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Loss of ‘Core cooling’ at low power and cold condition of VVER-1000/V320

P.P. Groudev, E.L. Georgieva*

Institute for Nuclear Research and Nuclear Energy – Bulgarian Academy of sciences, Tzarigradsko Shaussee 72, Sofia 1784, Bulgaria

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A B S T R A C T

This paper presents the results of thermal–hydraulic calculation of accident scenarios that involve the loss of critical safety function (CSF) “Core cooling” for VVER-1000/V320 units at Kozloduy nuclear power plant done during the development of symptom based emergency operating procedures (SB EOPs) for this plant at low power and cold condition. The main purpose of this analysis is to provide the response of monitored plant parameters to identify symptoms available to the operators and define timing for reaching the following stages during the development of processes in the reactor system:

- Reaching the saturated temperature at the outlet of the assembly;
- Beginning of reactor core uncovery;
- Heating up of fuel;
- Defining the transition time between EOPs and SAMG at temperature of 923 K;
- Restoring of water level in the reactor;
- Defining the CSF “Core cooling” status and the time of its loss.

The results of the thermal–hydraulic analyses have been used to assist KzNPP specialists in analytical validation of EOPs at low power and cold condition. The principal acceptance criteria for EOPs are averting the onset of core damage.

The RELAP5/MOD3.2 computer code has been used in performing the analyses in a VVER-1000 nuclear power plant (NPP) model. A model of VVER-1000 based on Unit 6 of KzNPP has been developed for the systems thermal–hydraulics code RELAP5/MOD3.2 at the Institute for Nuclear Research and Nuclear Energy – Bulgarian Academy of Sciences (INRNE – BAS), Sofia. The low power and cold condition and the modifications after the modernization program are taken into account.

1. Introduction

Emergency operating procedures (EOPs) analyses are designed to provide the response of monitored plant parameters to identify operators’ symptoms available, timing of the loss of critical safety functions and timing of operator actions to avoid the loss of critical safety functions or core damage. The analytical validation objective is an evaluation performing of the EOPs in order to confirm written correctness of the procedure, and to ensure that technical and human factor concerns have been properly incorporated. The methodology, which was used in developing the symptom based emergency operating procedures (SB EOPs) for KzNPP VVER-1000/V320 is an elaboration of Beelman (1999).

During the development of SB EOPs at Kozloduy nuclear power plant (KzNPP), a number of thermal–hydraulic analyses for KzNPP have been performed at the Institute for Nuclear Research and Nuclear Energy – Bulgarian Academy of Sciences (INRNE – BAS) using RELAP5/MOD3.2 computer code. The scenarios, which have been developed by plant specialist at KzNPP, contain failures of equipment. The purpose of the scenarios is to predict the behavior of NPP and to help correctly validate the operator actions for validation and verification of EOPs.

Abbreviations: BRU-A, steam dump to atmosphere; BRU-K, steam dump to condenser; COP, cold overpressure protection; CSF, critical safety function; EOPs, emergency operating procedures; INRNE –BAS, Institute for Nuclear Research and Nuclear Energy of Bulgarian Academy of Sciences (Sofia, Bulgaria); KzNPP, Kozloduy nuclear power plant; LPIS, low-pressure system; MCP, main coolant pump; NPP, nuclear power plant; PRZ, pressurizer; SAMG, Severe Accident Management Guide; SB EOPs, symptom based emergency operating procedures; SG, steam generator; SV, safety valve; VVER, Russian-style pressurized water reactor; TQ, active part of emergency core cooling system.

* Corresponding author.
E-mail addresses: pavlinpg@inrne.bas.bg (P.P. Groudev), e_georgieva@inrne.bas.bg (E.L. Georgieva).

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The reference power plant for this analysis is Unit 6 at Kozloduy NPP site. This plant is a typical VVER-1000 model V320 (Groudev et al., 1999a) pressurized water reactor. The basic design of a VVER-1000 plant comprises a pressurized water reactor of 3000 MW thermal power with four primary loops and one turbogenerator producing 1000 MW of electric power. Each loop includes one main circulation pump and a horizontal U-tube steam generator (SG). The steam generators are fed by two different feed water systems. Each system consists of turbine-driven pumps and piping connecting the feed water line at four different locations in each steam generator. The emergency core cooling system consists of three high-pressure injection systems, four low-pressure systems (LPISs) and four safety injection tank accumulators. All elements of the primary circuit are situated in a steel-lined, cylindrical, prestressed concrete containment vessel. Systems and equipment of the KzNPP, Unit 6 operates according to the design requirements for corresponding level of the reactor low power and cold condition (Groudev et al., 1999a).

RELAP5/MOD3.2 computer code has been used to simulate the transients for VVER-1000/V320 NPP model (Groudev et al., 1999b). The model has been developed at INRNE – BAS for analyses of operational occurrences, abnormal events, and design basis scenarios. The actual four-loop system has modeled by four single loops for primary and secondary sides. The model provides a significant analytical capability for the specialists working in the field of NPP safety. In the RELAP5 model for VVER-1000/V320 NPP are included reactor vessel; core region represented by three channels; pressurizer system including heaters, spray and relief valves; safety system – low-pressure injection pumps, cold overpressurization protection. In the model also is presented a make up/drain system including connection (control) with pressurizer. Secondary side is developed too and is presented by eight steam generator safety valves, four BRU-A valves, BRU-K valves, steam pipe lines (including main steam header) and turbine including regulating valve in front of the turbine. The horizontal SG has been modeled. A separator model and the perforated sheet have been modeled in SG model, too. Main cooling pump (MCP) has been developed using homologous curves of real pumps.

The results of the thermal–hydraulic analyses (Groudev et al., 2008) have been used to assist KzNPP specialists in analytical validation of EOPs at low power. The results of analyses in this report present part of information required by KzNPP for assessment of the EOPs at low power and cold condition issue.

2. General philosophy of EOPs analyses

EOPs thermal–hydraulic analyses are performed for accident scenarios which involve the loss of critical safety functions (usually evaluate the accidents beyond the automatic capabilities of the engineered safety features where operator intervention is required). When performing the task to identify the scope of coverage of the EOPs, a good knowledge of the thermal–hydraulics of the plant (Groudev et al., 1999a,b) is necessary to identify the possible challenging accidents.

The objective of analytical validation (Pavlova et al., 2008) is to perform an evaluation of the EOP in order to:

- confirm written correctness of the procedure, and
- ensure that technical and human factor concerns have been properly incorporated.

This assessment is accomplished by systematically evaluating the procedures using specialized thermal–hydraulic computer codes designed for nuclear reactor plant simulation (Fletcher and Schultz, 1995). The calculations are performed to simulate the symptoms presented to the operator to diagnose challenges to the CSFs.

3. Initial and boundary conditions

The reactor is at shut down and cold condition before Planned Preventive Maintenance. All control rods are fixed in the lowest position in reactor core. TQn2 channel of LPIS is in stand by regime.

All other characteristics are selected as boundary conditions:

- Subcritical reactor – 2%;
- Residual heat – 18 MW;
- Primary pressure – 0.55 MPa;
- Secondary pressure – 0.10 MPa;
- Core outlet temperature – 363 K;
- PRZ water level – 8.50 m (minimal);
- Drained SGs;
- TQ12D01 pump flow rate in planned cooling (make up and let down) regime 0.125 m^3/s;
- Switched off MCPs;
- Cold overpressure protection (COP) system – in stand by;
- Make up/let down system – in stand by (not used).

In correspondence with the used philosophy three scenarios have been developed for selected initiating event.

3.1. Base case scenario

- Initiating event – TQ12 system failure in 0.0 s;
- Actuation of protection signal YZ due to $\Delta T_{SI} < 283$ K which automatically actuates TQn2 channel of LPIS;
- Possible COP system starting up;
- PRZ SV opening after reaching of their set points;
- Reactor core uncovering;
- Transition between EOP and SAMG at fuel temperature 923 K.

3.2. Failed case scenario

- Initiating event – TQ12 system failure in 0.0 s;
- Failure of protection signal YZ actuation due to $\Delta T_{SI} < 283$ K and TQn2 channel of LPIS;
- Possible COP system starting up;
- PRZ SV opening;
- Reactor core uncovering;
- Transition between EOP and SAMG at fuel temperature of 923 K.

3.3. Operator actions scenario

- Initiating event – TQ12 system failure in 0.0 s;
- Actuation of protection signal YZ due to $\Delta T_{SI} < 283$ K and TQn2 channel of LPIS;
- Possible COP system starting up;
- PRZ SV opening;
- Operator actions:

  Routine operator actions – Restoring TQn2 channel of LPIS in planned or maintained cooling (make up and let down) regime. This case will not be analyzed because of initial conditions restoring.

  Alternative operator action – Opening of PRZ SV and actuation of TQn2 channel of LPIS in standard regime – injection in primary circuit, after actuation of protection signal YZ due to