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Lungmen ABWR containment analyses during short-term main steam line break LOCA using GOTHIC

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ABSTRACT

Lungmen Nuclear Power Plant in Taiwan is a GE-designed twin-unit Advanced Boiling Water Reactor (ABWR) plant with rated thermal power of 3926 MWt. Both units are currently under construction. In the Lungmen Final Safety Analysis Report (FSAR) section 6.2, the calculated peak drywell temperature during the short-term Main Steam Line Break (MSLB) event is 176.3 °C, which is greater than the designed temperature of 171.1 °C. It resulted in a controversial issue in the FSAR review process conducted by the Atomic Energy Council in Taiwan. The purpose of this study is to independently investigate the Lungmen ABWR containment pressure and temperature responses to the MSLB using the GOTHIC program. Blowdown conditions are either calculated by using a simplified reactor vessel volume in GOTHIC model, or provided by the RELAP5 transient analysis. The blowdown flow rate from the steam header side is calculated with a more reasonable pressure loss coefficient of the open main steam isolation valves, and the peak drywell temperature is then reduced. By using the RELAP5 blowdown data, the peak drywell temperature can be further reduced because of the initial liquid entrainment in the blowdown flow. The drywell space is either treated as a single volume, or separated into a upper drywell and a lower drywell to reflect the real configuration of the Lungmen containment. It is also found that a single drywell volume may not present the overheating of the upper drywell. With more realistic approaches and assumptions, the drywell temperature can be reasonably below the design value and the Lungmen containment integrity during the MSLB event can be maintained.

1. Introduction

Lungmen Nuclear Power Plant owned by the Taiwan Power Company is the fourth nuclear plant in Taiwan. The units 1 and 2 of the Lungmen Plant are the GE-designed Advanced Boiling Water Reactor (ABWR), each with rated thermal power of 3926 MWt and dome pressure of 7.17 MPa A (1040 psia). Both units of the Lungmen plant are currently under construction, and the Lungmen Final Safety Analysis Report (FSAR, 2010) has been reviewed by the Atomic Energy Council (ROCAEC) in Taiwan.

Containment is a structure surrounding the reactor pressure vessel (RPV) and is a barrier to prevent the radioactive material from releasing to the outside atmosphere. A containment shall withstand the pressure and temperature transients caused by a loss of coolant accident (LOCA). The schematics of the Lungmen ABWR containment under the MSLB LOCA are shown in Fig. 1. The RPV is encompassed by the drywell. Not like the typical Mark I, Mark II, or Mark III pressure suppression containments, the drywell is separated into two spaces: the upper drywell (UDW) and the lower drywell (LDW). The volumes of the UDW and LDW are 5331.6 m^3 and 1806.84 m^3, respectively. The UDW and LDW are not directly adjacent to each other but connected by 10 drywell-connecting vents. Each drywell-connecting vent has a flow area of 1.8 m^2. Ten vertical vents with a diameter of 1.2 m extend downward from the drywell connecting vents. Each vertical vent is connected to three horizontal vents at different elevations (top, middle, and bottom). The distances between the vent centerline and the suppression pool bottom are 3.5 m, 2.13 m and 0.76 m for the top, middle and bottom horizontal vents. Each horizontal vent has a diameter of 0.7 m.

The wetwell (or the suppression chamber) is a cylinder structure composed of an air space filled with nitrogen and a suppression pool filled with water normally. To assure that the blowdown steam can be well condensed, the suppression pool level is required to be maintained above the top horizontal vents. The high level of the suppression pool specified by the Lungmen Technical Specification is 7.1 m, which corresponds to a pool volume of 3544.32 m^3, and an

Abbreviations: ABWR, advanced boiling water reactor; DW, drywell; ECCS, emergency core cooling system; FSAR, Final Safety Analysis Report; HPCF, high pressure core flooder; LDW, lower drywell; LOCA, loss of coolant accident; LPFL, low pressure flooder; MSIV, main steam isolation valve; MSLB, main steam line break; RCIC, reactor core isolation cooling; RHR, residual heat removal; ROCAEC, Atomic Energy Council, Republic of China; RPV, reactor pressure vessel; UDW, upper drywell; WW, wetwell (suppression chamber).

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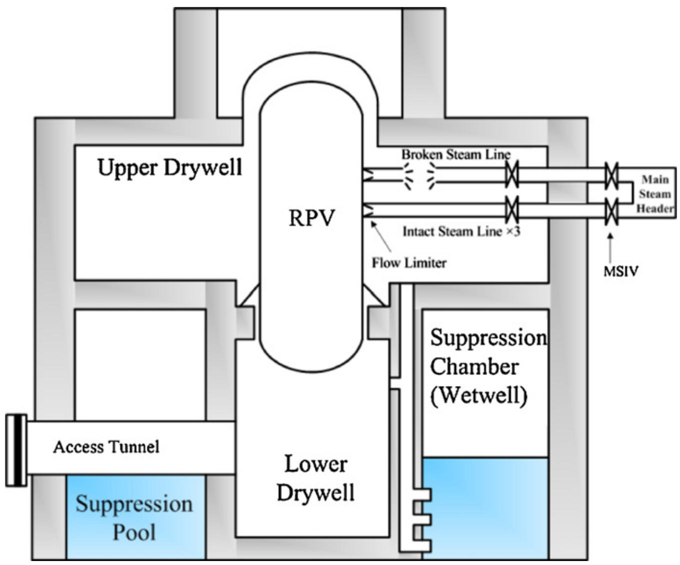

Fig. 1. Schematics of the Lungmen ABWR containment.

airspace volume above the pool of 5946.65 m^3. There are five suppression pool return paths between the vertical vents and the LDW space. Water within the LDW can be vented to the pool when the accumulated level is higher than the elevation of the suppression pool return paths.

The design-basis accident analyses of the containment are presented in FSAR section 6.2. The short-term pressure/temperature analyses of the Lungmen containment are carried out using the M3CPT code (Bilanin, 1974; Lasher, 1979). The limiting case for the drywell pressure is the double-ended feedwater line break. The calculated peak drywell pressure due to the feedwater line break is 278.5 kPa G, which is below the design pressure of 310 kPa G (45 psig). The limiting case for the drywell temperature is the double-ended main steam line break. However, the calculated peak drywell temperature due to the MSLB is 176.3 °C, which is greater than the design temperature of 171.1 °C (340 °F). The overheating duration, which is the period when the drywell temperature is greater than the design temperature, is merely 1.1 s, so the containment structure integrity will not be damaged. However, it is not consistent with the Standard Review Plan 6.2.1.1.C (SRP, 2007), which states that the calculated peak values of pressure and temperature for the drywell and wetwell shall not exceed the respective design values.

In this study, the containment thermal hydraulic program (GOTHIC 7.2a, 2006a,b) is used to analyzed the Lungmen ABWR containment responses due to the short-term MSLB LOCA. GOTHIC has been verified with many separate effects and integrity experiments (GOTHIC 7.2a, 2006c; George and Singh, 1996), including the early Marviken experiments in Sweden (GOTHIC 7.2a, 2006c) and the recent PANDA facility in Switzerland (Paladino et al., 2010; Andreani and Paladino, 2010; Andreani et al., 2010). This program can also produce excellent agreement with the ABWR containment analyses for the South Texas Project Units 3 and 4 (Douglass et al., 2009).

The short-term containment responses are strongly related to the blowdown conditions, such as the flow rate and the fluid enthalpy. In the FSAR analysis, a simplified RPV volume is used to calculate the short-term MSLB blowdown conditions. In this study, the short-term MSLB blowdown conditions are generated from two different ways. Similar to the FSAR analysis, the first way is to use a simplified RPV volume to calculate the blowdown flow by Moody's homogenous equilibrium critical flow model. In the other way, the blowdown conditions are obtained by the RELAP5 transient analysis (Dai, 2010). A detailed model of the Lungmen ABWR reactor and related piping is constructed in the RELAP5 model to simulate the thermal hydraulic behavior inside the RPV. The blowdown condition calculated by the RELAP5 analysis is then provided as boundary conditions to the GOTHIC containment model. The RELAP5/GOTHIC methodology is similar to that used by the authors' previous study about the Mark I containment of the Chinshan Station (Chen et al., 2011).

Two effects influencing the blowdown conditions are investigated. One is the RPV mixture level swell and the other is the pressure loss coefficient via the open MSIVs. The calculated containment responses are presented and compared with the Lungmen FSAR results.

2. Lungmen ABWR containment modeling

The drywell of the Lungmen containment is divided into the upper drywell and the lower drywell, as shown in Fig. 1. In the FSAR analysis, only one drywell node is used, and the node volume is assumed to be the sum of the UDW and 50% of the LDW for conservatism (FSAR, 2010). In the GOTHIC models presented in this study, the UDW, LDW, and the drywell connecting vents can be treated as separated volumes. Fig. 2 is the schematics of the GOTHIC model used in this study. In Fig. 2(a), the drywell is treated as one single volume similar to the FSAR analysis. In Fig. 2(b), the UDW and the LDW are treated as separated volumes, which is more realistic to the Lungmen containment configuration.

The wetwell is a cylinder structure outside the lower drywell, and is divided into 11 subvolumes in this study, as shown in Fig. 3. The bottom, middle, and top horizontal vents are connected to the subvolume 1, 2, and 3, respectively. There are two tunnels penetrating the suppression chamber space. One is the personnel tunnel, and the other is the equipment hatch. Both tunnels have an outer diameter of 4.34 m. The occupation of the tunnels is modeled by the cylinder blocks function of GOTHIC. The initial suppression pool level is assumed to be at the high level of 7.1 m from the pool bottom. Initially, the subvolumes below 7.1 m are assumed to be filled with water. The subvolumes above 7.1 m are assumed to be initially filled with nitrogen and oxygen since inerting is required for the Lungmen containment during normal operation.

The wetwell pressure is the airspace pressure without the water head of the pool depth, and is calculated by averaging the pressure of the vapor occupation of each subvolume:

$$P_{WW} = \frac{\sum_i^{11} (\alpha_{vap} VP)_i}{\sum_i^{11} (\alpha_{vap} V)_i} \tag{1}$$

where P_{WW} is the average wetwell pressure (kPa G); α_{vap} is the vapor volume fraction of each subvolume; V is the volume of each subvolume (m^3); P is the pressure of each subvolume (kPa G).

The suppression pool temperature and wetwell airspace temperature calculated by GOTHIC are presented as mass-weighted temperature in this study. That is, for suppression pool:

$$T_{SP} = \frac{\sum_i^{11} (\alpha_{liq} \rho_{liq} V T_{liq})_i}{\sum_i^{11} (\alpha_{liq} \rho_{liq} V)_i} \tag{2}$$

Similarly, for the wetwell airspace temperature:

$$T_{WW,air} = \frac{\sum_i^{11} (\alpha_{vap} \rho_{vap} V T_{vap})_i}{\sum_i^{11} (\alpha_{vap} \rho_{vap} V)_i} \tag{3}$$

where T_{SP} is the mass-weighted suppression pool water temperature (°C); $T_{WW,air}$ is the mass-weighted wetwell airspace temperature (°C); α_{liq} is the liquid volume fraction of each subvolume; ρ_{liq} is the liquid density (kg/m^3); α_{vap} is the volume fraction of the vapor mixture including steam and non-condensable gases;