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MATHEMATICAL MODEL OF THE NPP KRŠKO PCFV SYSTEM FOR THE RELAP5 COMPUTER CODE

SUMMARY

Containment building is the final barrier for radioactive releases from a nuclear power plant (NPP). Preserving its integrity will minimize these releases even in a case of a severe accident with core degradation and melt discharge in the containment accompanied with the pressure and temperature increase. Installation of a venting system with ability to filter radioactive fission products is a preferred way to deal with the issue in present and future NPPs, especially after the Fukushima accident. Such system, called passive containment filtered venting system (PCFV), was installed in 2013 in the NPP Krško. Thermal hydraulic model of the PCFV system which included aerosol and iodine filters, associated pipings and valves was developed for the best-estimate computer code RELAP5. Main results and discussion are presented and compared with relevant plant documentation.

Key words: Containment, NPP Krško, PCFV system, RELAP5 code

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1. INTRODUCTION

Upgrades of existing safety systems and installation of new systems are the most important actions in strengthening safety of nuclear installations and their ability to withstand accident conditions. Containment building represents the last physical barrier in the defence in depth concept for a nuclear power plant (NPP) because it prevents radioactive releases to the environment. Pressure increase caused by decay heat losses in the containment atmosphere and supported by the accumulation of incondensable gases produced during the molten corium concrete interaction may challenge the integrity of the containment wall. A containment filtered venting system based on the dry filter method (DFM) enables the plant to effectively mitigate the consequences of a severe accident by reducing the pressure and the level of fission products releases to the environment during the venting process. This system provides high decontamination factors for aerosols such as caesium iodide and caesium hydroxide and for both elemental and organic iodine. The system can operate in a fully passive manner and does not require other support functions like cooling or electricity and is therefore named as passive containment filtered venting (PCFV) system.

Following the lessons learned from the accident at the nuclear power plant Fukushima in Japan and according to the Slovenian Nuclear Safety Administration (SNSA) Decree No.: 3570-11/2011/7 on September 1, 2011 [1], the NPP 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. Consequently, one of the first modifications that NEK implemented during the outage 2013 is the installation of the PCFV system. The system is based on the dry filter method and designed to be used in case of severe accident conditions involving core relocation from the pressure vessel. The resulting pressurizing gas-vapour mixture in the containment can be discharged through the PCFV to the environment. This pressure relief is used to prevent the failure of the containment as a result of slow containment pressurization to levels above the containment vessel design pressure. The filter system protects the environment and surrounding population from airborne radioactive aerosols containing caesium which can enter the food chain and gaseous radioactive iodine and its organic compounds which can accumulate in the human thyroid.

The system operation was simulated using the system code RELAP5. RELAP5 is a state-of-the-art thermal hydraulic code which has a broad verification basis and is able to simulate the complete venting process for the whole range of design conditions and the different operation modes. An explicit model was developed based on NEK isometric drawings [2] and component design data. Since the system is needed for beyond design basis accident situations, the verification analysis is based on best-estimate assumptions. The steady state calculation was performed to verify the nodalization by comparing the results with the design operating parameters (pressure, temperature, gas velocity). The transient calculation, in the absence of the measured data, was run with the boundary conditions extracted from the calculations performed with the code MELCOR in scope of the supporting calculations for the plant reported in relevant documents [3] and papers [4], [5]. The knowledge gained in this analysis will be later used to develop a model for the integral plant simulation with explicit models of all power plant systems, including the model of the PCFV system.

2. PCFV SYSTEM DESCRIPTION AND MATHEMATICAL MODEL

2.1 PCFV system outline

The passive containment filtered venting system, a system specially designed for light water reactor NPPs to work without external power supply, is used to filter radioactive aerosols, gaseous iodine, iodine organic compounds and to control the containment pressure.

The PCFV system consists of aerosol filters, the iodine filter, the rupture disc, valves, expansion orifices, instrumentation and associated piping, Figure 1. The venting gas first passes aerosol filter modules, leaves the containment via piping through a containment penetration, passes the iodine filter and discharges to the environment through a stack.

Figure 1. PCFV system layout, taken from [6]

Aerosol filters (five units on the right hand side in Figure 1) remove solid particles and aerosols from the vented gases by mechanical filtering using a metal fiber filter. They are connected with piping, which leads the vent stream out of the containment through the containment penetration and then splits into a passive and an active actuation line. The passive actuation of the system will occur once the containment pressure exceeds the rupture disk burst pressure of 0.6 MPa. The vented gases will then flow through two normally-opened isolation valves and the pressure relief valve. The pressure relief valve isolates the passive actuation line at low containment pressure in order to prevent too low pressure conditions inside the containment. The valve maintains the pressure inside the containment between 0.41 MPa and 0.49 MPa. The active actuation of the system can be achieved through the opening of the two normally closed isolation valves, either manually with the remote handwheels or from a control room with motor actuators. In the analysis, only the passive line with the rupture disc and the relief valve was simulated.

Before entering the iodine filter, gases flow through an orifice which controls the mass flow and maximum humidity of the vented gas stream. In the filter beds, the gaseous radioactive iodine and its organic compounds are removed through chemical sorption with silver as an active material with the designed filter efficiency.

In addition, nitrogen is used for long term storage and inerting of the zeolite filter material of the iodine filter. Also, injection of nitrogen prevents too low pressure conditions due to steam condensation when venting is stopped and the system cools down. Nitrogen is provided by a separate nitrogen supply system connected to system piping downstream of the actuation lines.

2.2 RELAP5 model and nodalization

The code version used in the calculation was RELAP5/MOD3.3 [7]. The nodalization scheme of the PCFV system is shown in Figure 2. All major components which are required for the filtered venting functions of the PCFV have been considered and were implemented in the model. The model consists of 160 control volumes, 159 junctions and 154 heat structures with 924 mesh points. A PCFV system sketch with piping dimensions is shown in Figure 3 and its RELAP5 representation with the main control volume (CV) data is presented in Table I.

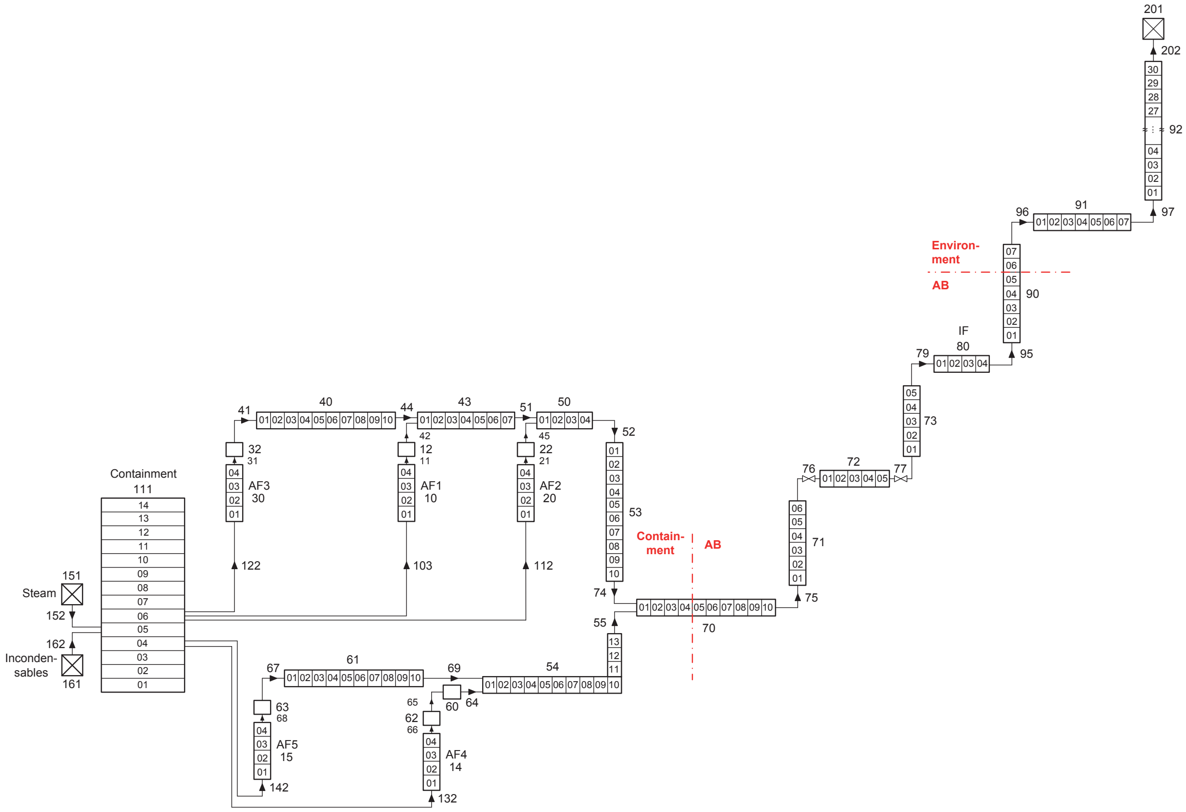

Figure 2. RELAP5 nodalization of the PCFV system

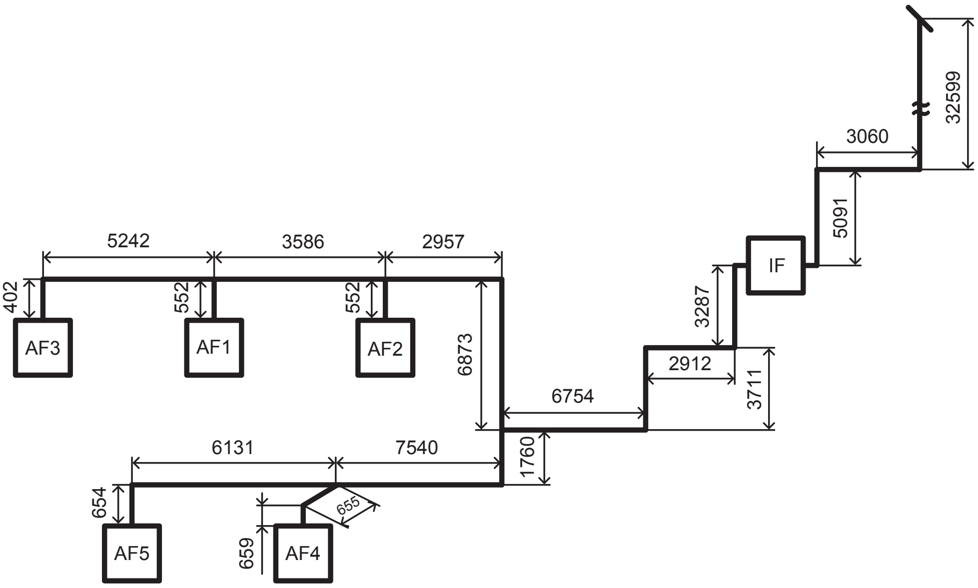

Figure 3. PCFV system piping outline

Table I. Description of RELAP5 control volumes

Control volume	Segments	Length [m]	Flow area [m^2]	Hydraulic diameter [m]	Vertical angle
111	14	61.46	650	14.4	90°
AF1-10	4	2.42	2.2149	1.484	90°
AF2-20	4	2.42	2.2149	1.484	90°
AF3-30	4	2.42	2.2149	1.484	90°
AF4-14	4	2.42	1.5356	1.2	90°
AF5-15	4	2.42	2.2149	1.484	90°
12	1	0.552	0.032	0.2032	90°
22	1	0.552	0.032	0.2032	90°
32	1	0.402	0.01824	0.1524	90°
40	10	5.242	0.01824	0.1524	0°
43	7	3.586	0.032	0.2032	0°
50	4	2.957	0.05	0.254	0°
53	10	6.873	0.05	0.254	–90°
62	1	0.659	0.032	0.2032	90°
63	1	0.654	0.032	0.2032	90°
60	1	0.655	0.032	0.2032	0°
61	10	6.131	0.01824	0.1524	0°
54	13	9.3	0.032	0.2032	0°/90°
70	10	6.754	0.05	0.254	0°
71	6	3.711	0.05	0.254	90°
72	5	2.912	0.05	0.254	0°
73	5	3.287	0.1	0.356	90°
IF-80	4	1.6	19.5	0.27	0°
90	7	5.091	0.29	0.6096	90°
91	7	3.06	0.29	0.6096	0°
92	30	32.599	0.29	0.6096	90°

Control volumes 10, 20, 30, 14 and 15 represent aerosol filters 1-5, respectively. The iodine filter is modelled with CV 80. Filters' flow areas, hydraulic diameters and friction factors were adapted to obtain correct steady state gas velocities. All other control volumes represent PCFV piping. Pressure loss coefficients have been modelled to account for elbows and branches. Wall roughness is set generally to 10^{-6} m. The volumes are nodalized in such way that the node length is approximately 0.5 m to accurately track the gas composition as well as to support computation of pressure wave loads. The general Courant rule that the minimal time step applied corresponds with flow velocity and the length of the nodes has been respected.

The rupture disc is modelled as a trip valve component 76 which opens when the containment pressure reaches 0.6 MPa. The relief valve (component 77) is also modelled as a trip valve but with pressure hysteresis behaviour. The valve needs to keep the pressure inside the containment between 0.41 MPa, closing pressure, and 0.49 MPa, opening pressure, after the failure of the rupture disc. Thus, valve operation is characterized by two setpoint pressures: an opening pressure and a "reseat" (closing) pressure. As system pressure is increased, the valve opens at the opening pressure and remains open until the system pressure falls below the reseat pressure. This process therefore involves hysteresis; operation of the valve is not only dependent on the pressure but also on whether the valve is currently open or closed. This behaviour was modelled by a simple script:

```
20605020 p 111010000 gt null 0 4.1e5 n

20605030 p 111010000 gt null 0 4.9e5 n

20610010 502 and 1002 n

20610020 503 or  1001 n
```

First, variable trips 502 and 503 are defined to compare the current system pressure against the two setpoint pressures. Control volume 111 represents containment and 'p' stands for pressure. Next, logical trips 1001 and 1002 are used to combine the information from the variable trips with the information on the current valve status into a trip that will control the valve. Trip 1001 is true only if the valve was open on the previous time step and the current pressure is above the closing setpoint pressure. Trip 1002 is true only if the pressure exceeds the opening setpoint pressure or the valve was open on the previous time step and the current pressure is above the closing setpoint pressure. Therefore, the status of trip 1002 is used to control the model valve position: opened when the trip is true and closed when the trip is false.

The orifice at the inlet in the iodine filter used to control operating conditions in the filter is modelled as a single junction component with an abrupt area change option.

The heat losses to the environment through the pipe walls, aerosol and iodine filter internal and housing structures were modelled as heat structures. The conduction through these structures was assumed to be one-dimensional and a stainless steel heat conductivity and volumetric heat capacity data were used. Heat convection from the hot gases to the walls was calculated internally by the code and for the heat transfer to the environment three sets of data were used, according to [8], depending on the outside conditions:

- containment atmosphere: heat transfer coefficient (HTC) 20 W/m^{2}K, temperature 443 K,
- auxiliary building atmosphere: HTC 10 W/m^{2}K, temperature 353 K,
- outside air: HTC 20 W/m^{2}K, temperature 318 K.

3. ANALYSIS RESULTS

3.1 Steady state calculation

The input model was verified by checking its output results and comparing them with design parameters reported in [8]. Boundary conditions for the steady state were modelled using the time-dependent volume 151 and time-dependent junction 152 components. The working fluid was pure steam, as specified in the afore-mentioned document, at pressure 0.6 MPa and temperature 443 K with a mass flow rate 7 kg/s. The outlet conditions were set to atmospheric pressure 101.325 kPa and temperature 293 K (time-dependent volume 201).

The main results of the steady state analysis are listed below:

- The designed relief capacity of 7 kg/s of pure steam at 0.6 MPa in the containment is reached (Figure 4).
- The average gas velocity in the aerosol filters does not exceed the limit of 0.22 m/s, while in the zeolite beds of the iodine filter steam velocity is less than 0.5 m/s (Figure 5).
- The maximum pressure in the piping system is below 0.65 MPa from downstream of aerosol filters to the main orifice and below 0.12 MPa downstream of iodine filter inlet orifices (Figure 6).
- The average temperature of the piping walls is less than 523 K in aerosol filters and 493 K in the iodine filter (Figure 7).
- No condensate accumulates in the piping during steady state downstream of the main orifice (Figure 8).

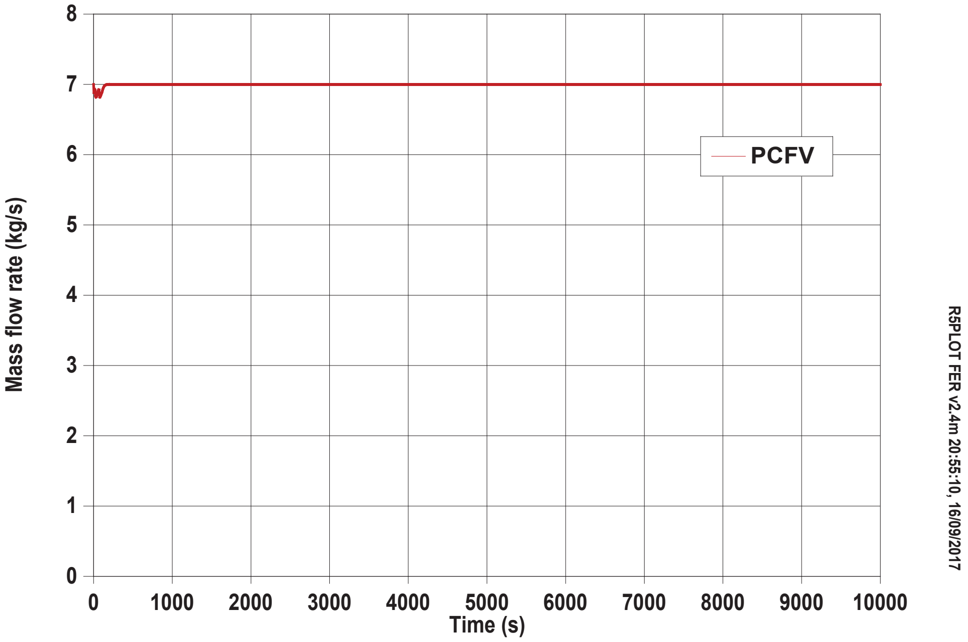

Figure 4. Steam mass flow rate through the PCFV system

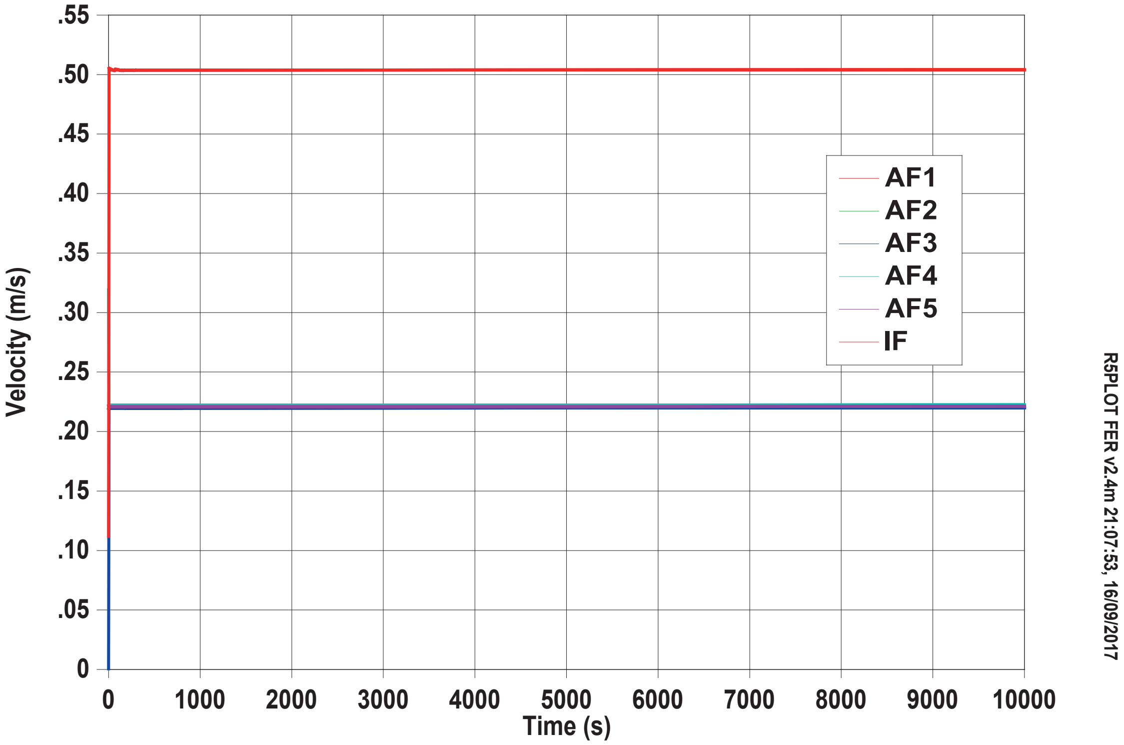

Figure 5. Gas velocities in aerosol and iodine filters

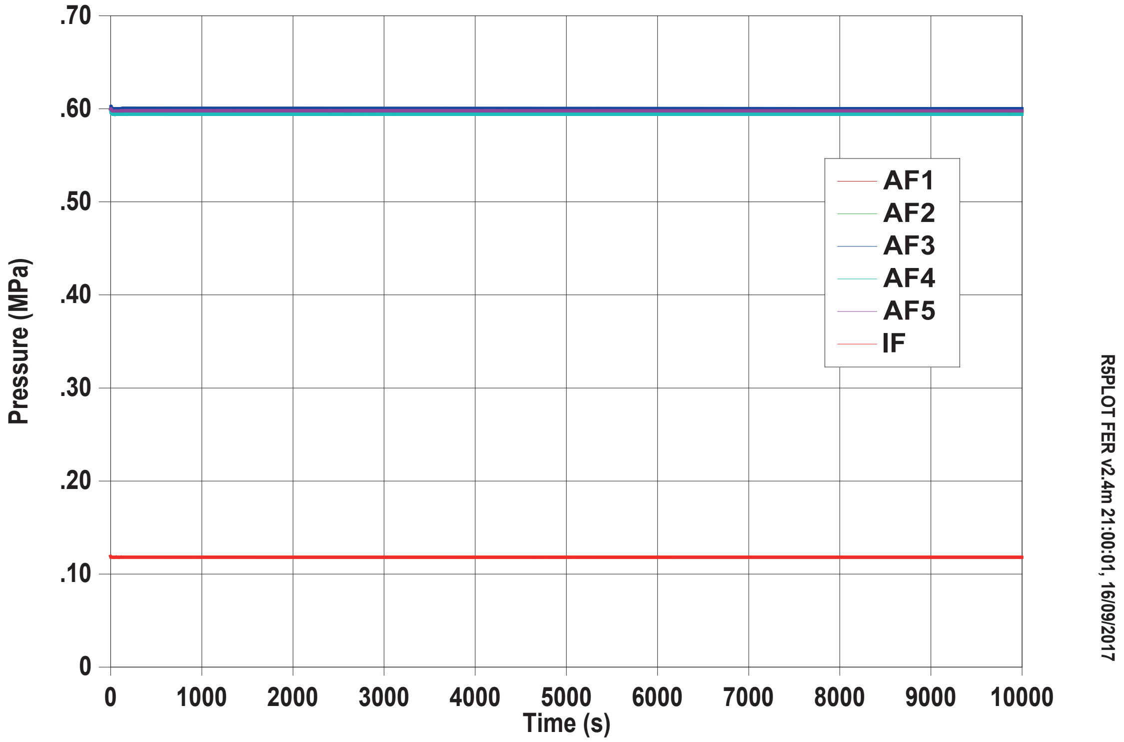

Figure 6. Gas pressures in aerosol and iodine filters

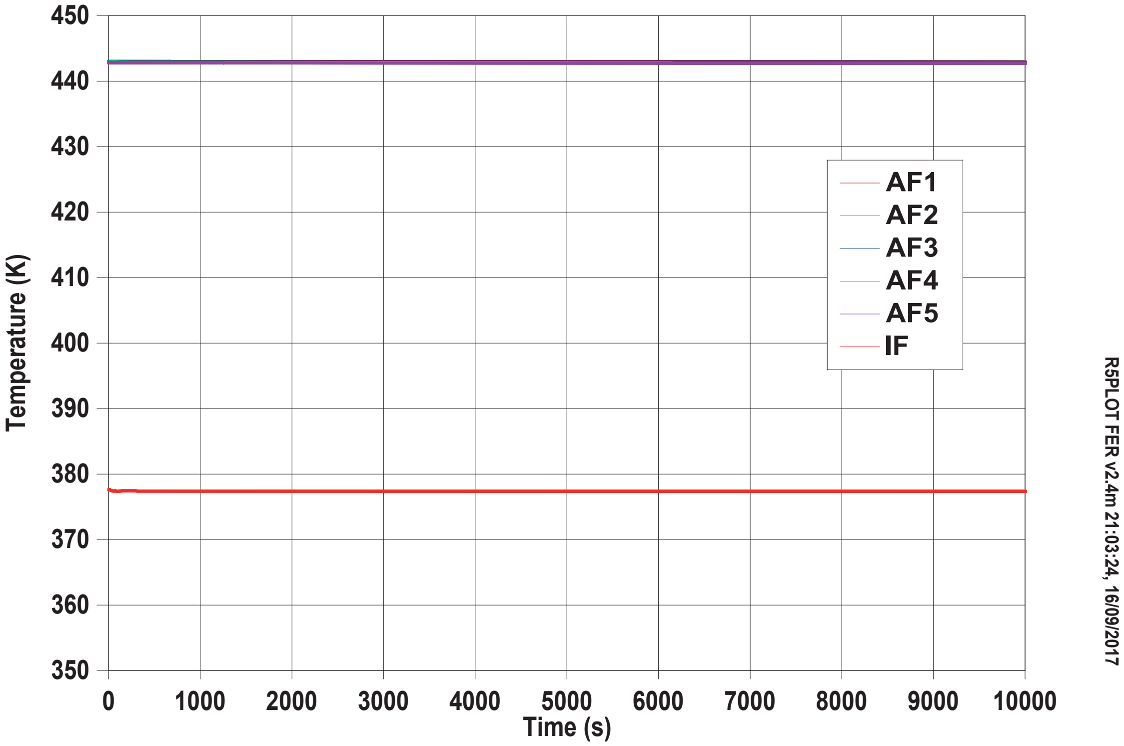

Figure 7. Gas temperatures in aerosol and iodine filters

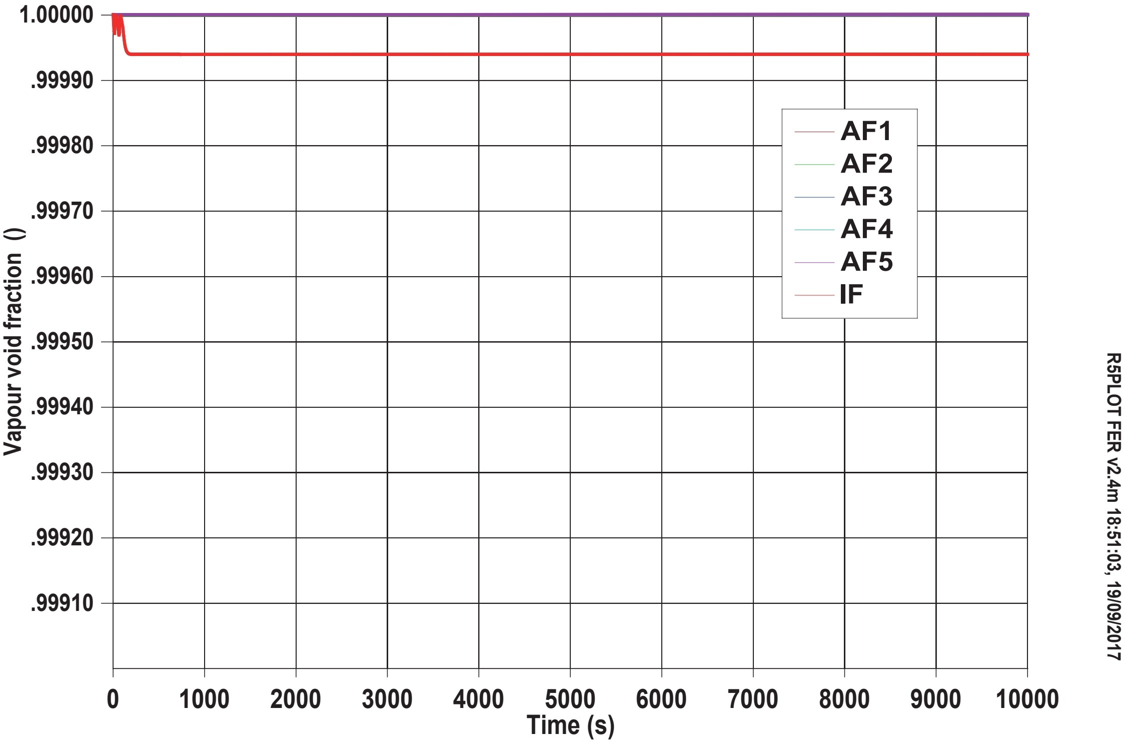

Figure 8. Steam void fraction in aerosol and iodine filters

3.2 Transient calculation

In the absence of measured data, the transient calculation was performed with boundary conditions provided by the MELCOR run [3]. The scenario was a station blackout with core damage and the release of corium in the containment. The molten corium concrete interaction took place in the cavity compartment resulting with production of steam and incondesable gases, hydrogen, carbon dioxide and carbon monoxide. The majority of stem was released from the primary system through the breaks formed at the reactor coolant pumps after degradation of pump seals as a consequence of the loss of electrical power. The steam and incondesable gases mass flow rates were taken from the MELCOR calculation and used as input boundary conditions for this analysis (Figure 9). Initially, the steam flow rate was low to account for containment environmental conditions and the PCFV system that was filled with air. The steam fraction increased rapidly afterwards following the coolant release out of the primary system.

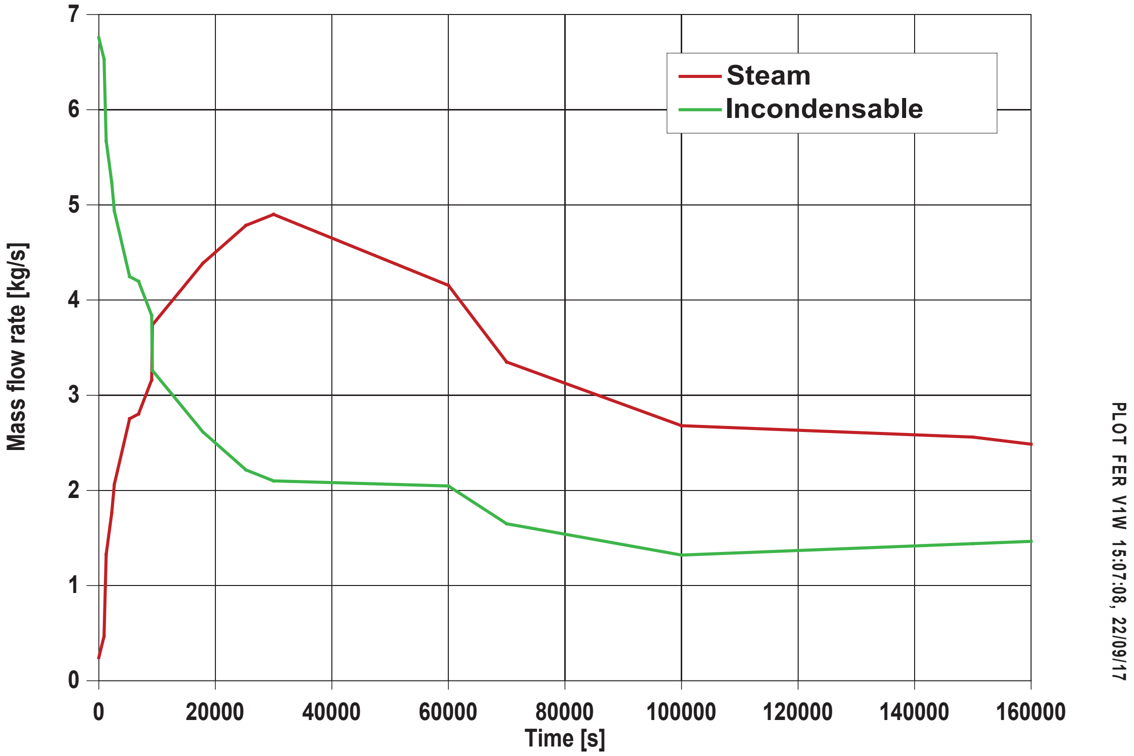

Figure 9. Steam and incondensable gases mass flow rates at the PCFV system inlet

Discharge of reactor coolant in the containment is responsible for the initial containment pressure increase. When the containment dome pressure reaches 0.6 MPa (the first pressure peak), the rupture disc in the PCFV line will break causing containment gases to be released in the environment. The pressure drops fast to 0.41 MPa prompting the relief valve in the PCFV line to close. Following the valve closure, the pressure rises once again. After reaching 0.49 MPa, the relief valve opens and again some containment inventory is released. Later, the pressure continues to cycle between 0.41 MPa and 0.49 MPa by the operation of the PCFV pressure relief valve, Figure 10 (MELCOR result is shown in the same figure for the easier comparison). That kind of valve behaviour is important for preserving containment integrity and minimizing radioactive releases.

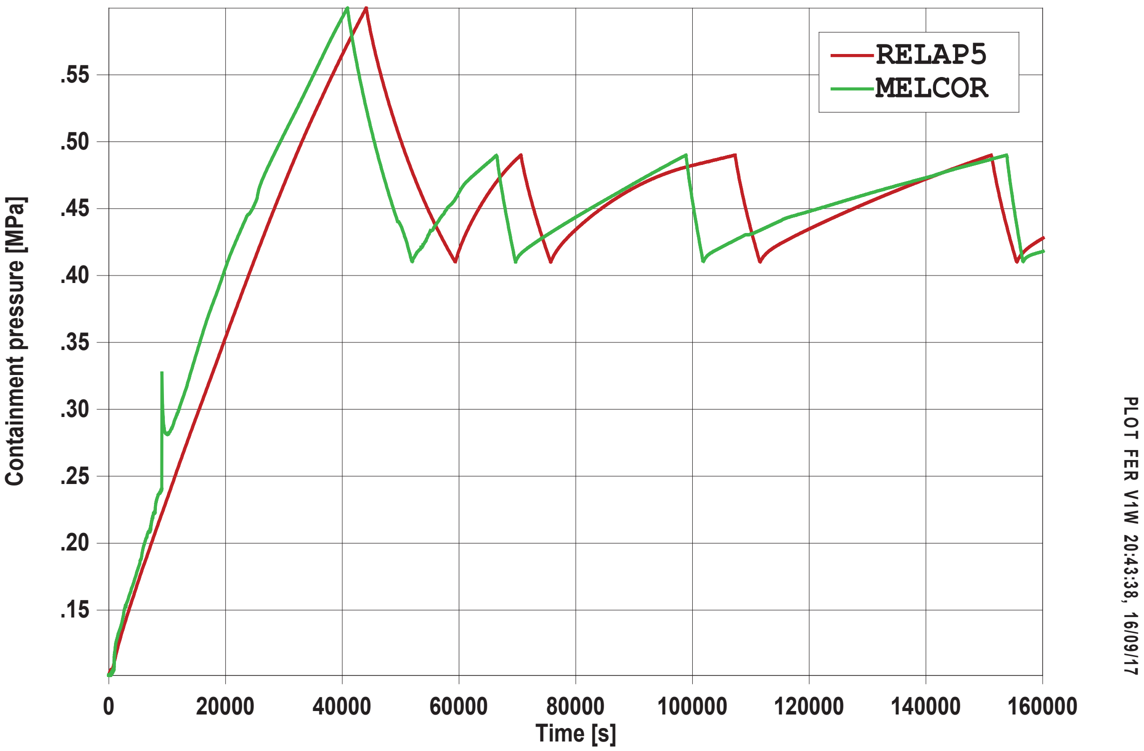

Figure 10. Containment upper plenum pressure

The big concern is the possibility of hydrogen ignition in the system components during the venting phase. There are two mechanisms of hydrogen production:

- Oxidation of zirconium fuel cladding alloy with steam at temperatures above 1200 K. Zirconium is transformed into zirconium dioxide in form of a ceramic oxide shell on the fuel rods, while hydrogen is released as another product of that reaction.
- Molten corium concrete interaction during which steam released from the concrete reacts with steel reinforcement iron. Here, iron oxide and hydrogen are the reaction products.

Hydrogen flammability depends on composition of air-steam-hydrogen mixture. The minimum mole fraction of hydrogen that could lead to its ignition is 4-5 % [9]. The maximum fraction calculated by the RELAP5 was less than 3% (Figure 11) and, thus, no ignition could take place. The figure indicates the rise in hydrogen concentration in the late venting phase but that is irrelevant since no more oxygen is released from the containment and, due to the high back-pressure, no oxygen could also enter in the system from the outside. The oxygen in the containment was consumed earlier by the operation of the hydrogen autocatalytic recombiners which induce the reaction between oxygen and hydrogen until all oxygen has reacted. An integral analysis of the whole NEK containment was performed with three system codes: ASTEC, MELCOR and MAAP with emphasis on the containment thermal hydraulic behaviour when the PCFV system is in the operation [5]. Figure 12 shows the gas mixture composition throughout the transient and it is visible that conditions for possible hydrogen ignitions were not achieved in any time period during the calculation.

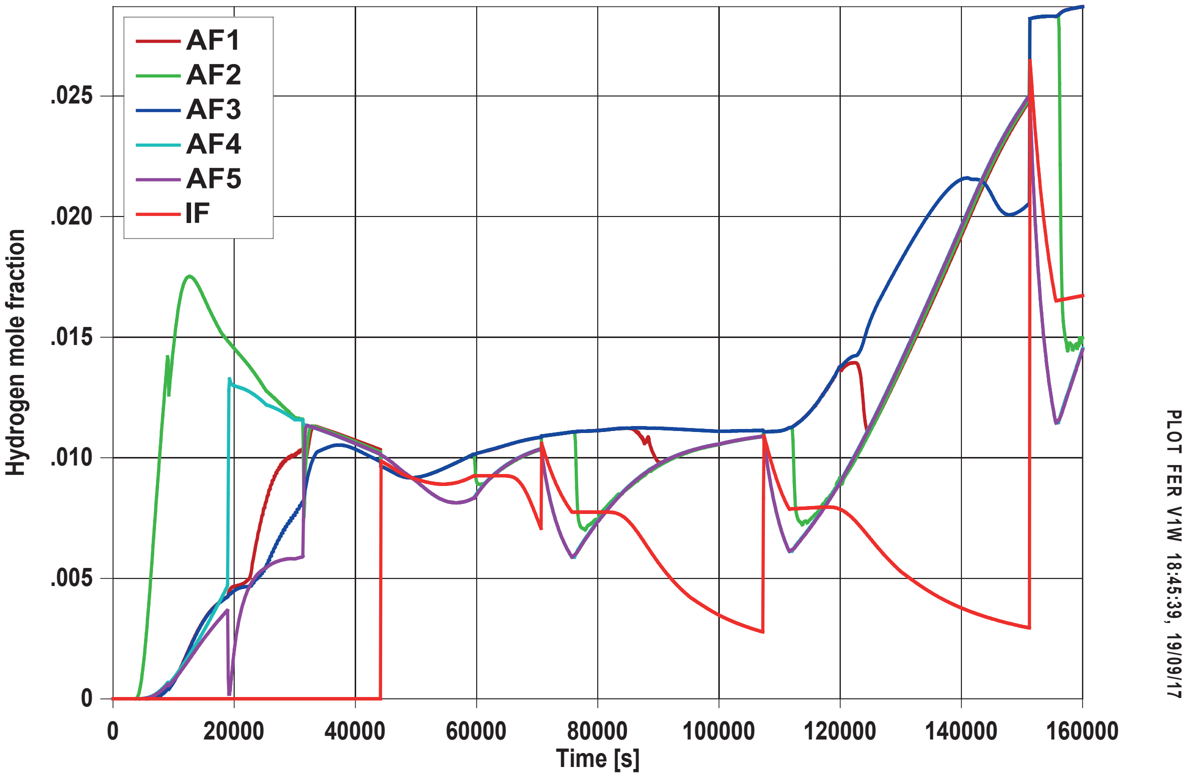

Figure 11. Hydrogen concentration in aerosol and iodine filters

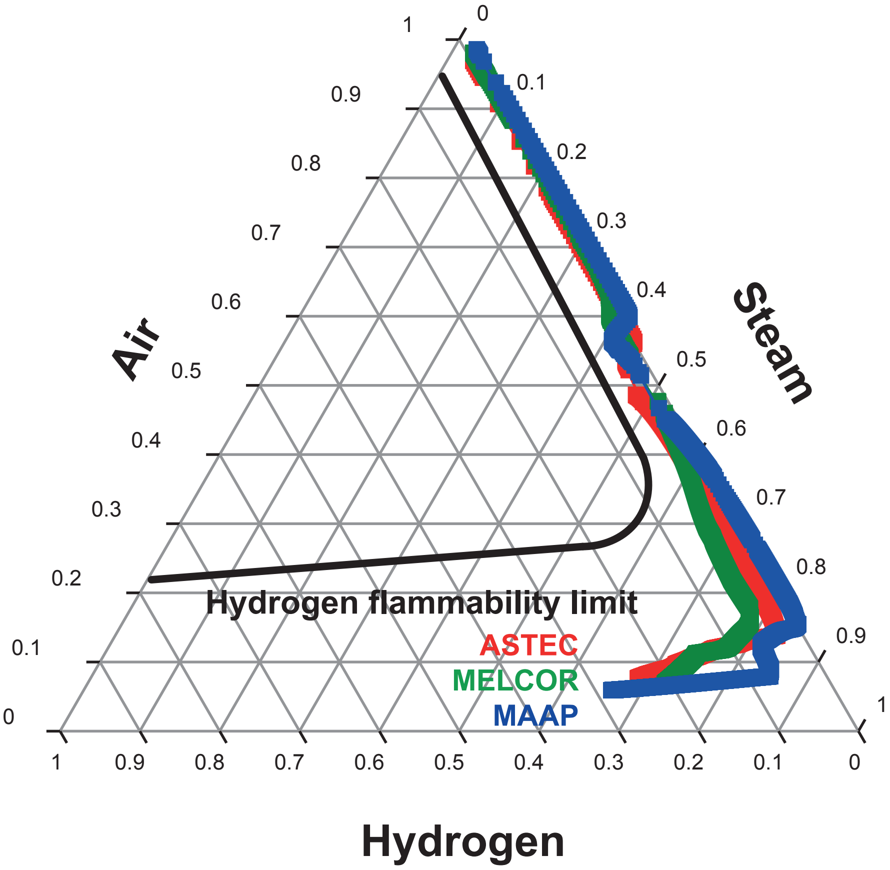

Figure 12. Containment conditions as calculated by 3 codes represented in ternary diagram of air-steam-hydrogen mixture

4. CONCLUSIONS

A detailed explicit model of the NPP Krško PCFV system was developed for the best-estimate thermal hydraulic code RELAP5. The best-practice code options in constructing the nodalization were adopted. The model was tested on the steady state and transient levels.

The steady state calculation was performed to verify the model by comparing the results with the system design parameters: gas mass flow rates and velocities, system pressure and heat structure temperatures. Pressure loss coefficients and hydraulic diameters for equipment with complex geometry, such as aerosol and iodine filters, were fine-tuned to obtain satisfactory steady state behaviour. The gas composition and boundary conditions were prepared to be in accordance with the plant documentation.

Transient calculation scenario was a station blackout with the complete loss of the electrical power. The simulation was used to check the system behaviour in accidental conditions, primarily the relief valve operation in keeping the pressure between prescribed setpoints: 0.41 MPa and 0.49 MPa. Results were compared with a similar calculation conducted with the code MELCOR because this was the only relevant plant analysis with the PCFV system in operation. They showed similar trends in pressure evolution during several relief valve opening/closing cycles. The conclusion is that the RELAP5 model is qualified for safety analyses of both the steady state and transient scenarios. The last thing checked was the hydrogen concentration in the different parts of the system. The gas mixture was always below the hydrogen flammability limit and no fire danger, or explosion, exists when the PCFV system is in operation.

5. REFERENCES

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