Annals of Nuclear Energy 89 (2016) 1–18

Contents lists available at ScienceDirect

Annals of Nuclear Energy

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

Station blackout mitigation strategies analysis for Maanshan PWR plant using TRACE

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ARTICLE INFO

Article history:
Received 12 May 2015
Received in revised form 12 August 2015
Accepted 3 November 2015
Available online 19 November 2015

Keywords:
Station blackout
PWR
TRACE

ABSTRACT

Maanshan nuclear power plant (NPP) is a two-unit Westinghouse three-loop PWR NPP. This research focuses on the analysis and simulation of Maanshan NPP station blackout (SBO) accident that happened on 18th March, 2001, and thermal–hydraulic phenomena of the plant during SBO with and without mitigation strategies. There are two main steps in this study. The first step was the establishment of Maanshan NPP SNAP/TRACE models. These models were tested and the results of TRACE were compared with the startup test and FSAR data. Analysis results indicate that Maanshan NPP SNAP/TRACE models predict not only the behaviors of important plant parameters consistently with the startup test and FSAR data, but also their associated numerical values with respectable accuracy. The next step was the SBO accident simulation and analysis of Maanshan NPP SNAP/TRACE model. The results of TRACE show good agreement with the plant data. Several mitigation strategies were simulated and studied by using this model in this research.

1. Introduction

Tragedy in Fukushima Daiichi, Japan shows significant consequences of the plant facing beyond design basis accident without proper emergency equipment and mitigation strategies. Taiwan is located at the intersection of two tectonic plates where earthquake frequently happen. With the fact that all NPPs sit near the shore, enhancing the capability of dealing with earthquake induced tsunami or other beyond design basis accident is a must.

Maanshan NPP is a two-unit Westinghouse three-loop PWR operated by Taiwan Power Company since 1984. If an intense earthquake and tsunami hit the plant, the sea water pumps, switch yard, onsite electric systems, emergency diesel generator or its fuel supply may be damaged and hard to recover. With no AC (alternating current) power available, only turbine driven auxiliary feedwater system (TDAFW) can deliver cold water to steam generator (SG) to maintain the water level inside SG. If TDAFW trip for some reasons, water in the SG will boil off eventually, primary side will lose the heat sink. Emergency core cooling system (ECCS) cannot operate without AC power so that there is no cooling water injection capability in the reactor coolant system (RCS) except passive accumulators (ACC) action (when RCS pressure is lower than ACC nitrogen gas pressure). Under such circumstance without using any mitigation equipment or strategies, core damage will happen within a few hours.

Taiwan Power Company has enhanced the capability of coping with extended SBO situation by using mitigation strategies and alternate injection systems. In addition to regular ECCS and auxiliary feedwater system, some alternate injection systems such as diesel engine auxiliary feed pump and fire engine pump can also inject water into SG or RCS, but the operating pressure of the alternate systems is much lower than regular system, and onsite operators have to line-up the injection piping manually. The water sources of alternate injection systems can be either condensate storage tank (CST), raw water reservoir, or sea water. The mitigation strategies that were suggested by Taiwan Power Company put emphasis on removing the decay heat rapidly by controlling the SG pressure while maintaining the SG water level at the same time by using any kind of injection method. If decay heat can be removed successfully via SGs, RCS pressure will not build up to the opening set point of power operated relieve valves (PORV) of the pressurizer. Therefore, the inventory of RCS can be kept. The

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http://dx.doi.org/10.1016/j.anucene.2015.11.015
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purpose of using this kind of mitigation strategies is to bring the plant to safe condition as soon as possible and to keep the fuel covered with water.

The advanced thermal hydraulic code named TRACE has been developed by U.S. NRC for NPP safety analysis. According to the TRACE manual (U.S. NRC, 2014), one of the features of TRACE is its capacity to model the reactor vessel with 3-D geometry. It could support a more accurate and detailed safety analysis of nuclear power plants. TRACE has the greater simulation capability than other legacy codes (TRAC-P, TRAC-B, RELAP5 and RAMONA), especially for events such as LOCA. Additionally, a graphic user interface program, SNAP, which processes inputs, outputs, and animation models for TRACE, is also developed by U.S. NRC. TRACE includes several components: PIPEs, PRIZERs (pressurizers), CHANNELs (BWR fuel channels), PUMPs, JET PUMPs, SEPARATORs, TEEs, CONTANs (containment), VALVEs, and VESSELs. Powered and heated components are POWER and HEAT STRUCTUREs. FILL and BREAK components supply the coolant-flow and pressure boundary conditions. Accordingly, an increasing number of researchers are using TRACE code to analyze NPPs. Gajev et al. (2014) developed the TRACE/PARCS models of Ringhals-1 and Oskarshamn-2 BWRs. They used these models to perform stability studies and sensitivity analysis. Queral et al. (2011) established Almaraz NPP PWR TRACE model. They studied operator action and single failure criteria in steam generator tube rupture (SGTR) sequences by using this model (Jimenez et al., 2013). Montero-Mayorga et al. (2014) used TRACE to perform PWR's SBLOCA simulation and study the effect of delayed reactor coolant pump (RCP) trip in this transient. Gonzalez-Cadelo et al. (2014) performed the analysis of cold leg LOCA with failed HPSI (high pressure safety injection) transient for PWR by using TRACE.

This research studied the SBO accident that happened on 18 March, 2001 by using SNAP/TRACE. There are two main steps in this research. The first step was Maanshan NPP SNAP/TRACE models' establishment. These models were tested with the startup test and FSAR data. The next step was the SBO accident simulation and analysis of Maanshan NPP SNAP/TRACE model. Several mitigation strategies were simulated and studied by using SNAP/TRACE models.

2. Introduction to Maanshan NPP SBO accident

During spring season in Taiwan, salty wind from the ocean can degrade the insulation of power transmission line and causing the instability of off-site power in nearby nuclear power station. On March 17th, 2001, 3:23 am, 345 kV off-site power line was lost due to seasonal salty wind and 161 kV off-site power was remained available. Unit 1 reactor tripped and was maintained at hot standby condition by operators. At 0:46 am, March 18th, a malfunctioned breaker in on-site AC power electric system accidentally grounded, which produced electric arc damaging other electric systems. Subsequently, the SBO happened. At 0:57 am, TDAFW started automatically to provide cold water into SGs. At 0:58 am, reactor operators started to initiate the emergency operating procedure (EOP) to depressurize the SG. Auxiliary feedwater flow rate, SG pressure and water level were controlled and maintained manually by the operators. At 2:54 am, the emergency diesel generator successfully supplied AC power to emergency 4.16 kV bus B, SBO situation was terminated (Atomic Energy Council, 2001).

Duration of SBO is about 2 h, starts from 0:46 am to 2:54 am, March 18th, and the temperature and pressure of reactor decreased from 564 K, 15.3 MPa to 472 K, 4.2 MPa respectively. Fuels were covered with water and no radioactive materials were released during the whole accident. Summary of accident scenario is shown in Table 1. The analysis of SBO accident was performed by SNAP and TRACE. SNAP/TRACE model and simulation results are introduced in the following sections. The simulation results are compared against measured data in Maanshan NPP unit 1, and further studies on Maanshan NPP SBO mitigation strategy are done using this model.

Table 1
Maanshan NPP SBO accident scenario.

Time (h)	Simulation time (h)	Event
0 (March 17th, 3:23 am)	–	345 kV off-site power lost Reactor trip
21.12	0	Simulation start with hot standby condition
21.38 (March 18 th, 0:46 am)	0.26	Breaker failure (SBO)
21.57	0.45	Turbine driven auxiliary feedwater (TDAFW) start
21.58	0.46	Initiate EOP 570.20 (SG & RCS cooling)
23.52	2.4	SBO terminated
24.12	3	End of simulation

3. The establishment of SNAP/TRACE models for Maanshan NPP

Maanshan NPP is the only Westinghouse-PWR in Taiwan. The RCS has three loops, each of which includes a reactor coolant pump and a SG. The pressurizer is connected to the hot-leg piping in loop 2. Because of the complexity of the equipment and systems at the Maanshan NPP, establishing component models first, for integration into a whole plant model, is the most effective approach. With reference to the TRACE user manual (U.S. NRC, 2014), and related information (Wang et al., 1987, 1988, 1989; Wang and Wang, 1988; Lyie et al., 1997), component models of the pressurizer, SG, control system and steam dump control system were established. The pressurizer and its control systems were described in Section 3.1. The steam generator with feedwater control system was presented in Section 3.2. The Section 3.3 depicted the steam dump control system. The Maanshan NPP SNAP/TRACE model was shown in Section 3.4. Additionally, Section 3.5 described the modeling of Maanshan NPP SBO accident by using the above SNAP/TRACE model.

In our previous research (Wang et al., 2009; Chen et al., 2014, 2013a, 2013b; Lin et al., 2011, 2014), we established Maanshan NPP (PWR), Chinshan NPP (BWR/4), and Lungmen NPP (ABWR) SNAP/TRACE models successfully by using TRACE v 5.0–v 5.0 patch 3 and SNAP v 0.26.7–v 2.2.1. However, U.S. NRC released the latest version TRACE v 5.0 patch 4 and SNAP v 2.2.9 in 2014. Subsequently, based on the successful experience from the above models, we modified and updated Maanshan NPP SNAP/TRACE model which focused on the simulation of SBO and mitigation strategies by using TRACE v 5.0 patch 4 and SNAP v 2.2.9.

The methodology of Maanshan NPP SNAP/TRACE model is presented in Fig. 1 as follows:

(1) The startup tests and FSAR data of Maanshan NPP (Wang et al., 1987, 1988, 1989; Wang and Wang, 1988; Lyie et al., 1997) were collected.
(2) The SNAP/TRACE models for several important components (pressurizer, steam generators, feedwater control system and steam dump control system) were established.
(3) The startup tests and FSAR data were used to confirm the accuracy of the above SNAP/TRACE models.
(4) The other necessary components (e.g. vessel and main steam piping) were added into the SNAP/TRACE models mentioned above to construct Maanshan NPP SNAP/TRACE model.