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RRESPONSE OF THE KRŠKO NUCLEAR POWER PLANT COINTAINMENT TO THE LOSS OF COOLANT ACCIDENT IN COMPUTER CODE APROS 6

ODZIV ZADRŽEVALNEGA HRAMA NEK NA NESREČO S PUŠČANJEM PRIMARNEGA HLADILA V RAČUNALNIŠKEM PROGRAMU APROS 6

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Abstract

Containment is a combination of a steel shell and concrete shield building enclosure, completely surrounding a nuclear reactor, designed to prevent the release of radioactive material in the event of an accident. The NEK (Krško Nuclear Power Plant) reactor containment building nodalization in APROS 6 computer code has been developed based on the plant's available documents and GOTHIC nodalization. The heat structure's data are based on USAR (Updated Safety Analyses Report) Chapter 6 passive heat structures. In all other aspects, realistic calculations based on containment geometry have been performed except for the interior concrete, which has been explicitly calculated.

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An original containment nodalization based on 10 control volumes is proposed, taking into account the containment layout (well-defined physical boundaries and corresponding communication openings) and accident behaviour. The nodalization is suitable for containment thermal-hydraulic modelling according to design basis accidents. In the end, APROS nodalization is prepared based on the same 10-volume nodalization, for which annulus-volume is also included in the model, connecting the reactor building to the environment. The containment model was tested for transient response for conditions, which occur in a Double-Ended Hot Leg Guillotine Break accident.

Povzetek

Zadrževalni hram je zgradba, v kateri so komponente znotraj tlačne meje reaktorskega hladila, ki predstavljajo pregrado pred nenadzorovanim sproščanjem radioaktivnosti v okolje. V programu APROS je na podlagi razpoložljivih dokumentov in nodalizacije programa GOTHIC zmodeliran model zadrževalnega hrama jedrske elektrarne NEK. Podatki za izračune posameznih struktur so povzeti iz dokumenta USAR (posodobljenega varnostenga poročila) - poglavje 6, ki opisuje pasivne toplotne strukture. Model zadrževalnega hrama, ki je sestavljen iz 10 (fizikalno dobro definiranih) povezanih prostorov, je primeren za simulacijo jedrskih nesreč. APROS model zadrževalnega hrama vsebuje tudi vmesni prostor, ki povezuje notranjost zadrževalnega hrama z zunanjim okoljem. Z modelom je bil preverjen odziv modela zadrževalnega hrama na prehodni pojav, ki nastane pri dvojnem giljotinskem zlomu vroče veje reaktorskega hladilnega sistema.

1 INTRODUCTION

Nuklearna Elektrarna Krško (NEK) containment systems consist of a steel shell containment, concrete shield building, penetrations, and directly associated systems such as the containment isolation system, the containment spray system, the containment air recirculation and cooling system, and the combustible gas control system.

The Containment System is designed for all break sizes, up to and including the most severe breaks. Additionally, the containment system is capable of reducing containment pressure to an acceptable value one day following any loss-of-coolant accident. This capability is maintained by the Containment System even assuming the worst possible single active failure affecting the operation of the Emergency Core Cooling System, Containment Spray System, and the reactor containment fan coolers during the injection phase; and the worst possible active or passive single failure during the recirculation phase

Following a postulated rupture of the Reactor Coolant System (RCS), steam and water are released into the Containment System. Initially, the water in the RCS is subcooled at high pressure. When the break occurs, the water passes through the break where a portion flashes to steam at the lower pressure of the containment. These releases continue until the RCS depressurizes to the pressure in the containment (end of blowdown). At that time, the vessel is refilled by water from the accumulators and Safety Injection (SI) pumps. The analysis assumes that the lower plenum is filled with saturated water at the end of blowdown, to maximize steam releases to the containment. Therefore, the water flowing from the accumulators and SI pumps starts to fill the downcomer, causing a driving head across the vessel which forces water into the hot core.

The LOCA analysis calculation model is divided into three phases:

1. blowdown, which includes the period from accident occurrence (when the reactor is at steady state full power operation) to the time when zero break flow is first calculated,
2. refill, which is from the end of blowdown to the time the ECCS fills the vessel lower plenum, and
3. reflood, which begins when water starts moving into the core and continues until the end of the transient.

Nodalization of the NEK reactor containment building model in APROS 6 computer code was developed based on the plant's available documents and available NEK GOTHIC nodalization, *[1]*. The NEK containment system consists of the steel shell containment, concrete shield building (Reactor Building), penetrations and the directly associated systems (Reactor Building Fan Coolers and Containment Spray System) upon which the containment safety functions (confinement of the radioactive fission products during design basis accident and prevent radioactive material releases in the environment) depend. The heat structures' data, except for interior concrete, which is explicitly calculated, are based on USAR Chapter 6 passive heat structures.

APROS nodalization is based on 10 control volumes (well-defined physical boundaries and corresponding communication openings) for simulations of accident behaviour. The nodalization is suitable for the thermal-hydraulic analysis of containment responses during design basis accidents. The interior of the Reactor Building (RB) steel containment shell is modelled with nine volume nodes and one additional node for the annulus, where the annulus-volume is the volume between the RB steel shell containment and concrete building. Heat is transferred from nine connected free volumes located inside the RB steel shell containment towards the annulus-free volume through four connecting (passive) heat structures. The Reactor Building of the Krško Nuclear Power Plant has a cylindrically shaped body, spaced between nearly spherical cups. For nodalization purposes, this Reactor building modelled with nine discrete compartments after a Loss of Coolant Accident (LOCA) can be seen in the nodalization containment scheme, presented in *Figure 1*.

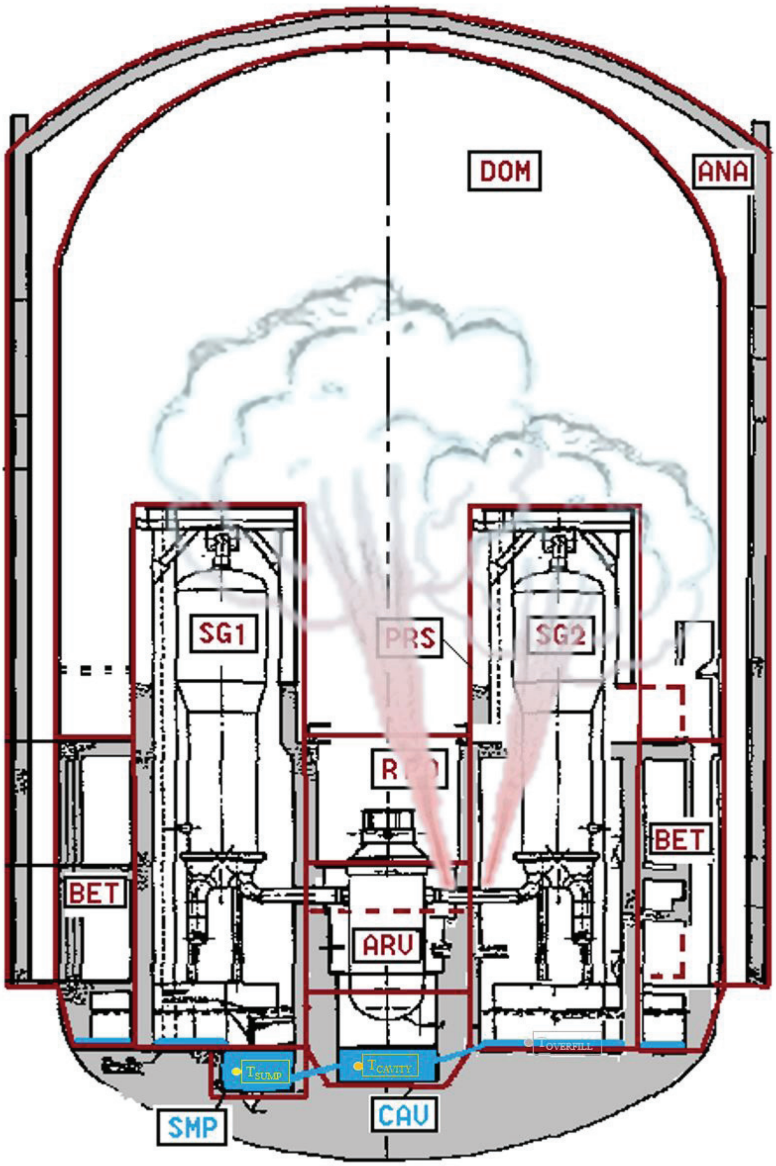

Figure 1: *Reactor Building Nodalization Scheme of NEK during LOCA*

The containment systems are designed so that for all break sizes, up to and including the Double-Ended Hot Leg (DEHL) guillotine break of a reactor coolant pipe or a main steam line, the peak containment pressure is below the design pressure with an adequate margin. Additionally, the containment systems are capable of reducing containment pressure to an acceptable value one day following any loss-of-coolant accident.

2 APROS MODEL DESCRIPTION

APROS nodalization is based on a nodalization scheme with nine control volumes. The model includes two additional free volumes representing the annulus and the outside environment, which are modelled as two serial connecting volumes. The numbering of APROS Containment compartments is equivalent to GOTHIC nodalization (1-10). The user view of APROS containment nodalization, where connections between free volumes, gas branches, water branches and containment sumps arrangement can be seen as presented in Figure 2.

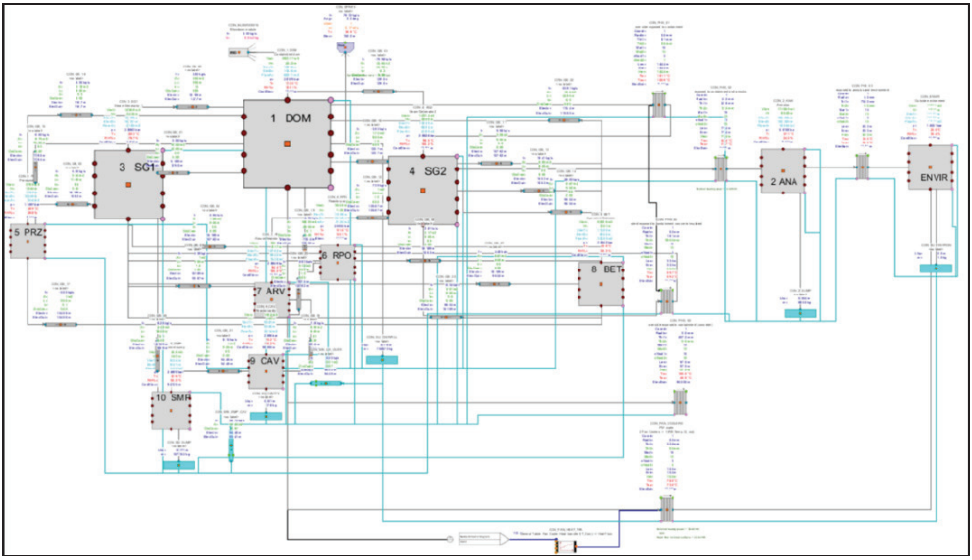

Figure 2: *User view of APROS containment nodalization*

2.1 Nodalization of containment free volumes

All free spaces (compartments) in the containment are modelled with APROS Containment node modules, which include a gas region and a water droplet phase (mist). The atmosphere of each node is assumed to consist of a homogeneous mixture of water vapour and non-condensable gases. The largest and consequentially most important volume in the containment model is module CON_1_DOM, where the majority of measurements of all transient is measured. All effects that are causing transients, such as heat exchangers and spray modules, are connected to the containment dome module.

2.2 Nodalization of containment sumps

The bottom space of the NEK containment is modelled with APROS sump modules, which are basically water pools on the bottom of the reactor building, where the water of the deposited droplets (that has not fallen/ been transferred to another node) is placed. The water sumps are connected to the containment node and allow the heat and mass transfer calculation between the sump surface and node atmosphere.

Every containment node is connected to at least one sump and represents the bottom of a particular free volume with identical geometry. Connections between three water sumps, representing the bottom surface of the RB building are connected to the overflowing configuration.

Gas branches are used in all of the inside connections in the NEK containment model, representing open orifices. If the sump water level reaches the inlet elevation of any gas branch, the gas branch is assumed to be closed.

The water branch is a flow path between the water pools of the adjacent nodes. The sump connection allows the heat and mass transfer calculation between the sump surface and node atmosphere. Only two water branches, which serve as flow paths between three water pools (sump modules), were used in this model of NEK containment.

During the blowdown phase, a large amount of steam is injected into the reactor building, and a large portion of the steam is condensing on the walls and condensate water flows directly into the containment sumps.

2.3 Containment heat structures

Each heat structure module is connected to the desired drain water sump, where atmospheric and/or surface heat transfer is assumed to be the sum of the sensible heat transfer and latent heat transfer from vapour condensation or evaporation. The heat transfer area used for the connections is defined on the basis of the water pool elevation, *[2]*.

In the current version of the APROS NEK containment model, five heat structures were modelled. The amount of input data needed for a more complex heat structure model, as in NEK GOTHIC is high, especially when large numbers of heat structures with numerous nodes are modelled. However, validation showed that the number of heat structures is adequate. The current model was prepared just to evaluate briefly whether APROS is able to predict accurately the containment response to a Double-Ended Hot Leg (DEHL) guillotine break LOCA similar to USAR, *[3]*, and analysis done during the NEK modernization project (SG replacement and power uprate), *[4]*. In both of those studies, the heat structure model is more simplified in comparison to the NEK GOTHIC model, *[1]*.

The heat structure geometry data of APROS 6 heat structures is calculated on the basis of 14 CONTEMPT heat sinks modelled as described in NEK USAR, *[3]*, and SSR-NEK-7.8 (Containment Response to LOCA) documents, *[4]*. The area and masses of the passive heat sinks considered are joined on the basis of heat structure exposure and material.

The heat transfer calculation between the heat structure and the node gas region on the inner surface is calculated with mass diffusion theory for the heat and mass transfer between the structure and gas region based on Ackermann's approximate corrections. In the case of forced convection, the correlation for the average Nusselt number is chosen.

2.4 Containment spray

The heat and mass transfer between the droplets and atmosphere is solved by APROS in detail, for example, droplet interface temperature is separately iterated (using the secant method) due to its strong influence on the combined heat and mass transfer. Furthermore, the drop mean temperature is iterated simultaneously with the surface temperature with Newton's method. Transfer coefficients are corrected by the influence of mass and heat capacity fluxes, *[2]*. Heat conduction within a droplet is modelled using a simplified method. No interactions between spray and fog droplets are modelled. The spray droplets can also fall down (are deposited) from an upper node to the lower one if the proper input connections of the spray modules are activated, *[1]*.

Water mass flow and temperature of water flowing from the containment spray are set in the time-dependent values of the input table of the internal spray system, similar to an analysis performed in the light of the mentioned USAR Section 6, *[3]*.

Since the water for spraying is set to the temperature of the Refuelling Water Storage Tank (RWST), the entire heat capacity of the spray from the RWST temperature to the temperature of the containment atmosphere is available for energy absorption.

2.5 APROS fan cooler heat transfer

The fan cooler heat removal capability is dependent on the containment temperature. The heat removal dependency function of the containment temperature and the component cooling water temperature is provided in NEK USAR, *[3]*, as RBCU Data. The heat transfer of fan coolers in APROS was realized with a boundary condition module, in which the heat transfer of the heat structure is controlled as a function of temperature in the containment dome.

3 APROS MODEL VALIDATION

The APROS containment model was verified and validated based on a comparison of simulated analysis conditions from SSR-NEK-7.8.2, describing Containment Response to LOCA, *[4]*. The analysis peak containment pressures from the postulated double-ended hot leg (DEHL) break were compared between APROS and existing analyses. This peak pressure is a blowdown peak (occurring at the end of initial reactor coolant system blowdown). Both analyses, APROS and SSR-NEK-7.8.2, incorporate the effects of power uprate and steam generator replacement.

3.1 Input data and assumptions

In the APROS containment model, there are three events, (blowdown, fan coolers start, and spray start) that cause thermo-hydraulic transients during simulations. Before the simulation, parameters of containment nodes such as temperatures, humidity, pressures, etc., were set as initial conditions (IC) in the model. The model of containment was not connected to any source of heat losses (dissipation sources such as a reactor or RCS loops) and was set based on the Krško Technical Specifications (TS).

The assumed mass and energy release data during the RCS blowdown phase are from SSR-NEK 7.8.1, *[4]*, which are used as boundary and initiating conditions (not calculated by APROS). The worst peak containment pressure is obtained during the blowdown phase with the double-ended hot leg break. As the long-term containment pressure and the temperature are bound by the double-ended pump suction break with minimum safety injection, only the pump suction break cases require post-reflood calculation, *[4]*.

The input data of the Double-Ended Hot Leg Guillotine (DEHL) Break LOCA is described in SSR-NEK 7.8.1, *[4]*. Mass/energy releases also known as blowdown data start at the beginning of simulation (0 seconds). Energy release during DEHL LOCA is released from two break paths in compartments ARV and SG2. Break path No. 1 discharges from the reactor vessel (ARV) to break point and break path No. 2 discharges from the steam generator (SG2) side to breakpoint (see Figure 1). Data from the DEHL LOCA table used in are presented in Figure 3.

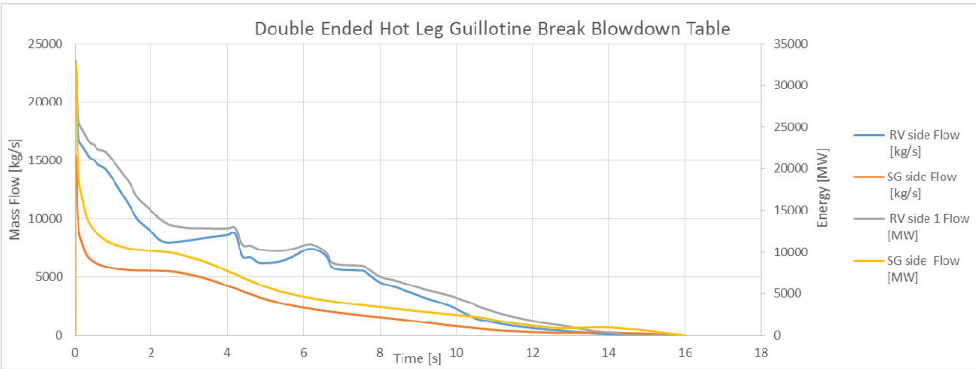

Figure 3: *Visual presentation of blowdown mass/energy releases*

The containment spray (CI system) fill time is 45 seconds (including pump start and diesel generator loading sequencing). The diesel start time is 10 seconds. The total time to spray actuation is 55 seconds assuming the containment HI-3 setpoint is reached prior to the diesel coming up to speed. After the initial DEHL LOCA, the containment fan coolers (RCFC) start 35 seconds after an accident. As explained in section 3.4, the 35-second delay is assumed to be an initial condition for the actuation of RB Fan Coolers in this analysis.

3.2 Initial Conditions

The initial RB pressure assumed is 0.14 kp/cm². The initial RB temperature 48.9°C (120°F) is the maximum Technical Specification value. The RWST maximum temperature is 37°C (98.6°F) and the initial RB relative humidity assumed is 30%. These parameters were entered into all APROS containment nodes, representing free volumes of the reactor building. Initial conditions set for containment annulus is set to 0.8 bars and 30°C, with the RB free volume with four heat structures.

3.3 Containment blowdown pressure simulation

The APROS simulation was run up to 60 seconds, longer than in SSR-NEK, *[4]*. Transients such as RB Fan Coolers start at (at 35 seconds) and containment spray start at 55 seconds. Simulated variables of six vertical containment node volumes, representing the reactor building from the top to the bottom (DOM, SG1, RPO, ARV, SUP and CAV in Figure 2) were monitored. Temperatures in containment volumes vary depending on the node elevation and proximity to sumps, where water that is the result of condensation is gathering and consequentially cooling the nearby volumes.

3.4 RB pressure Results comparison

The Double-Ended Hot Leg (DEHL) LOCA transient results in the maximum calculated containment pressure. This analysis was evaluated only to the end of blowdown since the long-term containment environmental conditions will be controlled by the pump suction breaks.

The APROS Containment model results (blowdown starts at 0 seconds) were compared to results from SSR-NEK, *[4]*. The DEHL LOCA transient from SSR-NEK, *[4]*, was recalculated to absolute values and SI units. Comparisons of APROS simulation results of Containment pressure during DEHL LOCA transient and SSR-NEK, *[4]*, results are presented in Figure 4.

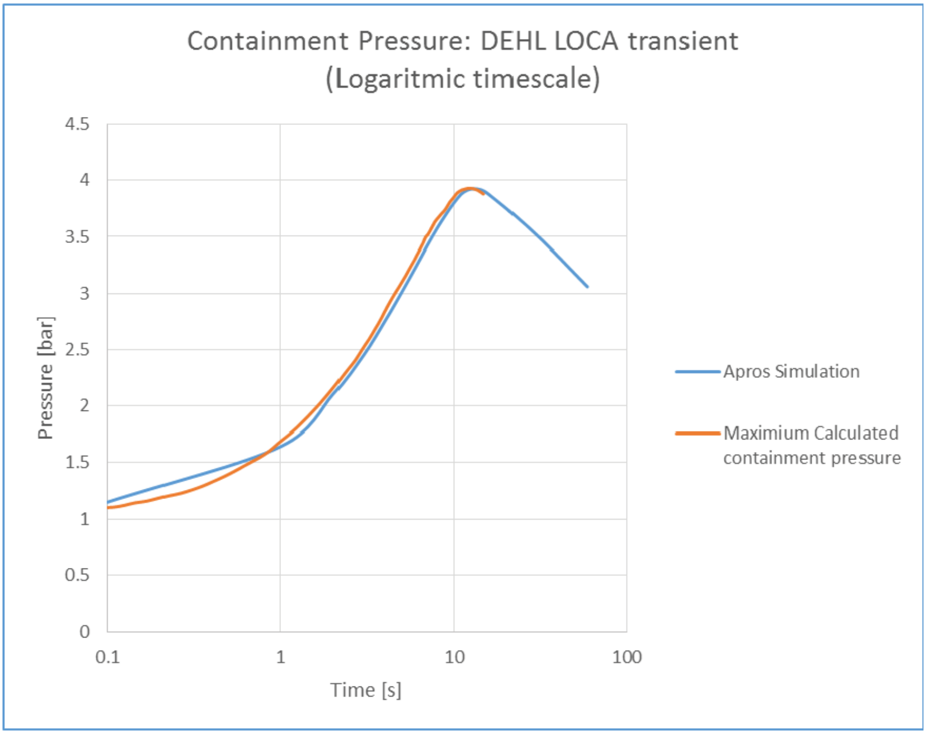

Figure 4: *Comparison of APROS and SSR-NEK results: containment pressure during DEHL LOCA transient*

Good alignment (<0.01%) can be seen between the APROS peak pressure values of the simulated results and the postulated results calculated from SSR-NEK-7.8.2, [4], during the first 15 seconds after the DEHL LOCA transient. Peak pressures in the APROS results occur 13.2 seconds after blowdown is started and in SSR-NEK-7.8.2 after 12.05 seconds, which is only a minor difference.

The results show that the containment peak pressure is below the design pressure with an adequate margin and, therefore, shows that containment can survive the postulated transient. After the peak pressure is attained, the performance of the safeguards systems additionally reduces the containment pressure and temperature.

4 CONCLUSION

Following a postulated rupture (DEHL LOCA) of the Reactor Coolant System (RCS), steam and water are released into the Containment System. Initially, the water in the RCS is subcooled at high pressure. When a break occurs, the water passes through the break where a portion flashes to steam at the lower pressure of the containment. These releases continue until the RCS depressurizes to the pressure in the containment (end of blowdown). The analysis assumes that the lower plenum is filled with saturated water at the end of blowdown, to maximize steam releases to the containment.

Good quantitative and qualitative agreement between APROS simulated results and results from SSR-NEK-7.8.2, *[4]*, during the first 15 seconds after the DEHL LOCA transient were obtained. Simulation of surface temperatures and water volumes in the sumps representing freshly condensed water from a blowdown event, lasting from 0 to 15 seconds, yields realistic results.

References

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Nomenclature

ANA	Annulus - compartment
APROS	Software for modelling and dynamic simulation of processes and power plants developed by Fortum and VTT.
ARV	space Around Reactor Vessel
BET	Between - compartment (space outside listed volumes)
CAV	Reactor cavity - compartment
DEHL	Double Ended Hot Leg (guillotine break)
DOM	Containment dome - compartment
IC	Initial Conditions (settings in Apros model)
LOCA	Loss of Coolant Accident
NEK	Nuklearna Elektrarna Krško
PRZ	Pressurizer -compartment
RB	Reactor Building
RBCU	Reactor Building Cooling Unit
RCFC	Reactor Containment Fan Coolers
RCS	Reactor Coolant System
RPO	Reactor Pool - compartment
RV	Reactor (pressure) Vessel
RWST	Refuelling Water Storage Tank
SG1	Steam generator 1 - compartment
SG2	Steam generator 2 - compartment
SMP	Containment Sump - compartment
USAR	Updated Safety Analyses Report