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Verification of GOTHIC Multivolume Containment Model during NPP Krško DBA LOCA

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ABSTRACT

New containment multivolume model of NPP Krsko for GOTHIC code is developed. It is based on plant drawings and other available data. It is supported by developed SketchUp 3D containment model. The model is subdivided in volumes following physical boundaries and clearly defined flow paths. All important concrete heat structures are taken into account. Metal heat structures are based on plant's SAR Chapter 6 licensing model. RCFC (Reactor Containment Fan Cooler) units are explicitly modelled as well as all main ventilation ducts. The model includes two trains of containment spray system. PARs (Passive Autocatalytic Recombiner) and PCFV (Passive Containment Filter Venting) filters added during plant safety upgrade project are part of the model too.

It was intention to use model for both DBA (Design Basis Accident) and for DEC (Design Extended Conditions) and BDBA (Beyond Design Basis Accident) calculations. Based on the same discretization and data, and on experience acquired during GOTHIC model development and use, containment models for MELCOR and MAAP integral codes are developed too.

As part of initial verification of the GOTHIC model containment DBA LOCA calculation is performed using SAR MER (Mass and Energy Release) data. The influence of different break positions on peak containment atmosphere pressure and temperature was studied. The results were compared against results obtained in single volume containment licensing model. Beside local effects due to different containment subdivision similar results are obtained when comparing containment dome from multivolume and the single volume in licensing model. Special attention was paid to distribution of water in lower part of the containment during recirculation phase. In this case much more valuable information are obtained in multivolume model with explicit volumes for main sump, recirculation sump and sump pit. Another point of interest was influence of containment spray duration on long term pressure and temperature behaviour. The intention was to study consistency of assumed different spray operation times used in safety analyses, EQ analyses and SAMGs and related consequences for plant operation during DBA LOCA.

Keywords: *containment, LOCA, GOTHIC, multivolume model, spray operation time*

1 INTRODUCTION

New containment multivolume model of NPP Krsko for GOTHIC code is developed/upgraded [1]. It is based on plant drawings and other available data. It is supported by developed Sketch-up 3D containment model. The model is subdivided in volumes following physical boundaries and clearly defined flow paths. All important concrete heat structures are taken into account. Metal heat structures are based on plant's SAR Chapter 6 licensing model. RCFC (Reactor Containment Fan Cooler) units are explicitly modelled as well as all main ventilation

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ducts. The model includes two trains of containment spray system. PARs (Passive Autocatalytic Recombiner) and PCFV (Passive Containment Filter Venting) filters added during plant safety upgrade project are part of the model too.

It was intention to use model for both DBA (Design Basis Accident) and for DEC (Design Extended Conditions) and BDBA (Beyond Design Basis Accident) calculations. Based on the same discretization and data (geometry data base), and on experience acquired during GOTHIC model development and use, containment models for MELCOR and MAAP integral codes are developed too. The objective of the paper is to verify multi compartment containment model response to DBA LOCA used in development of EQ (Environmental Qualification) conditions. The results are compared to single volume containment model developed for SAR type calculation. In addition, influence of longterm containment spray availability to pressure and temperature qualification profiles was studied.

2 GOTHIC MODEL OF THE NPP KRŠKO

2.1 Single compartment model

The computer code GOTHIC [2][3] was used for calculation of containment thermal hydraulic behavior. The code solves conservation of: mass, momentum, and energy equations for multiphase (vapor phase, continuous liquid phase, droplet phase) multicomponent (water, air, H2, noble gases) compressible flow. Constitutive relations predict interaction between phases for nonhomogenous, nonequlibrium flow. Heat structures are modeled as 1D heated or unheated structures. Hydraulic volumes use 1D, 2D, 3D or lumped approach. It is possible to simulate operation of engineered safety equipment: pumps, fans, valves and doors, vacuum breakers, spray nozzles, heat exchangers, heaters and coolers, controlled by trip logic based on: time, pressure, vapor temperature, liquid level, conductor temperature. The code is tested and qualified to perform calculations similar to this analysis.

Single compartment NPP Krsko containment model is developed for SAR and EQ type of analyses. The total free volume of the containment was modeled as one compartment, compartment number 1 on Figure 1. The containment annulus was modeled as another separate volume, compartment number 2. The values needed for model preparation are taken from USAR [4]. Initial conditions inside containment were chosen to maximize containment pressure (48.9 ^{o}C, 101.325 kPa, 30% RH). The temperature of the outside air was 34 ^{o}C.

Containment heat structures were modeled as 14 different heat structures, according to USAR. The heat structures 1 and 2 are used for representing steel liner (vessel cylinder and dome) and structures 3 and 4 are used for concrete containment wall (cylindrical and hemispherical part). All other heat structures are internal containment heat structures. HVAC cooper heat structure is additional passive heat structure. Material thermal properties were determined based on USAR data. 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. In addition, in case of LOCA, Tagami heat transfer correlation was used for internal metal heat structures during blowdown. For internal heat structures right side of the structure is isolated. For structures 3 and 4 right side is exposed to the environment with fixed temperature (34 ^{o}C) and fixed heat transfer coefficient of 11.36 W/m^{2}K.

Seven flow boundary conditions are present in the model (7F is hydrogen source when needed). Boundary conditions 1 and 2 were used for single sided breaks. In case of double side break boundary conditions 4 and 5 are used to model second side of the break. Two flow boundary conditions per break side can be used to split fluid flow in liquid and gas phases explicitly or, as was case in LOCA calculation, to model blowdown and reflood discharges separately. Boundary condition 6F was used only during LOCA recirculation phase to model part of the fluid removed from the sump by RHR system. Flow paths 1, 2, 6, 7 and 11 are associated with flow boundary conditions. Boundary condition 3F and flow path 3 (10 for recirculation) were used for modeling of spray flow from RWST tank (water temperature 37 °C). GOTHIC spray nozzle component was used at the end of flow path to convert all water flow to droplets. Constant spray mass flow rate was used (75.8 kg/s) during both injection and recirculation phase. Flow path 10 together with pump and spray nozzle 2N was used for modeling of spray line during recirculation phase of LOCA. Each reactor containment fan cooler was modeled separately as volumetric fan cooler (1Q) + standard single-pass, finned tube counterflow air-to-water heat exchanger (1H). The dimension of the tubes and fins, total heat transfer area and other RCFC operational data were realistically taken into account. Flow paths 4, 5, 8 and 9 are used to model flow of steam and air mixture over RCFC units 1 to 4 cooling surfaces. The influence of RCFC units was not taken into account during normal operation (before break) due to lack of the model for heat losses from the primary side. Actuation of both sprays and RCFC units is prescribed by (35 and 55 s respectively for analysed DEPSG MIN SI sequence) accident scenarios.

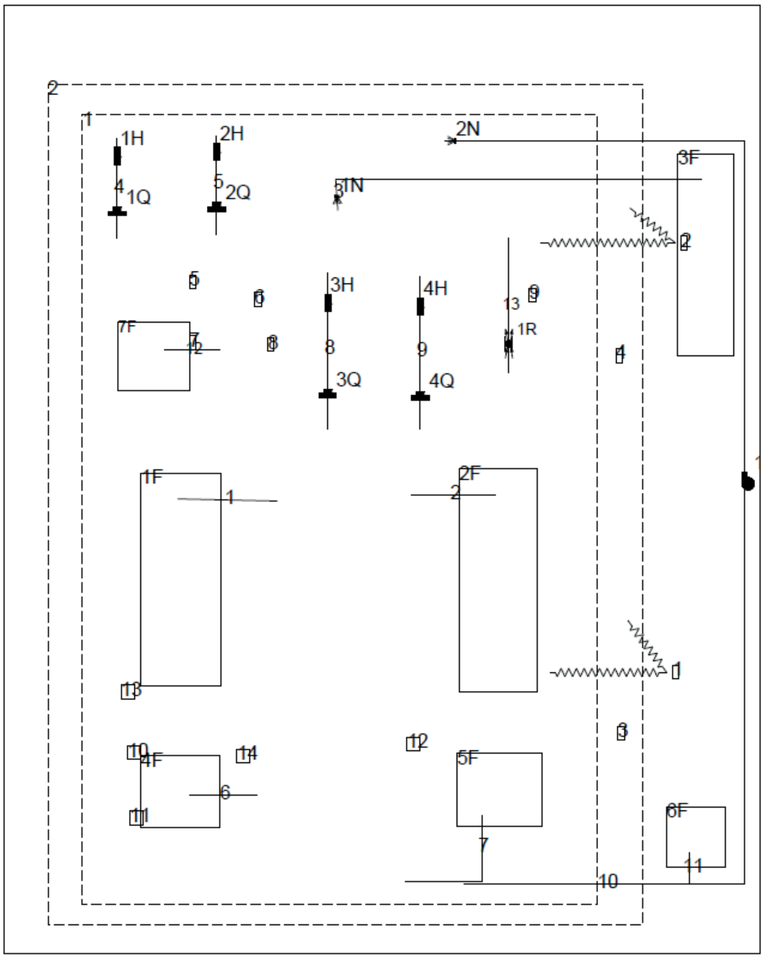

Figure 1: GOTHIC single compartment LOCA model

2.2 Multi compartment model

NPP Krško GOTHIC multi compartment model of containment is developed from described licensing model. Free volumes were recalculated during Krško modernization project as well as heat structures related data. All other containment engineering safety features are the same as used in licensing type of calculations. The explicit model of RCFC ducts is included in the model. The same flow boundary conditions are used in single and multi compartment model, but they are connected in different way.

Based on additional drawings available during Krško modernization project a new referent containment nodalization using 10 main control volumes/compartments was developed. Each control volume of the model is so defined to have clear physical boundaries and well defined openings based on physical containment compartment's boundaries, Figure 2.

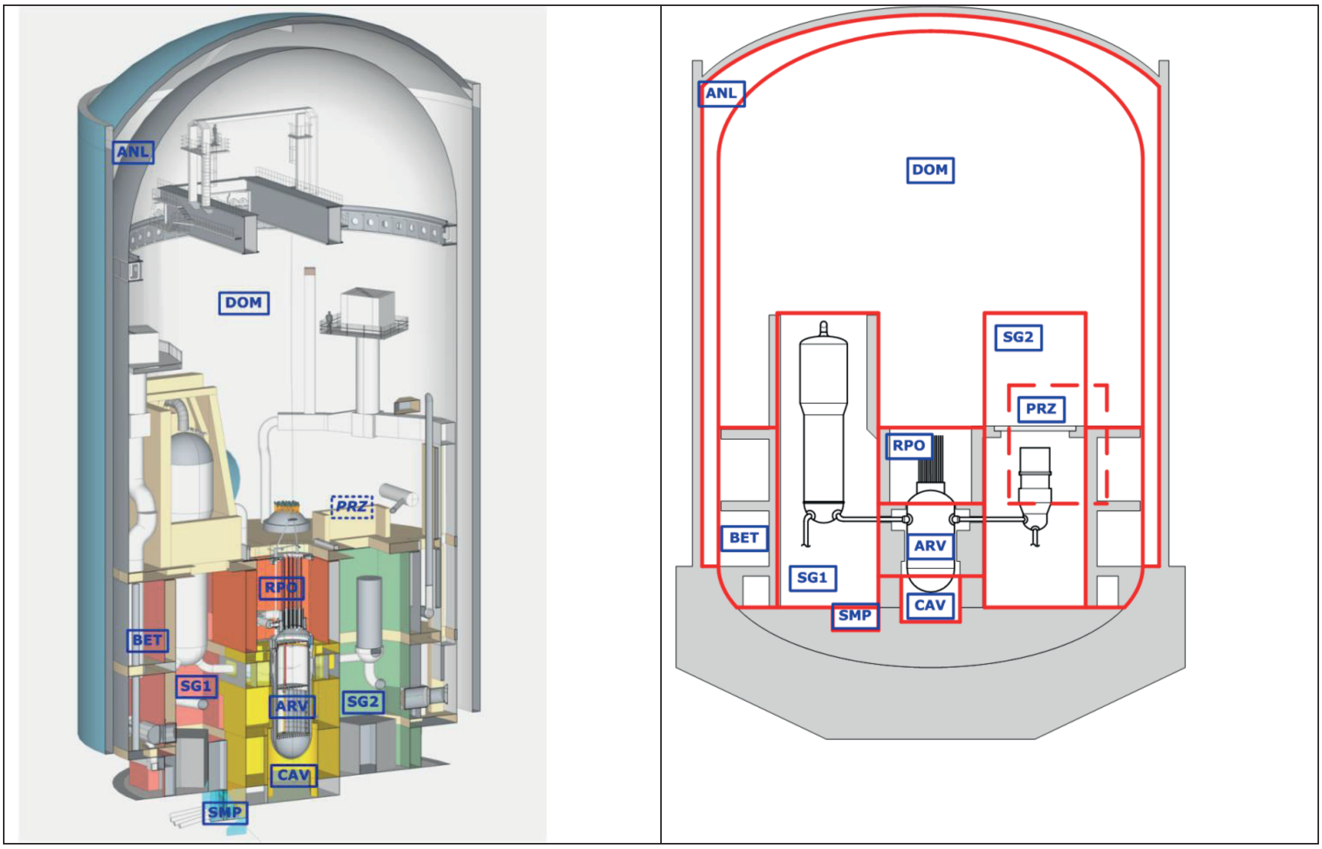

Figure 2: NEK containment layout and proposed basic subdivision

During development of the nodalization it was decided to build 3D geometry data base using SketchUp code. Whole model is decomposed in concrete heat structures and empty volumes following main containment elevations, Figure 3. Based on that main compartment volumes where developed, with enough data to enable further subdivision if needed. By using physical compartment boundaries in the development of the model local effect of different breaks can be better studied (e.g. LOCA can be within SG compartment or close to the reactor vessel), Figure 4.

As part of the model upgrade the connection between the sump and the cavity is better defined, and the sump is divided in three control volumes to reflect the real containment design, Figure 5. Additional junctions are connected to sump CVs to simulate accurately water drainage from other compartments into the sump, and the sump connections with the SG1 compartment and the cavity. All lower compartments are checked from point of flooding volume corectness.

The corresponding nodalization scheme is shown in Figure 6, together with bounding elevations. Containment dome (DOM) is control volume number 1. The annulus (ANA) space is control volume number 2. Steam generator 1 and 2 (SG1 and SG2) compartments are control volumes 3 and 4. The pressurizer compartment (PRZ) is volume 5. The reactor pool (RPO) and space around reactor vessel (ARV) are volumes 6 and 7. The reactor cavity (CAV) and containment sump (SMP) are volumes 9 and 10. The space outside listed volumes up to the containment liner and below elevation 115.55 m is called between (BET) and it is volume number 8. The reactor pool is modelled as a separate volume in order to take into account shutdown cases with opened vessel and pool filled with water. The total volume is almost the same as single compartment model described in licensing data. Concrete heat structures are based on real bounding walls and floors between the compartments. The metal heat structures are based on licensing model and are subdivided using engineering judgment between separate compartments in multi-volume model.

The flow paths in the model are based on real openings and communications between the compartments. More than one opening is used between the same volumes if they are located at different elevations to promote internal thermal mixing flow, what can be important for long term containment transients. When required, it is possible to join more flow paths in one equivalent flow path. The leakage (based on design leakage) flow paths exist between containment dome and annulus and between annulus and the environment. All main ventilation ducts were taken into account, what resulted in increase of used control volumes beyond the number used for main compartments. The nodalization can be in addition subdivided axially using floor elevations and laterally in two halves. Each volume can have internal axial elevations (useful in SG. PRZ and ARV compartments). The containment dome can be further subdivided using GOTHIC 3D capability in 2x2x4 subvolumes, Figure 7.

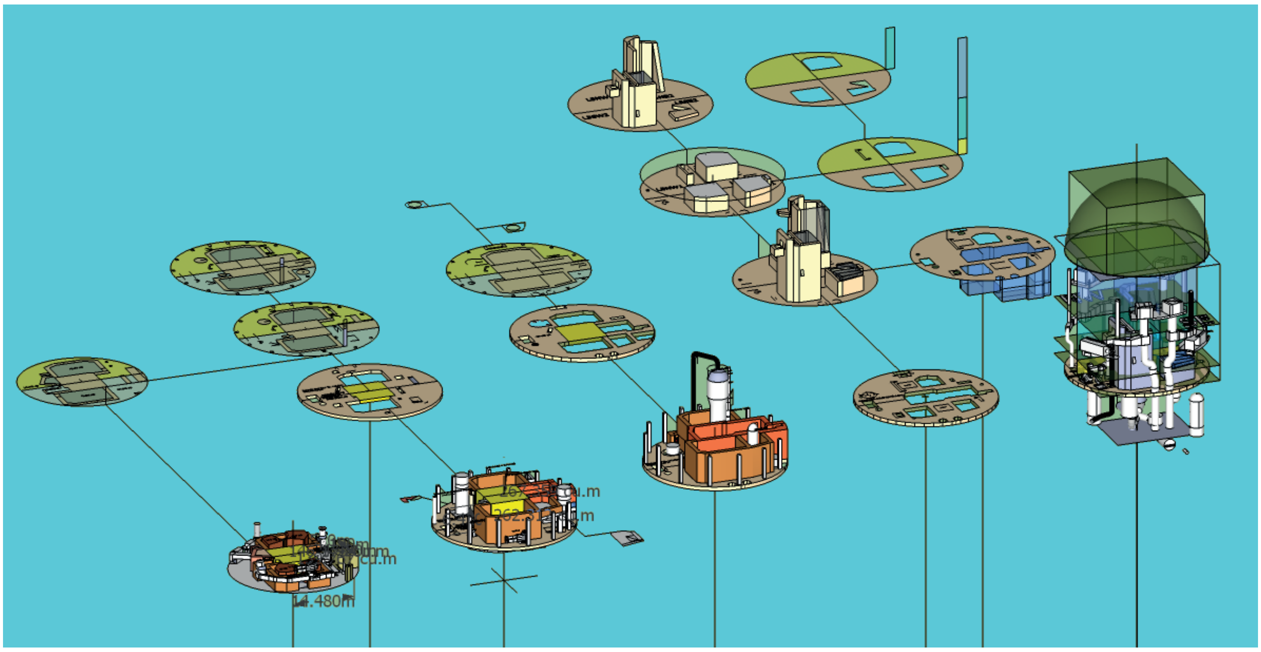

Figure 3: Decomposition of containment geometry

3 ANALYSIS AND RESULTS

3.1 DBA LOCA Calculation, single compartment model

DBA LOCA case, 0.6 Double Ended Pump Suction Guillotine break DEPSG with minimum SI (0.6 DEPS min SI, one RCFC and one spray train in containment), was used as representative case for thermal hydraulics testing of the model. For DEPSG MINSI LOCA mass and energy releases were taken from USAR Chapter 6.

For single compartment model 3.e6 s simulation time is used (the same as used in EQ calculation). Due to longer running time of the multi compartment model and rather small difference between single and multi-volume containment model, the simulation time for multi compartment model was limited to 1.e5 s.

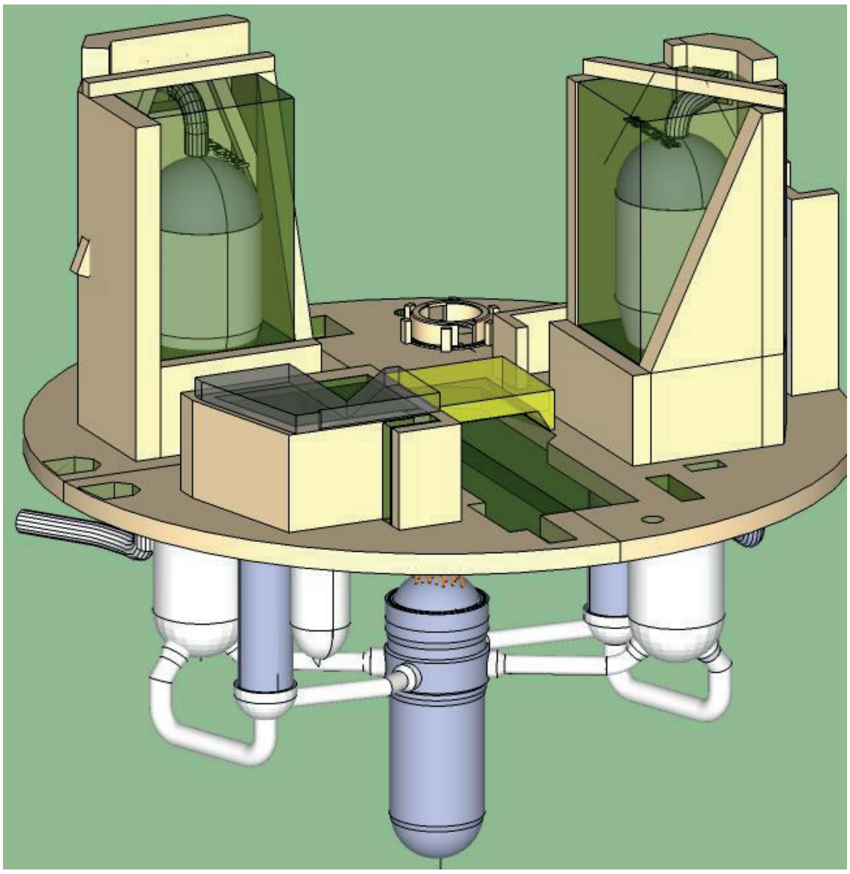

Figure 4: Break localization

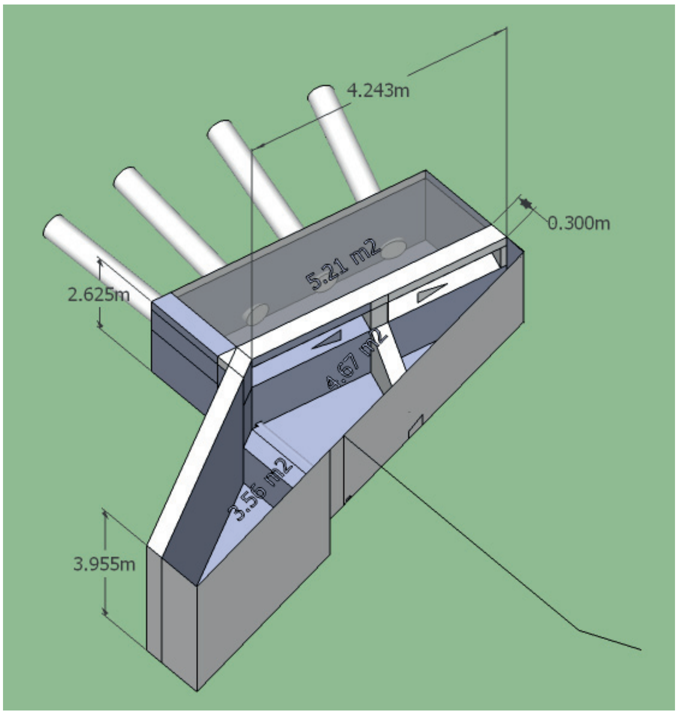

Figure 5: Containment sump geometry

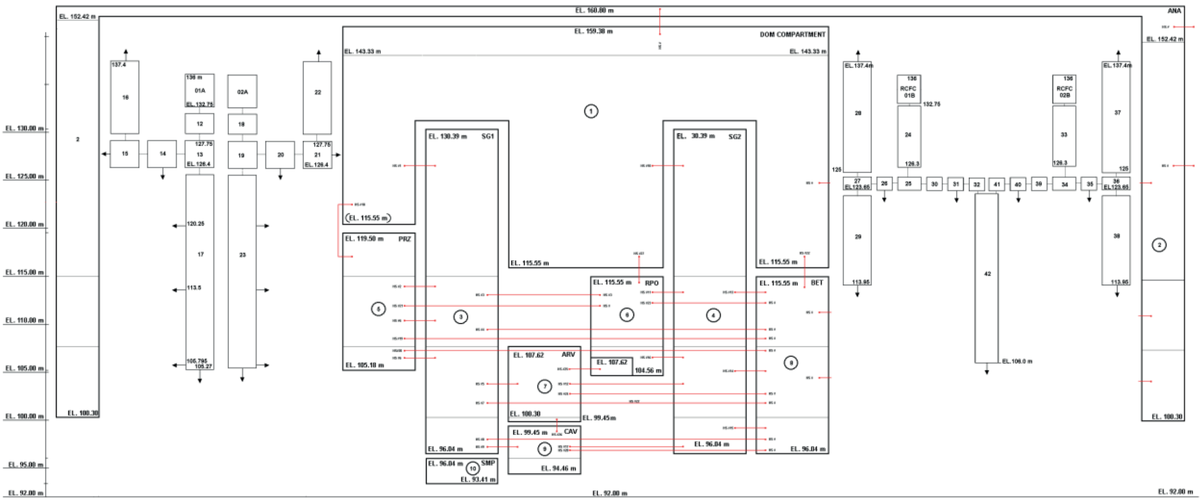

Figure 6: GOTHIC multivolume containment model

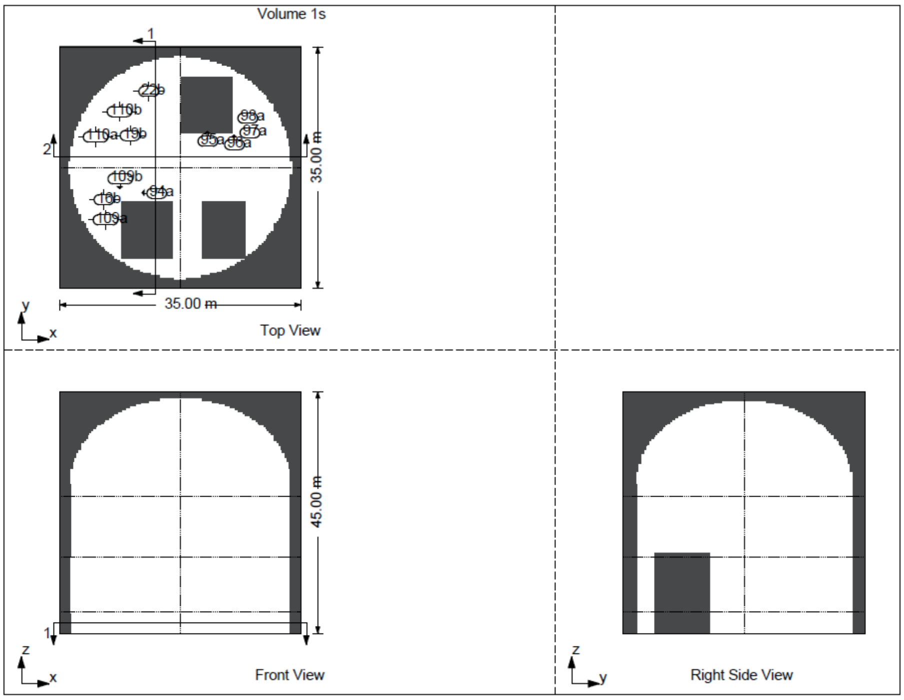

Figure 7: GOTHIC containment dome subdivision

Following scenarios were covered by single compartment model:

- spray switched off at 1day after break (EQ assumption), label: spray off 1 day,
- spray switched off per EOP (containment pressure below 1.6 kp/cm^2 gauge, 258.23 kPa), if before recirculation and shorter than minimum 2 hours per NUREG-0800 than limited to 2 hours, label: spray off 2 h,
- spray off, limiting case without spray after recirculation, label spray off,
- spray on, limiting case with spray on all the time, label: spray on.

For analysed sequence time to recirculation was 3292 s.

Containment pressure and temperature for different spray operation time are shown in Figure 8 and Figure 9, respectively. Up to the point of recirculation there is no difference in response, then both pressure and temperature start to increase after spray switch of. All values above profile obtained in original EQ calculation (spray off 1 day) can mean some invalidation of EQ envelopes. Pressure and temperature peaks are not affected due to their time position.

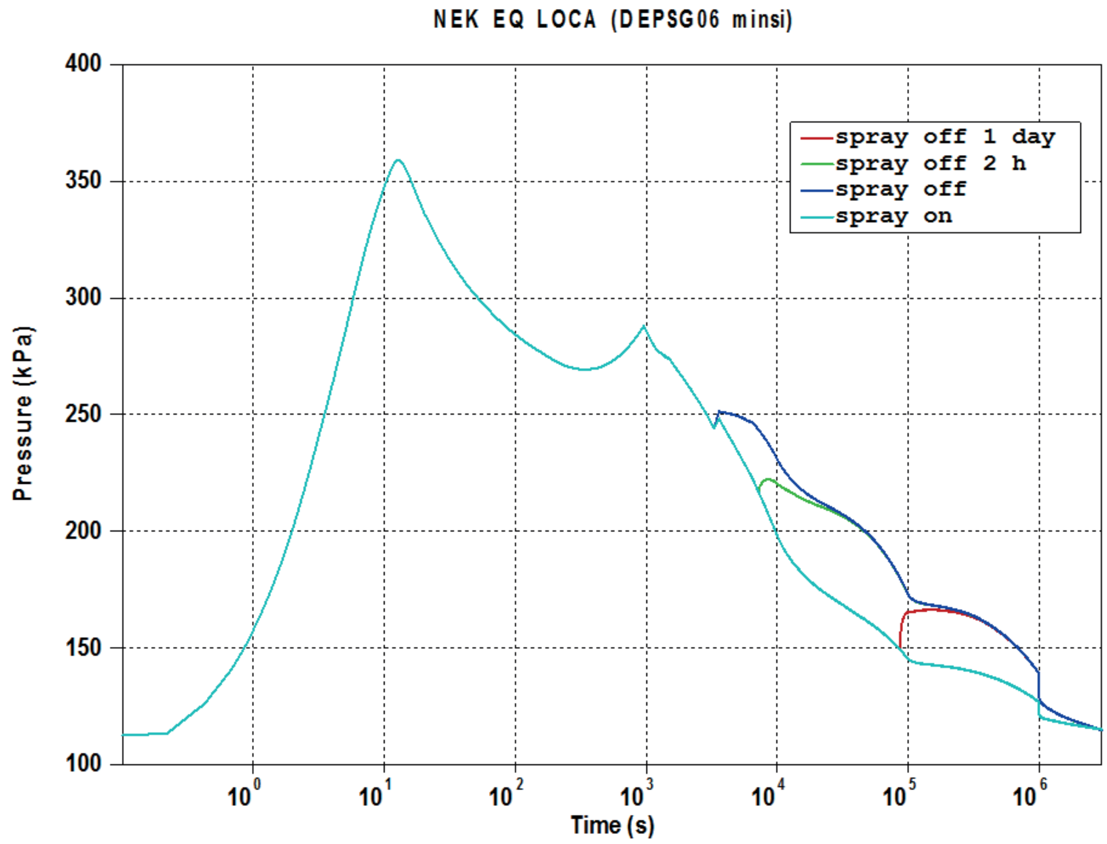

Figure 8: Pressure in containment, EQ LOCA

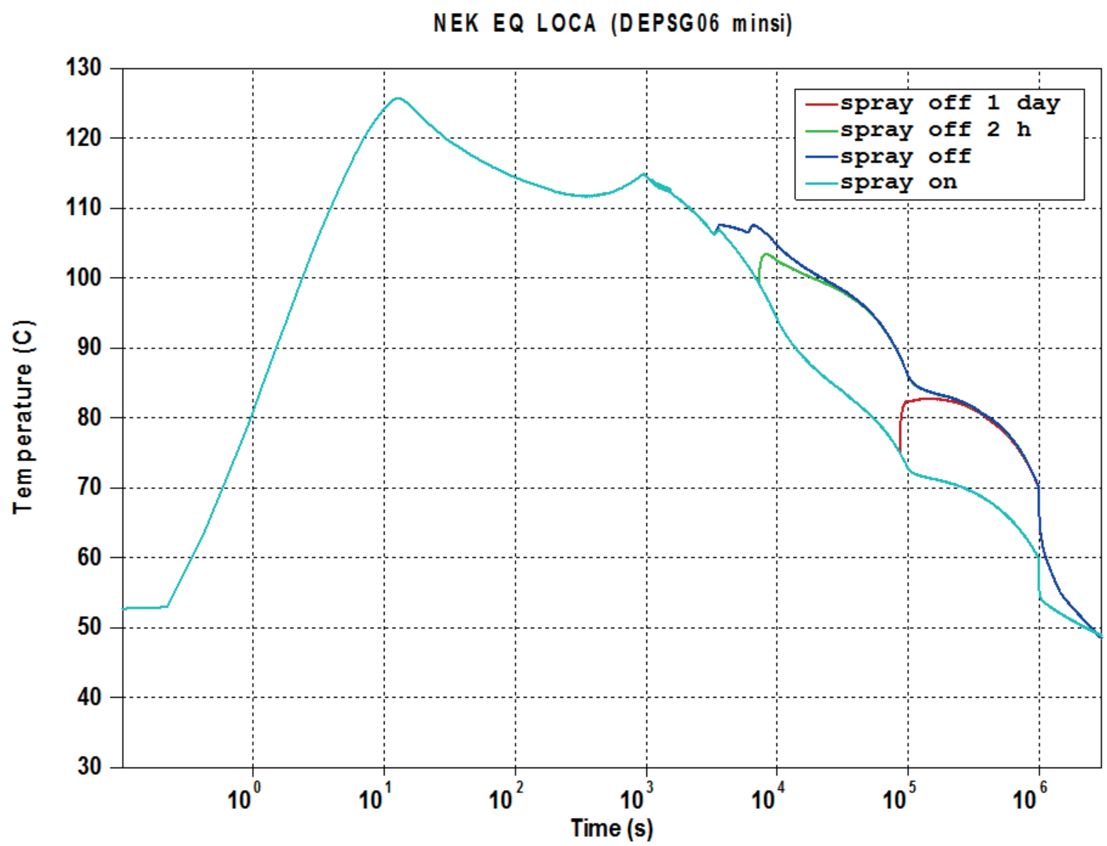

Figure 9: Temperature in containment, EQ LOCA

3.2 DBA LOCA Calculation, multi compartment model

For multi compartment containment model the same four cases are calculated as for single compartment model, but simulation time was up to 1.e5 s. The break location was in SG1 compartment and in free space above operating deck (to simulate situation close to the break within only volume in simple model). Only results for cases without spray actuation in recirculation were shown. Other cases results show similar trends. Only results within 16 containment dome volumes were used to follow the same logic as in single compartment model. In rest of the containment volumes the temperatures can be both lower and higher than in containment dome depending on location of the break. Pressure distribution is always rather uniform. Figure 10 shows pressure in lowest and highest subvolume of the containment dome (multi compartment model), for break in SG1 compartment and in containment dome, as well as referent single compartment pressure. Pressure response in multi compartment model is rather uniform except in early beginning of the transient. Both multi compartment responses give higher pressures than single compartment model (smaller effective free volume and condensation surfaces in multi compartment model). For break in containment dome due to similar reasons initial pressure increase is faster as well as later pressure decrease. Figure 11 shows gas temperatures for the same situation. Temperature distribution between subvolumes of multi compartment model is not uniform. Initial peak temperatures are again higher in multi compartment model than in single compartment model. Long term behaviour of the temperature for the break in SG1 is closer to the temperature behaviour in single compartment model what was not expected. The condensation heat transfer model is typically more effective in multi compartment model. The results with spray actuation in recirculation model show similar trends in multi compartment and single compartment model.

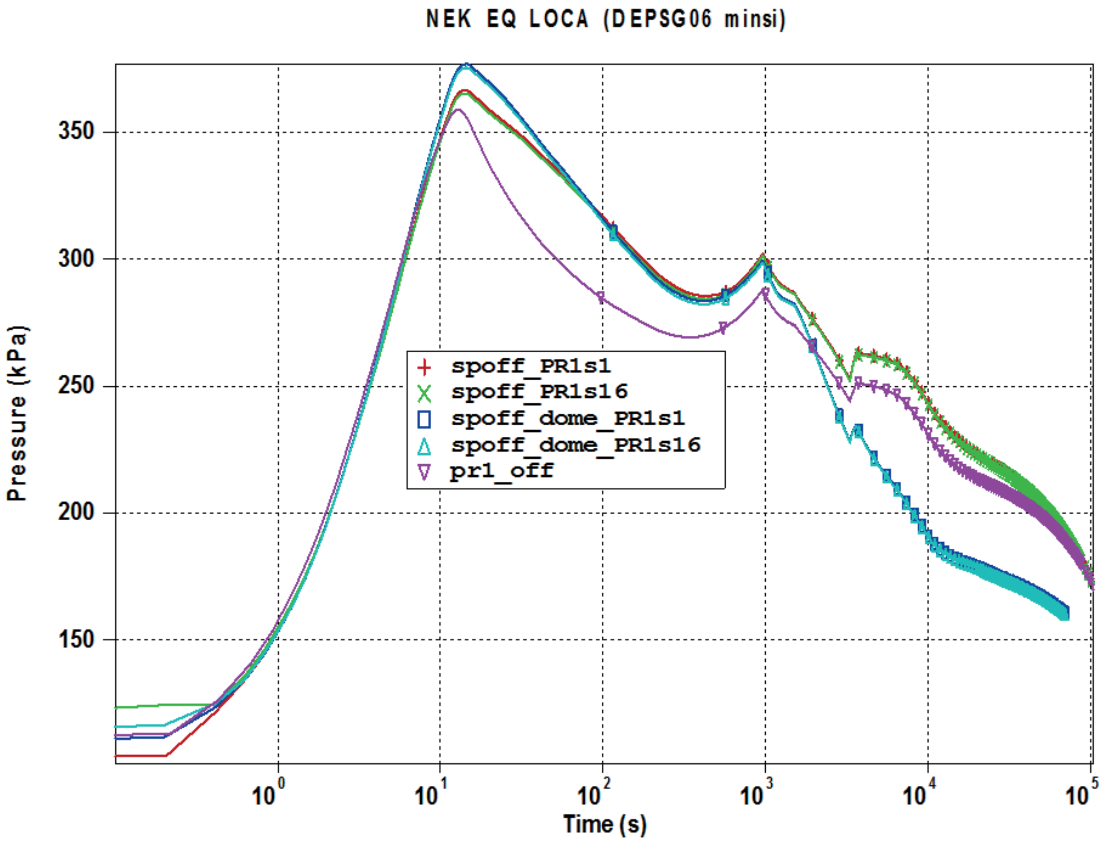

Figure 10: Pressure in containment upper plenum, EQ LOCA

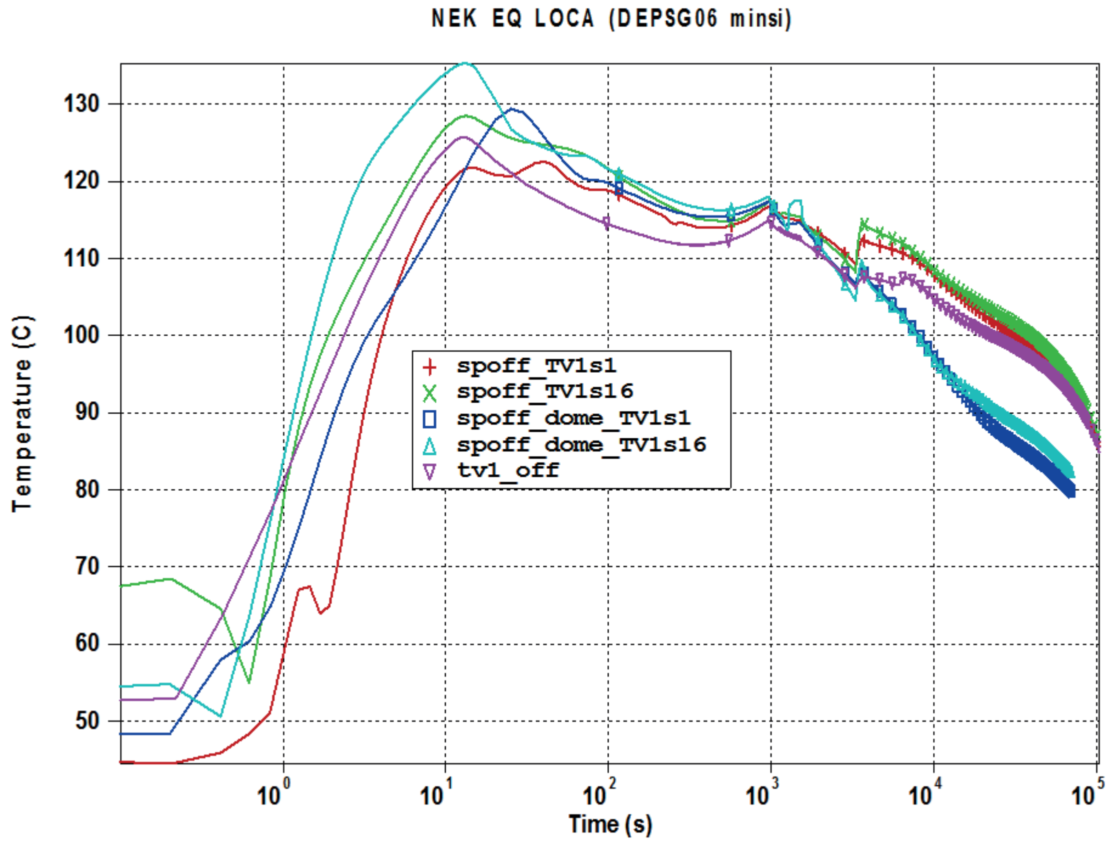

Figure 11: Temperature in the containment upper plenum, EQ LOCA

4 CONCLUSION

As part of initial verification of upgraded multi compartment GOTHIC model containment DBA LOCA calculation is performed using SAR MER (Mass and Energy Release) data for both single and multi compartment model. Beside local effects due to different containment subdivision, similar results are obtained when comparing containment dome values from multivolume and the single volume values from licensing model. Local redistribution of, mostly temperatures, is present when break location is changed in multi compartment model.

Another intention of the paper was to study consistency of assumed different spray operation times used in safety analyses, EQ analyses and SAMGs. Due to different assumed spray operation times (1 day in EQ, shorter for EOPs), based on the obtained results for spray influence, all values above profile obtained in original EQ calculation (spray off 1 day) mean some invalidation of calculated EQ envelopes (higher pressure and temperature values). Pressure and temperature peaks are not affected due to their time position.

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