Annals of Nuclear Energy 40 (2012) 221–228

Contents lists available at SciVerse ScienceDirect

Annals of Nuclear Energy

journal homepage: www.elsevier.com/locate/anucene

Review

Investigation of critical safety function "Heat sink" at low power and cold condition for Kozloduy Nuclear Power Plant WWER-1000/V320

M. Andreeva *, M.P. Pavlova, P.P. Groudev

Institute for Nuclear Research and Nuclear Energy, Tzarigradsko Shaussee 72, Sofia 1784, Bulgaria

A R T I C L E   I N F O

Article history:
Received 24 November 2010
Received in revised form 17 October 2011
Accepted 18 October 2011
Available online 15 November 2011

Keywords:
Thermal–hydraulics RELAP5/MOD3.2
Nuclear Power Plant Safety
WWER
Critical safety function
Low power and cold condition

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) "Heat sink" for WWER-1000/V320 units at Kozloduy Nuclear Power Plant (KNPP), 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 core.
- Defining the CSF "Heat sink" status and the time of its loss.

The results of the thermal–hydraulic analyses have been used to assist KNPP 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 WWER-1000 Nuclear Power Plant (NPP) model. A model of WWER-1000 based on Unit 6 of Kozloduy NPP 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.

Contents

Abbreviations: BRU-A, Steam Dump to Atmosphere (SDTAF); BRU-K, Steam Dump to Condenser; CSF, critical safety function; ECCS, emergency core cooling system; EFW, emergency feed water; EFWP, emergency feed water pump; FWP, feed water pump; HP, high pressure; HPP, high pressure pump; HPIS, high-pressure system; HHPP, high high pressure pump; INRNE-BAS, Institute for Nuclear Research and Nuclear Energy of Bulgarian Academy of Sciences (Sofia, Bulgaria); KNPP, Kozloduy Nuclear Power Plant; LPP, low pressure pump; LPIS, low-pressure system; MCP, main coolant pump; NPP, Nuclear Power Plant; PRZ, pressurizer; RCS, reactor coolant system; SAMG, severe accident management guidance; SB EOPs, Symptom Based Emergency Operating Procedures; SG, Steam Generator; SV, Safety Valve; WWER, water water energy reactor.

* Corresponding author. Tel.: +359 2 71 44 585; fax: +359 2 975 36 19.
E-mail addresses: m_andreeva@inrne.bas.bg (M. Andreeva), pavlova@inrne. bas.bg (M.P. Pavlova), pavlinpg@inrne.bas.bg (P.P. Groudev).

0306-4549/$ - see front matter
doi:10.1016/j.anucene.2011.10.012

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 objective of analytical validation is to perform an evaluation 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 KNPP WWER-1000/V320 is an elaboration of Ronald Beelman (1999).

During the development of SB EOPs at Kozloduy Nuclear Power Plant (KNPP), a numbers of thermal–hydraulic analyses for KNPP 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 KNPP, contain failures of equipment. The purpose of the scenarios is to predict the behavior of NPP and to help correctly validate the operator action for validation and verification of EOPs.

The reference power plant for this analysis is Unit 6 at Kozloduy NPP site. This plant is a typical WWER-1000 Model V320 (Groudev et al., 1999a) pressurized water reactor. The basic design of a WWER-1000 plant comprises: a pressurized water reactor of 3000 MW thermal power with 163 hexagonal fuel assemblies in the core, and 10 absobing rod banks, located in 61 fuel assemblies; four primary loops and one turbogenerator producing 1000 MW of electric power. The reactor vessel has four inlet nozzles of Ø850 mm and four outlet nozzles of Ø850 mm to connect to the primary loops. There are also four inlets of Ø280 mm for safety injection of boron solution to the upper and lower plena in case of primary loss of coolant. Each loop includes one main circulation pump and a horizontal U-tube Steam Generator (SG). The behavior of the horizontal SG is very different compared to Western-style vertical SG (Groudev et al., 1999a). For example, the secondary side of the horizontal SG contains much more water and loss-of-feedwater transients are slower. Steam Generators play a very important role in the safe and reliable operation of WWER power plants. They determine the thermal–hydraulic response of the primary coolant system during operational and accident transients. There are three different feedwater systems on secondary side: Main Feed Water System (MFWS) with two turbine-driven pumps; Auxiliary Feed Water System (AFWS) for normal start up, shutdown and cooldown; emergency feed water system (EFWS) with three trains or $3 \times 100\%$ redundancy, important for this analysis. The Emergency Core Cooling System (ECCS) consists of high-pressure safety injection system (HPSIS), low-pressure safety injection systems (LPSISs) with redundancy $3 \times 100\%$ and four hydro-accumulators. All elements of the primary circuit are situated in a steel-lined, cylindrical, prestressed concrete containment vessel. Systems and equipment of the KNPP, Unit 6 operates according to the design requirements for corresponding level of the reactor power (Groudev et al., 1999a).

RELAP5/MOD3.2 computer code has been used to simulate the transients for WWER-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. In modifying of the RELAP5 input data describing the model of the reactor WWER-1000 the low power and cold condition and the modifications after the modernization program are taken into account. 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 WWER-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 and cold overpressurization protection. Cold Overpressure Protection (COP) is installed during modernization program for KNPP. COP has the task to mitigate the consequences of faulty injection of pressure increasing devices by switching off of components of pressure increasing systems, respectively by closing of injection lines and to open emergency gas removal system or the 1st safety valve. 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 SG 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 Steam Generator (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 KNPP specialists in analytical validation of EOPs at low power. The results of analyses in this report present part of information required by KNPP for assessment of the EOP at low power and cold condition issue.

2. General philosophy of EOP 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 et al., 1995). The calculations are performed to simulate the symptoms presented to the operator to diagnose challenges to the CSFs.

The main steps in performing of EOI analyses are as follows:

- Identify Fission Product Barriers (FPBs).
- Identify CSF appropriate to that Barrier.
- Identify Plant Processes Essential to maintaining that CSF.
- Identify Perturbations in that Plant Process, which would challenge that CSF.
- Identify Hypothetical Initiating Events, which would produce that Perturbation.