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MAAP 4.07 Analysis of Long Term Containment Heat Removal After Reactor Vessel Failure (DEC-B) for Nuclear Power Plant Krško (NEK)

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ABSTRACT

The paper presents the MAAP 4.07 analysis of containment heat removal after reactor vessel failure resulting from the initial Station Blackout (SBO) accident. The accident is analysed considering mitigation measures for heat removal from the containment using alternative equipment (Alternative Residual Heat Removal (ARHR) pump and heat exchanger (ARHX) and, also, Alternative Safety Injection (ASI) pump). The mitigation actions are taken according to NEK Severe Accident Mitigation Guidelines (SAMG).

There are several possibilities to remove the heat from the containment once the reactor vessel fails and, for all of them, the necessary condition is to have the sufficient source of water (Residual Water Storage Tank (RWST), Alternative Boron Water Tank (ABWT) or other) and the appropriate heat exchanger available. Two options are presented within this paper:

1. Injection to the Reactor Coolant System (RCS) using ASI pump and recirculation (sump to RCS) through ARHR system via ARHX,
2. Spraying the containment through Containment Spray (CI) system using ARHR pump and, then, recirculation (sump to spray) through CI and ARHR systems via ARHX.

The results show that the containment heat removal can be done with either of analysed ways if the water is provided for recirculation (assumed containment level 3.9 m ~ 760 m^3). However, with the fact that the reactor cavity is not flooded, the cooling using ASI will initially result in considerable containment pressure increase because the water is spilled through the RCS over the hot molten core debris. Therefore, it must be stated that the preferable way of containment pressure reduction, once the vessel has failed, is by using the containment spray. On the other hand, if RWST is not available, then the initial water delivery cannot be made from ABWT via CI system because this option does not exist. It shall also be pointed out that, if the active containment heat removal is started early enough, the Passive Containment Filtered Vent System (PCFVS) opening would be prevented and no fission products shall be released to environment.

Keywords: *station blackout (SBO), containment heat removal, design extension conditions (DEC), MAAP 4.07, Nuclear Power Plant Krško (NEK)*

1 INTRODUCTION

Following the lessons learned from the accident at the nuclear power plant Fukushima Daiichi in Japan and according to the Slovenian Nuclear Safety Administration (SNSA) Decree No.: 3570-11/2011/7 on September 1, 2011 [1] Nuclear Power Plant Krško (NEK) decided to take the necessary steps for upgrade of safety measures to prevent severe accidents and to improve the means to successfully mitigate their consequences.

The potential plant upgrades of existing structures, systems and components (SSC) and other measures and new systems that are important to provide nuclear safety during severe accidents are focused in the following areas:

1. AC power supply from external and internal sources,
2. Reactor core cooling with primary (injection to primary system) and secondary systems (reactor cooling through the steam generators),
3. Containment integrity at high temperature conditions, overpressure and high Hydrogen concentrations,
4. Controlled releases from the plant to the environment (less than 0.1 % of aerosols and particulates from core fission products),
5. Core cooling and control during severe accidents from the alternative control room and,
6. Alternative cooling of spent fuel pool.

One of the modifications that NEK has implemented is the installation of alternative RHR pump and alternative RHR heat exchanger (RCS and Containment Alternative Cooling). This modification, among the other already existing systems, serve for the purpose of reactor decay heat removal either from the RCS or from the containment once the core and RCS are severely damaged.

This paper presents the analysis of the NEK containment response following DEC-B ([2], [3]) accident considering mitigation measures for heat removal from the containment. DEC-B (Design Extension Condition B), as defined in IAEA SSR 2/1 [2] and WENRA RL [3], are those conditions that involve severe damage of the reactor core. Presented analysis is focused on containment heat removal after reactor vessel failure resulting from the initial SBO accident. It also addresses the containment cooling for the period before and after reactor vessel failure with the aim to prevent the operation of PCFV system.

The analyses were performed using MAAP 4.07 computer code. As a result, the methods of containment cooling are described with benefits and possible negative aspects.

2 METHODS – BACKGROUND INFORMATION

2.1 Modular Accident Analysis Program (MAAP) description

The Modular Accident Analysis Program (MAAP) Version 4.0.7 is a computer code [4] that can simulate the response of light water reactor power plants, like NPP Krško, during severe accident sequences, including actions taken as part of accident management. The code quantitatively predicts the evolution of a severe accident starting from full power conditions given a set of system faults and initiating events through events such as core melt, reactor vessel failure, and containment failure. Furthermore, models are included to represent the actions that could stop the accident by in-vessel cooling, external cooling of the RPV or cooling the debris in containment (ex-vessel cooling).

MAAP4 treats the spectrum of physical processes that could occur during an accident including steam formation, core heatup, cladding oxidation and hydrogen evolution, vessel failure, core debris-concrete interactions, ignition of combustible gases, fluid (water and core debris) entrainment by high velocity gases, and fission product release, transport, and deposition. MAAP4 addresses all of the important engineered safety systems such as emergency core cooling, containment sprays, fan coolers, and power operated relief valves. In addition, MAAP allows operator interventions and incorporates these in a flexible manner, permitting the user to model operator behaviour in a general way. Specifically, the user models the operator influence by specifying a set of variable values and/or events which are the operator intervention conditions combined with associated operator actions.

MAAP is fast running code and most of the processes are modelled using ordinary differential equations without spatial dependency and phenomenological models were used. Such code is capable to predict correct overall behaviour of the system, but local conditions are approximate due to both used models and rather crude subdivision (nodalization) of the object. Different parts of the model, including containment, have recommended ways how to prepare subdivision dependent on the type of the plant.

2.2 NEK MAAP model

The plant itself, its systems and regions (nodalization) is modelled through parameter file, described below. The event sequence is externally controlled through input decks. A structured (symbolic) language can be used to model operator actions, control output of variables or model the deficiencies in the engineered safety features.

The MAAP parameter file [5] primarily represents a database describing Krško nuclear power plant in some detail. It focuses on reactor coolant system, engineered safeguards and containment. The second important role of the parameter file is to supply control parameters, user and code controlled messages, print file parameters aimed at accurate simulation of plant operation.

In general , the Krško parameter file can be broken into six major categories.

1) Control Parameters
2) Reactor Core Parameters
3) Primary System/Safety System parameters
4) Containment/Auxiliary Building Parameters
5) Specific Plant Feature Parameters
6) Event Code Parameters

Control parameters describe input parameters for: model selection and program control; key phenomenological models; defining the thermo-physical properties of concrete; timing control; integration control; selection of variables to be written to data files for plotting; selection of variables to be written to the tabular and/or log files.

Reactor Core Parameters describe input parameters for reactor core setup and fission products.

Primary System/Safety System parameters describe input parameters for: initial conditions; the reactor pressure vessel geometry and setup; pressurizer geometry and setup; steam generator geometry and setup; the engineered safeguard safety systems; the generalized engineered safety system pump properties.

Containment/Auxiliary Building Parameters describe input parameters to: assign the compartment indices; assign elevations for primary system - containment interfaces; set up the containment/auxiliary building compartment geometry; set up the containment/auxiliary building flow paths between compartments; the corium debris pools in the containment; heat sink thermal properties used for distributed and lumped heat sinks; distributed heat sinks such as walls and floors; lumped heat sinks such as structural materials; modeling the containment outer wall stress/strain.

NEK containment building is divided into ten compartments: Reactor Cavity (1), Lower (2), Upper (3), Annular (4), Steam Generators (5 & 6), Spherical (7), Sump (9), Pressurizer (10) Compartments. The MAAP4 recommendation is to represent the free standing steel containment wall and the shield building wall as two distinct walls with gap between them modeled as a compartment, Annulus (8).

Figure 1 shows MAAP nodalization of primary, secondary and Emergency Core Cooling System (ECCS) for NPP Krško. Figure 2 presents containment nodalization scheme for NPP Krško used in MAAP code.

For the transient analysis the input file shall also be developed. Input file defines the sequence of transient: accident initiators, operator actions, time/sequence control, changes to parameter file, file setup, output specification

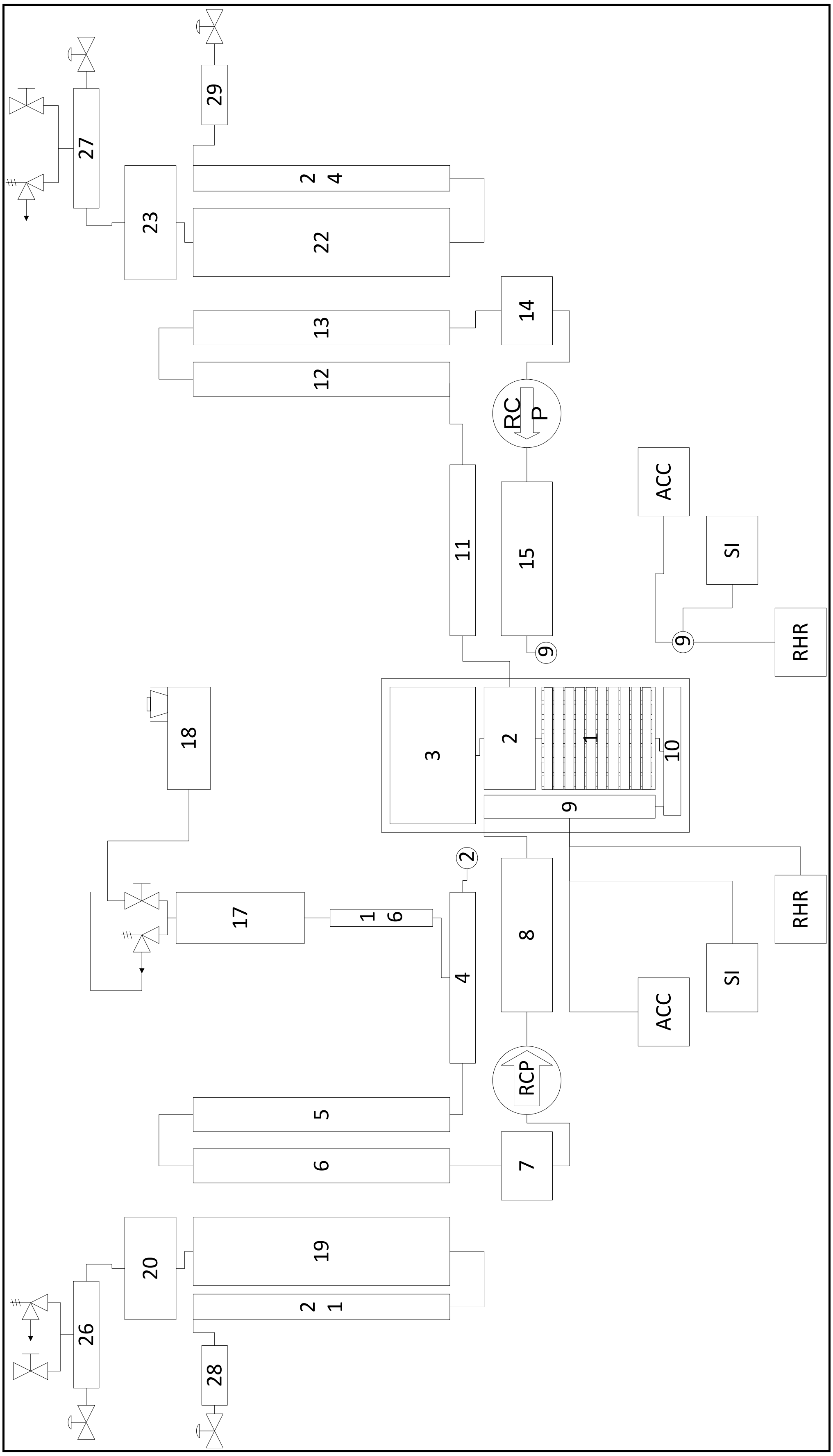

Figure 1: NPP Krško nodalization of primary system, secondary system and ECCS

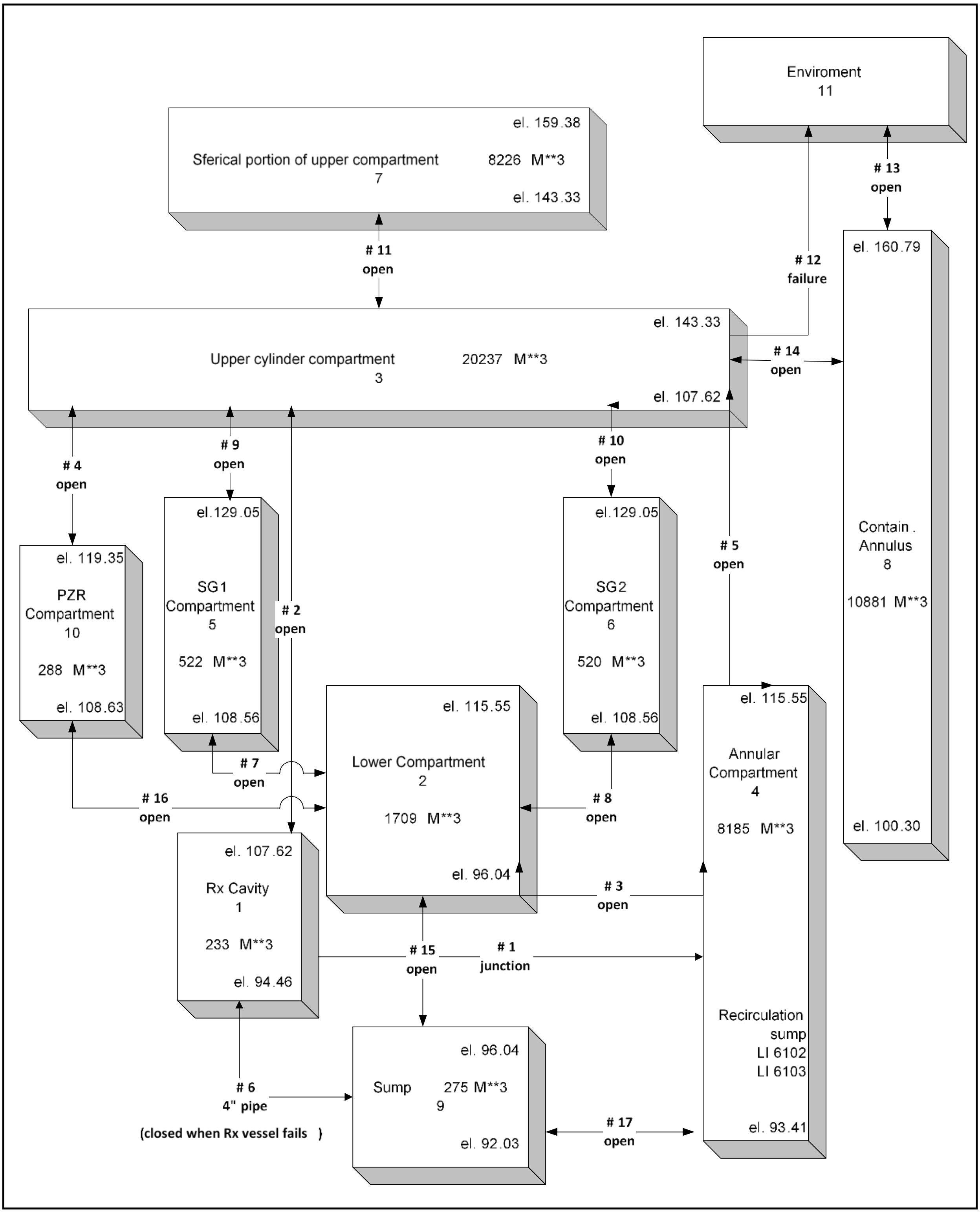

Figure 2: NPP Krško containment nodalization scheme

3 ANALYSIS, EVALUATION, CALCULATION

3.1 Transient Description

The analyses are focused on long term containment heat removal after reactor vessel failure (DEC-B) resulting from the initial SBO accident. SBO scenario involves a loss of offsite power, failure of the redundant emergency diesel generators, failure of AC power restoration and the eventual degradation of the RCP seals resulting in a long-term loss of coolant. It is assumed that AC power exists only on the AC buses powered by inverters connected to the station batteries. Loss of all AC power results in unavailability of all normal electrical equipment and most of the safety electrical equipment. The only possible corrective actions are reactor trip and residual heat removal using steam generator (SG) safety and relief valves and turbine (steam) driven auxiliary feedwater (TD-AFW) pump if available. The loss of coolant increases the probability of core melt. The potential locations for coolant losses are primary coolant pump seals, letdown relief valve and pressurizer valves.

Following the loss of all AC power the RCP seals would lose their cooling support systems and would experience a serious thermal transient. This conservative assumption remains regardless the fact that the High-Temperature RCP seals were installed recently. The charging and letdown system would not be available so that there would be no make-up water supply to the seals. Component cooling water to the RCP thermal barrier heat exchanger would also be unavailable. Leakage of RCS fluid through the RCP seals would be a small LOCA without makeup capability which will lead to core uncovery and heat-up, and, possibly, to a core damage. Depending of the availability of heat sink and the RCP seal leakage rate, the SBO transient can result in vessel and containment failure.

3.2 Initial and Boundary Conditions for Long Term Station Blackout

The following is the scenario of SBO accident:

- loss of offsite power,
- failure of the emergency diesel generators,
- failure of AC power restoration,
- degradation of the RCP seals resulting in a long-term loss of coolant. The seal leakage rate is 21 gpm/RCP
- letdown line isolation and, consequently, opening of letdown relief valve if RCS pressure is greater than 42.2 kp/cm^2

The main assumptions for the SBO analysis are:

- reactor trip from 100 % power,
- RCPs trip,
- turbine trip,
- main steam line isolation (MSIVs trip),
- feedwater closure (trip of MFW and motor-driven AFW pumps),
- RCPs seal flow not available,
- steam dump not available,
- charging and letdown flow not available,
- high pressure injection system (HPIS) not available,
- low pressure injection system (LPIS) not available,
- pressurizer proportional and backup heaters not available,
- SG Power Operated Relief Valves (PORVs) available
- TD AF pump not available (total loss of heat sink is assumed)
- Containment spray not available
- Containment fan cooler not available

No operator actions are assumed prior to the core damage and are focused on mitigation of consequences in order to prevent the containment failure. The following cases were analysed with respect to the operator actions:

1. Mitigation after vessel failure using CI and ARHR recirculation
2. Mitigation after vessel failure using ASI injection and ARHR recirculation

3.3 Analysed cases

There are several possibilities to remove the heat from the containment once the reactor vessel fails and, for all of them, the necessary condition is to have the sufficient source of water (RWST, ABWT or other) and the appropriate heat exchanger (HX) available. These possibilities are:

1. Recirculation from sump to reactor coolant system (RCS) through RHR system (either standard or alternative path) using standard or alternative RHR HX. For this purpose, it is necessary to deliver water into containment in either of the achievable ways:
    a. Injection to RCS using alternative SI (ASI) pump or another available pump
    b. Containment spray (CI) system
    c. RWST gravity drain
    d. Injection to containment via dedicated penetration (RH-1043-0460).
    e. Fire Protection (FP) system using Severe Accident Management Equipment (AE), what is already foreseen as one of the Severe Accident Management action.

2. Recirculation from sump to Containment Spray (CI) via alternative RHR system (ARHR) and alternative RHR heat exchanger (ARHR HX). It is also necessary to deliver water to the containment at the same way as described above.

3. Recirculation through ARHR HX via penetration RH-1043-0460. The prerequisite for this action is to have sufficient amount of water to enter the reactor cavity.

4. Use of containment fan coolers (RCFC). This is DBA equipment which is not considered to function under DEC, therefore, this option is not relevant.

The analyses presented here were done for containment heat removal considering options 1 (RCS – (A)RHR HX) and 2 (CI – ARHR HX) above. The water was delivered from ABWT or RWST via ASI and CI pump, since other options (c, d and e above) for water delivery are impossible or rather complicated to model within MAAP computer code. The actual characteristics of alternative RHR heat exchanger and alternative RHR pump have been incorporated into MAAP model. The maximum expected ASI flowrate is approximately 285 m^3/h (the maximum standard SI pump flow rate is ~160 m^3/h). In the MAAP model the normal spray line-up is used and the characteristics of spray pump is changed to the characteristics of ARHR pump.

The start of recirculation is assumed at containment water level 3.9 m (measured with sump level indicators LI 6102 and LI 6103) which is SAMG set-point and the corresponding volume is around 760 m^3. To protect the containment vessel against hydrogen burn it is necessary to limit the heat removal so the mitigation action is stopped at 1.5 kp/cm^2 and the heat removal is again started at 3.15 kp/cm^2, (SAMG set-point [6]). This action remained for 2 days after the recirculation has started (arbitrary) regardless low hydrogen concentration. After that period the set-points were changed to -0.1 kp/cm^2 to 0.28 kp/cm^2 (all mention set-pints are gauge pressure).

For each of the evaluated options (1 and 2 above) 3 different cases, with respect to the mitigation start (regardless of the required containment pressure set-point), was analysed:

- mitigation starts at 8 h,
- mitigation starts at 24 h (before the first PCFVS venting),
- mitigation starts at 40 h (after the first PCFVS Venting).

3.4 Containment heat removal using containment spray (CI) aligned to ARHR

Figure 3 to Figure 5 present the comparison of the accidents for different start of containment heat removal using containment spray (CI). It was assumed that the water is initially delivered from RWST using standard CI pump and then recirculated by ARHR pump via ARHR HX, as described above. If RWST is not available, then the initial water delivery cannot be made from ABWT or other tank via CI system because these options do not exist.

From the figures below, it can be clearly seen that the heat removal is successful. The pressure reduction starts immediately after CI initiation. The increase of the pressure, that can be noticed (Figure 3) for all three cases, starts around 2.5 hours after beginning of spraying and pressure reduction. It is the result of water evaporating after spilling into the reactor cavity though ventilation duct over molten core debris. This evaporation results in the second PCFVS opening (Figure 3 and Figure 4), for the case when cooling starts at 40 h, when pressure rises above set-point of 4.9 bar abs. The total release of noble gases is around 40% (Figure 4). For other two cases the cooling is effective and there is no PCFVS opening. Over the longer time scale the pressure behaviour is dictated by the operator actions required in SAMGs [6], as described in the above (heat removal cycling between 1.5 kp/cm^2 and 3.15 kp/cm^2, and changed to -0.1 kp/cm^2 to 0.28 kp/cm^2 two days after recirculation has started). The hydrogen production during Molten Core Concrete Interaction (MCCI) is quite extensive (Figure 5) except for the case when spraying starts at 8 hours and the water is spilled over the ventilation duct before substantial MCCI begins. It shall be mentioned that, for all cases, the MAAP code predicts that the MCCI is stopped immediately once the water is spilled over the molten core debris.

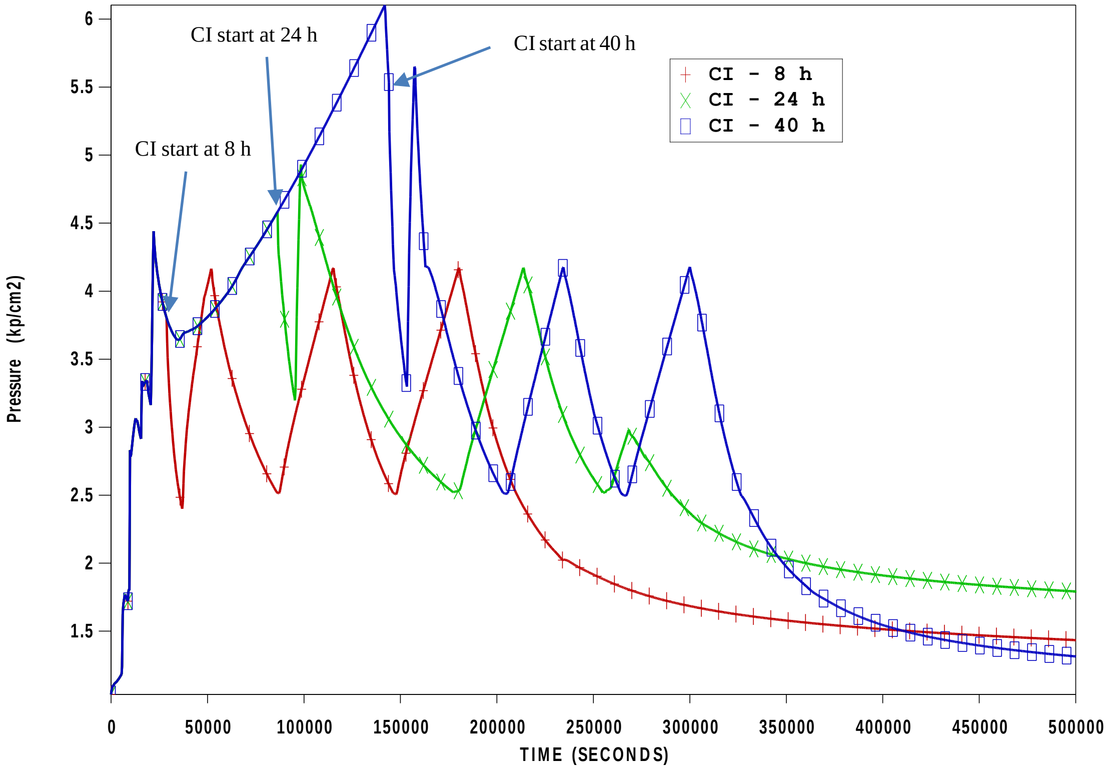

Figure 3: Containment pressure – cooling with CI + ARHR

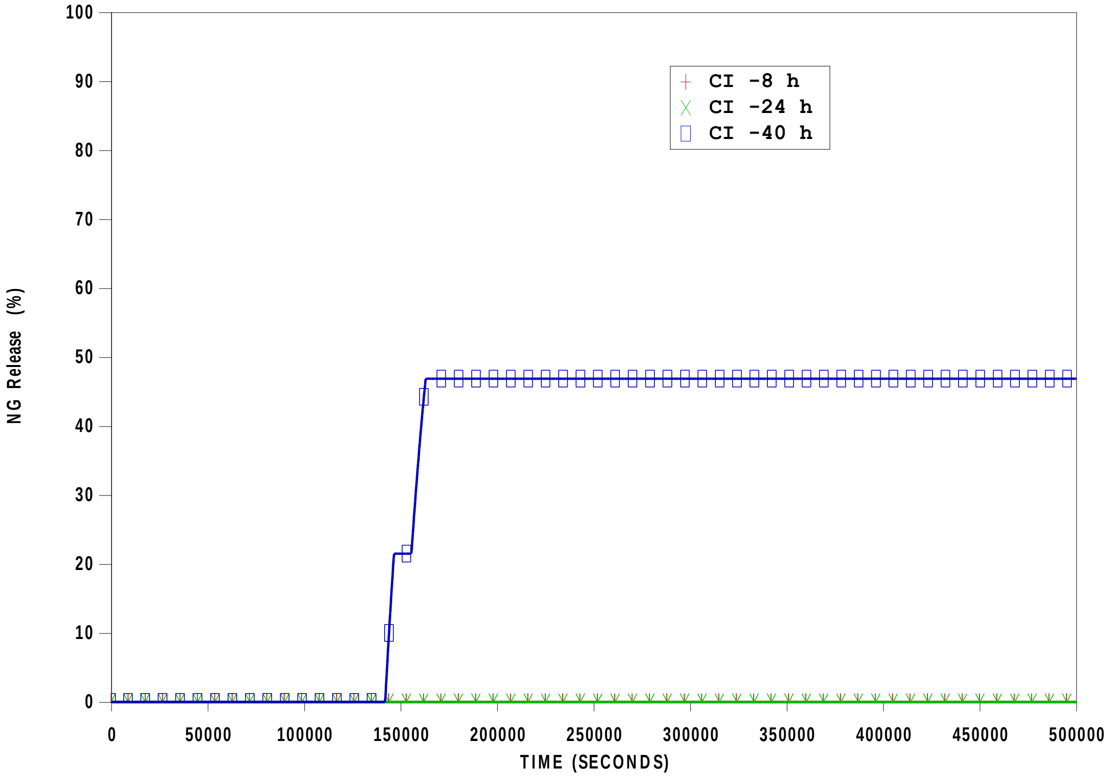

Figure 4: Noble gases release from containment - cooling with CI + ARHR

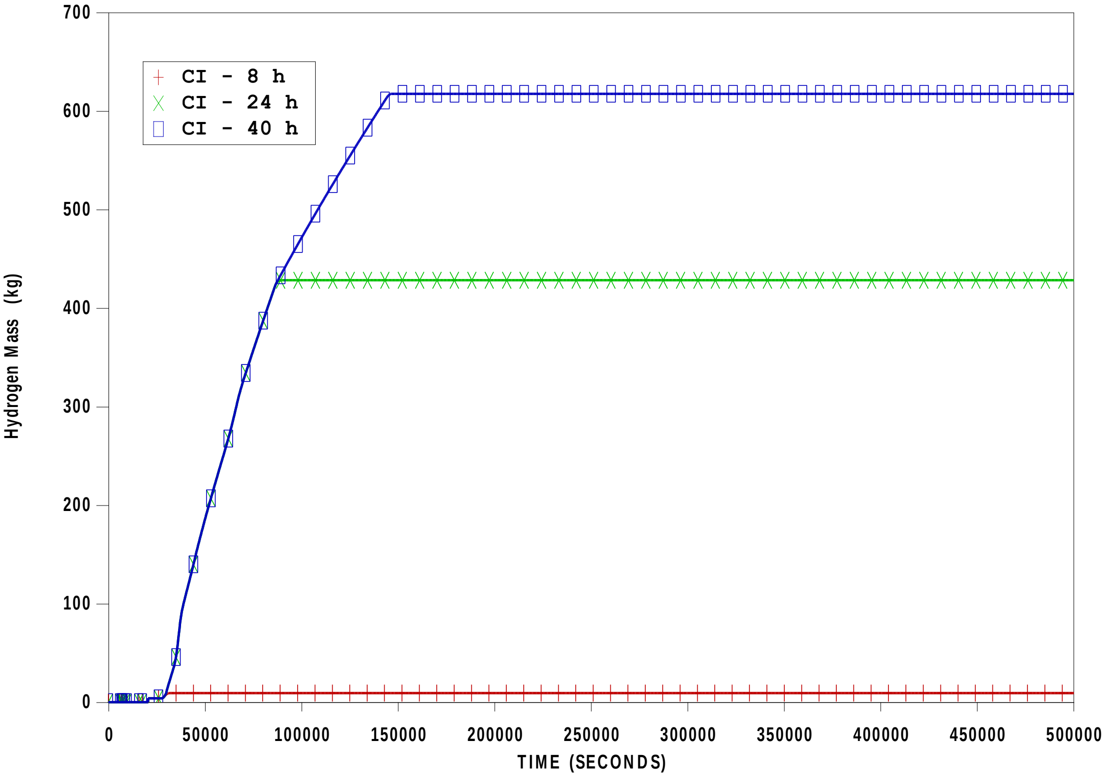

Figure 5: Hydrogen produced during MCCI – cooling with CI + ARHR

3.5 Containment heat removal using ASI to RCS and ARHR recirculation

There is significant difference between heat removal using ASI injected to RCS, then recirculated via ARHR, and the cases above (CI + ARHR). This is evident from the high pressure peaks in the Figure 6 below. These peaks are caused by extensive evaporation when the water spills over the hot molten core debris after it is injected to the RCS and exits through the failed reactor vessel. The capacity of the PCFV system is not sufficient (limited by 4” diameter orifice) to prevent pressure rise above 6 bar abs. The containment pressure increases far above this point, even over 7 bar abs, highly exceeding 5% failure probability at containment fragility curve what is required in the design of PCFV system. Only for the earliest injection (8 hours) the pressure increase is not challenging, and there is no PCFVS opening. For other two cases the PCFVS opening results in the release of noble gases below 40 % (case 24 h) and around 60 % (case 40 h). Hydrogen produced during the MCCI (Figure 8) is comparable to the case with containment spray initiation, even slightly below due to the earlier core debris flooding. Similarly, as for the previous case, on the long time scale the pressure behaviour is dictated by the operator actions required in SAMGs.

The comparison to the case with CI initiation for start of heat removal at 24 hours (Figure 9) shows the clear indication of pressure differences described above. Therefore, it must be stated that the preferable way of containment pressure reduction, once the vessel has failed, is by using of containment spray. The Fire Protection (FP) sprays for reactor coolant pumps can also be used for this purpose. Using of RCS injection shall be avoided if enough water is not assured in the reactor cavity to cover the core debris and/or the containment pressure is already high.

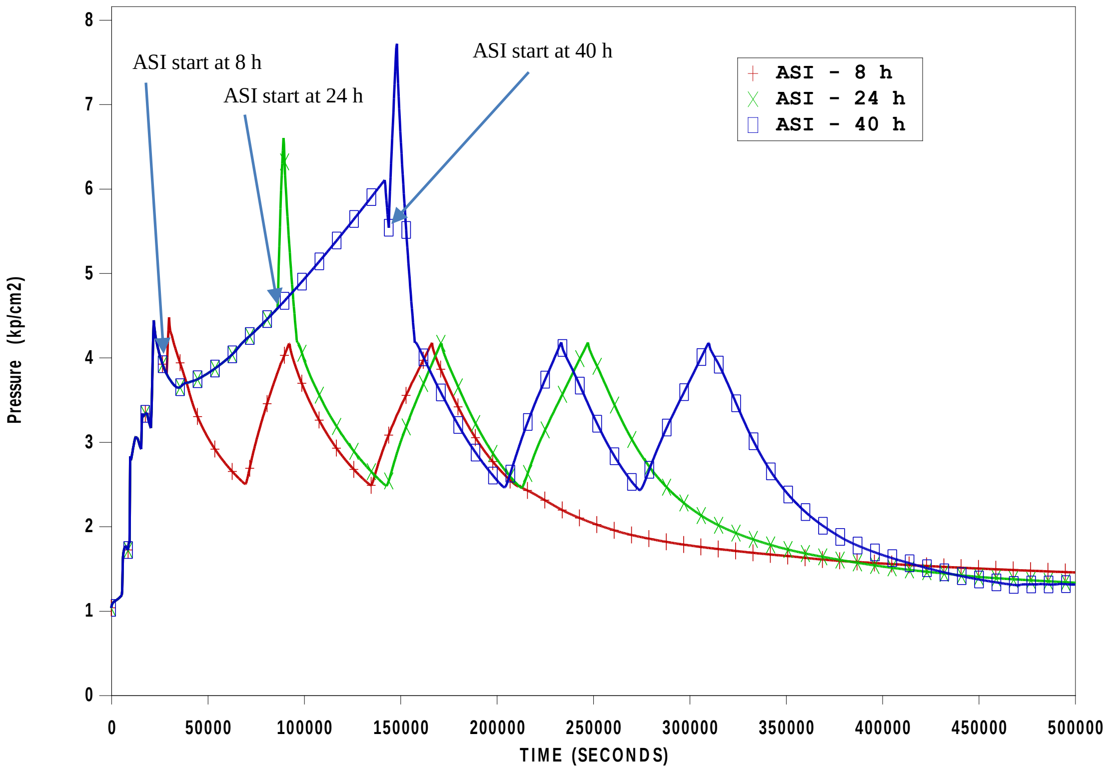

Figure 6: Containment pressure – cooling with ASI + ARHR

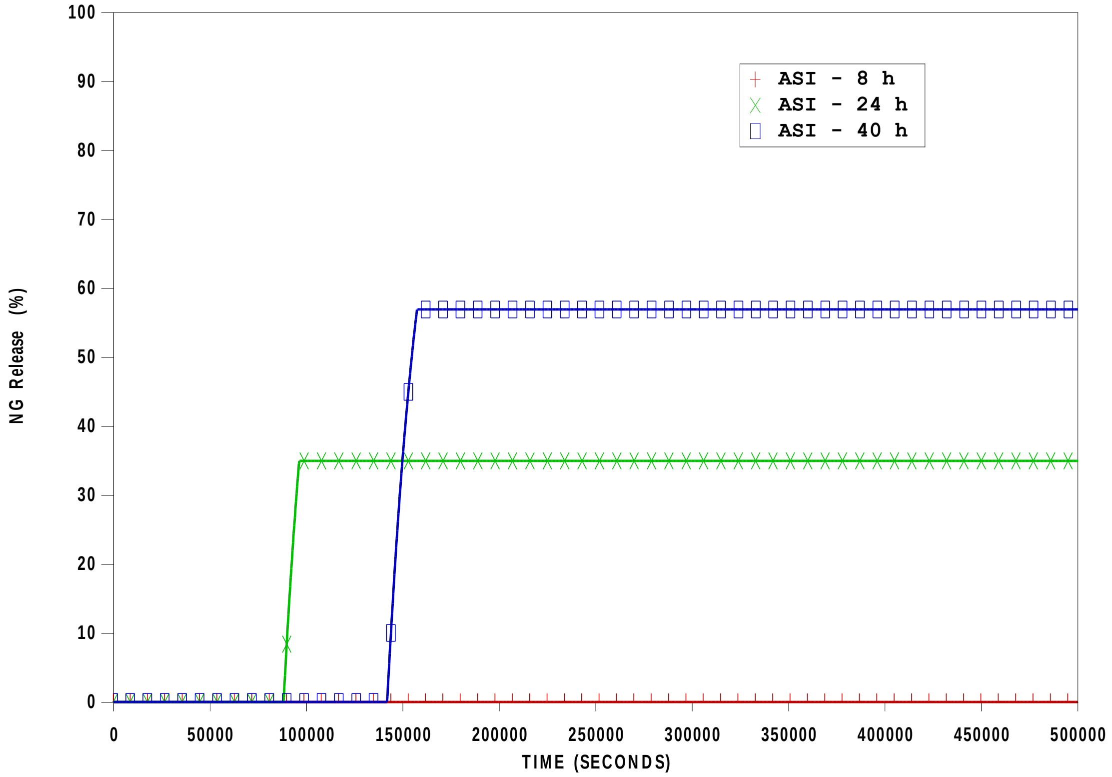

Figure 7: Noble gases release from containment – cooling with ASI + ARHR

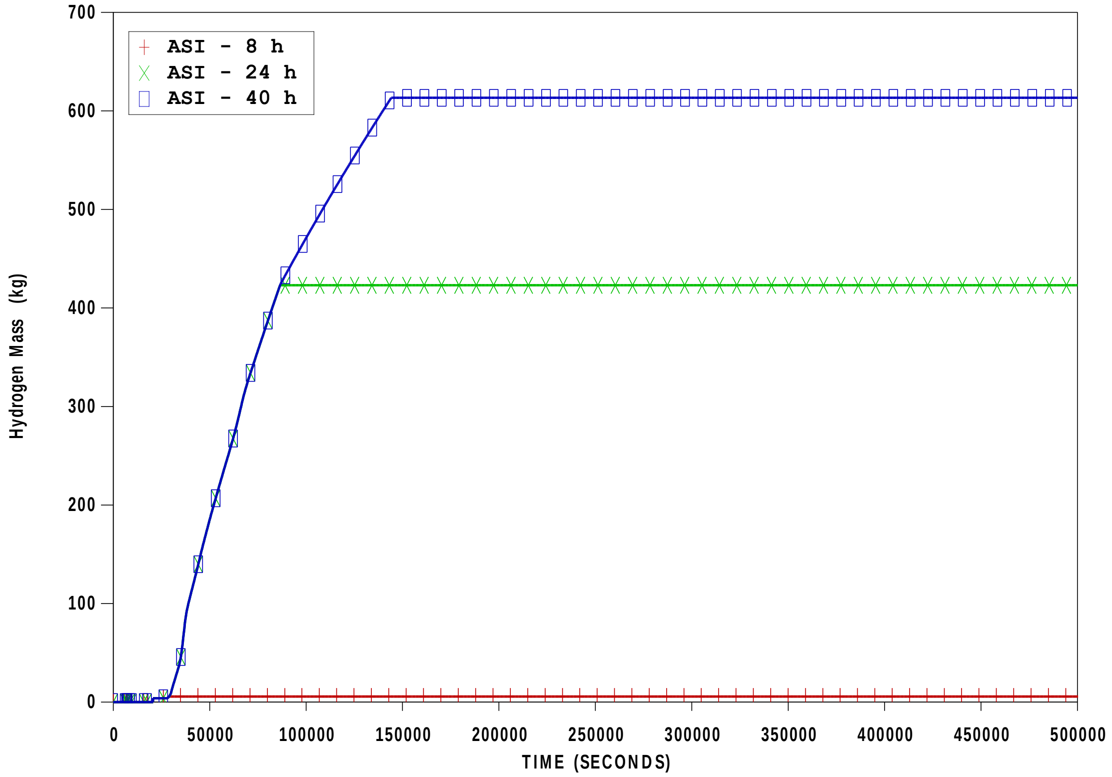

Figure 8: Hydrogen produced during MCCI – cooling with ASI + ARHR

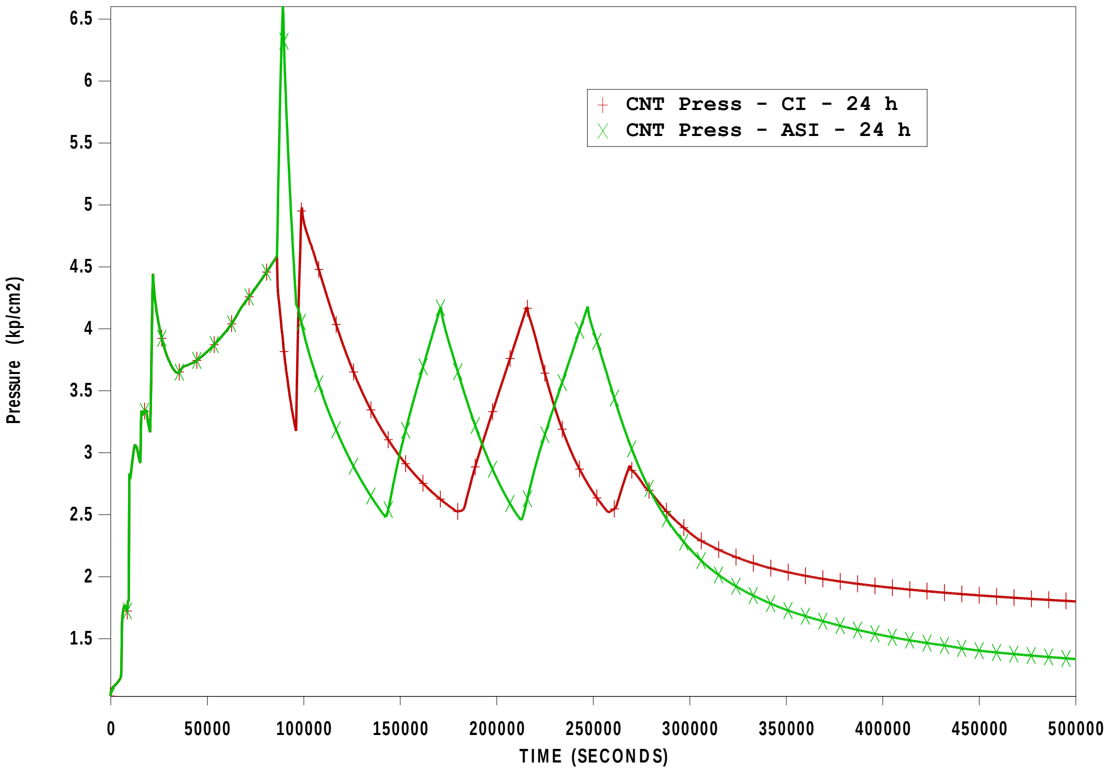

Figure 9: Containment pressure, cooling start at 24 h, comparison for cooling with CI and ASI

4 CONCLUSION

This paper presented the analyses of long-term containment heat removal after reactor vessel failure (DEC-B) resulting from the initial SBO accident. It also addresses the containment cooling for the period before and after reactor vessel failure with the aim to prevent the operation of PCFV system. The analyses considered modification within NEK Safety Upgrade Project - installation of alternative RHR pump and alternative RHR heat exchanger.

The containment heat removal was analysed assuming that ARHR pump and ARHR HX, and also ASI pump, have the actual characteristics as implemented in the plant modifications. It shall be pointed out that cooling can be done with either of analysed ways - ASI, ARHR pump and ARHR HX or CI, ARHR pump and ARHR HX if the water is provided for recirculation (assumed 3.9 m ~ 760 m^3) either from RWST, ABWT or any other available source. However, the cooling using ASI will initially result in significant containment pressure increase (over PCFVS opening set-point) because the water is spilled through the RCS over the molten core. Therefore, it must be stated that the preferable way of containment pressure reduction, once the vessel has failed, is by using of containment spray (CI). On the other hand, if RWST is not available, then the initial water delivery cannot be made from ABWT or other tank via CI system because these options are not foreseen. The Fire Protection (FP) sprays for reactor coolant pumps can also be used for this purpose. Using of RCS injection shall be avoided if enough water is not assured in the reactor cavity to cover the core debris and/or the containment pressure is already high. It shall be also stated that if the active containment heat removal is started early enough the PCFVS opening would be prevented and no fission products shall be released to environment.

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