest thermal loading, leading to accelerated creep deformation, wall thinning, and partial local melting. This location therefore represents the most probable site of lower-head failure, as illustrated in Figure 1. The focusing effect, however, can be substantially mitigated if the upper surface of the metal layer is externally or internally cooled - for example, by concurrent in-vessel injection, external spraying of the upper RPV region, or by RCS circulating hot gases in a way that enhances heat transfer to the SG's; although it endangers the overall accident with the possibility for SG U-tube creep failure, threatening with containment bypass releases regarding gaseous and aerosol fission products.

2.2.4 Time window

Regarding accident management, 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 [3]. The time period will be examined by application of deterministic analysis by MAAP 5.03 code, for some of scenarios with most dominant plant damage states (PDS) – which are based on Level 2 probabilistic safety analysis (PSA).

2.2.5 Long term mitigation capabilities

Once as successful ERVC strategy of vessel cooling has established IVR, regardless of initial success for maintaining the RPV integrity, a heat removal from the RPV and containment stays crucial for long term severe accident mitigation. This requires constant water inflow to RPV as well and systems for containment decay heat removal [4].

3 EVALUATION OF NPP KRŠKO CURRENT POSSIBILITY FOR ERVC APLICATION

3.1 IPE Level 2 (1994)

Results from the NPP Krško IPE Level 2 assessment [5] indicated that effective external reactor vessel cooling could remove sufficient decay heat by nucleate boiling on the vessel exterior to potentially prevent lower-head failure during severe core-melt scenarios. The study concluded that timely external vessel flooding is essential for maintaining these cooling conditions. Practical considerations in that time included the proposed "wet cavity" modification, enabling free water communication between lower compartments and the RPV cavity, and the finding that, even with this configuration, the RWST tank alone (as dedicated water source in that time for containment injection) would not provide enough water to fully flood the lower vessel region - requiring additional containment injection for a viable IVR strategy. Based on the accumulated evidence from that study, vessel flooding was recommended as a future ERVC severe-accident management measure for NPP Krško [6].

3.2 NPP Krško reactor cavity flooding evaluation

The NPP Krško's Reactor Cavity Flooding Evaluation Report [7] examined and justified flooding the region beneath the reactor vessel as an effective severe-accident mitigation measure, while confirming that such flooding would not adversely affect design-basis accidents or normal plant operation. The flooding function was shown to support two primary objectives: protecting the containment floor concrete and enabling external reactor vessel cooling. A secondary benefit - achieved when these main goals are met - is enhanced scrubbing of fission-product aerosols released from ex-vessel corium.

3.3 NPP Krško wet cavity modification (2001)

In 2001, NPP Krško implemented modification adopting a wet-cavity configuration by removing the sump check valve. The change aimed to improve severe-accident response by allowing cavity flooding for debris quenching, potential external vessel cooling, and enhanced fission-product scrubbing. However, because the RWST was the only available water source and analyses showed insufficient capability to achieve timely ERVC conditions, the external cooling strategy was not adopted [8]. The modification was ultimately implemented solely to improve protection of the cavity floor concrete.

3.4 Post Fukushima upgrades - Plant safety upgrade project

Following the experiences of NPP Fukushima-Daiichi accident in 2011, NPP Krško implemented the Safety Upgrade Program, introducing various mobile and more robust plant-built specific Design Extended Condition (DEC) equipment to manage beyond-design-basis accidents [9]. These upgrades added new water sources and systems aimed for preventing core damage and mitigate post-core damage containment challenges associated with RPV failure, including the post-core damage dedicated systems: passive containment filtered vent system (PCFV) for overpressure protection and passive autocatalytic recombiners (PAR's) for hydrogen control.

3.5 RPV cavity flooding flowpath

Currently reactor cavity flooding in NPP Krško is during the initial phase of accident performed through one 4 inch floor drain line (Figure 3 - left).

Figure 3: NPP Krško’s RPV cavity floor drain opening protected with sieve (left), and RPV compartment ventilation entry (right)

Afterwards, when containment level is sufficient high, water can enter through reactor compartment ventilation ducts (Figure 3 - right). Therefore, there are no flow limitations for timely performance of the cavity flooding strategy regarding containment to reactor cavity compartment injection.

3.6 Containment water level needed for IVR

The cavity water level must reach at least the height of the relocated molten core inside the RPV - approximately 1 m above the lower-head inside surface, plus an additional safety margin of 0.5 m (see Figure 4) [7].

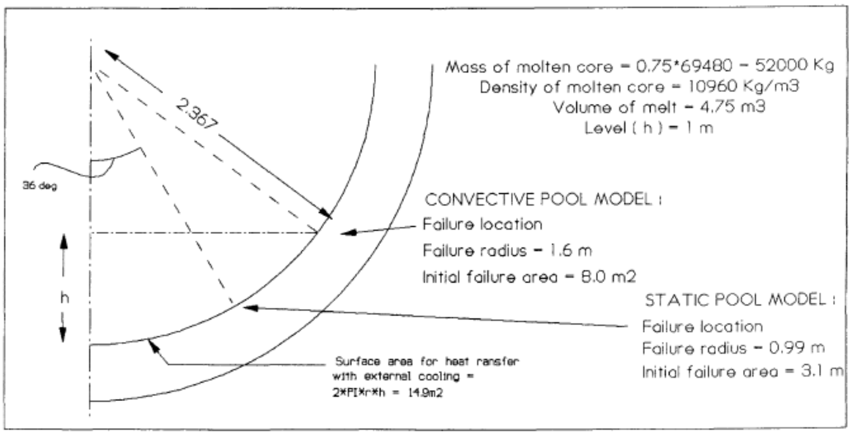

Figure 4: NPP Krško in-vessel corium pool geometry calculation [3]

This corresponds to a water height at elevation 99.2 m or approximately 170 m^3 of water in the cavity, or approximately 1500 m^3 of water in the containment if the cavity and sump are connected (see Figure 5). RPV cooling by “only cavity flooding” regarding NPP Krško case study is only hypothetical assumption (details in Figure 6).

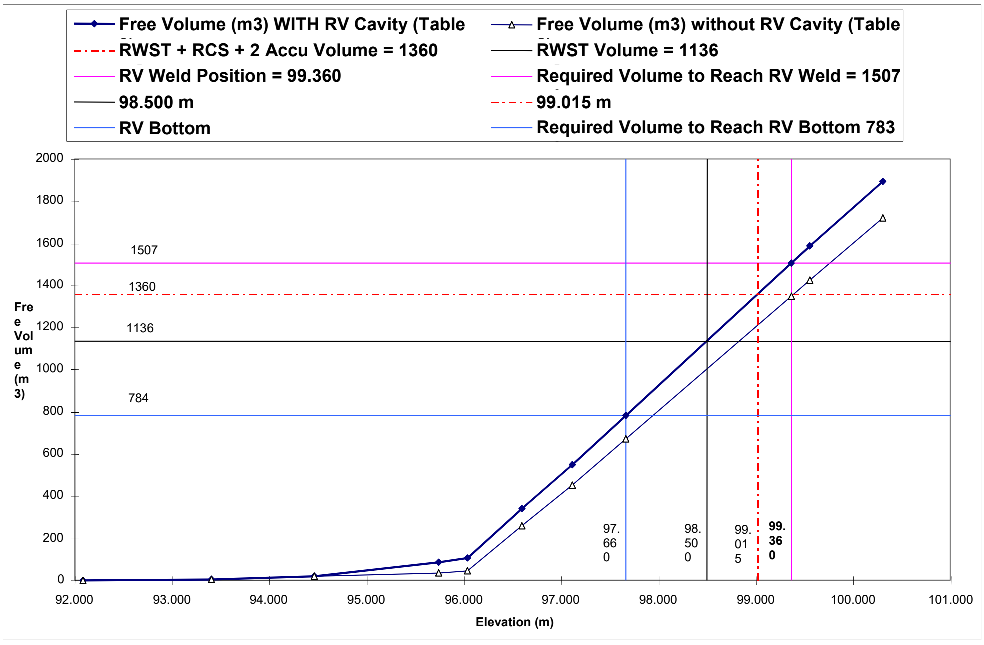

Figure 5: NPP Krško RB flooding level evaluation [3]

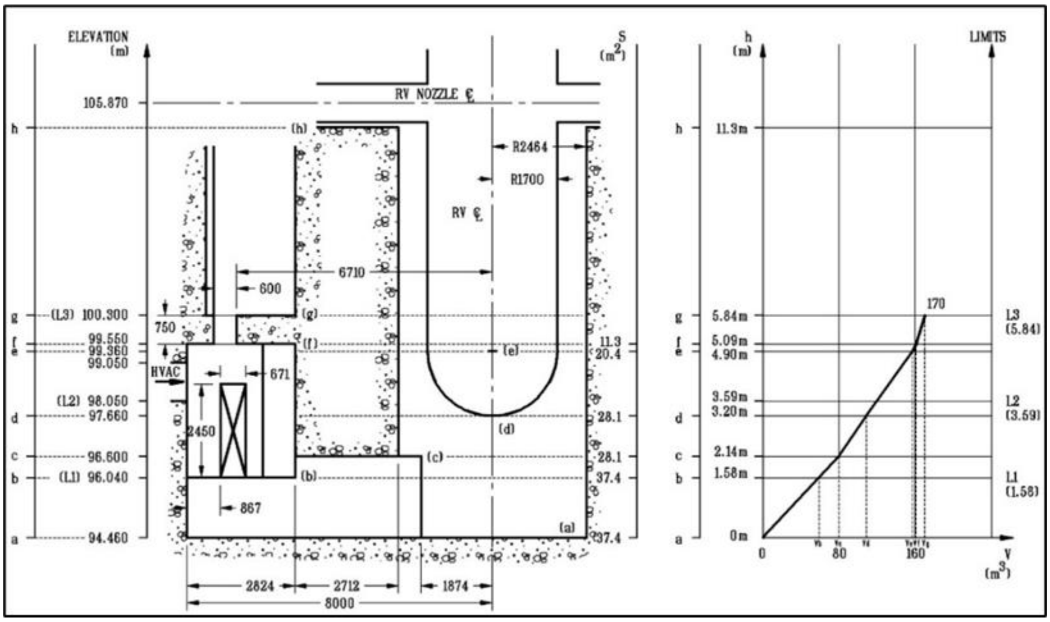

Figure 6: NPP Krško RPV (only) cavity section and free volume in function of height [3]

In Table 1 are represented NPP Krško containment water volumes, elevations and plant instrumentation measured levels. Information's are collected from [7], [10], [11] and [12].

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

Level / RB plant elevation	**Containment injected water volume**	**Hypothetic case with only cavity injected volume***	**Containment sump measurement (MCR / ECR)**	**Description**
92.080 m	-	-		Reactor building sump bottom
93.410 m	-	-		Containment sump bottom
93.560 m	-	-	0 m	Cont. sump bottom measurement
94.460 m	-	0 m^3	0.9 m	RPV Cavity floor bottom

Level / RB plant elevation	**Containment injected water volume**	**Hypothetic case with only cavity injected volume***	**Containment sump measurement (MCR / ECR)**	**Description**
95.500 m	75 m^3	80 m^3	1.94 m	RPV Cavity concrete protection
97.110 m	-	-	3.55 m	Minimum recirc. sump operability with (+) 0.3 m for EOP / SAMG sp..m
97.660 m	784 m^3	100 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	Ventilation opening (top)
99.160 m	**1440 m^3**	-	5.60 m	Min. RPV external cooling sp. [8]
99.360 m	**1507 m^3**	**160 m^3**	5.80 m	Beginning of the cylindrical portion of the RV = 99.36 m [11]
99.560 m	-	-	6 m	Cont. recirculation sump level top LI 6102 / LI 6103 (MCR)
100.30	-	**170 m^3**	6.74 m	ERVC level fully established (ECR sump measurement - LI6170)

*- assuming that cavity and containment volumes are separated / not connected

3.7 Containment equipment flooding limitations

Regarding beyond design basis accidents and already adopted NPP Krško SAMG [14], equipment flooding is predicted per NEK SAMG [13] (see Table 2), where detailed information of potential effected equipment was evaluated (as seen in Table 1).

Table 2: NPP Krško SAMG detail regarding flooded equipment, example [13]

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**

3.8 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 [6] and EPRI [4] 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.

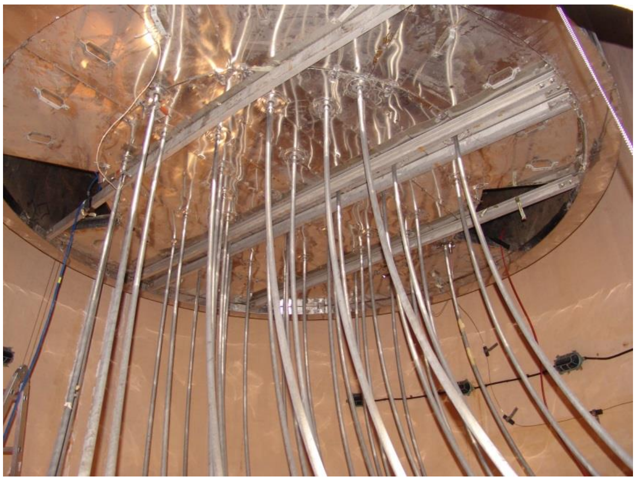

Figure 7: NPP Krško RPV insulation details (1) – opened inspection openings

Document Final Independent Review of NPP Krško Design Modification Package [8] reviewed plant modification 347-FD-L “Containment sump check valve removal”. The conclusions are in accordance with findings from [6]. According to [1] and [4], various experimental evidence exist that insulation would not impede the ingression of water because it is not watertight. However, new insights (Dai et al., [32], and Zhao et al., [33]), provide different conclusions which are highly dependent regarding general plant-specific RPV insulation design features.

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

Figure 9: NPP Krško RPV insulation details (3) – insulation - concrete gap

3.9 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. [7]), 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 [8] 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).

3.10 Steam explosions

Steam Explosions phenomena for NPP Krško are addressed in phenomenological evaluation [6], and site specific report [15]. Approaches to the issue of steam explosions which have been used in various analyses have also been reviewed.

Based on the reviews, evaluations and calculated 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.

3.11 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 [5], [6]:

- 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 [17].

3.11.1 Release Categories Definitions and Frequencies regarding ERVC

As a example, a NPP Krško plant specific results are taken from [16]. The release categories (RCV3 and RCV5) are determined due to the installation of plant specific Passive Containment Filtered Vent (PCFV) System and Passive Autocatalytic Recombiners (PAR). Due to same reason, four release categories (RC3A, RC3B, RC5A and RC5B) were redirected to others (mainly to RCV3 and RCV5). Explanation of release categories selection applicable for ERVC:

- RC1 in vessel, no need for ERVC
- RC2 ex vessel in containment, relevant (as 4)
- RC6, 7A,B, not relevant , seismic more than 1.1.g
- RC8A,B, V3 and V5 relevant

Table 3: New NPP Krško Release Category (RC) definitions and their frequencies and fractions regarding ERVC applicability based on [16]

RC	Definition	Frequency [/ry]	Fraction	ERVC applicable
RC1	Core recovered in-vessel, no containment failure	4.24E-08	0.1%	-
RC2	No containment (cont.) failure	9.25E-06	21.5%	YES
RC3A	Late (time frame IV) cont. failure, no MCCI	0.00E+00	0.0%	-
RC3B	Late (time frame IV) cont. failure, MCCI	0.00E+00	0.0%	-
RC4	Basemat penetration	1.86E-06	4.3%	YES
RC5A	Intermediate (time frame III) cont. failure, no MCCI	0.00E+00	0.0%	-
RC5B	Intermediate (time frame III) cont. failure, MCCI	0.00E+00	0.0%	-
RC6	Early (time frame I or II) cont. failure	3.23E-07	0.7%	-
RC7A	Isolation failure, no MCCI	5.34E-07	1.2%	-
RC7B	Isolation failure, MCCI	3.71E-07	0.9%	-
RC8A	Bypass, scrubbed	4.41E-07	1.0%	YES
RC8B	Bypass, unscrubbed	1.69E-07	0.4%	YES
RCV3	Vent (time frame IV)	1.29E-05	29.9%	YES
RCV5	**Vent (time frame III)**	**1.72E-05**	**39.9%**	**YES**
TOTAL	N/A	4.31E-05	100.0%	97.0%

3.11.2 MAAP 5.03 calculation

For example, The RCV5 is dominated by PDS TEHNNN. This release category covers sequences in which containment vent occurs [18].

Table 4: RCV5 Major Event Sequence for TEHNNN

TIME (seconds)	TIME (hours)	EVENT DESCRIPTION
0	0	Fire in MCR HPI, LPI, CFC, MFW, AFW, charging FORCED OFF
0	0	Rx trip, RCP trip, MSIV closed
5448	1.5133	Broken SG dry
5455	1.5153	Unbroken SG dry
5673	1.5758	PRT rapture disc broken
6463	**1.7953 (1.8)**	**Core uncovery**
8533	2.3703	Core temperature exceeded 2499 K
9397	2.6103	Broken hot leg creep rapture
9555	2.6542	Accumulator water depleted
15590	**4.3306 (4.3)**	**Relocation of core materials to lower head started**
21767	**6.0464 (6.0)**	**RPV failed**
43933	12.2036	Start of 1st containment vent
59302	16.4728	End of 1st containment vent

3.11.3 Most dominant plat PDS scenarios applicable to ERVC

Table 4 represents example of MAAP 5.03 calculated other NPP Krško PDS scenarios with dedicated time for ERVC. Calculated time for ERVC performance (criterion per [6]), for successfully strategy performance is 2.5 hours for TEHNNN plant damage state (PDS) scenario (39% of total CDF participation - as it was used for design of passive containment filtered vent system (PCFV) [19]). The 2-hour window is short from operational perspective to implement ERVC by containment flooding.

Table 5: NPP Krško most dominant PDSs applicable to ERVC, MAAP 5.03 results [18]

Most dominant PDS contributors to overall CDF **	Core uncovered (CET>650 °C *) (hours) **(A)**	Core relocation begins (hours) **(B)**	RPV failed, (hours) (C)	Time for ERVC performance 1) **(B) - (A)** [4] hours (h)
TEHNNN	**1,8**	**4,3**	**6,0**	**2,5 h**
TEHANN	1,8	4,3	6,0	2,5 h
TEHAYN	0,5	2,6	3,7	2,1 h
UXXXXB	1,9	4,5	5,7	2,6 h
SELAYN	4,2	8,7	10,4	4,5 h
WUUUUB	19,3	22,1	23,5	2,8 h

* After core uncovers, roughly 250 to 500 seconds (depending on overall scenario length) is needed that CET rises from 370 °C (saturation water temperature), to 650 °C (SAMG entry).

** TEHNNN – Loss of all FW; failure of all AFW, ECCS and CNT heat removal – essentially this is SBO; TEHANN – same as TEHNNN, but with CNT spray (only for injection); TEHAYN - loss of CCW with loss of all AFW; HP injection and HP recirculation not available; UXXXXB - catastrophic seismic event (>1.1) ; direct core damage and direct release from CNT; similar to TEHNNN but with CNT breach; SELAYN – loss of CCW with successful AF TD pump; WUUUUB – SGTR with LPI/LPR and CII/CIR 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 [20] could be extended up to 4 hours.

3.12 Procedures for accident management regarding ERVC application

The most simply upgrades regarding ERVC for accident scenarios where core damage is imminent or occurring is to upgrade the plant generically based procedures for accident management – such as Emergency Operating Procedures (EOP's) – which apply before core damage occurs, and Severe Accident Management Guidelines (SAMG's), which applies after core damage is observed by CET. For this reason, the most contributing effect is timely initiation of IVR actions to establish ERVC, as well as prioritizing them specifically, if it is recognized that IRV might be reasonably successful for hampering effects of severe accident progression by RPV failure.

There is also a set of newly introduced procedures guidelines for site disruptive events named Extensive damage mitigating guidelines (EDMG's), where IVR by ERVC could be viable strategy regarding the fact that they were intended to be used with severely hampered plant capabilities to mitigate the accident (example is lost command and control, major explosions and fire, etc.).

A combined severe accident management (SAM) actions could be also applied (such as combining containment flooding for ERVC, RCS depressurization and in-vessel injection), although this would require better assessment of their combined effects and potential negative consequences [21].

3.12.1 Emergency operating procedures

For PWROG's set of EOP's procedures [22], for NPP Krško it is adopted to start early flooding in their beyond-design basis part of procedures such as in EOP ECA-0.0 (for loss of all AC power) – in specific step cases where the exit in SAMG's exists.

3.12.2 Severe accident management guidelines

Regarding SAMG's [14], taking into account that there is limiting time for successful ERVC performance measured in few hours, the most suitable guidelines are those where MCR operating personnel still execute the actions (such as WOG's SACRG-1 or PWROG's SAG-1 and SAG-0) – and the action for establishing ERVC should be amongst the first priority's; executed in parallel with other compensatory actions. As a part of plant emergency response organization, there must be dedicated personnel and resources to execute this action with high confidence in success. A major help to the operators must be supported by plant design.

3.12.3 Extensive damage mitigating guidelines

These are relatively newly introduced procedures/guidelines for site disruptive events named Extensive damage mitigating guidelines (EDMG's) [23], where IVR by ERVC could be viable strategy regarding the fact that they were intended to be used with severely hampered plant capabilities to mitigate the accident (example is lost command and control, major explosions and fire, etc.; but concurrent with core damage evidences). It should be noted that after a command and control is established, a re-entry from EDMG's into the EOP or SAMG's procedures will be performed; nevertheless, the initiated action may provide important reaction time for successful containment flooding for establishing ERVC.

4 FEASIBILITY ASSESSMENT OF ENHANCEMENTS AT NPP KRŠKO FOR ERVC IMPLEMENTATION

To obtain more realistic results of study, the feasibility assessment of structures and components at Generation II PWR is based on the design of NPP Krško, which has already demonstrated the ability of ERVC implementation with reasonable confidence in success [17].

4.1 Introducing early containment flooding strategy per accident management procedures

To support timely establishing of ERVC, the accident management procedures such as ERG EOP's and/or SAMG's should be reevaluated to contain new prioritization for establishing ERVC. A combined SAMG actions could be also applied, although this would require better assessment of their combined effects and potential negative consequences [3].

4.2 Supporting ERVC in accident management

4.2.1 RCS depressurization

RCS depressurization is an important mean for enhancing RPV's structural response during the IVR process. In technical manuals and scientific research's, there is consensus that ablated RPV under significant pressures is more reluctant to failure. Moreover, it was found that vessel fails above roughly 40 bars [24], and technical manuals and accident management procedures are directing the operators lo lower the pressure inside RCS to 20 bars and less [10], [11]. Therefore, the RCS depressurization is important in severe accident management phenomenology also because low pressure sources of water might be injected into the core thus providing additional benefits regarding available accident management strategies for mitigating core damage. Regarding NPP Krško, as a part of Safety Upgrade Project there were introduced additional RCS depressurization means [25].

4.2.2 In-vessel injection (in conjunction with ERVC)

Although the core damage had occurred because there was no cooling water into the core; there might be insufficient water sources available to inject into the reactor core (with less than adequate flow to remove decay heat by steaming). Although this in-vessel insufficient flow could aggravate steam-zirconium reaction (with negative consequences such as additional hydrogen production and adding the oxidation heat to already existing stored heat and decay heat), in long term, and with conjunction with ERVC it could support IVR by cooling of the top of melted pool inside the vessel. It should be noted that beside normal injection into the vessel through downcomer - through vessel injection lines, or cold leg injection; a hot leg injection might be applied too with direct flow path to the top of the melted core. Other positive effect by doing so is retention of radioactive aerosols inside the vessel, which consequently have positive effect on overall doses inside containment.

Regarding high power reactors, a positive example is the APR1400 design, which is equipped with a cooling system that simultaneously floods the reactor internally in addition to the external reactor vessel cooling [26].

By EPRI SAMG TBR [3], [4] it is recommended to inject into the melted core even if water sources (flow) is insufficient, and by applying such combined IVR, both actions have more confidence in success to halt the accident progression [27].

4.3 Creating additional water / steam openings on RPV reflective insulation

Regardless of initial RPV reflective insulation geometry and their ability to ingress water and discharge steam, it is recommended to apply that strategy even with limiting confidence for successful ERVC. Nevertheless, for more certain positive outcome, it is recommended to reevaluate RPV reflective insulation. By example [7], NPP Krško needs 8 m^3/h of water inflow for performing IVR by ERVC through nucleate boiling. Based on literature and technical reports, RPV reflective insulation is not watertight – and it would not impede the ingression of water (0.23 kg/s/m per EPRI), which means there is available satisfying 60 m^3/h of water inflow due to insulation water ingression.

Beside water ingression capabilities of RPV reflective insulation, there must be considered other insulation geometrical proprieties like the plant-specific insulation vessel skirt on weld joint of spherical to cylindrical area. By EPRI document [3] the key element for successful IVR is ability for steam bubbles forming on the exterior surface of the lower head by nuclear boiling to be vented to allow for the replenishment of cooling water. These are dictated by the hydraulic resistance around the lower head which is dependent on the lower head geometry and can be affected by support skirts and specific insulation features. Additional openings might be crated on dedicated insulation points for enhanced water ingression and steaming flowpaths.

4.4 Creating smaller cavity volume for flooding the RPV bottom only

Making a modification of plant structures to allow flooding of minimum volume around RPV will have multiple positive influence regarding plant ability to timely perform ERVC with minimum water sources and with minimum time, thus avoiding other negative effects of massive containment flooding.

Regarding NPP Krško case study, Figure 6 represents a hypothetical reduction of RPV cavity flooding volume for ERVC performance which might be applied if RPV cavity will be modified in such manner that it is specifically created for RPV flooding. Then it will be necessary only to purposely inject 170 m^3 of water (instead of current minimum of 1500 m^3) [11] which will allow timely and more suitable vessel cooling, including the overall RPV walls up to RCS nozzles hight.

It should be noted that this approach would need dedicated system for containment (RPV cavity) injection, because ECCS water source (such as borated water tanks - designated RWST and ABWT) are primarily intended to be used by dedicated systems for in-vessel injection and later recirculation purposes (assuming RPV and containment volumes are separated).

Also, there will be need for constant injection flow into the cavity because otherwise the steamed water will steamed-out of RPV cavity. Currently for NPP Krško, such water inflow is assured through opening on ventilation ducts and floor drain system, which will be unavailable for hypothetically modified leak tight RPV cavity space.

4.5 RPV bottom head spray system

Spray cooling is a versatile technology for various cooling applications involving high surface heat fluxes, thus finding an approach to ERVC application. The tests were conducted as a series of consequent steady states realized at stepwise increasing power and surface heat fluxes up to the maximum values of 2.97 MW/m^2, which is more than achieved by natural convection by vessel flooding (1-2 MW/m^2) [28]. Beside that positive capability, there is advantage because when applying RPV spray system it would almost instantly remove the in-vessel corium heat from RPV surface, including area with focusing effect.

The key element for the success of IVR-ERVC strategy to any powered reactor is that the heat fluxes on the internal surface of the vessel imposed by the molten corium should not exceed the thermal limit at the external RPV surface, that is, the CHFs at water boiling over the entire lower head. It is formidable to prove IVR with high confidence due to challenges in determining the precise wall heat fluxes set by molten corium which are strongly affected by in-vessel severe accident phenomena and accident scenarios. Due to the limitations in the understanding of the phenomena and the scenarios, developing an external cooling system with a sufficient heat flux margin can be considered as a primary solution for the IVR-ERVC success. Among the prospects, the liquid-to-vapor phase change based external cooling systems such as convective boiling (forced circulation), jet impingement and spray cooling, which can be realized with active and passive safety system, has emerged as viable cooling solutions by capitalizing on the highest convective heat transfer coefficient required to curb the current cooling demands [29]. Spraying the RPV is also feasible from the water preservation points:

- if it is assumed that reactor compartment and containment are connected, the drained part of sprayed water of the outside RPV surface will normally flow into the reactor recirculation sump - which is also beneficial for long term cooling capabilities bay current active means (by RHR pumps in recirculation mode).
- if it is assumed that reactor compartment is watertight to the rest of the containment, a non-steamed water will fill the compartment and eventually establish the ERVC. Once when there will be reached sufficient level for ERVC by flooding the outside vessel surface, the spray inflow will assure constant cooling, although some sort of recirculation capability from ECCS system might be considered.

The major drawback of the use of spray cooling is that it may require fluid pumping power (active system – see section 4.6) which might be unavailable regarding overall accident conditions.

4.6 Active cavity injection

Active RPV “only” cavity injection system, although it needs to be powered by pump, had an advantage that simplifies design of the RPV flooding related systems, as well to have an option that it may be applied as RPV bottom head spray system (see section 4.5), due to instant and maximum decay heat removal capabilities during initial phases of core degradation into the RPV bottom head area with heat focusing effect. Application of this system does not require separation of “RPV cavity” area from containment, and it could also include some sort of containment recirculation capabilities for long term accident mitigation.

4.7 Passive cavity injection capability

Passive cavity injection systems – based on gravity drain, or by pressurized accumulators – is possible design feature which might allow simple and effective flooding of reactor cavity; specifically for the examples when it is not possible to perform overall containment flooding due to insufficient ECCS water sources or with minimum available personnel (see section 4.5). To maximise benefit from this system it would be optimal to separate “RPV cavity” area from containment, and to presume injection capabilities during containment overpressure conditions. However usage of such system for long term accident mitigation might be hampered by losses of injected fluid due to steaming effects of ERVC cooling.

4.8 Applying special coating on the vessel wall to increase CHF

A notable improvement to the ERVC strategy involves applying a micro-porous aluminium or copper coating to the outer surface of the reactor vessel head. Testing revealed that the CHF near the equator of the coated head increased by approximately 80% compared to an uncoated surface. Among the materials tested, micro-porous aluminium demonstrated superior durability, maintaining its integrity even after multiple cycles of steady-state boiling, unlike copper coatings which showed signs of degradation due to long term RPV normal power operations [30].

5 FURTHER METHODS FOR QUANTIFICATION OF ERVC BENEFITS

While the present work demonstrates the technical feasibility and potential safety benefits of ERVC implementation for Generation II PWRs, as illustrated by the NPP Krško case study, additional research is required to support its full qualification as a licensable severe accident mitigation measure. Further methodological development is needed to more closely integrate deterministic thermal-hydraulic analyses with probabilistic safety assessments, enabling a consistent evaluation of ERVC performance across a wide range of accident scenarios.

Future work should refine the proposed framework for defining ERVC boundary conditions, prerequisites, and limitations, with particular emphasis on optimizing design modifications and accident management strategies that improve ERVC reliability and timeliness in existing plants. Performance assessment should increasingly rely on risk-informed metrics, including reductions in Large Early Release Frequency (LERF) and plant-specific radioactive source terms.

To strengthen the linkage to Level 3 PSA, ERVC benefits should also be quantified in terms of off-site radiological consequences, containment performance, and potential reductions in public dose and land contamination. Remaining uncertainties related to CHF behavior under prototypical conditions, long-term water inventory management, and operator action reliability should be addressed through targeted experimental programs and high-resolution computational analyses to support best-estimate, risk-informed ERVC evaluations.

6 CONCLUSION

This study evaluates the feasibility of implementing External Reactor Vessel Cooling (ERVC) as a severe accident mitigation measure at Generation II PWR’s not originally designed for in-vessel retention (IVR). Although intrinsic design limitations such as restricted critical heat flux margins, large water inventory requirements, and narrow time windows challenge direct ERVC application, the analyses demonstrate that these constraints can be effectively mitigated through targeted plant specific enhancements.

Structural, component, and procedural improvements including optimized reactor cavity flooding, primary system depressurization, in-vessel injection, reactor vessel spray cooling, and revised accident management guidelines were identified as key enablers of timely and effective ERVC initiation. Deterministic MAAP 5.03 analyses for specific case study indicate that sufficient response time exists for dominant accident sequences.

Overall, the preliminary assessment results confirms that ERVC may represent a credible and robust additional layer of defense-in-depth for severe accident mitigation at Generation II PWRs. However, the study also identifies the need for further research to quantify such enhancements by defining performance indicators for ERVC in terms of reducing the probability of radioactive material release into the environment and the associated radiological consequences.

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