

KUOSHENG BWR/6 CONTAINMENT PRESSURE AND TEMPERATURE RESPONSES AFTER RECIRCULATION LINE BREAK USING GOTHIC CODE

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Abstract

In this study, we presented the calculated results of the containment P/T (pressure and temperature) response after the recirculation line break (RCLB) accident of a GE-designed twin-unit BWR/6 plant, which can be served as the design basis for the containment system. During the simulation, a power of SPU (stretch power uprate) range was used and a model of the Mark III type containment was built using the GOTHIC (Generation of Thermal-Hydraulic Information for Containments) code. The calculated results, similar to the FSAR (Final Safety Analysis Report) results, indicate the GOTHIC code has the capability to simulate the containment P/T response to the RCLB accident.

1. Introduction

The power uprate of commercial nuclear power plants has been implemented successfully worldwide for economic profit and operation efficiency. For example, in Spain [1], Cofrentes was uprated 2% in 1988, another 2.2% in 1998, 5.6% in 2002 and 1.9% in 2003, taking it to 112% of original capacity; in USA [2], to the end of September 2010, the Nuclear Regulatory Commission has approved 135 uprates totaling 5810MWe. In Taiwan, Taiwan Power Company (TPC) considers the power uprate of nuclear power plants as an important policy. From 2005, three MURPU (Measurement Uncertainty Recapture Power Uprate) projects for Kuosheng, Chinshan and Maanshan nuclear power plants, each having two units, were initiated and so far there are four units totally successful in commercial operation after MUR PU. In addition, a sequential project of SPU (Stretch Power Uprate) projects for Kuosheng plant will be implemented in the near future.

The containment safety analysis is one of the tasks requiring reanalyzing before the power uprate. In such an analysis, the containment and drywell shall withstand the peak transient pressure and temperatures that could occur due to the postulated design basis accident (DBA) under the power uprate conditions such that they can maintain their functional integrity. For Kuosheng nuclear power plant, the main steam line break (MSLB) accident, which is the design basis for the containment system analysis according to Kuosheng FSAR [3], was analysed using the GOTHIC code [4]. In addition to the MSLB accident, the analysis of the RCLB accident was also performed using M3CPT (Mark III Containment Pressure/Temperature) code in Kuosheng FSAR [3], which could provide the information for the comparison between the FSAR results and the associated simulation results.

The purpose of this study was to assess the capability of GOTHIC for simulation of pressure and temperature (P/T) responses of the Kuosheng BWR/6 containment to the RCLB accident. In this study, the geometry and modelling of the Mark III containment of Kuosheng plant were presented first. Then, the simulation conditions for short- and long-term were given. Finally, the comparisons of the simulated results and the FSAR results were presented. For conservatism, the containment system analysis in this study was performed at 3039 MWt, compared to the rated power of 2894 MWt, which fell into the category of the SPU.

2. Kuosheng Mark III containment modelling

2.1 Kuosheng Mark III containment

Fig. 1 shows the schematics of Kuosheng Mark III containment. The underlined component means the region it occupies. The outer structure of the primary containment is a steel-lined concrete cylinder topped with a dome roof. The Reactor Pressure Vessel (RPV) is surrounded by a drywell, which is an unlined concrete cylindrical structure. The drywell provides shielding to reduce radiation levels and a structure to support the upper pool. The Mark III containment incorporates two pools: the upper pool providing shielding for the steam dryer and moisture separator storage, and the suppression pool (SP) located in the bottom of the primary containment. The SP is a 360-degree annular pool located between the drywell wall and the primary containment wall. The SP could provide a means to condense the steam released in the drywell as a result of a LOCA (Loss of Coolant Accident) or the steam discharged through quenchers from safety/relief valves operation. The Mark III arrangement uses horizontal vents to conduct steam from a LOCA into the SP. The drywell is penetrated by a series of 27.5-inch inside diameter horizontal openings at three specific levels. At each level, 34 horizontal vents are evenly distributed at the circumference of the drywell wall. Thus, there are 102 horizontal vents in total. The vent annulus is between the inner drywell wall and the weir wall. The large single-receiver volume of the drywell and the single flow area of the vent annulus ensure uniform distribution of steam to all horizontal vents.

When a LOCA occurs, a buildup of pressure in the drywell will force the water down in the vent annulus. When the water level decreases down to the upper row of horizontal vents, the steam is conducted through the horizontal vents into the SP and condensed. If the drywell pressure is high enough, the water level in the vent annulus continues to decrease, and then clears the middle and bottom rows of horizontal vents. Immediately following the clearing of the horizontal vents, a mixture of drywell air and blowdown steam leaves the drywell and enters the SP. The steam will condense in the pool water but the non-condensable air will form a bubble underneath the pool surface, resulting in a significant upward displacement of the pool level. When the bubbles break through the pool surface, a large amount of water is expelled upward in the form of a two-phase mixture of air and water. This spray mixture is expelled upward until it reaches the hydraulic control unit (HCU) floor elevation, which represents a point of flow restriction for the spray mixture. The air space between the HCU floor and the SP surface is called the wetwell.

In Kuosheng FSAR [3], there are four key design parameters which the calculated results should be less than, shown as follows with design values in parentheses: the primary containment design pressure (205 kPa), primary containment design temperature (366 K), drywell design pressure

(291 kPa), and drywell design temperature (439 K). The first two parameters will be considered in a long-term analysis, and the other two in a short-term analysis. Also, the SP temperature associated with the operation of RHR (Residual Heat Removal) pumps is considered in the long-term analysis. Adequate NPSH (Net Positive Suction Head) should be ensured and has been calculated in FSAR, which was based on the maximum SP temperature of 373 K.

2.2 Containment thermal-hydraulic modelling

In this study, the GOTHIC code was used to establish the model of Kuosheng containment. The model comprises several control volumes and boundary conditions connected by flow paths (i.e., junctions). Mass, energy, and momentum conservations of the gas phase (steam and air), liquid, and drop phases are solved during the simulation. Due to the transient nature, two different models were built, the short-term and long-term models. Figs. 2 and 3 are the schematics of short-term and long-term models, respectively. The former is used for the analysis of the drywell P/T responses, which starts from the opening of the LOCA and lasts until 100 seconds; the latter for the analysis of the primary containment P/T responses, and the SP temperature response, which starts from the LOCA and lasts until 72 hours. The drywell is modeled as a single control volume. The vent annulus, horizontal vents, suppression pool are modelled as subdivided control volumes. Fig. 4 shows the detailed subdivided volume diagram of the SP containing a liquid region with nine levels at the bottom and an air space (i.e., the wetwell) with one level at the top. It indicates the different initial water levels for the short- and long-term models according to Kuosheng FSAR [3].

The purpose of the short-term analysis is to calculate the peak pressure and temperature of the drywell. The RPV and ECCS (Emergency Core Cooling System) are not included in the short-term model since the peak P/T of the drywell occurs within one hundred seconds after LOCA, during which the ECCS is still not actuated. The flow rate and enthalpy of the blowdown flow come from FSAR. The blowdown information is then applied to the short-term model as boundary conditions shown in Fig. 2.

The ECCS of the Kuosheng power plant contains one High Pressure Core Spray (HPCS) system, one Low Pressure Core Spray (LPCS) system, one Automatic Depressurization System (ADS), and three Low Pressure Coolant Injection (LPCI) systems. The RHR system contains three independent loops, two of them equipped with a heat exchanger for each.

The purpose of the long-term analysis is to find the peak temperature of the SP and the peak pressure and temperature of the primary containment. No initial detailed blowdown information is required since the desired physical values above occur in tens of thousands seconds after the LOCA. Thus, one simplified single volume representing the RPV is included in the long-term model, referred to Fig. 3. The blowdown flow rate is calculated by a built-in homogeneous equilibrium model in GOTHIC. For conservatism, the heat sinks in the long-term model are the SP and the RHR heat exchanger cooling water; the heat sources are the decay heat and the ECCS pump heat. After the reactor scram occurs, the decay heat is generated continuously and is dissipated into the reactor coolant. The heated coolant flows through the break into the drywell, the vent annulus, horizontal vents, and finally into the SP. The SP water is suck into the RHR pump, cooled by the RHR heat exchanger and then discharged back to the SP. It is assumed the RHR pump and heat exchanger are actuated manually 30 minutes after the LOCA. For

conservatism, one heat exchanger is assumed to be inoperable; as a result, the calculated peak temperatures of the SP and the containment will be higher.

2.3 Assumptions and initial conditions

Main assumptions used in the simulation are described as follows. The initial thermal power is 3,039 MWt, equivalent to 105.1 % OLTP (Original Licensed Thermal Power). Heat generation rate of 232,112 W for metal-water is included. The effective accident break area of MSLB is 0.2068 m², with the break type of an instantaneous guillotine rupture at discharge side of the recirculation pump. The single failure effect is applied with two LPCI's, one HPCS and six ADS's available. During the simulation, only one vacuum breaker is operable.

2.3.1 Assumptions for the short-term analysis

The RPV is not included into the computation domain. The blowdown flow is provided by Kuosheng FSAR, with liquid and steam separated. The suppression pool cooling mode of the RHR system is not considered. The simulation duration is 100 seconds.

2.3.2 Assumptions for the long-term analysis

The blowdown flow is calculated by built-in Homogeneous Equilibrium Model of GOTHIC with a simplified RPV volume. The blowdown flow discharges from both broken ends of the recirculation line. The other break side is closed by MSIVs immediately after the LOCA. The RHR system (suppression pool cooling mode) is actuated 30 minutes after the LOCA. Two RHR pumps and one RHR heat exchanger are assumed to be in operation. The vacuum breaker is actuated when the drywell differential pressure is below -3,447 Pa (i.e., the DW pressure is 3,447 Pa lower than the RB pressure) .

2.3.3 Initial conditions

The initial conditions are summarized as follows. Drywell pressure, temperature and humidity are 101 kPa, 330 K, and 50%, respectively. Primary containment pressure, temperature, and humidity are 101 kPa, 311 K, and 50%, respectively. Suppression pool temperature is 311 K. The suppression pool levels of the short- and long-term are 5.91 m and 5.76 m, respectively. The air spaces of the drywell and primary containment are filled with air initially.

3. Results and discussions

3.1 Short-term P/T responses

Immediately following the rupture, the high-energy fluid rushes into the drywell, resulting in an abrupt increase in the drywell pressure. This increasing pressure forces the water in the vent annulus to be expelled through horizontal vents and into the SP. Fig. 5 is the comparison of the calculated short-term pressure responses of the drywell (DW), wetwell (WW), and reactor building (RB; i.e., primary containment), and those in FSAR. It indicates similar trends between the calculated results and those in FSAR. As shown in Fig. 5, the DW pressure increases sharply

to a maximum of 234.3 kPa (at 1.5 seconds), which is slightly higher than the peak DW pressure of 233.7 kPa (at 1.2 seconds) in FSAR and far lower than the design value of 291 kPa. Meanwhile, the top horizontal vents (Top HV) have been cleared completely at 1.5 seconds, and the middle horizontal vents (Mid HV) and bottom horizontal vents (Bot HV) are cleared partially, guiding the high-energy fluid into the SP and then causes the water level of the SP to rise gradually (see Fig. 6). Also, the water level change of the vent annulus (VA) is also observed. Accordingly, the DW pressure is released; however, it is still high enough to support the static head of the SP, with horizontal vents remaining cleared. The calculated peak value of the WW pressure bump is about 147.7 kPa (at 2.5 seconds), which is higher than the wetwell pressure of 124.9 kPa (at 2.5 seconds) in FSAR. The HCU floor represents a point of flow restriction and reduces the flow vented from the volume beneath the HCU floor (i.e., the wetwell). Since the DW venting process continues for the first 10 seconds of the blowdown transient, the resulting air flow mismatch caused a transient pressurization of the wetwell. Fig. 7 shows the comparison of the short-term responses of the calculated DW temperature and SP temperature, and those in FSAR. The calculated SP temperature curve shows a good agreement with the FSAR result. Though there is a little discrepancy between two DW temperature curves, the peak calculated result of 402.6 K is still below the design value of 438.7 K.

In general, the calculated results are fairly consistent with the FSAR results analyzed by the M3CPT code by GE. In Fig. 5, the discrepancy existing between the calculated results and the FSAR results might be caused by different nodalisation of the models. For example, the HCU floor is only described as a flow restrictor and its structure is not declared clearly in FSAR. In addition, each level of the horizontal vents was divided into five cells in this simulation, instead lumped into a single control volume in the FSAR.

3.2 Long-term P/T responses

In the long-term analysis, a simplifier RPV control volume was used to calculate the blowdown flow. The decay heat was calculated based on ANS-1971 plus 20 %. Two LPCI pumps are actuated when the RPV level reaches L1 level [5] and one of them switched to the operation of RHR suppression pool cooling mode at 1,800 seconds.

Fig. 8 shows the long-term calculated RB pressure and DW pressure (No relevant figure available in FSAR). The peak RB pressure of 144 kPa (at 49,716 seconds) is lower than the FSAR result of 157 kPa and far lower than the design pressure of 205 kPa. The condensation of the steam in the drywell causes the drywell pressure to decrease gradually and below the RB pressure at about 1,250 seconds. To avoid excessive external pressure upon the drywell, a vacuum break between the drywell and the RB actuates to release the pressure differential and keep it within 3,447 Pa for the rest of the simulation. The jagged portion on the DW pressure curve in Fig. 8 indicates the actuation of the vacuum breaker.

Fig. 9 shows the long-term calculated RB temperature and SP temperature. The corresponding RB and SP curves are not available in FSAR, and only the peak values of 353 K are presented. The peak RB temperature of 349 K (at about 53,216 seconds) is below the design value of 366 K, with a considerable margin. The SP temperature is the effective temperature contributed by three phases (vapor, liquid, and drop). The calculated peak SP temperature of 356 K (at about

17,205 seconds), slightly higher than the FSAR result (353 K) , is below the temperature (373 K) on which the NPSH calculation is based.

In addition, a sudden increase in the SP temperature at about 880 seconds was observed, which resulted from an overflow flowing from the drywell over the weir wall, into the vent annulus, and then into the SP. The overflow came from the recirculation line break after cooling the fuel core, which was provided by HPCS and LPCI pumps sucking the SP water. However, the rise of the RB temperature starts around 1,100 seconds, in which heat takes time to transfer from the SP to the RB. Besides, the ramp slope of the SP temperature decreased at about 1,800 seconds due to actuation of the RHR heat exchanger.

4. Summaries

In this study, the P/T responses of Kuosheng Mark III containment to the recirculation line break analyzed using the GOTHIC code are presented. The power used is 3,039 MWt (equivalent to 105.1 % OLTP), falling the category of the range of SPU. The calculated peak pressures and temperatures of the drywell and primary containment, and the corresponding results analyzed using the M3CPT code in FSAR are summarized in Table 1.

In the short-term analysis, the calculated peak DW pressure is 234.3 kPa, slightly higher than the FSAR result of 233.7 kPa and far lower than the design value with a considerable margin of 56.7 kPa. The calculated peak DW temperature of 402.6 K is slightly higher than the FSAR result of 392.6 K; however, its impact on the drywell structure is negligible due to its short duration. Besides, the peak WW pressure of 147.7 kPa, higher than the FSAR result of 124.9 kPa, could also be simulated with a similar trend. The phenomenon of vent clearing is also obviously observed in this simulation.

In the long-term analysis, the calculated peak RB pressure of 144 kPa is far lower than the FSAR result of 204.8 kPa with a considerable margin. Similarly, the calculated peak RB temperature is 349 K, far lower than the FSAR result of 353 K. Additionally, the calculated peak SP temperature is 356 K, below the temperature (373 K) on which the NPSH calculation of the RHR pumps is based.

5. Conclusion

From the above comparisons, we can state that the GOTHIC code has the capacity for simulation of P/T responses of the Kuosheng BWR/6 Mark III containment to the recirculation line break LOCA and the simulation results could be served as an analysis reference for an SPU project in the future.

6. References

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- [2] WNA (World Nuclear Association), “Nuclear Power in the USA”, < www.world-nuclear.org/info/inf41.html>”, 30 September, 2010.

- [3] Taiwan Power Company, “Final Safety Analysis Report-Kuosheng Nuclear Power Plant Units 1 and 2”, 2007
- [4] A. Lin, J.R., Wang, R.Y., Yuann, and C. Shin, “Kuosheng BWR/6 containment safety analysis with GOTHIC code, Proceedings of ICON19, Chiba, Japan, May 16-19.
- [5] AREVA NP Inc, “Guideline of Generating Principal Plant Parameters for Reload Licensing Analyses of Kuosheng Unit 1 and 2” , 2009.

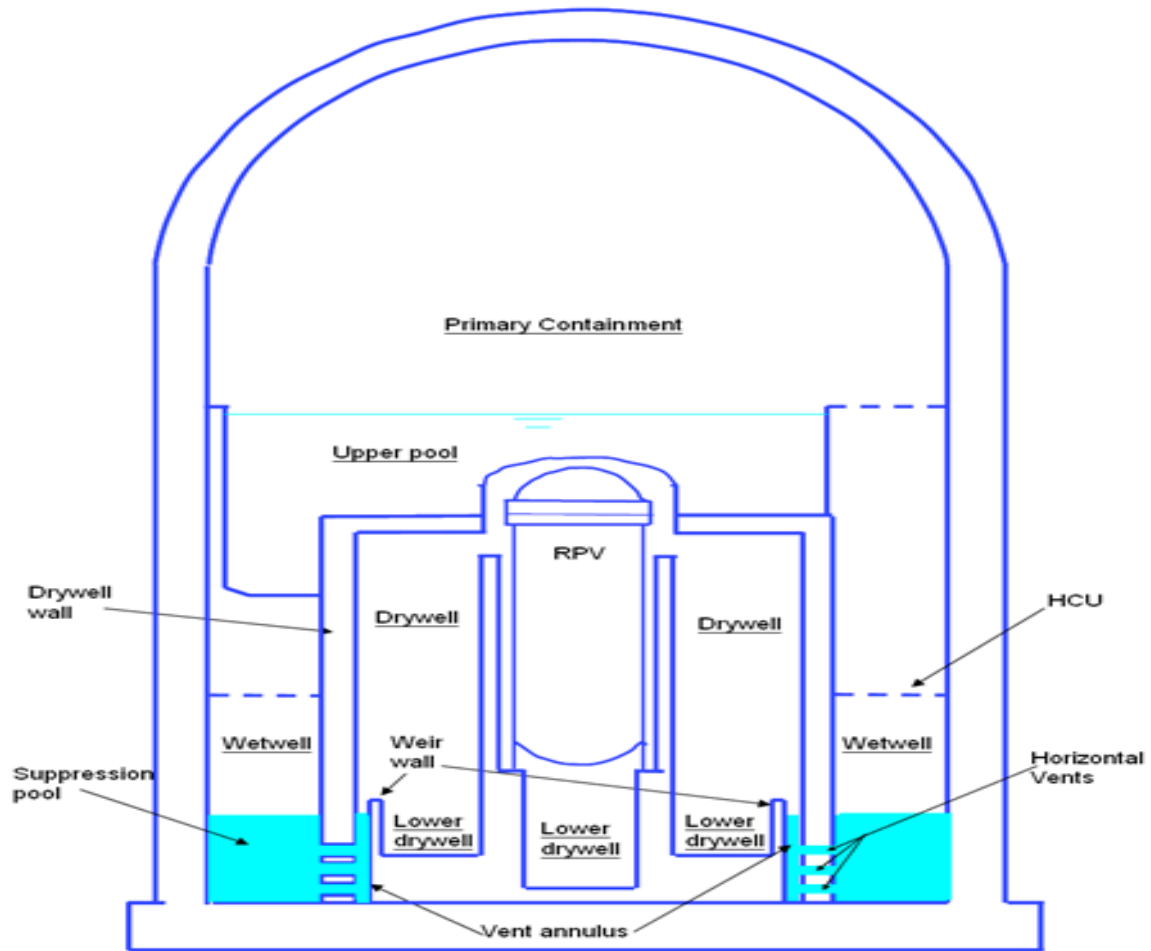


Fig. 1 Schematics of Kuosheng Mark III containment

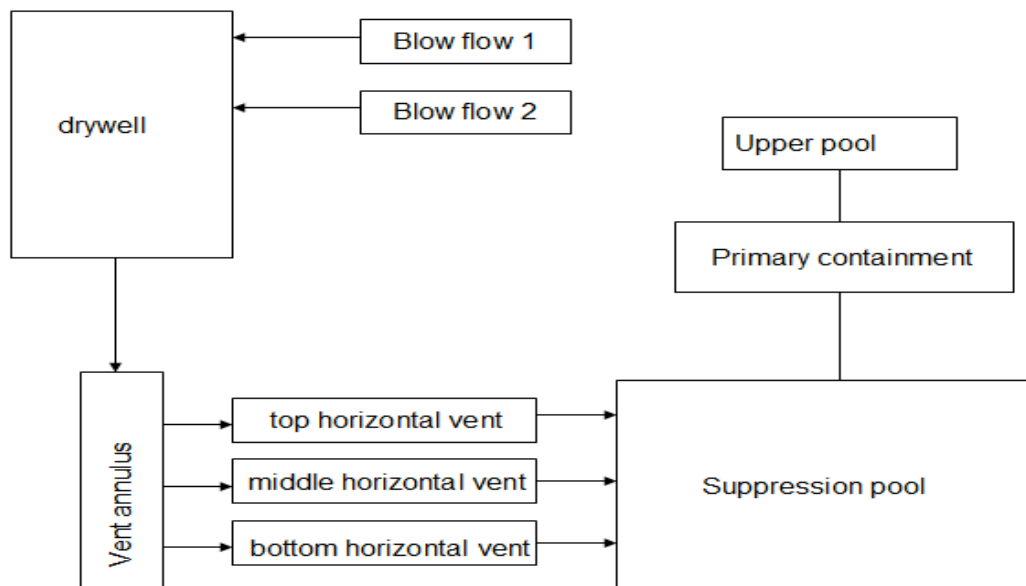


Fig. 2 Schematics of the short-term model

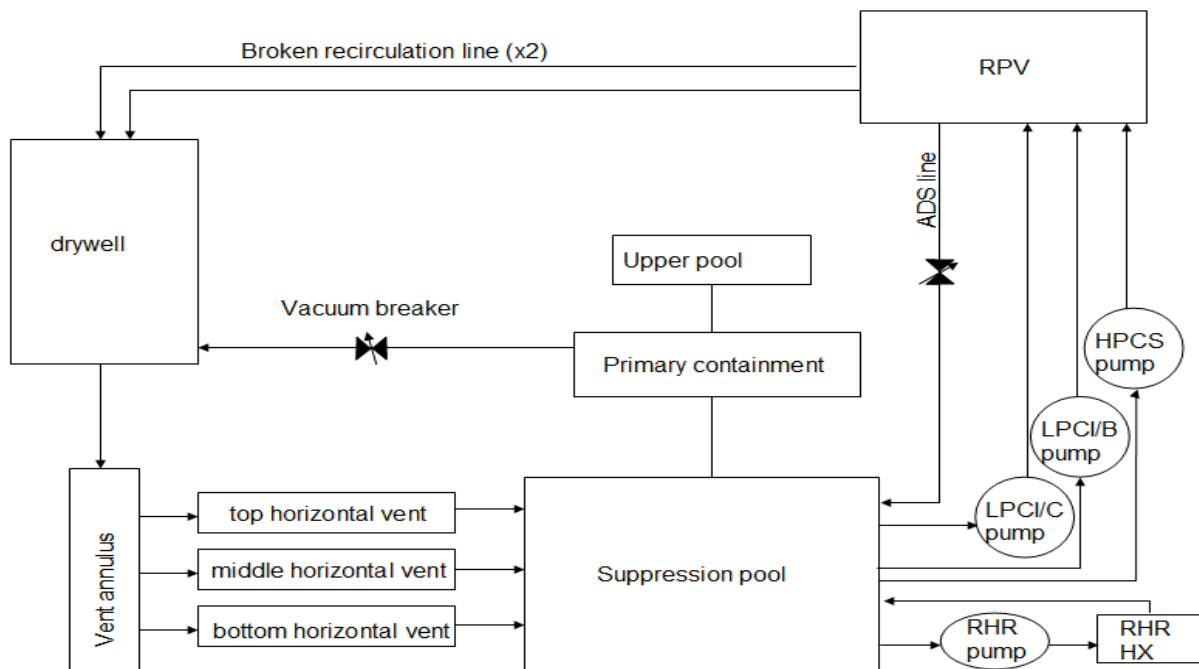


Fig. 3 Schematics of the long-term model

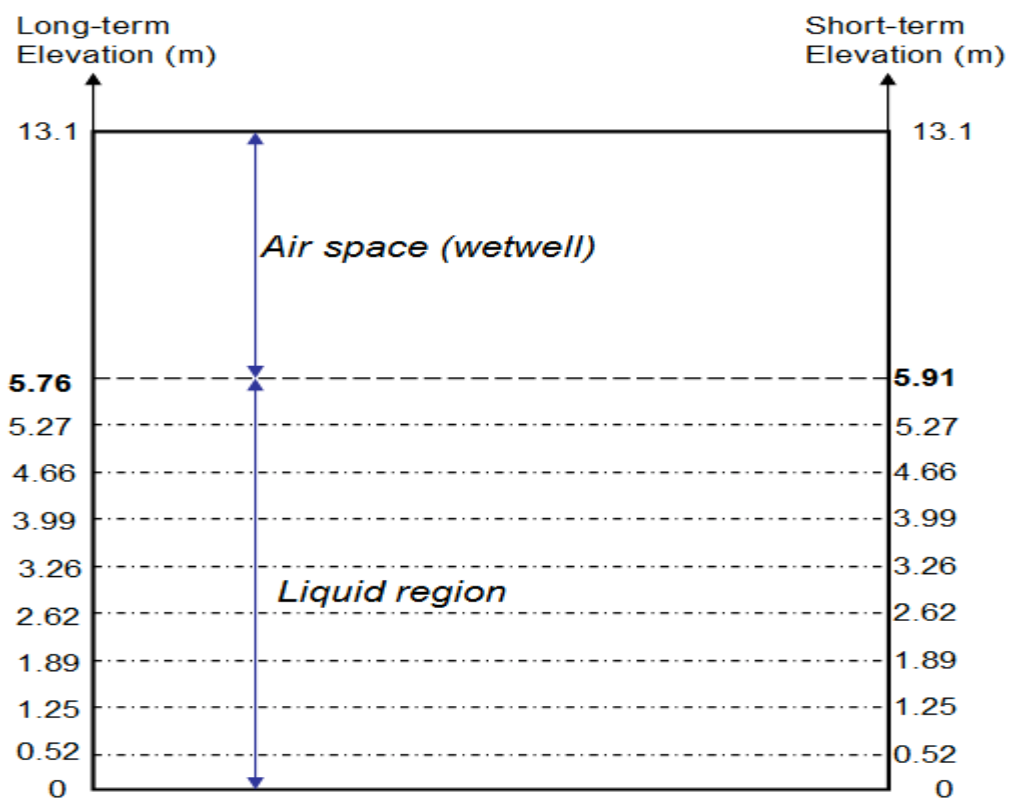


Fig.4 The detailed subdivided volume diagram of the suppression pool

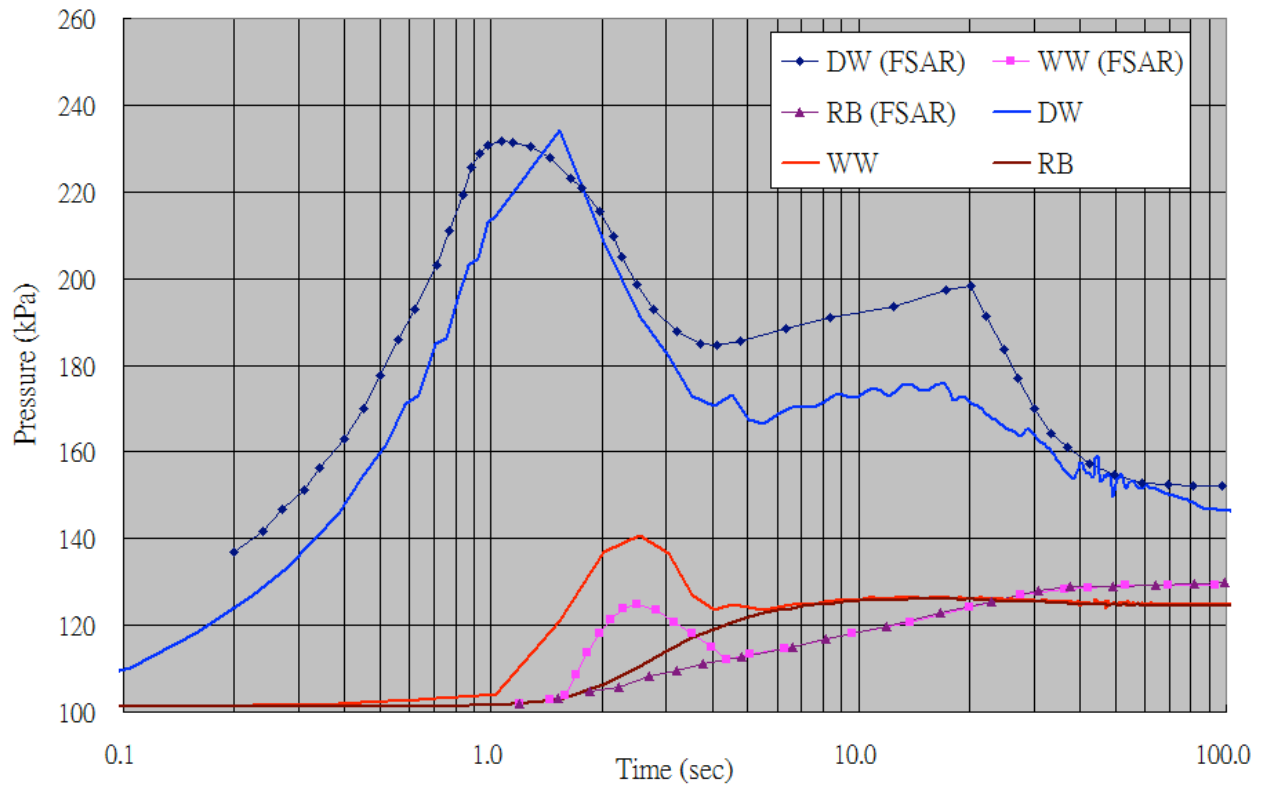


Fig. 5 Comparison of the calculated short-term pressure responses and those in FSAR

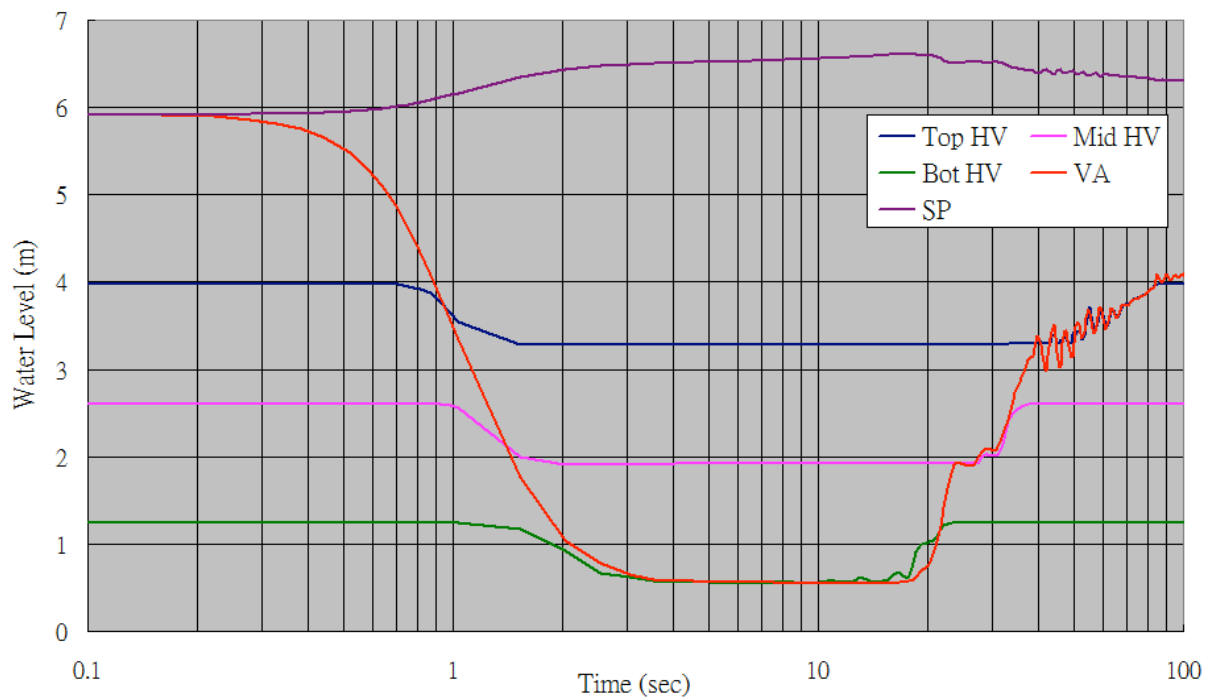


Fig. 6 Water levels of the horizontal vents, vent annulus and suppression pool

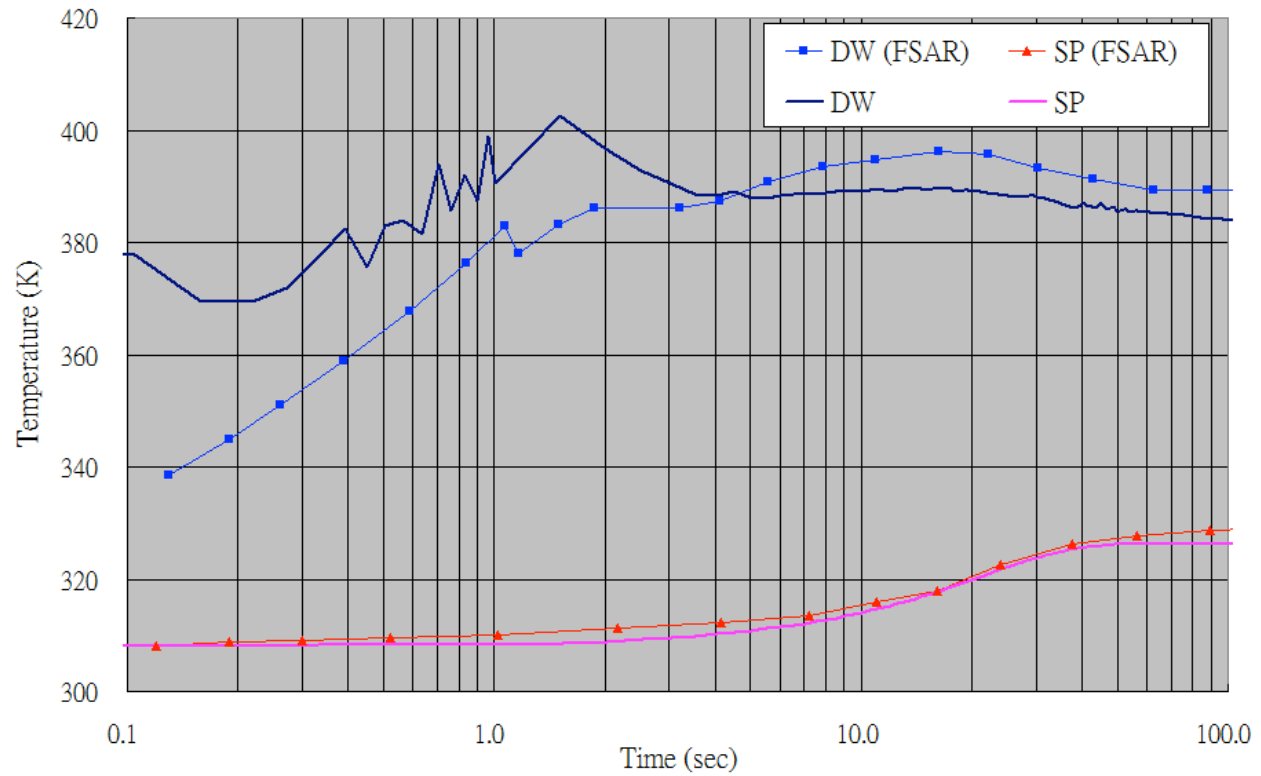


Fig. 7 Comparison of the short-term temperature responses of the calculated results and those in FSAR

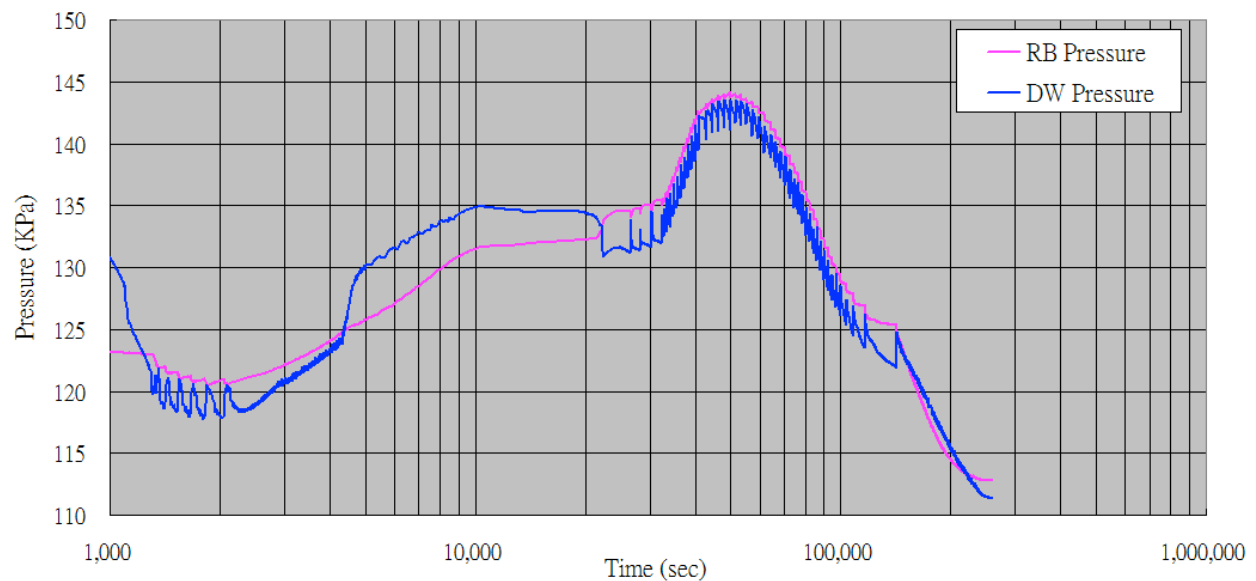


Fig. 8 The long-term calculated RB pressure and DW pressure

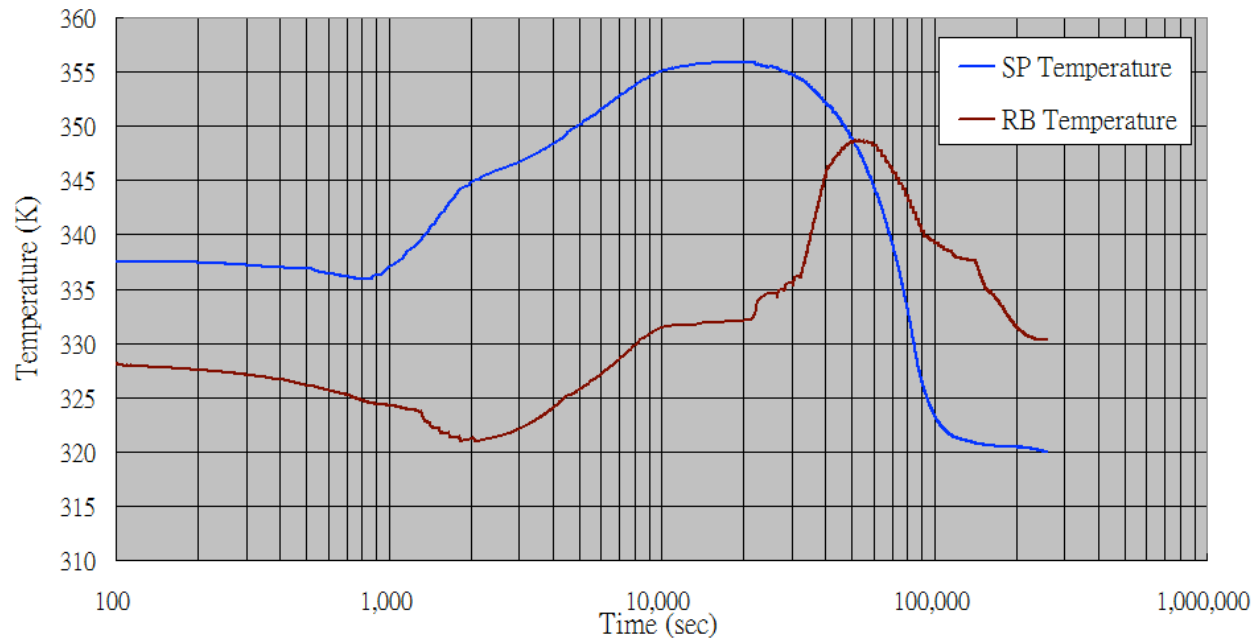


Fig. 9 The long-term calculated RB temperature and SP temperature

Table 1 Peak values of P/T of the DW and RB

	FSAR	GOTHIC	Discrepancy
Peak drywell pressure (kPa)	233.7	234.3 (1.5 sec.)	0.6
Peak drywell temperature (K)	396.1	402.6 (1.5 sec.)	6.5
Peak reactor building pressure (kPa)	157	144 (49,716 sec.)	-13
Peak reactor building temperature (K)	353	349 (53,216 sec)	-4