

## Protection System Setpoints for Steam Line Break Accident Containment Response Analysis for NPP Krško

Vesna Benčik, Davor Grgić, Siniša Šadek, Paulina Družijanić, Petra Strmečki

University of Zagreb Faculty of Electrical Engineering and Computing

Unska 3, 10000 Zagreb, Croatia

vesna.bencik@fer.hr, davor.grgic@fer.hr, sinisa.sadek@fer.hr, paulina.druzijanic@fer.hr,  
petra.strmecki@fer.hr

### ABSTRACT

The steam line break inside the containment may result in significant releases of high-energy fluid to the containment atmosphere. The mass and energy release depends on a number of different parameters, e.g., nuclear kinetics characteristics, stored energy in both the reactor coolant system and the main steam system, main and auxiliary feedwater operations, safety systems operation and break characteristics. Therefore, for each postulated break size different plant operating conditions prior to the break (power levels) should be considered in order to find the most adverse case regarding containment pressure and temperature. Usually, from point of view of containment parameters main steam line break (MSLB) is limiting for containment temperatures (both atmosphere and liner temperature) and loss of coolant accident (LOCA) is limiting for containment pressure.

In the paper the influence of changes in steam line break protection signal parameters (lead/lag constants) for steam line isolation and safety injection (SI) initiation on containment pressure and temperature was evaluated. The steam line break was analyzed using coupled code R5G. Coupled code R5G is a result of direct explicit coupling of RELAP5/mod3.3 and EPRI's GOTHIC 7.2b(QA) code. Large Double Ended Rupture (LDER) and split break were analyzed for different power levels (30%, 70% and 102%). For split break, the maximum break area was found where the steam line isolation does not occur on low steam line pressure signal. The containment thermal hydraulic behaviour and design margins were calculated using GOTHIC part of the coupled code.

**Keywords:** main steam line break, protection setpoints, SIS actuation, containment limits, RELAP5/MOD 3.3, GOTHIC, R5G

### 1 INTRODUCTION

Steam line break occurring inside the containment building may result in significant releases of high-energy fluid to the containment atmosphere which could possibly result in high containment temperatures and pressures. The aims of the analysis of containment response in the case of steam line break accident are threefold. First, the containment structure is designed to withstand a limited internal pressure. In addition, the temperature differential across containment steel structures (dome and cylinder) is used in containment stress analysis. Secondly, the analyses of containment behaviour should demonstrate that the pressure and temperature during the accident do not jeopardize equipment functionality that is not qualified to perform its function in an adverse containment atmosphere. The containment response following a steam line break depends on plant operating conditions at the time of the break, the size and position of the break as well as on the operation of safety and protection systems. In particular, for different initial power levels there are

opposing effects due to larger stored energy for larger initial power levels on one side and larger initial secondary pressure for smaller initial power level, which makes it difficult to determine the worst case without analysing the whole spectrum of initial power levels.

In the paper the main steam line break analysis for NPP Krško (NEK) was performed using coupled code R5G. Coupled code R5G is a result of direct explicit coupling of RELAP5/mod3.3, e.g., [1] and EPRI's GOTHIC 7.2b(QA) code, e.g., [2]. In the case of interaction of the reactor system and containment, usually two independent runs are performed. First the mass and energy release rates (MER) are calculated by a system code using conservative assumption of low containment pressure, and then containment response is calculated using the calculated MERs as a boundary condition. Instead of two step method described above, here the best estimate method using coupled code was used. The applied coupling strategy is simple and basic operation of constituent codes as well as corresponding input data are unaffected by the coupling process. RELAP5 has the leading role during the time advancement in the coupled code calculation. Containment conditions from the old time step calculated by GOTHIC are used in the RELAP5 new time step system calculation. At the end of each converged RELAP5 calculation time step, interface subroutines transfer boundary condition data to GOTHIC. GOTHIC then performs one or more time steps and then interface subroutines prepare containment conditions for next RELAP5 time step. The variables transferred from GOTHIC to RELAP5 are total pressure, liquid and vapour specific internal energy, vapour void fraction, and non-condensable gas quality. The variables transferred from RELAP5 to GOTHIC are mixture mass flow rate, mixture enthalpy, total pressure, liquid volume fraction, steam pressure ratio, and gas pressure ratios for each of non-condensable gases. Detailed description of the coupled code is provided in [6].

The protection system functions in the case of steam line break are primarily the safety injection actuation, which limits the nuclear power increase due to overcooling and main steam line isolation. Both SI and steam line isolation are actuated (among other signals) on low steam line pressure signal. In the paper, the influence of changes of lead/lag constants in low steam line pressure signal logic was analysed. First, the Large double ended break (LDER MSLB) in the loop 1 (loop with the pressurizer) for three different initial power levels (30%, 70% and 102%) was performed. For LDER MSLB the steam line isolation as well as safety injection (SI) signal are actuated on low steam line pressure signal very early after transient begin. The LDER MSLB analysis was performed for currently used lead/lag constants at NEK (48/8 s). Secondly, the break on one side of steam line (split break) upstream of the main steam isolation valve in loop 1 was analysed. For conservatism purposes, for split break the maximum break area was found where steam line isolation does not occur on low steam line pressure or it is actuated late in the transient thus maximizing the containment pressure and temperature. For split break, also three initial power levels (30%, 70% and 102%) were analysed. In the analysis, maximum auxiliary feedwater (AFW) to affected SG (SG 1) was assumed in order to maximize discharge to the containment and the AFW flow is minimum to SG 2 in order to reduce the heat transfer from the unaffected SG. One train of reactor containment fan coolers (RCFC, two units) and one train of containment spray were modelled in GOTHIC input.

## **2 CALCULATION MODEL**

### **2.1 RELAP5 Nodalization of NEK Primary and Secondary System**

At FER a detailed RELAP5/MOD 3.3 model for NPP Krško is being developed, ref. [3] and [4]. The scheme of NPP Krško nodalization for RELAP5/mod 3.3 is shown in Figure 1. The model is being constantly updated to reflect changes after plant modernization and modifications, e.g., Steam Generators (SG) replacement and power uprate in 2000., Resistance Temperature Detector Bypass Elimination in 2013 and Up-Flow Conversion in 2015. RELAP5 model contains detailed nodalization of NPP Krško Safety Injection (SI) system, Main feedwater and Auxiliary feedwater



## 2.2 Nodalization of NEK Containment for GOTHIC Code

GOTHIC containment model is simple model usually used in containment design basis accident calculation. It is the model that has 2 volumes, Figure 2. First volume models free volume of the containment and volume number 2 is containment annulus. In this paper that model is called one-volume model. The values used for containment volume initialization (48.9 °C, 101.325 kPa, 30% RH) are usual for design basis calculation and they were chosen to maximize containment pressure increase during accident. The temperature of the outside air is 34 °C.

Containment heat structures were modelled as 14 different heat structures. The heat structures 1 and 2 are used for representing steel liner and structures 3 and 4 are used for concrete containment wall. All other heat structures are internal containment heat structures usually found in NEK Safety Analysis Report Chapter 6. The heat transfer coefficient was based on Uchida condensation correlation and natural convection heat transfer coefficient, for all heat structures exposed to the containment atmosphere. For internal heat structures one side of the structure is isolated. For structures 3 and 4 right side is exposed to the environment with fixed temperature and fixed heat transfer coefficient of 11.36 W/m<sup>2</sup> K. Three flow boundary conditions are used in the model for double ended break accident. Boundary conditions 1F and 2F together with flow paths 1 and 2 are representing flow paths from two ends of the double ended break (from SG side and turbine side, respectively). Boundary condition 3F and flow path 3 were used for modelling of spray flow from RWST tank (water temperature 37 °C). Fixed water mass flow of 75.81 kg/s was used for each of two spray lines (in the analysis one of them is assumed available).

GOTHIC spray nozzle component (1N) was used at the end of flow path 3 to convert all water flow to droplets. The containment spray pumps are started on signal of HI-3 containment pressure (delay for starting of SI pumps 47 seconds). Only 2 of the existing 4 reactor fan coolers are taken into account. The reactor containment fan coolers were modelled separately as volumetric fan coolers (1Q, 2Q) + standard single-pass, finned tube counterflow air-to-water heat exchangers (1H, 2H). Flow paths 4 and 5 are used to model flow of steam and air mixture over RCFC cooling surfaces. The fan coolers are started on HI-1 containment pressure signal with delay (37 seconds).

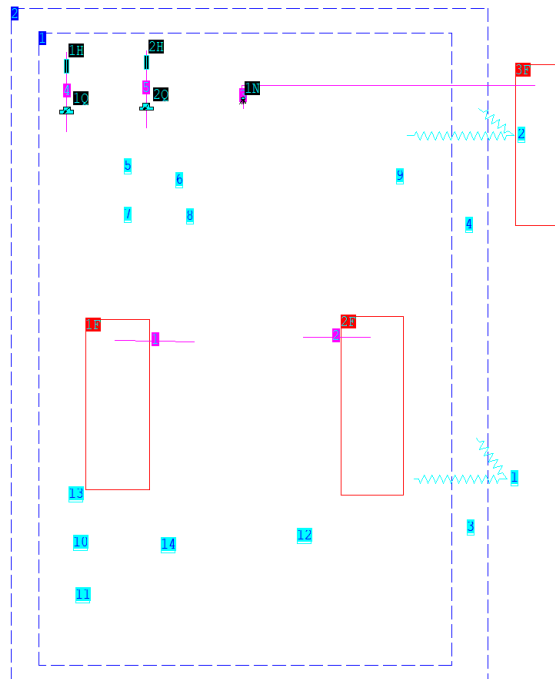


Figure 2: GOTHIC nodalization (double ended break MSLB) scheme of NEK containment

### 3 ANALYSIS OF STEAM LINE BREAK ACCIDENT

#### 3.1 Analysis of large double ended steam line break accident

Double ended guillotine break was assumed in steam line 1 (loop with the pressurizer) between volumes 457 and 459 (Figure 1). Double ended break is modelled by opening of the valves connecting the ends of pipe 457 and 459 to containment and by closing the valve connecting the steam line pipe ends before the start of the accident. Following the break initiation the low steam line pressure signal (loop 1) is actuated early in the accident (2.1 seconds after transient begin). The calculated time of actuation of low steam line pressure signal is the same for all three groups of lead/lag time constants. Here, the results are presented for lead/lag constants equal to the currently used values at NEK (48/8 s). Safety injection as well as steam line isolation are actuated on low steam line pressure. Reactor trip is actuated on SI actuation, see Table 1. After initial steep rise, break flow from the SG side is reduced as the secondary pressure is reduced and the break flow from the steam header side is reduced rapidly after main steam line isolation, see Figure 3. In the analysis it was conservatively assumed that the auxiliary feedwater flow in the affected SG is maximal to maximize break flow to the containment and the flow to unaffected SG is minimal to reduce its capability to remove the heat to the secondary side. Heat transfer in unaffected SG reverses due to intensive heat removal by the break flow on one side and due to injection of the cold auxiliary feedwater flow on the other side, see Figure 3. After initial rise immediately after turbine trip, the unaffected SG pressure is reduced due to heat transfer reversal, see Figure 4. LDER MSLB results in a significant liquid entrainment during the first 100 seconds of the transient, see Figure 6. Containment fan coolers (1 train, two units) and containment spray (one train) that are actuated on high-1 and high-3 containment pressure reduce containment pressure and temperature after break initiation, see Figure 5 and Figure 7. Maximum containment pressure and temperature were obtained for break from 70% power (308.04 kPa and 117.99 °C, respectively). The maximum containment steel dome temperature was obtained for 102% power (111.9 °C), see Figure 8. One should note that in the current 1-volume containment model, containment dome steel liner is represented with much smaller heat capacity (mass) than the steel cylinder. Consequently, the steel liner dome temperature response was considerably faster and the maximum dome temperature was larger than the containment steel cylinder temperature.

Calculated values for maximum containment pressure (308.04 kPa), containment steel liner dome (111.9 °C) and steel cylinder temperature (110.19 °C) are well below design values (410.21 kPa, 125.6 °C and 119.4 °C).

Table 1: LDER MSLB, 70% power: Time table of main events

Event	
Start of the accident	0.0 s
Low steam line pressure signal	2.07 s
Safety injection actuation (on low steam line pressure signal)	2.07 s
Steam line 1 and 2 isolation (on low steam line pressure signal)	2.07 s
Reactor trip (on safety injection signal)	2.07 s
Turbine trip (on reactor trip)	2.07 s
Auxiliary feedwater actuation (on SI)	20.1 s (SG 1)/10.3 (SG 2)
Fan coolers actuation	40.8 s (on HI-1 pressure + 37 seconds delay)
Containment spray actuation	121.5 s (on HI-3 pressure + 47 seconds delay)

Table 2: LDER MSLB: Maximum containment pressure and temperature

Event	30% power	70% power	102% power
Maximum containment pressure	307.89 kPa (124 s)	308.04 kPa (119 s)	303.07 kPa (99 s)
Maximum containment atmosphere temperature	117.97 °C (124 s)	117.99 °C (119 s)	117.19 °C (99 s)
Maximum containment steel dome temperature	110.1 °C (831 s)	111.02 °C (1082 s)	111.9 °C (1367 s)

NEK MSLB R5G calculation, LDER, 70% power

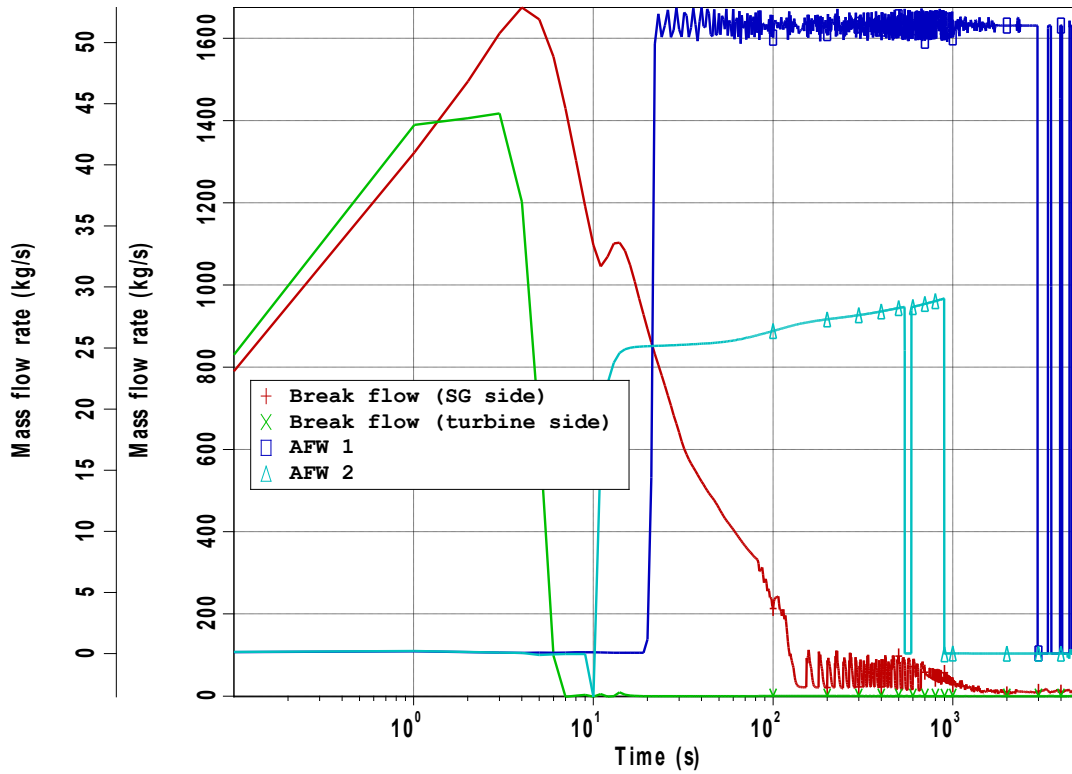


Figure 3: LDER MSLB, 70% power, Break flow and AFW flow

NEK MSLB R5G calculation, LDER, 70% power

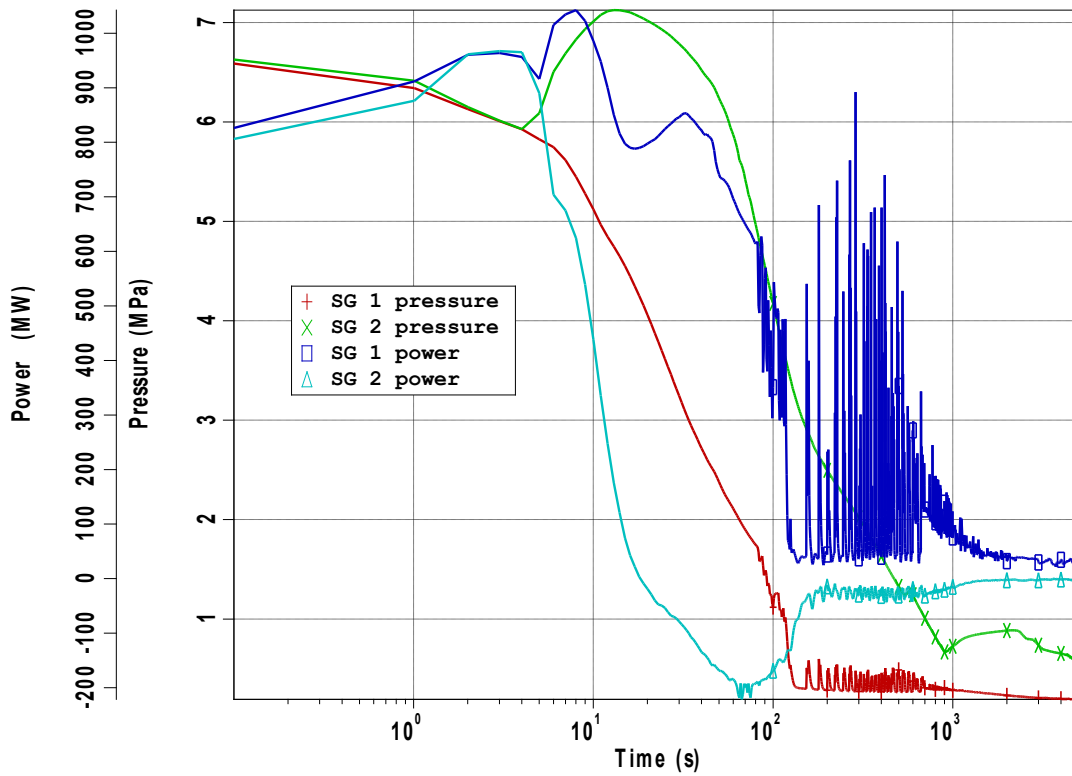


Figure 4: LDER MSLB, 70% power, SG pressure and SG power

NEK MSLB R5G calculation, LDER

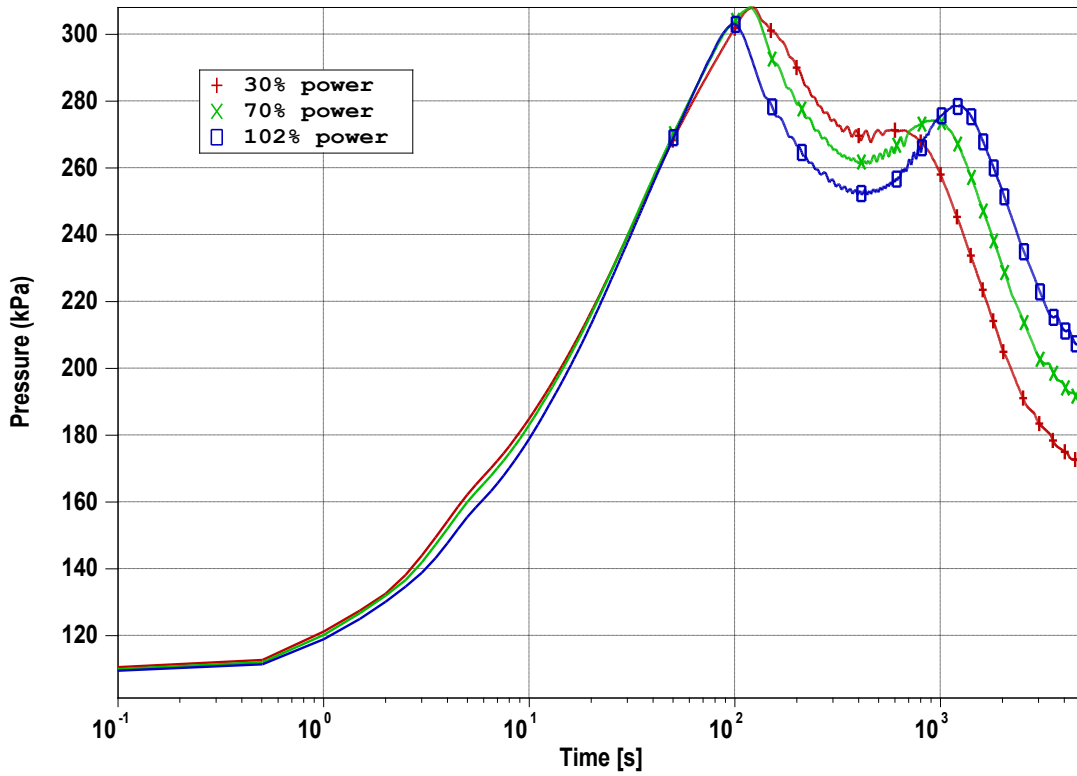


Figure 5: LDER MSLB, Containment pressure

NEK MSLB R5G calculation

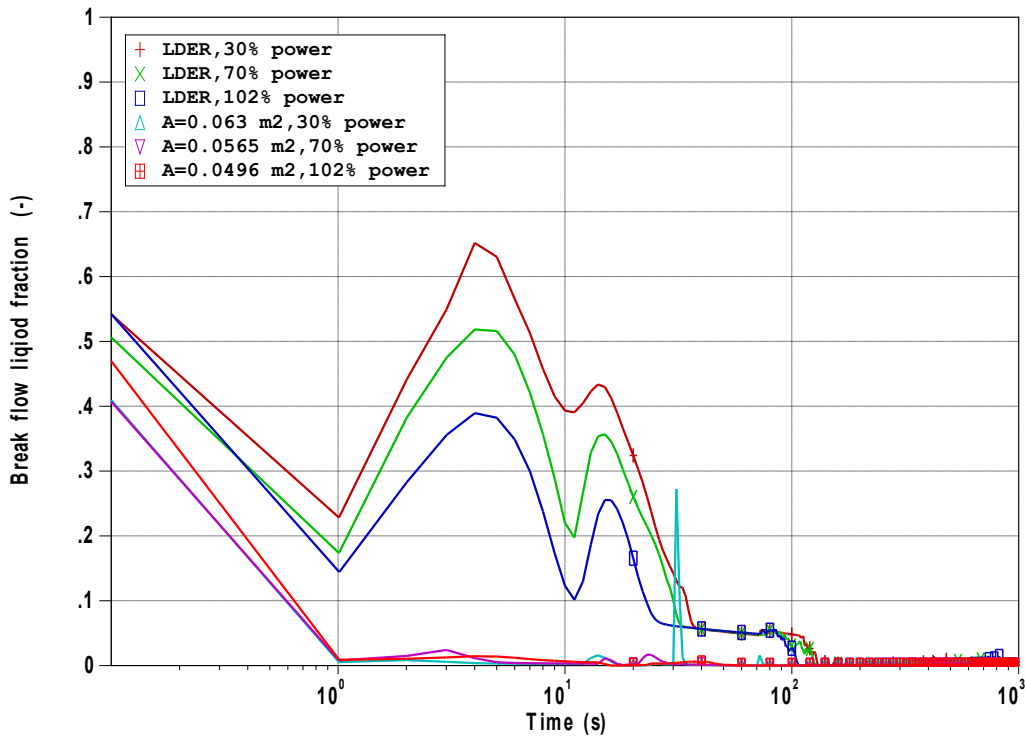


Figure 6: MSLB, Break flow liquid fraction (LDER and split break with maximum containment temperature)

NEK MSLB R5G calculation, LDER

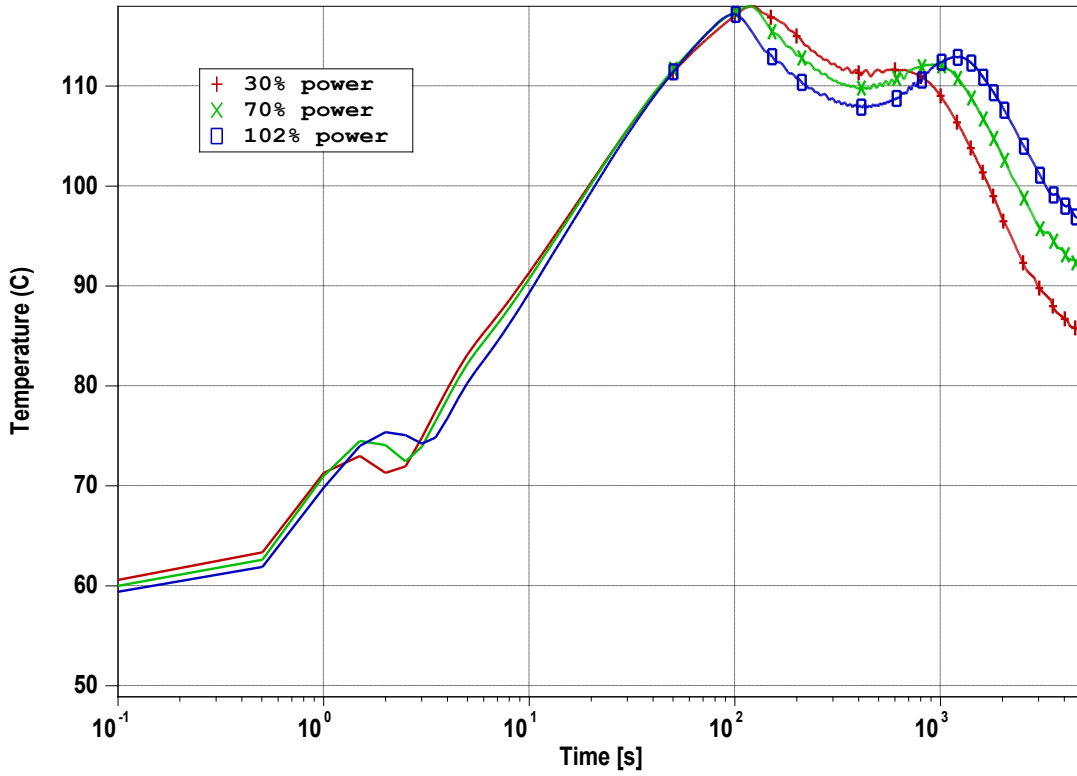


Figure 7: LDER MSLB, Containment temperature

NEK MSLB R5G calculation, LDER

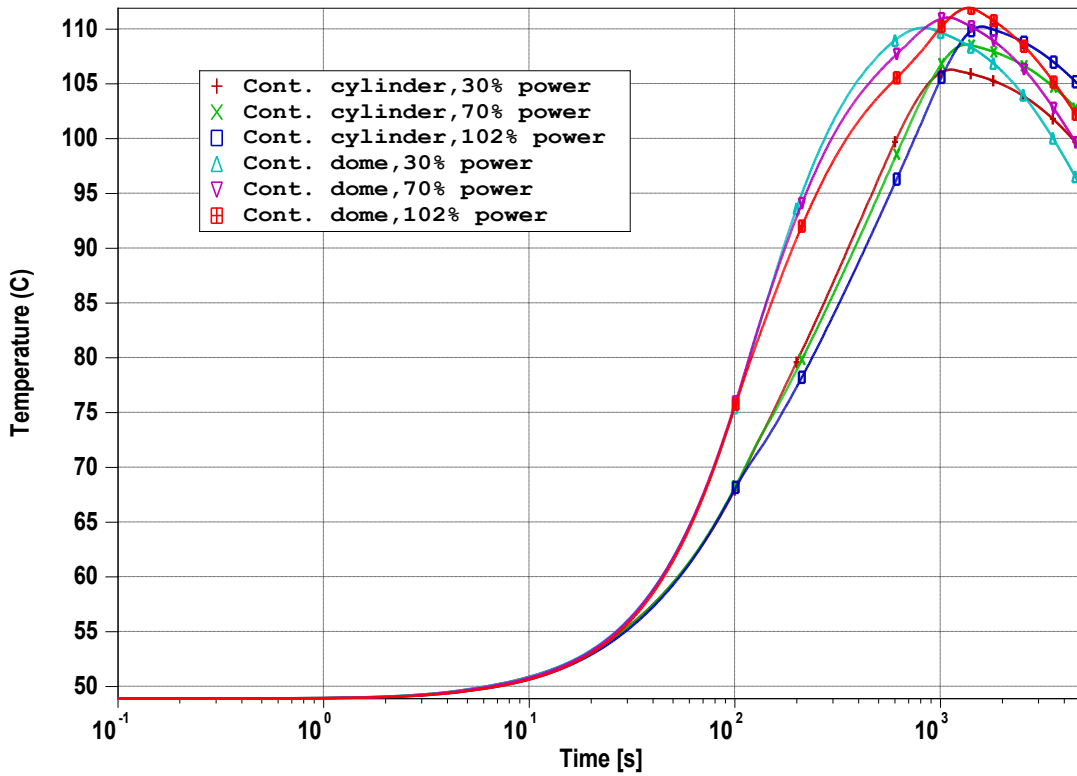


Figure 8: LDER MSLB, Containment cylinder and dome steel liner temperature

### 3.2 Analysis of steam line split break accident

Split break is modelled by a valve connecting the outlet of pipe 457 (loop with the pressurizer) and the containment. Whilst for LDER liquid entrainment is significant during the first 100 seconds of the transient, for split break dry steam is discharged into containment and much larger containment atmosphere temperature than for LDER is obtained, see Figure 6 for liquid entrainment, Figure 7 for LDER containment temperatures and Figure 10 for split break containment temperatures. For different power levels and different groups of lead/lag time constants for low steam line pressure signal (48/8, 36/6 and 24/4 s) the most adverse case regarding the containment thermal behaviour was investigated. Thus, the maximum break area was found where the steam line isolation occurs on signal different from the low steam line pressure signal or the low steam line pressure signal that leads to steam line isolation occurs late in the transient (after 50 seconds from transient begin). First, for each combination of initial power level and lead/lag time constant the minimum break area was found where the steam line isolation occurs on low steam line pressure signal. In the next step the slightly smaller break area was analysed when the steam line isolation occurs on different signal. The results are summarized in Table 3. In general, the minimum break area for actuation of steam line isolation on low steam line pressure signal increases by decreasing the lead/lag constants. Subsequently, by decreasing the lead/lag time constants the maximum containment pressure and temperature increase along with break area increase. Maximum containment pressure (301.13 kPa) was obtained for 102% power, lead/lag constants equal to 24/4 seconds and break area=0.0496 m<sup>2</sup>. Maximum containment temperature (153.48 °C) was obtained for 70% power, lead/lag constants equal to 24/4 seconds and break area equal to 0.0565 m<sup>2</sup>. Transient outcome (maximum containment pressure and temperature are greatly influenced by containment spray actuation. In the cases where the containment spray is actuated (30% power, A=0.063 m<sup>2</sup>, 70% power, A=0.0431 m<sup>2</sup> and A=0.0565 m<sup>2</sup>, and all 102% power cases containment pressure and temperature were stepwise reduced after spray flow initiation. In general, maximum containment atmosphere temperature was reached before containment spray initiation. Containment steel liner cylinder and dome temperature, see Figure 11 and Figure 12 reach their maximum values later (approximately 800 – 1000 seconds after transient begin). Containment steel liner dome and cylinder temperature will be lower due to containment spray operation. Thus, the most adverse containment steel dome temperature response (114.23 °C) was obtained for 70% power, A=0.0364 m<sup>2</sup>, lead/lag constants 48/8 s, where the containment spray was not actuated at all although the maximum containment atmosphere temperature for that case (143.56 °C) is much lower than the maximum atmosphere temperature reached during the same case (153.48 °C, 70% power, A=0.0565 m<sup>2</sup>, lead/lag constants 24/4 s). Maximum steel liner cylinder temperature (112.48 °C 1587 seconds after transient begin) was also obtained for 70% power, A=0.0364 m<sup>2</sup>.

Calculated values for maximum containment pressure (301.13 kPa), containment steel liner dome (114.23 °C) and steel cylinder temperature (112.48 °C) are well below design values (410.21 kPa, 125.6 °C and 119.4 °C).

Table 3: MSLB split break: Table of main events

Low steam line pressure lead/lag (48/8 s)	30% power (0.0398 m <sup>2</sup> )	70% power (0.0364 m <sup>2</sup> )	102% power (0.0322 m <sup>2</sup> ), cont. spray ON
Reactor trip	on SI signal at 18.94 s	on SI signal at 21.97 s	OPDT trip at 17.24 s
Safety injection	18.94 s on high-1 containment pressure	21.97 s on high-1 containment pressure	24.7 s on high-1 containment pressure
Steam line isolation	52.05 s on low steam line pressure	64.53 s on low steam line pressure	81.88 s on low steam line pressure
Max. containment pressure	282.76 kPa (440 s)	290.36 kPa (718 s)	291.84 kPa (610 s)
Max. containment temperature	144.18 °C (84 s)	143.56 °C (158 s)	140.34 °C (213 s)
Max. containment steel dome temperature	111.91 °C (940 s)	114.23 °C (1086 s)	112.61 °C (979 s)

<b>Low steam line pressure lead/lag (36/6 s)</b>	<b>30% power (0.0481 m<sup>2</sup>)</b>	<b>70% power (0.0431 m<sup>2</sup>), cont. spray ON</b>	<b>102% power (0.0381 m<sup>2</sup>), cont. spray ON</b>
Reactor trip	on SI signal at 15.61 s	on SI signal at 18.47 s	OPDT trip at 15.63 s
Safety injection	15.61 s on high-1 containment pressure	18.47 s on high-1 containment pressure	21.25 s on high-1 containment pressure
Steam line isolation	25.28 s on signal: high SL flow, low T <sub>avg</sub> and SI	37.17 s on signal: high SL flow, low T <sub>avg</sub> and SI	74.61 s on low steam line pressure
Max. containment pressure	288.82 kPa (395 s)	294.49 kPa (323 s)	294.95 kPa (335 s)
Max. containment atmosphere temperature	147.38 °C (74 s)	148.53 °C (118 s)	143.88 °C (184 s)
Max. containment steel dome temperature	112.58 °C (872 s)	112.13 °C (859 s)	113.1 °C (941 s)

<b>Low steam line pressure lead/lag (24/4 s)</b>	<b>30% power (0.063 m<sup>2</sup>), cont. spray ON</b>	<b>70% power (0.0565 m<sup>2</sup>), cont. spray ON</b>	<b>102% power (0.0496 m<sup>2</sup>), cont. spray ON</b>
Reactor trip	on SI signal at 11.88 s	on SI signal at 14.1 s	OPDT trip at 14.02 s
Safety injection	11.88 s on high-1 containment pressure	14.1 s on high-1 containment pressure	16.8 s on high-1 containment pressure
Steam line isolation	21.26 s on signal: high SL flow, low T <sub>avg</sub> and SI	14.1 s on signal: high-2 SL flow and SI	37.3 s on signal: high SL flow, low T <sub>avg</sub> and SI
Max. containment pressure	298.03 kPa (206 s)	300.85 kPa (211 s)	301.13 kPa (216 s)
Max. containment atmosphere temperature	149.7 °C (71 s)	153.48 °C (107 s)	152.03 °C (117 s)
Max. containment steel dome temperature	111.65 °C (716 s)	112.99 °C (779 s)	113.84 °C (863 s)

NEK MSLB R5G calculation, split break

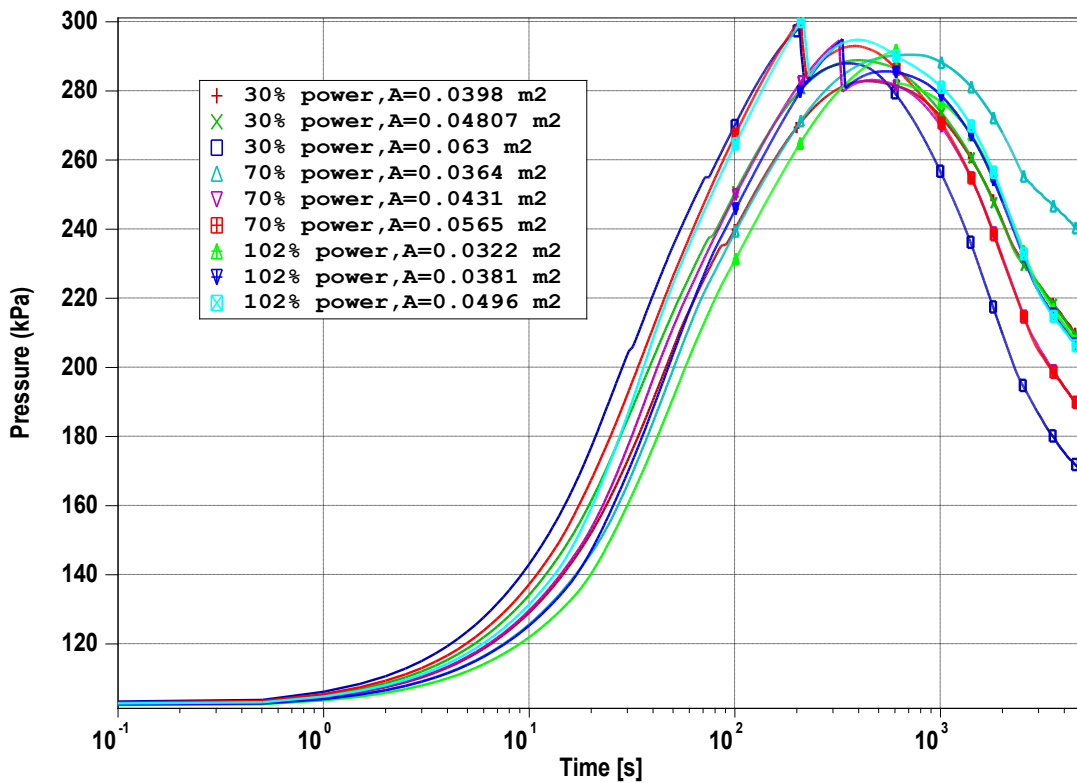


Figure 9: Split break MSLB, Containment pressure

NEK MSLB R5G calculation, split break

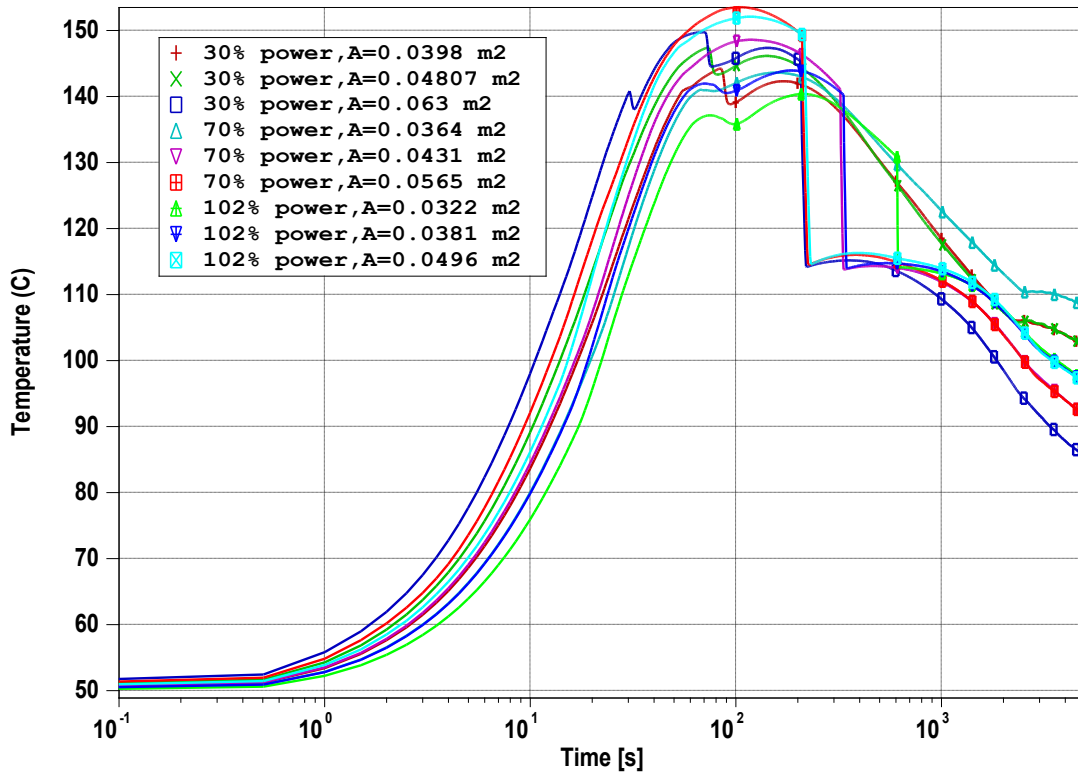


Figure 10: Split break MSLB, Containment temperature

NEK MSLB R5G calculation, split break

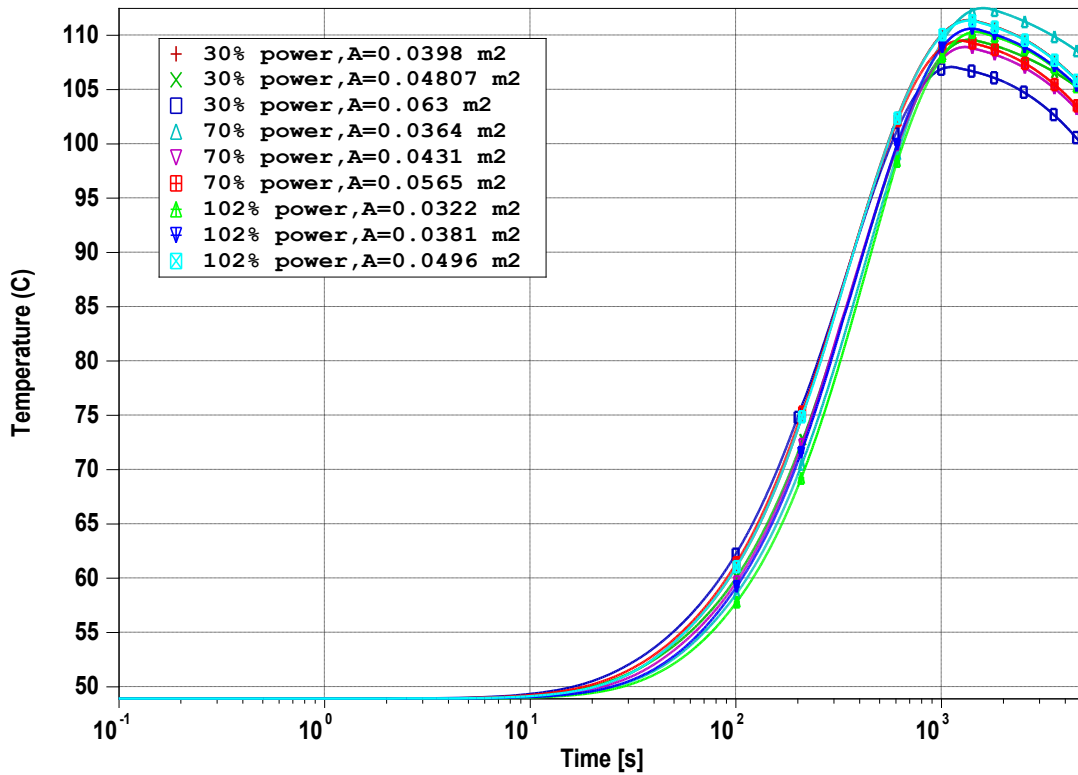


Figure 11: Split break MSLB, Containment cylinder steel liner temperature

### NEK MSLB R5G calculation, split break

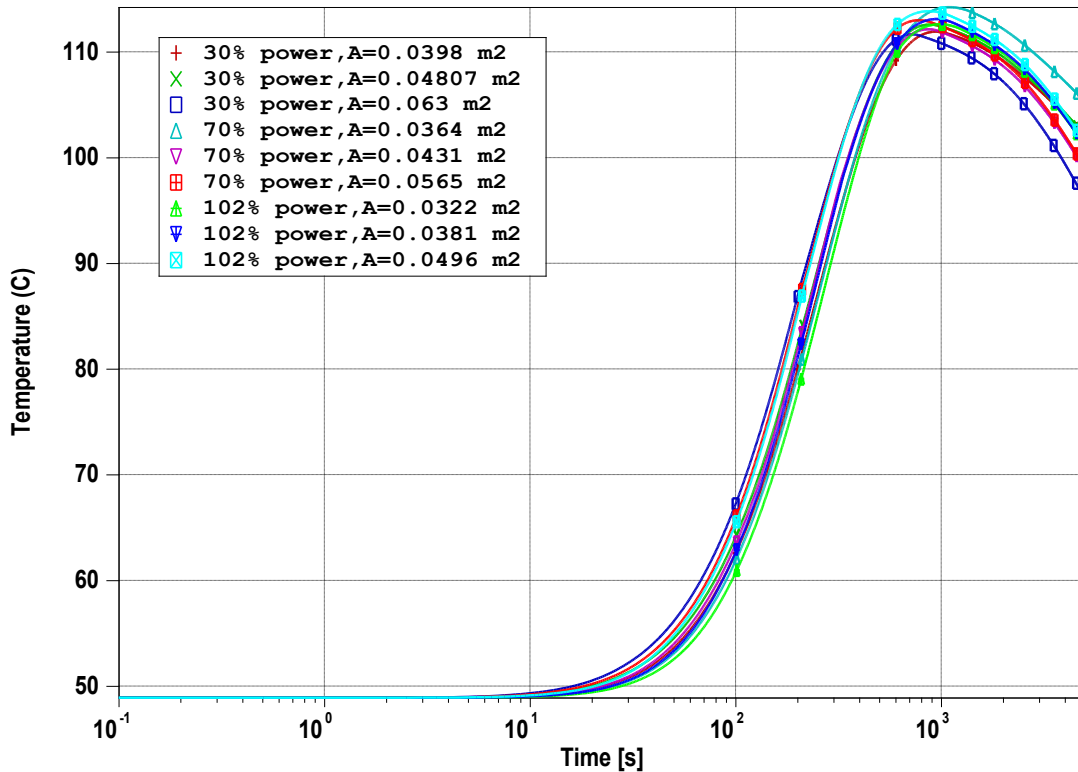


Figure 12: Split break MSLB, Containment dome steel liner temperature

## 4 CONCLUSION

In the paper the influence of different signal parameters for steam line isolation and safety injection (lead/lag constants in low steam line pressure signal logic) on containment thermal hydraulic response and design margins was analysed. Following conclusions can be drawn from the presented analyses.

In the calculation the low steam line pressure signal for large double ended (LDER MSLB) was generated at the same time for all three analysed groups of lead/lag constants. In the paper the results for currently used lead/lag constant (48/8 s) are presented. In LDER MSLB the heat produced on the primary side is removed through the break while the heat transfer reversal in the unaffected steam generator (SG 2) occurred very fast after transient begin. In LDER significant liquid entrainment occurred during the intensive break flow (until approximately 100 seconds after transient begin) when also the maximum containment pressure and temperature were reached. Further increase of containment pressure and temperature were stopped due to containment fan coolers and containment spray actuation. For LDER MSLB the maximum containment pressure among all analysed cases was obtained for 70% power (308.04 kPa).

For split break, the maximum break area was found where the steam line isolation is not actuated on low steam line pressure or the low steam line pressure signal is generated late in the transient. The minimum break area for actuation of steam line isolation on low steam line pressure signal increases by decreasing the lead/lag constants. In general, during the first 200 seconds of the transient the increase of break area leads to an increase of maximum containment pressure and temperature. Later in the transient the maximum containment pressure and temperature are influenced also by containment spray that was not actuated in some cases. Contrary to the LDER MSLB, in split break MSLB dry steam was discharged to containment and the maximum containment atmosphere temperature was significantly higher (153.48 °C, 70% power, A=0.0565

m<sup>2</sup>) than in the LDER case (117.99 °C, 70% power). The maximum containment pressure (301.13 kPa) for split break was obtained for 102%, A=0.0496 m<sup>2</sup>. Containment steel liner temperature was influenced by long term heat-up and cooling behaviour of containment atmosphere. Thus, the maximum containment steel liner dome temperature (114.23 °C) was obtained for the case where the containment spray was not actuated at all (70% power, A=0.0364 m<sup>2</sup>).

The presented analyses have shown that reduction of lead/lag constants for low steam line pressure signal from current value (48/8 s) to 36/6 s and 24/4 s does not lead to significant reduction of margin to design containment pressure and containment steel liner temperature. In LDER steam line break analyses calculated values for maximum containment pressure (308.04 kPa, 70% power), containment steel liner dome temperature (111.9 °C, 102% power) and steel liner cylinder temperature (110.19 °C, 102% power) are well below design values (410.21 kPa, 125.6 °C and 119.4 °C). The same is true for maximum containment pressure (301.13 kPa, 102% power), containment steel liner dome (114.23 °C, 70% power) and steel liner cylinder temperature (112.48 °C, 70% power) calculated in the analyses of steam line split break.

## REFERENCES

- [1] RELAP5/mod3.3 Users Manual, The RELAP Code Development Team, NUREG/CE-5535/Rev 1, Information Systems Laboratories, Inc., Rockville-Maryland, Idaho Falls-Idaho, January 2002.
- [2] Thomas George et al, GOTHIC Containment Analysis Package, Version 7.2b (QA), NAI 8907-02, Rev 18, Numerical Applications, Inc., Richland, Washington, USA, March 2009.
- [3] NEK RELAP5/MOD3.3 Post-RTDBE Nodalization Notebook, NEK ESD TR 02/13, Revision 1, Krško 2014.
- [4] NEK RELAP5/MOD3.3 Steady State Qualification Report for Cycle 33, NEK ESD TR 16/22, Revision 0, Krško 2022.
- [5] NEK Containment Nodalization Notebook, ESD-TR18/00, Revision 0, November 2002.
- [6] M. Keco, N. Debrecin, D. Grgić, Applicability of Coupled Code RELAP5/GOTHIC to NPP Krško MSLB Calculation, Proceedings of the International Conference "Nuclear Energy for New Europe 2005", Bled, Slovenia, September 5-8, 2005, pp. 169-1-169-13