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Effect of Air Temperature on Failure Prognosis of Passive Containment Cooling System in AP1000

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Passive Containment Cooling System is innovatively used in AP1000 reactor design in order to enhance the safety of new generation nuclear power plant. Since the system operation is based on natural circulation and air is the cold source, so physical process failure becomes one of the important failure modes, which should be considered in system failure prognosis, and air temperature has important effect on system failure probability. In this paper, Monte Carlo (MC) simulation is used to evaluate the system physical failure probability based on air temperature probability distribution, and the effect of air temperature probability distribution on failure modes and probability is analyzed under different system component configurations, the results of pressure distribution in the containment based on air temperature distribution are also gained.

1. Introduction

In recent years, especially after Three-Miles Island accident, probabilistic safety assessment (PSA) is developed wider and wider to enhance the safety of nuclear power plant (NPP). By this method, the risk raised by the NPP can be evaluated, moreover, the weak part in the design can be diagnosed and improved, and prognosis of system failure modes and probability is one of the important parts of PSA. In order to improve the safety of new generation nuclear power plant, passive containment cooling system is innovatively used in AP1000 reactor design (Schulz,2006), which is an important safety-related system. By this system heat produced in the reactor can be transferred to the heat sink – atmosphere depending on natural circulation, but not on the human behaviors or the operation of other equipments (Foret, 2003a and Winters, et al. ,2004). However, since the system operation is based on natural circulation, physical process failure (Zio and Pedroni, 2009 , Oh and Michael, 2008) – natural circulation cannot establish or keep – becomes one of the important failure modes, which should be considered in system failure prognosis. As it is well known, the driving force of the natural circulation is the density difference between the hot and cold fluid, so the temperature uncertainties of the heat source and heat sink have important influence on the system operation.

For the passive containment cooling system in AP1000, as atmosphere is the heat sink, so uncertainty (Zio, et al. , 2008) in air temperature has important effect on the system failure modes and probability. And for the containment design, if the pressure in the containment exceeds the design value, the containment will fail. So in this paper, the variety of the pressure in the containment according to the air temperature varying is analyzed firstly, and then the physical process failure probability under different system configurations is evaluated with Monte Carlo (MC) simulation.

2. System description

The passive containment cooling system(Foret, 2003a) in AP1000 is a safety-related system that functions to reduce containment temperature and pressure following a loss-of-coolant accident (LOCA) accident, a main steam line break (MSLB) accident inside containment, or other events that cause a significant

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increase in containment pressure and temperature. The system achieves this by removing thermal energy from the containment atmosphere to the environment via the steel containment vessel. The flow chart of the system is shown in Figure.1(Foret, 2003a).

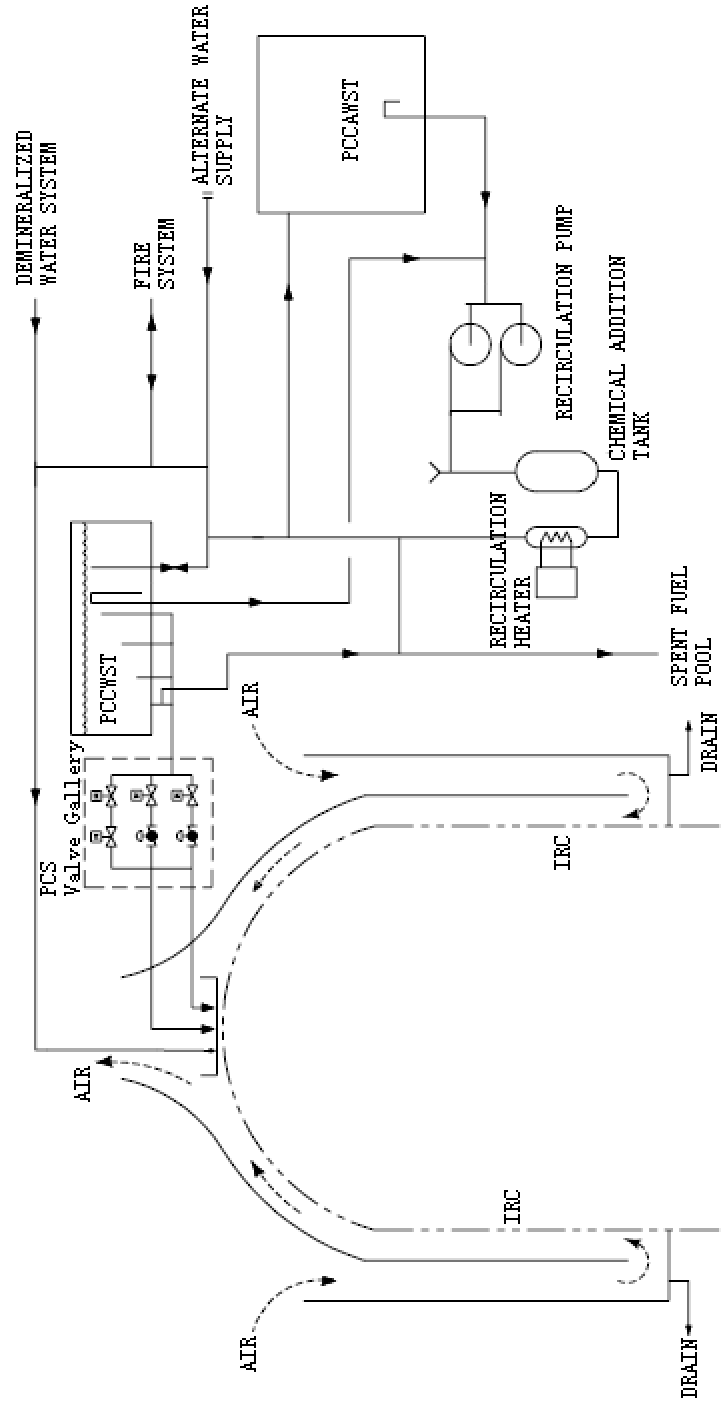


Figure.1 Flow chart of passive containment cooling system

Surrounding the containment, there are the steel containment vessel and the concrete shield building. And the passive containment cooling system is composed of following major components: the passive containment cooling water storage tank (PCCWST) which is incorporated into the shield building structure above the containment; air baffle, located between the steel containment vessel and the concrete shield building, which defines the cooling air flow path; air inlets and air exhaust, also incorporated into the shield building structure; and a water distribution system, mounted on the outside surface of the steel containment vessel, which functions to distribute water flow on the containment. The passive containment cooling system water storage tank outlet pipe is equipped with three sets of redundant isolation valves. In two sets, air-operated butterfly valves are normally closed and open upon receipt of actuation signals. The third parallel supply line contains a normally closed motor-operated valve. And each valve fails open on loss of power or loss of air. In addition to these normally closed valves, there is a normally open motor-operated valve in each of the three lines.

3. System reliability analysis

3.1 System failure modes

The system failure can be induced by equipment default and physical process failure, and part of the equipments failing may increase the failure probability of the physical process. For the system described in section 2, the air inlets are composed of three rows of air inlet holes, one or two rows failure may result in the decreasing of heat transfer capability. So in this paper, the effect of the air temperature on the system reliability is analyzed in three conditions:

- All the three rows of air inlet holes work well
- One of the three rows of air inlet holes fail
- Two of the three rows of air inlet holes fail

3.2 Success criteria

Since the design value of the containment pressure is 0.4 MPa, and if the pressure in the containment is beyond this value, containment failure is considered to happen, that is, the leak rate of the containment is inacceptable. So output of the thermal-hydraulic model is the pressure in the containment and the success criteria is:

$$P < 0.4\ MPa \tag{1}$$

3.3 MC simulation

MC simulation(Siu,1994 and Zhao et al., 2008) is powerful method to deal with the uncertainty problems, in this paper, the air temperature is sampled based on the probability density distribution. In each round of simulation, and then the system state can be calculated, after enough times of simulation, the system failure probability can be gained. The flow chart of MC simulation is shown in Figure.2.

4. Results

4.1 Residual heat analysis

As the heat source, residual heat power is another important effect factor of the system reliability. After reactor trips, the decay heat will drop rapidly in a short time and then tend to be stability. In this paper, the steady thermal-hydraulic model is used, so only the long time cooling phase is analyzed, the dynamic process is not included. The residual heat power is shown in Table 1 (Zhang, 2012).

Table 1: Residual heat power

Time (after reactor tripping)	Residual Heat (% full power)
1 s	6.5
10 s	5.1
100 s	3.2
1000 s	1.9
1 h	1.4
10 h	0.74
100 h	0.33
1000 h	0.11
8760 h	0.023

From Table1, it can be seen that the residual heat power will drop to about 0.74 percent of full power in 10 hours following reactor tripping, and then drop to about 0.33 percent of full power in the successive 90 hours. In the present, more attention is paid to the risk in 24 hours after initial event happens, and from the 10 to 24 hours after reactor trips, the residual heat power is about 0.61 % ~ 0.74 % full power, which is a relative steady curve, so the mean value of 0.68 %full power is used in the analysis of this paper.

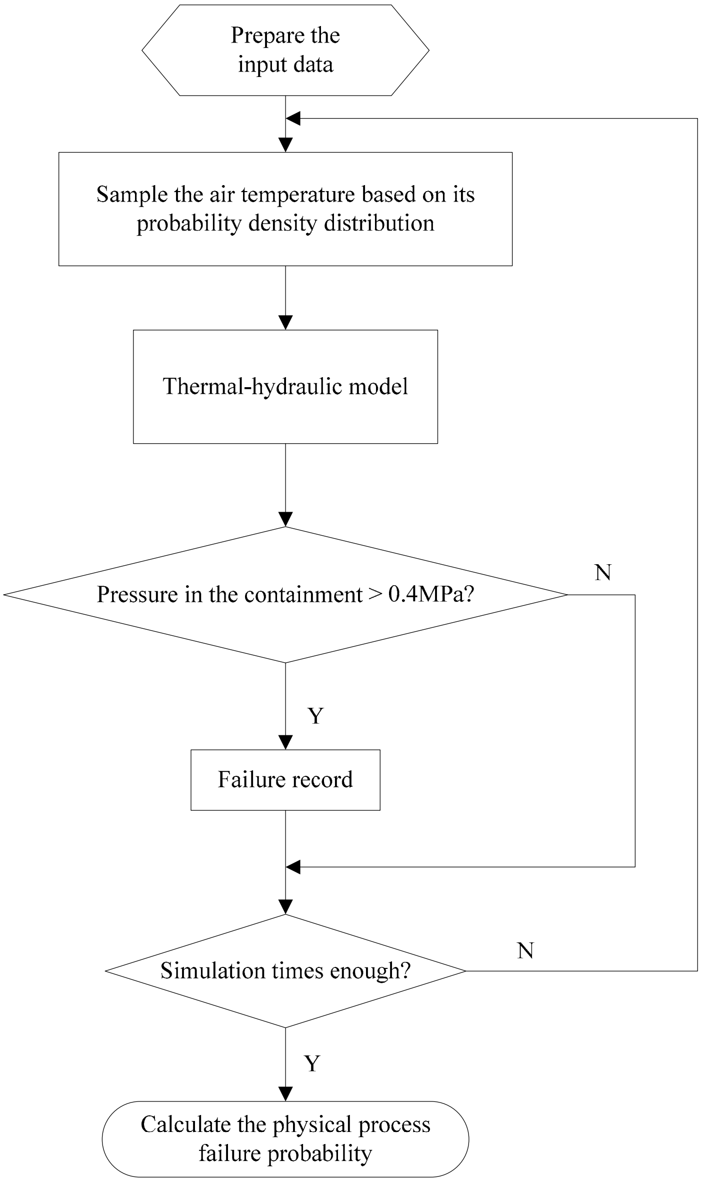


Figure.2 Flow chart of the MC simulation

4.2 Air temperature distribution

As the heat sink, a quite conservative value is used in the system design, such as the highest air temperature appearing in the thousand years. However, for the system reliability analysis, the real air temperature distribution should be considered, the probability density distribution shown in Figure.3 is used as an example in the analysis of this paper.

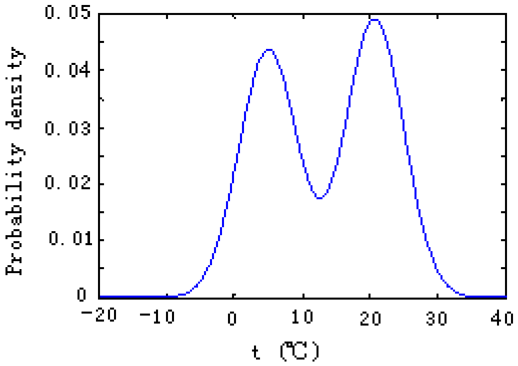


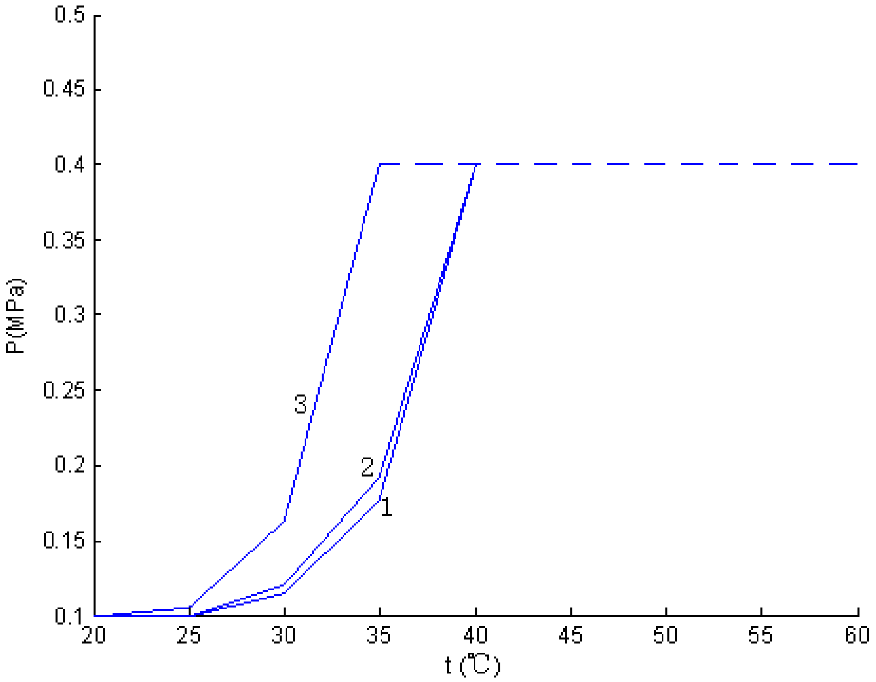
Figure.3 Air temperature distribution

4.3 Pressure in the containment

From the system description, it can be seen that there are three equipment conditions for this system, the effect of air temperature is evaluated in each condition, and the results are shown in Figure.4.

In Figure.4, the abscissa is the air temperature and the ordinate is the pressure in the containment. From this figure it can be seen that if two or three of the air inlet holes work well, the pressure in the steel vessel will exceed the design base of 0.4MPa when the air temperature is about 40 ℃ or higher, and if only one row of the air inlet holes can work well, the pressure in the steel vessel will exceed the design base when the air temperature is about 35 ℃.

The results can be used in system state monitoring to predict the system risk, for example, if the temperature is more than 30 ℃, the system state is safe when all of the three rows work well while the system state is dangerous when only one of the three rows can work.



1-- All the three rows of air inlet holes work well
2-- One of the three rows of air inlet holes fail
3-- Two of the three rows of air inlet holes fail

Figure. 4 Result of the pressure in the containment

4.4 Effect of air temperature on the system reliability

Based on the air temperature distribution shown in Figure.3, the effect of air temperature on the system physical process failure is evaluated in the three conditions mentioned above. The results are shown in Table 2.

Table 2: system physical process failure probability

Equipment condition	System physical process failure probability
All the three rows of air inlet holes work well	$< 1\times10^{-5}$
One of the three rows of air inlet holes fail	2×10^{-5}
Two of the three rows of air inlet holes fail	1.4×10^{-4}

From the results, it can be seen that under different equipment conditions, the effect of the air temperature on the system functional failure probability may be different in one or more order of magnitudes. And the system failure probability induced by the equipment defaults is 1.7×10^{-5} (Foret, 2003b), so the failure probability of physical process failure and equipment defaults are comparable, the contribution to the system failure of the two parts should also be considered.

5. Conclusions

From the results of this paper, it can be concluded that atmosphere as the heat sink air temperature is an important factor which should be considered in the system failure prognosis, and the results of this paper can be used in system state monitoring to predict the system risk While in order to get the whole system failure modes and probability, distribution of some other important factors such as residual heat and the equipment failure probability should be evaluated synthetically.

Acknowledgements

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