Modeling of coherent heat and mass-exchange phenomena for a specter of primary circuit leaks in a NPP with WWER-1000 type reactor

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(Abstract)
Subject of study are the inter-relations between the primary leak parameters, the containment pressure and the functioning of the WWER-1000/V320 plant systems. The model includes systems for normal operation and safety systems, which are actuated in the initial stage of the accident. The studied specter of primary leaks includes diameters from 10 to 60 mm. The model is based on the design features of unit 5 in NPP Kozloduy. This paper presents a fragment of the work, performed jointly by Atoma Consult Ltd and NPP Kozloduy Plc on the validation of the symptom oriented emergency operation procedures for units 5 and 6 in NPP Kozloduy.

1. Related WWER-1000/V320 plant systems

Primary (I-ry) side injection
Injection into the primary side is performed by:

- **one** system for **normal operation** make-up and blow-down (TK);
- **one passive** safety system (YT) – hydro-accumulators and
- **three active** safety systems: (TQ**2**; TQ**3** and TQ**4**) – injecting at **different** pressures.

Each active system for injection into the I-ry side contains three separate independent trains. Each train alone is capable of performing the system task, as specified in the reactor design.

Make-up and bleed system (TK)

System functions

The TK system is a system for normal operation with the following functions:

- provide constant bleed from the I-ry side for coolant purification.
- return the organized leakages of I-ry coolant;
- supply clean condensate for boric acid control in the primary circuit;
- supply sealing water to the Reactor Coolant Pumps;
- maintain the I-ry side inventory (PRZ level).

System operation

Make-up injection

The TK system includes three injection trains, connected to all four loops via a common collector. Two trains are kept available under normal conditions. One train begins to inject in case of Pressurizer Level (H_{PRZ}) decrease and the second one starts if necessary. The maximal injection rate is limited to 80 m^3/h by the flow capacity of the regenerative injection heater TK80W01, which also functions as a bleed cooler. The maximal injection head is 196 bar.

Bleeding

Two bleed lines – from loops 2 and 3 join upstream the bleed controller valve TK80S08, which limits the maximal bleed flow rate to 69 m^3/h.

PTS concerns

In order to avoid PTS risk, the difference between the bleed and injection temperatures at the I-ry loop nozzles is kept below 120 ^{o}C by adequate balance between the respective flow rates.

System isolation

The Loss of Off-site Power (LOOP) mode is not considered in this study.
The following signals for **TK system isolation** are considered:

- Plant protection signal **YZ** "Start-up of the Safety Injection Systems TQ-3 and TQ-2 by technological parameters in the I-ry side".
- Interlock **TQS01(2,3)** "containment isolation due to **pressure increase above 1.3 bar**".

Model of the TK system

The TK system model represents the bleed and injection flows at the I-ry loop nozzles and observes the following limitations:

Temperatures: Bleed: $T_{b1} \leq 290\ ^{o}C$ (I-ry, cold leg at full power);

Injection: $T_{i2} = T_{b1} - 120 \leq 170\ ^{o}C$.

Flows: The TK flows are defined by two factors:

- the injection flow G_i tends to match the stabilized break flow G_{Br} before SCRAM actuation but can not exceed 80 m^3/h = 21.6 kg/s;
- the thermal balance of the regenerative heater TK80W01.

The results of the preliminary calculations show, that the stabilized break flow G_{Br} before SCRAM actuation is larger than the maximal TK injection rate for all studied cases. Consequently, constant values of $\mathbf{G_b}$ and $\mathbf{G_i}$ are applicable without overfilling concerns.

Conclusion for the TK parameters in the model

TK Injection:	G_i = 21.6 kg/s (80 m^3/h);	T_i (at the I-ry loop nozzles) = 168 ^{o}C.
TK Bleed:	G_b = 11.9 kg/s (44 m^3/h);	T_b = Current temperature in the cold leg.

High pressure boron injection system (TQ4)

Function and components

Each of the three trains of the TQ4 system injects concentrated boric acid solution at primary pressure from 0.1 to 17.8 MPa. Each train functions independently of the others and includes:

- a Tank containing 15.8 m^3 concentrated (40 g/kg) boric acid solution ;
- a Pump with Capacity of 6.0 t/h (1.67 kg/s) and Delivery head (nom): 156.8 bar.

The TQ4 pumps are started in the event “loss of offsite power”, which is not subject of the current study. Besides, the TQ4 flow rate is negligibly small, compared to the other SI pumps.
Conclusion: The TQ4 system will not be considered in this study.

Impact of the containment pressure (Pc) on the functioning of the systems for normal operation and on the safety systems

Note: In this report all pressure values are **absolute**.

*Actuation of the Reactor SCRAM (**AZ-1**)*

According to [5], ch.17, p.17.2.3: "The Reactor SCRAM (AZ-1) is actuated **0.3 s** after the containment pressure reaches **Pc > 1.29 bar**. The time for insertion of control rods is **4 s**.

*Operation of the Reactor Coolant Pumps (**RCP**)*

According to [6]: "The RCP-s are tripped when the bearing oil pressure drops below 0.156 MPA due to the isolation of the oil supply line by the signal for containment pressure **Pc > 1.29 bar**". The RCP trip occurs **15 s** after the containment pressure signal.

*Operation of the Make-up / Blow down system (**TK**)*

In case of actuation of interlock TQS01(2,3) "containment isolation due to
increase of containment pressure: Pc > 1.29 bar",
the pneumatic valves on the TK injection lines **close with prohibition for opening**.

*Operation of the Safety Injection Systems (**TQ2, TQ3**)*

Two systems for safety injection in case of LOCA (Medium Pressure Safety Injection – TQ3 and Low Pressure Safety Injection – TQ2) are started up by the actuation of the YZ signal – ASSS (Automatic Staggered Start System) – III-rd program, caused by the Containment Pressure increase **Pc > 1.29 bar**. The start-up delay is 5 s for all TQ2 and TQ3 pumps.

*Evaluation of the **Containment Pressure** profile during LOCA accidents*

A series of calculations were performed by the following methodology:
1) Thermal-hydraulic calculations of a set of LOCA cases for evaluation of the flow rates and enthalpies of the fluids, leaking from the break (RELAP5/Mod3);

2) Calculation of the Containment Pressure profile (CONTAIN 1.1).
The following cases of LOCA were studied:
D=10 mm; D=18 mm; D=30 mm; D=40 mm; D=50 mm; D=60 mm.

The Containment Pressure profiles are presented on Fig. 1 below:

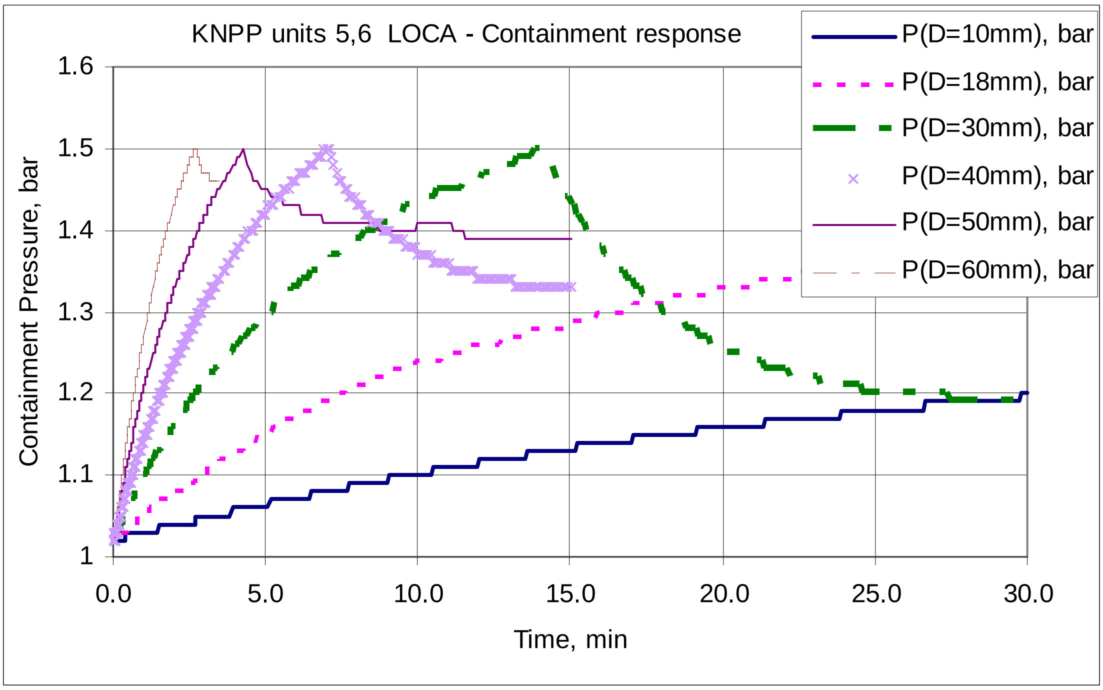

Fig. 1 Containment Pressure profiles

Conclusions :

1) All LOCA-s with **D>10 mm** increase the Containment Pressure **Pc > 1.29 bar** during the first 30 min (automatic response time), causing the following **automatic actions:**

- Reactor SCRAM is actuated after 0.3 seconds (the control rods insertion time is **4 s**).
- RCP-s trip after 15 seconds.
- Disabling of the TK system after 15 seconds.
- Start up of the SI system after 5 s (the **injection** starts when the I-ry pressure drops below the maximal injection (cut-off) head of the relevant pump).

2) For all LOCA-s with **D>10 mm** it is necessary to define the timing of **automatic actions**, **caused by the technological parameters of the primary circuit (P, T, dTs, Hprz).**

3) The scenario for the automatic response of the unit to each studied LOCA (30 min accident time) must be elaborated after **comparison between the times for automatic actions**, caused by containment pressure and by the technological parameters of the primary circuit.
Such comparison is presented in Table 1 below.

Table 1. Results of the calculations for definition of the Lower Limit for the study Actuation of SCRAM, TQ3 during the first 30 min.

	Actuation time (**TP**: by I-ry Tech. Parameters; **Pc**: by Cont. Pressure >1.29 bar)			
LOCA	SCRAM-**TP**	SCRAM-**Pc**	TQ3-**TP**	TQ3-**Pc**
D=10 mm	***None***	***None***	***None***	***None***
D=18 mm	**7.3 min**	16.2 min	None	**16.2 min**
D=30 mm	**1.3 min**	5.5 min	10.7 min	**5.0 min**
D=40 mm	**0.8 min**	3.1 min	5.2 min	**3.1 min**
D=50 mm	**0.4 min**	1.9 min	3 min	**1.9 min**
D=60 mm	**0.32 min**	1.2 min	1.9 min	**1.2 min**

Final Conclusion:

The following assumptions will be applied in the further analyses:

- **SCRAM actuation** by signal **"**Reactor power > 2250MW and P_1<14.81 MPa"**.**
- **TK stop,** and **TQ3, TQ2 actuation** by signal "Containment pressure P_c>1.3 bar **".**