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Comparison of Measured and Calculated Data for NPP Krško CILR Test

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Abstract: Containment is the last barrier for release of radioactive materials in the case of an accident in the nuclear power plant (NPP). Its overall integrity is tested during a containment integrated leak rate test (CILRT) at the design pressure, at regular intervals. Due to applied risk based licensing, the test intervals can be increased up to once in 10 years and beyond. Taking that into account it is important to prepare the test properly and to use obtained results to assess the real status of the containment. The test can be used to verify existing containment calculation models. There is a potential benefit of verified computer models usage for the explanation of some test results, too. NPP Krško has performed CILRT during the plant outage in 2016. The paper presents a comparison between measured data and results calculated using a multivolume GOTHIC (Generation Of Thermal Hydraulic Information For Containment) model. The test scenario was reproduced using limited available data up to the end of the pressurization phase. The depressurization phase is calculated by the code and measured leakage rate is implemented in the model. Taking into account the necessary adjustments in the model, overall prediction of the measured results (in terms of pressure, temperature and humidity) is very good. In the last phase of the test some non-physical behavior is noticed (without influence on overall test results), probably caused by the combination of air redistribution within the containment and influence of heat transfer to plant systems that were in the operation during the test. GOTHIC model was used to check sensitivity of the predicted pressure (leak rate) to different heat inputs and to investigate the influence that operation of only one reactor containment fan cooler (RCFC) train during pressurization can have on the mixing of air within the containment. In addition, the influence of currently used weighting factors (weighting of measured temperature, relative humidity and pressure data) on the used test methodology is investigated. The possible non-conservative direction of the influence (currently used weighting factors are giving lower leakage rate) was demonstrated and a new set of weighting factors is proposed too.

Keywords: NPP Krško; CILRT; GOTHIC code; containment; mass point method measurement; weighting factors

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1. Introduction

Containment leakage should be kept at the minimum rate in order to restrict possible radioactive emissions in the environment below acceptable limits. The maximum allowable containment leakage rate is defined at the peak containment internal pressure (410 kPa) caused by the design basis accident (DBA). In nuclear power plant (NPP) Krško (NEK) the design rate is 0.2% of air weight per day [1]. This value is usually denoted as L_a and is equivalent to a leakage rate of 3.75×10^{-3} m^3/s [2].

Regular testing is required to ensure the leak rate limits are not exceeded. There are three types of tests in the containment leakage rate testing program: Type A, B and C. Type A test is actually the containment integrated leak rate test (CILRT) intended to measure the reactor containment overall integrated leakage rate under conditions representing design basis loss of coolant accident (LOCA) peak pressure (410 kPa). Type B tests are intended to pneumatically detect and measure local leakage across each pressure retaining or leakage limiting boundary for containment mechanical and electrical penetrations. Type C tests are intended to pneumatically measure containment isolation valve leakage rates. The purpose of all tests is to ensure that leakage through the containment or systems and components penetrating the containment does not exceed allowable leakage rates specified in the NEK Technical Specifications. Integrity of the containment structure is maintained during its service life.

NPP Krško CILRT test was performed in October 2016 during the regular outage. Based on temperature, pressure and relative humidity (RH) measurements, the leakage rate was calculated in accordance with standard ANSI/ANS-56.8-2002 [3]. In order to independently verify test data, the existing GOTHIC plant model [4] was adapted to comply with the test alignment and conditions, and was used to simulate containment behavior during the CILRT. Both the measured and calculated results are presented and evaluated in paper.

2. Containment CILRT Test

Pressurizing a large structure, such as the containment with a free volume of about 40,000 m^3, is not an easy task. Careful planning, setting up containment systems and equipment in required positions, venting and draining connecting lines, preparing the testing equipment according to standards [3], etc. are prerequisites for this kind of work.

The test is divided in five phases:

1. Pressurization phase,
2. Stabilization phase,
3. Testing phase,
4. Verification phase,
5. Depressurization phase.

Before the test it was necessary to prepare the containment in a way to determine the local leakage rate using local leakage rate tests of types B and C. The pressure, temperature, relative humidity, dew temperature and volume flow were measured during the test.

During the pressurization phase, which lasted 18 h, the test pressure 408 kPa (absolute pressure) was achieved. The average pressurization rate was 17 kPa/h. Five mobile compressors connected to the CILRT test containment penetrations were used in that process. During the stabilization phase, which lasted 4 h, containment conditions were controlled in parallel with preparations for the testing phase. The intention of that phase was to obtain stable containment initial conditions (pressure, temperature) in order to obtain correct mass leakage rate measurements in the subsequent testing phase. The reactor containment fan cooler (RCFC) Train A was available during pressurization and stabilization phases.

The minimal time interval for the stabilization phase is 4 h. After that time interval, all criteria according to ANSI/ANS-56.8-2002 standard were obtained.

The testing phase lasted 8 h. The aim of this phase was to evaluate containment inventory mass decrease. Based on temperature and pressure measurements, the air mass was calculated using the ideal gas law:

$$m = \frac{p \cdot V}{R \cdot T}. \tag{1}$$

The processing of measured data was carried out by the plant, according to ANSI/ANS-56.8-2002 standard, using three standard procedures (mass point method, total time method and point-to-point method) for calculating containment leakage rate. The procedures were implemented in the Excel spreadsheet. There were 24 temperature measurements sensors installed throughout the containment and two pressure sensors, in addition to six relative humidity measurements and two verification flow measurements. The average containment temperature was calculated using measured temperatures and the weighting factors depending on the free volume of the area where the sensor is installed.

The maximum allowable leakage by the ANS (American Nuclear Society) standard is 0.75 L_a, which is equal to 0.15% of air weight loss per day.

Two criterion types are used to evaluate the testing phase: The as-found and as-left leakage rate requirements.

The as-found leakage rate is the leakage rate prior to any repairs or adjustments to the containment barrier being tested. The criterion is defined as:

$$UCL + \Delta L + TLS < L_a, \tag{2}$$

where UCL is the statistical upper confidence limit of the measured data, ΔL is the leak penalties for penetrations not prepared for CILRT due to a number of reasons, such as to keep the plant in safe condition during the test, to provide cooling in the case of an accident, etc. and TLS is the total leakage savings for penetrations with initial high leakage that were repaired after the test. The sum of these three terms was about 20% of maximum leakage L_a.

The as-left criterion prescribes the total leakage made of the upper confidence limit and leak penalties to be less than 75% of the maximum allowable leaking rate L_a:

$$UCL + \Delta L < 0.75 \cdot L_a. \tag{3}$$

This limit does not include leakage savings since the impaired penetrations are repaired after the test. The as-left criterion was measured to be 25% of the prescribed leakage of 0.75 L_a.

In the testing phase final hour (the testing phase lasted 8 h), some non-physical behavior was noticed (increase of air mass in the containment in the situation when the containment is at higher pressure than any surrounding building or environment). It is expected that some combination of air redistribution within the containment and influence of the heat transfer to plant systems that were in the operation during the test can cause such behavior. That result should be further studied in more detail, but, in overall, the testing phase proved that the containment is airtight and no significant radioactive releases could be expected in a case of a DBA or severe accident causing increased containment pressure.

The following verification phase, which lasted 4.5 h, was conducted in order to check the accuracy of the testing phase results. The superimposed leakage rate method was used to verify the containment air mass decrease calculation. A valve connecting the containment to the outside atmosphere was opened and the leakage was set to 3.083×10^{-3} m^3/s. According to specifications [3] that superimposed leakage rate needs to fit between 0.75 L_a and 1.25 L_a. The flow rate of 3.083×10^{-3} m^3/s corresponds to 0.82 L_a. The same method as in the previous phase was used to calculate the mass inventory. The results confirmed the accuracy of the mass calculations. The calculated mass in the containment decreased with the same rate as was the leakage through the valve. The acceptability criterion for the total verification phase leakage rate L_c is:

$$L_0 + L_{tc} - 0.25L_a < L_c < L_0 + L_{tc} + 0.25L_a. \tag{4}$$

The flow rate L_0 corresponds to the superimposed verification flow rate and L_{tc} to calculate the leak rate in the testing phase. Thus, the lower limit leak rate calculated in such way is 0.73 L_a and the upper limit 1.23 L_a. The calculated leak rate in the verification phase varied slightly with the mean value 0.8 L_a. The acceptability criterion was satisfied.

The final depressurization phase lasted 15 h. A controlled air release, the release rate was carefully monitored in order not to damage sensitive containment equipment, was performed to depressurize the containment to standard atmospheric conditions.

3. GOTHIC Model of the NPP Krško

The computer code GOTHIC [5,6] was used for calculation of containment thermal hydraulic behavior. The code solves the conservation of mass, momentum and energy equations for multiphase (vapor phase, continuous liquid phase and droplet phase) multicomponent (water, air, hydrogen and noble gases) compressible fluid flow. In order to predict the interaction between phases for non-homogenous, non-equilibrium flow, the constitutive relations were used. One dimensional finite difference discretization was used to model heated or unheated structures. Hydraulic volumes can be lumped or subdivided in 1, 2 or 3 dimensions. Special models were used to simulate the operation of engineered safety equipment: Pumps, fans, valves, doors, vacuum breakers, spray nozzles, heat exchangers, heaters and coolers. Each component can be controlled by trip logic based on time, pressure, vapor temperature, liquid level or conductor temperature. The version of the code used in calculations was 7.2b. The newer version (version 8.3) was available, but for this type of the problem both versions are expected to give the same results.

NPP Krško containment outline is shown in Figure 1.

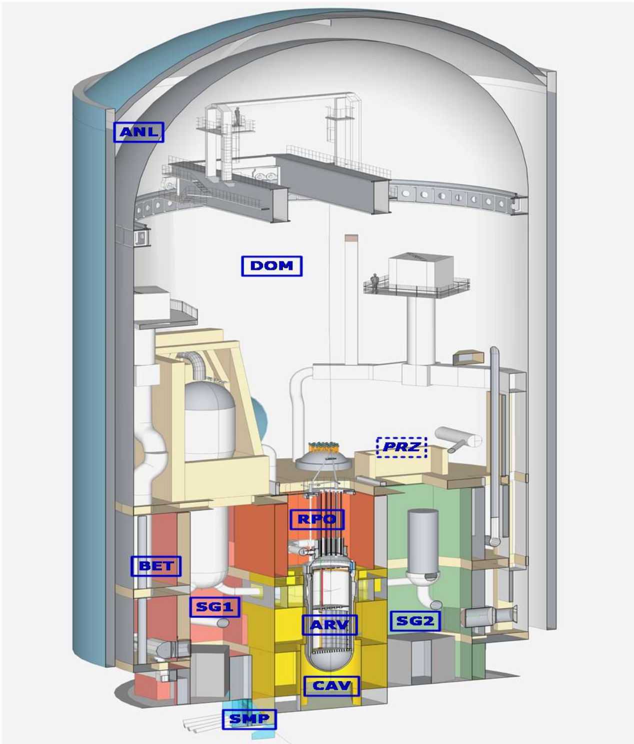

Figure 1. Nuclear power plant (NPP) Krško containment outline.

The GOTHIC multi compartment model of the containment was developed based on the plant's SAR (safety analysis report) Chapter 6 licensing model [7] and verified against the vendor's DBA LOCA analysis [4]. Figure 2 is taken directly from the GOTHIC code and shows the basic layout of used volumes and complexity of used internal flow paths and heat structures. In order to perform this calculation, the existing model is slightly modified. The initial conditions were adjusted to take into account real conditions in the plant in the beginning of the test. The flow path and the flow boundary condition were added to simulate the pressurization of the containment. However, the problem was that the plant personnel had not implemented a flow measurement for air added by the compressors. There was neither a measurement of the temperature nor RH of added air. The initial mass flow rate and thermodynamic parameters of the compressed air during pressurization were adjusted to obtain the measured rate of containment pressure and temperature increase. An iterative approach was used to reproduce initial phase of the test (during the pressurization) and to determine leakage flow path cross section (in the testing phase). A leak path cross section was selected to get a measured pressure behavior during the testing phase ($A = 10^{-6}$ m^2, $D_e = 1.128 \times 10^{-3}$ m, which is much less than the value usually used to model the containment design leak rate). Calculation of the verification phase was based on the cross section of the pipe and the measured discharge flow rate (real valve position was not known). The conditions during the last part of the test, the depressurization phase, were approximate. The plant personnel wanted to perform fast depressurization within allowable pressure decrease limits. Similarly, the calculation of that phase was just an attempt to follow a similar approach.

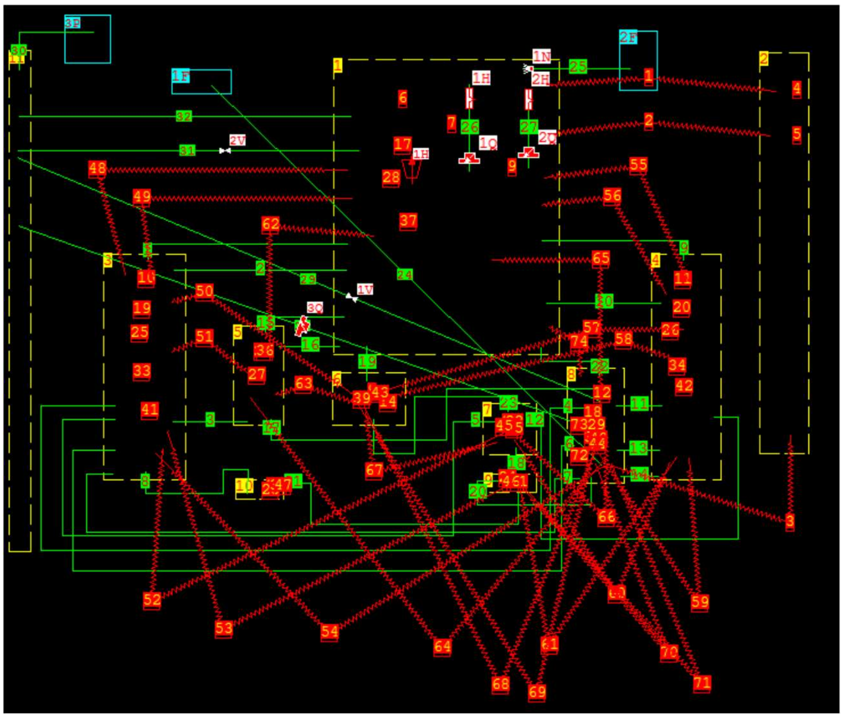

Figure 2. GOTHIC containment nodalization.

The containment was modeled with 10 hydraulic volumes representing the following compartments:

1. Containment dome (DOM),
2. Annulus (ANL),
3. Steam generator (SG) 1 compartment (SG1),
4. SG2 compartment (SG2),
5. Pressurizer (PRZ),
6. Refueling pool (RPO),
7. Space around reactor vessel (ARV),
8. Space around equipment compartments—containment lower plenum (BET),
9. Reactor cavity (CAV),
10. Containment sump (SMP).

There are 74 heat structures in the model. Steel liner, shield building wall, internal concrete walls and floors were explicitly modeled. Other internal heat structures (mostly carbon and stainless steel) were based on the SAR Chapter 6 containment design data. The heat structures were divided between control volumes depending on their approximate location. The internal heat structures were mainly heat capacities in the model so it was decided to preserve their mass and area exposed to the compartment. For bounding heat structures (both to the annulus and between compartments) the first priority was to determine the proper thickness and heat transfer area of the structures. The heat transfer coefficients were calculated internally by the code. Different combinations of Uchida condensation coefficients and natural heat transfer coefficients were used depending on the orientation of heat structures.

The flow paths in the model were based on real openings and communications between the compartments. More than one opening was used between the same volumes if they were located at different elevations to promote internal thermal mixing flow. That can be important for long-term containment transients. When required, e.g., in case of numerical difficulties, it is possible to join more flow paths in one equivalent flow path. The leakage (initially based on the design leakage) flow paths exist between the containment dome and annulus and between the annulus and the environment. In case of CILRT, the annulus was open to the environment and we were simply interested in the equivalent leak of the containment liner and that was the reason why we used a direct connection of the containment and environment (instead of the usual two step connection). Another reason for using a direct connection was that during containment depressurization a dedicated line was used to decrease the containment pressure by discharging containment air to the environment. In the model we used two parallel flow paths of different cross section areas (the discharge path had a valve and the leakage path was without it). The leak path is a connection of a very small cross section and it represents the whole containment leakage. It is possible, in a real situation, to have distributed the leak, but it is usual to address it with a concentrated leak path. GOTHIC has a separate model to address distributed leakage, however it was not used here because we wanted to keep connection with other codes (e.g., MAAP—Modular Accident Analysis Program) where the leak is expressed in terms of simple cross section area. All internal ventilation ducts can be taken into account (not used in this calculation), what will result in an increase of used control volumes beyond the number used for main compartments. In addition, the nodalization can be further subdivided axially using floor elevations and laterally in two halves taking into account existence of two RCFC trains and giving us opportunity to study the influence of a single train RCFC operation on the achieved initial conditions before the test. The additional subdivision of the containment was not used in this calculation, but it is planned for next analyses.

4. Results and Discussion

4.1. GOTHIC Calculation and Comparison With the Test Data

Containment pressure and temperatures are shown in Figures 3–5. Calculated values were in good agreement with the measured data. Pressurization, measurement and depressurization phases were clearly visible. Pressure scale during testing and verification phases was magnified to highlight the pressure decrease caused by leakage and the testing procedure (Figure 4). During the verification phase, an additional flow path between the containment and the environment was opened to calculate and verify the testing phase results. The calculated temperature decrease (label tv1_calc, other labels are used for representative locations measured temperature) in the depressurization phase was much faster than the measured data (Figure 5), due to the already mentioned approximate nature of the calculation in that phase (uncertainty of the boundary conditions—unknown depressurization rate).

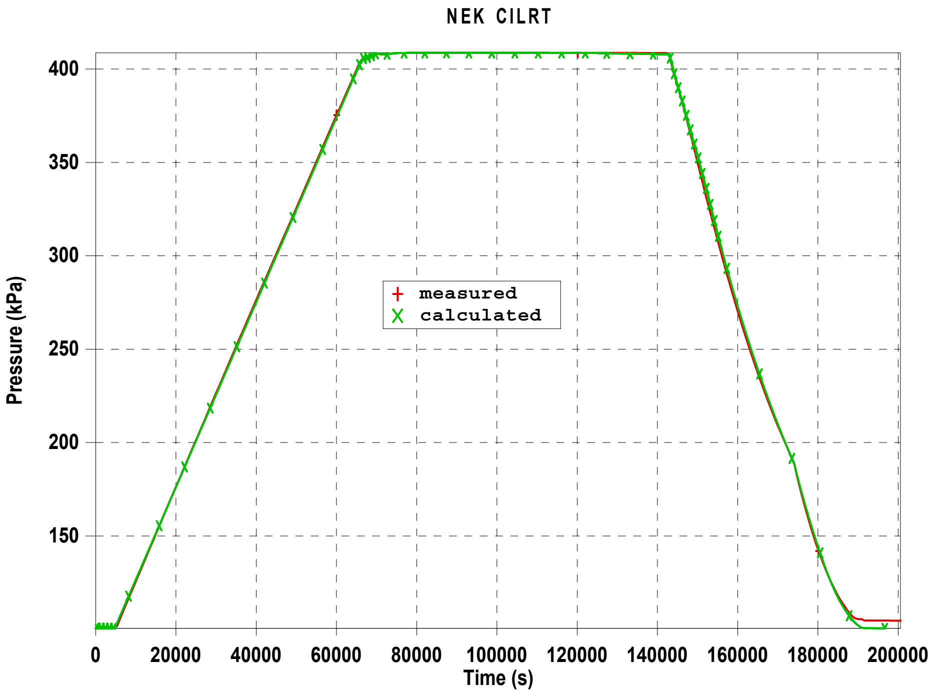

Figure 3. Measured and calculated containment pressures during the test.

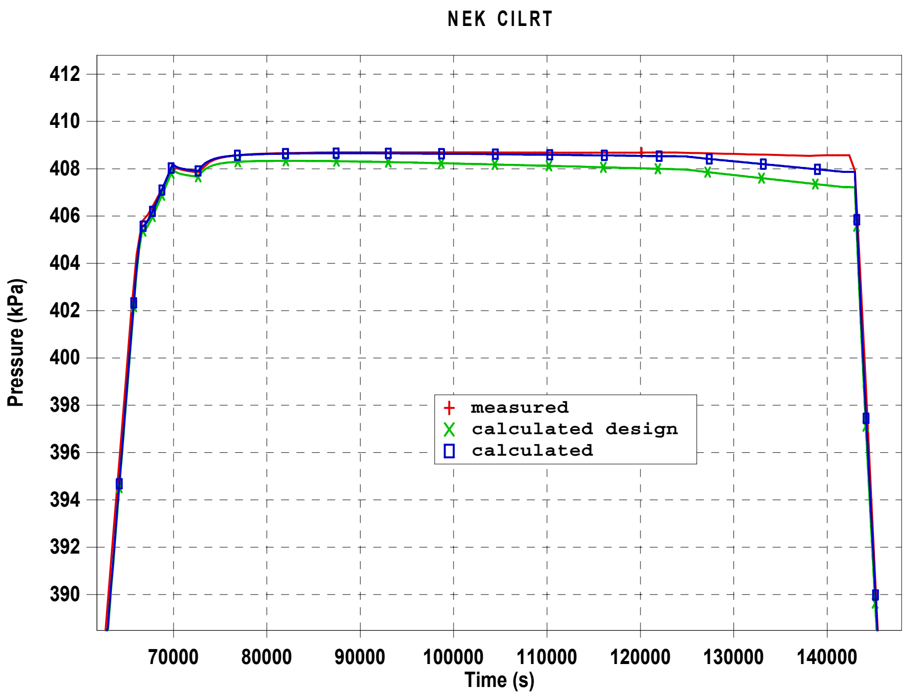

Figure 4. Decrease of the containment pressure due to leakage in the testing phase.

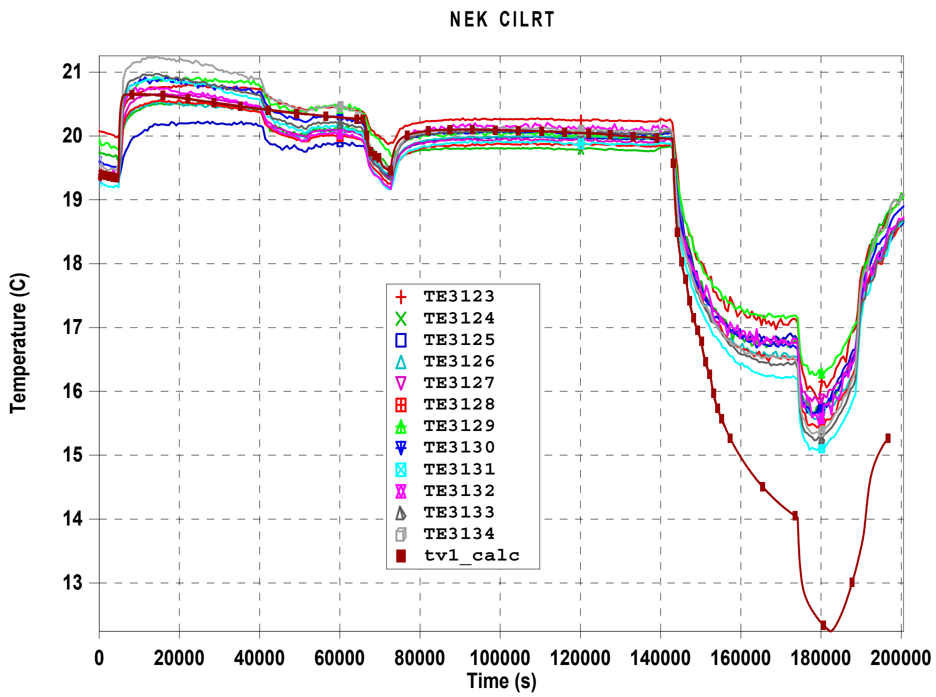

Figure 5. Measured and calculated containment temperatures during the test.

Measured (six positions) and calculated (RH1 calc, for RH in containment dome) relative humidity values are shown in Figure 6.

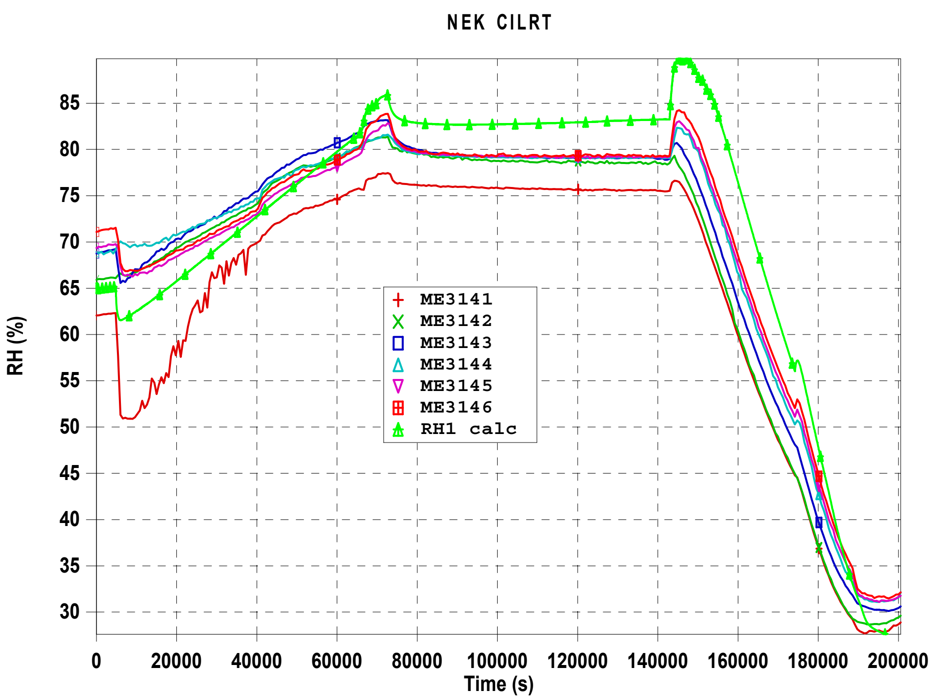

Figure 6. Measured and calculated containment relative humidity.

4.2. Sensitivity Calculations

Toward the end of the measuring phase, the increase of the air mass in the containment was calculated using measured data and the prescribed mass point method (Figure 7). The mass increase was characterized as an unphysical behavior because the high pressure in the containment was precluding any air inflow from the surrounding buildings or environment. The temperature transient alone can affect measurement results but cannot change amount of air available within the containment. In order to check reasons for such unphysical behavior, an additional run was performed by the GOTHIC code. A heat source with the power of 1 MW was introduced in the containment dome at 86400 s for the period of 100 s to determine sensitivity of the containment pressure and temperature (affecting measuring procedure) values on localized heat imbalance. In reality it was more likely that additional heat loss (instead of heat source) was present in the containment due to cold water in some systems.

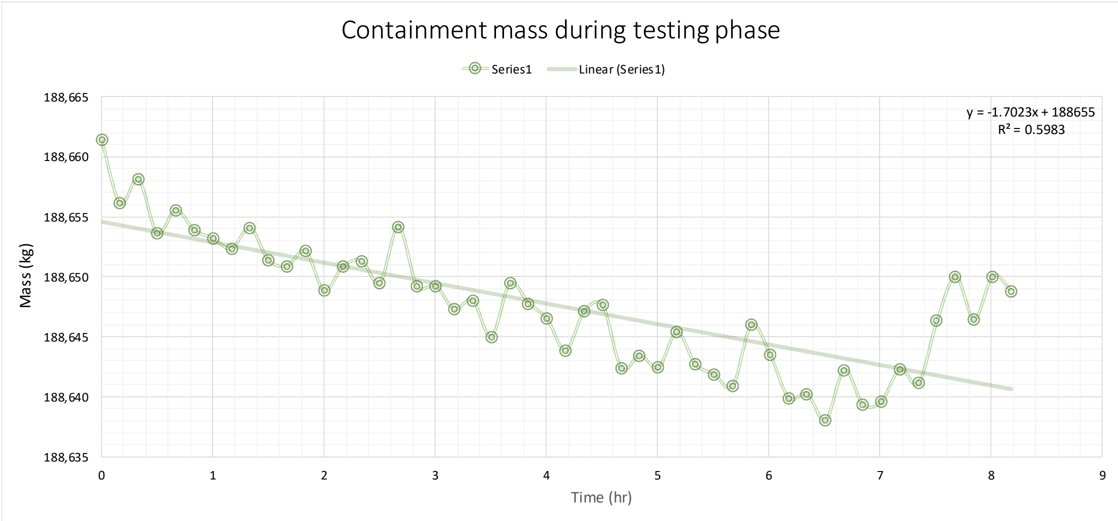

Figure 7. Calculated containment mass (linear fit) based on the testing phase measurement.

Sensitivity of the pressure to the presence of heat sources is shown in Figure 8. The resulting change in pressure and temperature distributions was not able to affect the calculation of air mass in the containment.

Figure 8. Containment pressure increase due to the addition of a localized heat source.

Another possible reason for such behavior could be related to the existence of air pockets having temperatures different than temperatures measured in available points and later redistribution of that air. The additional subdivision of the containment model could help to address that issue. We are planning to perform that calculation in next step. The main problem will be to find proper initial conditions (taking into account available measurements) and it will be more of the trial and error procedure to see what kind of initial distribution can cause a noticeable type of influence. In this paper, the primary interest was in collecting available measurements and performing the initial calculation. In addition, the model that was used in this article will be used for SAR calculations with real (based on CILRT) and design leakage. That way it will be possible to see the influence of real leakage on already performed calculations with conservative assumptions.

Taking into account that average values of temperature, RH and pressure were calculated from measured values using pre-calculated weighting factors we wanted to see what could be the influence of these factors to the calculated mass. The plant test procedure used volume factors to calculate volume averaged containment temperature from the temperatures measured at different locations. The temperature was used in the ideal gas equation to calculate dry air mass. The weighting factor is the ratio between the volume whose temperature is being "measured" by the detector located in the compartment and the total containment free volume. This paper used new factors calculated using a 3D model of the containment to post-process measured data (Figure 9). Even with an accurate 3D model, it was necessary to use some kind of arbitrary decision related to the placement of the boundary between more or less open areas.

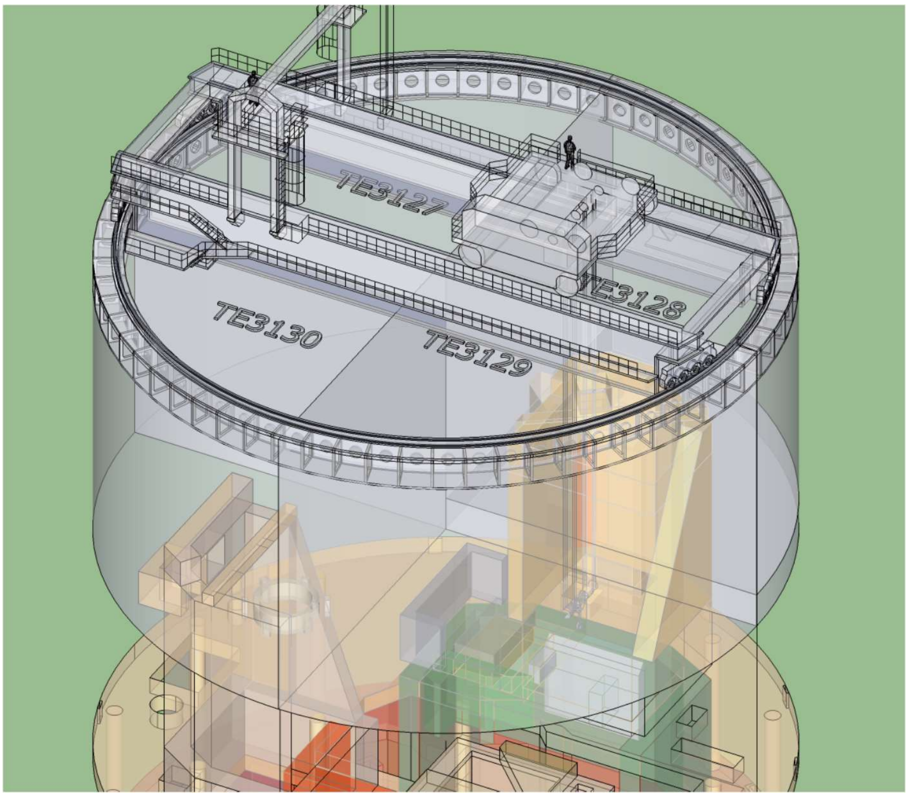

Figure 9. Subdivision of the upper containment part in the volumes for each instrumented location (volume weighting factors).

The old and new calculated volume weighting factors are shown for the available temperature measurement locations in Table 1 and for RH measurement locations in Table 2. The new weighting factors (even in the case when the change was rather significant), used with the measured temperature values, gave only a slightly higher average containment temperature (Figure 10) and, thus, lower containment mass, which means that the leakage rate was higher. Again, that influence could not explain the change in predicted air mass in the containment close to the end of measurement. The overall influence of new weighting factors to the calculation of leakage rates was relatively small ($L_{a,new}$ = 0.0217%/day, $L_{a,old}$ = 0.0207%/day), but they could be used to get more realistic leakage rates prediction in the future.

Table 1. Volume weighting factors for temperature measurements.

TE (Temperature Measurement Location)	Weighting Factors		TE (Temperature Measurement Location)	Weighting Factors	
	Old	New		Old	New
TE 3111	0.03	0.014106	TE 3123	0.068	0.046251
TE 3112	0.013	0.005118	TE 3124	0.058	0.057288
TE 3113	0.001	0.019656	TE 3125	0.049	0.042773
TE 3114	0.013	0.004162	TE 3126	0.053	0.059415
TE 3115	0.025	0.033087	TE 3127	0.073	0.077659
TE 3116	0.034	0.035967	TE 3128	0.073	0.075209
TE 3117	0.025	0.034235	TE 3129	0.073	0.077659
TE 3118	0.041	0.039981	TE 3130	0.073	0.075209
TE 3119	0.015	0.014223	TE 3131	0.058	0.058718
TE 3120	0.006	0.009623	TE 3132	0.058	0.058718
TE 3121	0.011	0.018807	TE 3133	0.058	0.058718
TE 3122	0.034	0.024691	TE 3134	0.058	0.058718

Table 2. Volume weighting factors for RH measurements.

ME (RH Measurement Location)	Weighting Factors	
	Old	New
ME 3141	0.057	0.043042
ME 3142	0.125	0.143270
ME 3143	0.066	0.067345
ME 3144	0.228	0.205730
ME 3145	0.292	0.305739
ME 3146	0.232	0.234875

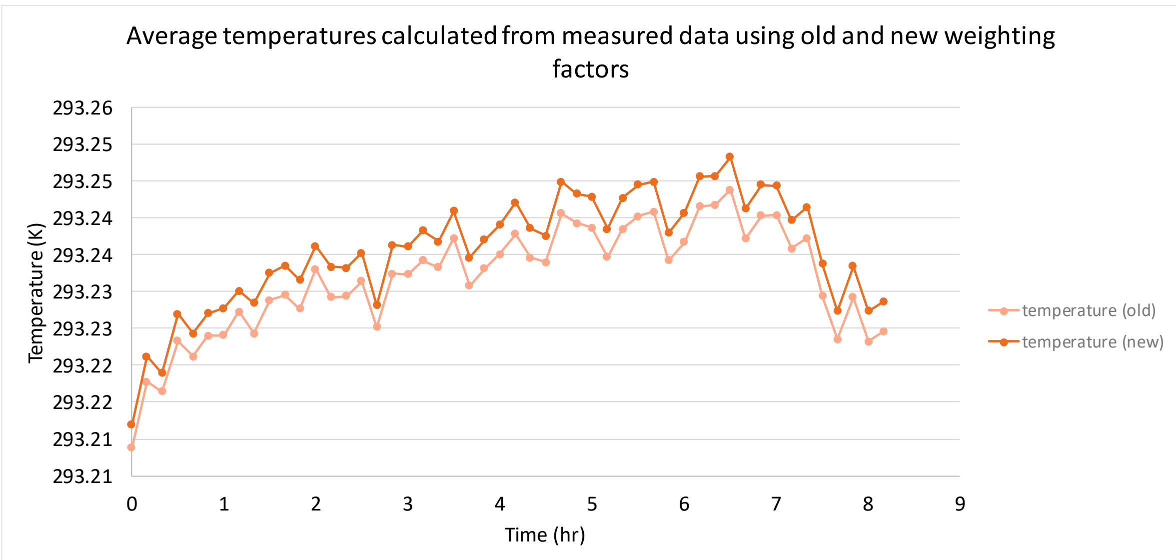

Figure 10. Average containment temperature change due to change in weighting factors.

5. Conclusions

During October 2016 an integrated leakage rate test was performed at full design pressure in the NPP Krško. Prerequisites for the test were local leakage rate tests of types B and C. The pressure, temperature, relative humidity, dew point temperature and the volumetric flow rate were measured during the test. The processing of measured data was carried out by the plant, according to the ANSI/ANS-56.8-2002 standard, using three standard procedures for calculating the containment leakage rate. The test results met all the criteria and showed that the leakage rate of the containment paths was below the prescribed limits.

In parallel to the processing of measured data, the calculation of the containment behavior was calculated using the GOTHIC 7.2b software package. The existing GOTHIC containment model was modified to reproduce the test results. Some of the data required for setting the model were not available and an iterative approach was used to determine the leakage flow path cross section. This way all the future analysis using this model can, in addition to the DBA leakage, take into account the proper (real) leakage rate of the system. It is now possible, during any possible accident, to see the pressure behavior of the containment and to estimate radiological consequences using a realistic leakage of the containment. To perform this type of the calculation, which is completely within the scope of the code, is just a matter of performing modeling in the proper way with proper data. It is expected that this type of calculation could be performed for any PWR (Pressurized Water Reactor) plant and similar agreement with the measured data could be obtained (if the required data is available and the test is properly conducted).

Toward the end of the measuring phase, the increase of the air mass in the containment was calculated using measured data and the prescribed mass point method. In order to check the reasons for such unphysical behavior, a sensitivity run was performed with the GOTHIC code and an additional heat source in the containment. We have expected that this run, together with careful examination of change in the containment and boundary conditions could help to find/quantify possible reasons for unphysical containment air mass increase toward the end of the test. The conclusion was that the measurement procedure is not inherently sensitive to localized change of the heat rate in containment. In addition, new weighting factors of the temperature and relative humidity sensors were determined using containment 3D geometry, just to be sure that representative average temperature and RH were correctly calculated from measured values. The influence of these new weighting factors is relatively small and unable to explain a change in the predicted air mass in the late phase of the test, but they can be used to get more realistic leakage rates in the future. In the next step we will try to explore, using a more detailed containment model, the possible influence of a single RCFC train operation in the initial phase of testing (asymmetry, air pockets) to test results.

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Conflicts of Interest: The authors declare no conflict of interest.

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