Annals of Nuclear Energy 114 (2018) 518–529

Contents lists available at ScienceDirect

Annals of Nuclear Energy

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

Safe reactor depressurization windows for BWR Mark I Station Blackout accident management strategy

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A R T I C L E I N F O

Article history:
Received 19 October 2017
Accepted 30 December 2017

Keywords:
Station Blackout
BWR Mark I
GOTHIC
Depressurization windows
Containment venting

A B S T R A C T

In order to evaluate the effectiveness of reactor depressurization within accident mitigation strategy and how to avoid core damage during Station Black-Out accident in a BWR Mark I plant, a GOTHIC model has been developed to support characterization of reactor safety systems performance. The GOTHIC model provides seamless coupled simulations of the reactor coolant system and the containment system. In this study, the time intervals (also called "safe reactor depressurization windows") to initiate the reactor depressurization in order to optimize the early cooling strategy by injecting fire water and avoid clad failure are studied based on the decay heat removal capability of the reactor vessel coolant. This concept is instructive for the operation of the safety systems during the SBO accident mitigation. Sensitivity studies of several key parameters like reactor power, mass flow rates through RCIC system and fire water injection, and full open discharge coefficient of SRVs are performed to evaluate their impact on the safe reactor depressurization windows.

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1. Introduction

There exist great challenges and uncertainties on the performance assessment of nuclear power plant and prediction of sequences during beyond design basis accidents (BDBA). On March 2011, Fukushima Daiichi nuclear power plants experienced extended Station Blackout (SBO) accidents initiated by a tremendous earthquake and the following massive tsunami. Core damage and fuel cladding-steam reaction happened in Units 1, 2, and 3. Hydrogen in the released gaseous mixture accumulated in reactor buildings' upper portions, formed a combustible mixture with air and resulted in large explosions with significant damage to reactor buildings. All Fukushima Daiichi Boiling Water Reactors (BWRs) are designed with Mark I containment, according to the TEPCO's report (TEPCO, 2012).

When all the engineered safety systems requiring Alternating Current (AC) electric power are incapacitated during SBO accidents, the early cooling of the reactor core is satisfied by Direct Current (DC) powered safety systems (TEPCO, 2014). Reactor Core Isolation Cooling (RCIC) system, Isolation Condensers (IC) and High Pressure Cooling Injection (HPCI) system are utilized to mainly provide early backup coolant for BWRs. The RCIC system was among a few of the safety systems that still could operate during the Fukushima Daiichi accidents after the tsunami hit the plants. Another passive coolant makeup system – the HPCI system, operates similarly as RCIC system; however, the operation of HPCI would rapidly depressurize the primary system due to its large steam release rate (one order of magnitude higher than RCIC system), which would disable the steam-driven turbines of RCIC and HPCI systems (Gauntt et al., 2012).

With more investigations performed on the accident units, the extent and impact of core damage now become well understood.

Abbreviations: 0-D, Zero-Dimensional; 1-D, One-Dimensional; 3-D, Three-Dimensional; AC, Alternating Current; ADS, Automatic Depressurization System; ANS, American Nuclear Society; BDBA, Beyond Design Basis Accident; BWR, Boiling Water Reactor; CFD, Computational Fluid Dynamics; CST, Condensate Storage Tank; DHRC, Decay Heat Removal Capability; DC, Direct Current; DW, Drywell; EOP, Emergency Operating Procedure; FOM, Figure of Merit; HPCI, High Pressure Cooling Injection; IC, Isolation Condenser; MOV, Motor Operated Valve; NPSH, Net Positive Suction Head; NPSHA, Available NPSH; NPSHR, Required NPSH; RCIC, Reactor Core Isolation Cooling; RISMC, Risk-Informed Safety Margin Characterization; RPV, Reactor Pressure Vessel; SBO, Station Blackout; SP, Suppression Pool; SRD, Safe Reactor Depressurization; SRV, Safety Relief Valve; TEPCO, Tokyo Electric Power Company; URG, Ultimate Response Guideline; WW, Wetwell.

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https://doi.org/10.1016/j.anucene.2017.12.063
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Fukushima Daiichi power plant containment analysis has been performed using GOTHIC (Ozdemir et al., 2015), MELCOR (Gauntt et al., 2014, Denman and Brooks, 2015) for Unit 1, and MELCOR (Cardoni et al., 201, Robb et al., 2014, Fernandez-Moguel and Birchley, 2015, Sevón, 2015), MAAP (Luxat et al., 2013), SAMPSON (Pellegrini et al., 2014), ASTEC (Bonneville and Luciani, 2014) for Unit 3, which investigated various aspects of the Fukushima Daiichi event with consideration of the effects of multidimensional modeling and vent heat transfer on the event simulations.

Many studies and numerous assessments have been performed on how to avoid the Fukushima Daiichi accident and improve SBO accident management. The simulations by Shih et al. (2014) showed that the consequences of an uncovered core and core melt can be avoided by adopting the proper reactor pressure vessel (RPV) depressurization and containment venting strategy. One opinion from Dr. Salomon Levy (Levy, 2012) is that, in the case of Units 2 and 3, RCICs were allowed to run for too long without the foresight and a clear priority given to implement reactor depressurization and fire water (fresh water or sea water) injection. It is proposed that, regardless of whether these backup coolant providers (i.e., RCIC and HPCI systems) are working or not, provisions like fire water injection should be initiated to the reactor vessel to ensure that: (1) the reactor core water level is sufficiently high to prevent cladding metal-steam reaction producing hydrogen; (2) the containment pressure is kept low enough for reactor depressurization and to avoid radioactivity leakage to the environment. This early reactor depressurization strategy has significant benefits compared to the regular reactor depressurization strategy based on the requirements specified in emergency operating procedures (EOPs): (1) the early relief of high-pressure-high-temperature threat on the containment vessels, (2) the prevention of the critical situations from sudden breakdown of backup coolant providers. However, the coolant flash evaporation in reactor vessel, due to sudden pressure drop and high decay heat during early accident, may lead to the decrease of water inventory followed by core uncovering and damage.

Taiwan Power Company built up another early reactor depressurization strategy for Fukushima-like accident called Ultimate Response Guideline (Liang et al., 2012). Instead of full depressurization, a controlled-depressurization operation is simulated based on Chinshan NPP, a BWR with Mark I containment, using MELCOR2.1/SNAP. As earthquake happened and reactor was shut down, RPV was firstly controlled to depressurize to a low value where the water level could be maintained and the generated steam could still drive the RCIC turbine-pump unit to achieve adequate core cooling. When SBO happened, RPV was then depressurized to fail the RCIC system and initiate fire water injection. The simulations showed that the cladding temperature following this controlled-depressurization strategy has lower potential to reach as high the value as following full-depressurization strategy. The multiple-steps-depressurization strategy avoids the sudden flash evaporation of RPV coolant inventory, but more safety and effectiveness studies of URG are required considering the complexity of the depressurization operation and RCIC system control.

In essence, the early coolant makeup systems are designed to make time for the recovery of AC power. The operation of reactor depressurization is expected to initiate fire water injection in case of the recovery of AC power is not available. It surely disables these passive coolant makeup systems and wastes their cooling capability, and the premature injection of raw water significantly raises the cost of cleaning for the reuse of the reactor and leads to early containment venting, which definitely releases the radioactivity to the environment. However, if fire water injection is delayed, high temperature and subsequent high pressure in the containment may threaten the containment integrity, with the potential for uncontrolled leakage of gas mixture if the containment is breached. Therefore, the decision making of reactor depressurization timing should take prevention of core damage, containment failure and practical issues into consideration.

The primary objective of this paper is to study the timing for reactor depressurization, then making efforts to support the decision making on both the reactor depressurization and containment venting strategy. The scope of the work presented in this paper includes the following:

1) Analyze the BWR Mark-I SBO accident progression with respect to the effectiveness of reactor depressurization and containment venting within accident mitigation strategy;
2) Propose the concept of "safe reactor depressurization window" to advise on how to avoid core damage by choosing a proper time to implement primary system depressurization and inject fire water before RCIC system loses its capability to maintain the core water level.

In this paper, Section 2 describes the GOTHIC model developed for the characterization of BWR Mark I safety systems performance and evaluation of the venting strategy. The demonstration SBO scenario simulation is represented in Section 3, followed by the development and sensitivity study of "safe reactor depressurization window".

2. Model description

2.1. GOTHIC approach

The study employs GOTHIC, a coarse-mesh CFD-like thermal-hydraulics simulation code that has been developed and generally applied in containment process modeling and analysis (EPRI, 2012). In the previous study, a demonstration GOTHIC model has been developed for BWR Mark I containment and successfully applied to investigate the performance of reactor safety system and containment venting processes during SBO accident scenario (Bao et al., 2015, 2016). GOTHIC has the capability to simulate the dynamical performance of reactor systems needed for analysis of reactor depressurization and containment venting. It is instructive to note that analysis of SBO scenarios within the context of Risk-Informed Safety Margin Characterization (RISMC) requires consideration of consequences associated with hydrogen combustion and fission product transport, and GOTHIC includes models for both of these phenomena. The GOTHIC code also allows an effective description and integration of plant components in 0-D (i.e., lumped parameter), 1-D (e.g., piping network), and 3-D (recirculation flow). This advanced capability in GOTHIC allows analysis of complex thermal-hydraulic scenarios involving 3-D flow patterns (e.g., in containment) and 1-D pipe network (in RCS).

2.2. GOTHIC model for BWR Mark I plant system

A BWR Mark I plant system model has been developed using GOTHIC, which includes the major components for the primary system and the safety system, including detailed reactor vessel, RCIC system, Safety Relief Valves (SRVs), condensate storage tank (CST), wetwell (WW), Drywell (DW) and containment venting components, as shown in Fig. 1. The reference design for this model is derived from the Peach Bottom Unit 2, a General Electric-designed BWR-4 Mark I plant, with a rated thermal power of 3293 MW (NRC, 1993). The parameters of the aforementioned components are shown in Table 1.

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