The 14th International Topical Meeting on Nuclear Reactor Thermalhydraulics, NURETH-14
Toronto, Ontario, Canada, September 25-30, 2011

NURETH14-597

STUDY ON CONTAINMENT OVERPRESSURE FRAGILITY CURVE AND ULTIMATE LOAD FOR CPR1000

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Abstract

Based on the results of international researches and design feature, the CPR1000 containment model was built with FEA method and the ultimate load was analysed. Besides, the uncertainties of main design parameters was identified and quantified and then the containment over-pressure fragility curves for CPR1000 were obtained with PSA method.

Introduction

The reactor containment serves as the last confinement barrier for fission products and it plays a crucial role to the nuclear safety. It is of great importance to study the ultimate pressure and overpressure fragility curve of containment for PSA level 2 and severe accident management Guideline research in nuclear power plant.

Without the research of containment overpressure fragility curve, the opening pressure(design pressure, 0.42Mpa(g)) of CPR1000 containment filtration and exhaust system(EUF) is lower than other similar nuclear power plants. It may result in a risk of earlier opening of EUF and radioactive release in severe accidents.

So, it is necessary to analyze containment overpressure failure probability and ascertain the reasonable opening pressure of EUF. With higher opening pressure, the opening time of EUF will be postponed and the activity release to the environment will be lower.

1. CURRENT RESEARCH SITUATION

The research of prestressed concrete containment has been conducted since 1960's around the world especially in the accident. EDF studied the linear & non-linear structure and leakage of 1:3 scale prestressed concrete containment model in 1997, Karlsruhe University studied concrete cracking by uniaxial tension and measured the leakage rate, Sandia National Laboratories(SNL) has been conducting research of large scale containment model in the past 20 years. A 1:6 scale prestressed concrete containment model was studied in 1986, an axisymmetric 3-dimentional finite element model is built and studied the failure behavior of a 1:4 scale prestressed concrete containment model. Zion, Surry and Robinson plants have completed the research of containment over-pressure fragility curve. The third generation nuclear power plants, for example, the EPR and AP1000, have also completed the research of containment over-pressure fragility curve and the achievements were applied to PSA level 2.

In China, the containment ultimate pressure have been studied by some research institutes, but the research of over-pressure failure probability with PSA method has not been conducted.

2. DESIGN FEATURE OF CPR1000 CONTAINMENT

The containment structure consists of a vertical prestressed concrete cylindrical wall which is closed at the bottom by a reinforced concrete slab and at the top by a torispherical prestressed concrete dome. The internal surface of the structure thus formed is covered entirely by a leaktight steel liner.

The containment dimensions provide the necessary free volume compatible with the hypothetical loss of coolant accident and sufficient space is available for a polar crane to handle the most cumbersome items of equipment. The inner diameter of the liner is 37 m. The inner height of the cylinder is approximately 54 m.

The thickness of the vertical concrete wall of the containment is approximately 0,90 m (except for some local areas where the thickness is increased). The concrete dome is 0,80m thick.

3. CPR1000 CONTAINMENT OVERPRESSURE FAILURE PROBABILITY

At present, generally there are 3 steps to study containment overpressure failure probability and ascertain opening pressure[2, 3].

1) Best estimate of containment structure response behavior. Identify important potential failure mode, anticipate the failure pressure and position, the failure mechanism and the size of break;

2) Determine containment overpressure fragility curve. Identify and quantify the uncertainties of main design parameters of containment, determine containment overpressure fragility curve with PSA method;

3) Determine the opening pressure of EUF. According to the achievements of containment overpressure fragility curve, select the pressure which has a lower failure probability as the opening of EUF. This chapter emphatically analyses the containment overpressure failure probability and recommend an opening pressure of EUF.

According to the experimental researchs of containment response behavior with different loads[1], SNL concluded that the leak/rupture cylinder wall is the main failure mode for large dry prestressed containment, therefore, a simplified hand calculation can be used to estimate the containment ultimate pressure.

Table 1 gives the main parameters of containment used in ultimate pressure analysis.

Table1 parameters of containment used in ultimate pressure analysis

parameters	meaning	parameters	meaning
ρ	reinforcement ratio	$\rho_{hoop,rebar} = \rho_{hr}$	reinforcement ratio of rebar
ρ_{liner}	reinforcement ratio of liner	$\rho_{hoop,tendons} = \rho_{ht}$	reinforcement ratio of rendons
t_{liner}	thickness of liner	t_{eq}	equivalent concrete thickness
t_c	thickness of concrete wall	$\sigma_0(concr)$	compressive concrete stress after prestressing
R	Inside radius of cylinder	$E_{rebar}, E_{c,} E_{liner}$	Young's Moduli of rebar, concrete, and liner,

			respectively
ε_{cr}	Concrete cracking strain	ε_{ry}	rebar yield strain
$\sigma_{bar,ult}$	rebar ultimate strength	$\sigma_{tendon,ult}$	tendon ultimate strength

Pressure at Which Cylinder Stress Overcomes Prestress, Po

The equivalent concrete thickness can be obtained from the following equation:

$$t_{eq} = (1 + \frac{E_{rebar}}{E_C}\rho_{hoop,rebar} + \frac{E_{liner}}{E_C}\rho_{\text{liner}})t_c \tag{1}$$

The total reinforcement ratio can be obtained by equation 2:

$$\rho_{total} = \rho_{hoop,rebar} + \rho_{liner} + \rho_{hoop,tendons} \tag{2}$$

The compression under tendon action is calculated as follows:

$$\sigma_0(concr) = -\rho_{tendon}\sigma_{itendon} \tag{3}$$

The pressure at which cylinder stress overcomes prestress is given by equation 4:

$$p_0 = \frac{-\sigma_0 t_{eq}}{R} \tag{4}$$

Cylinder Hoop Cracking Pressure, Phc

The total equivalent t including tendons is obtained from the following equation:

$$t'_{eq} = \left[1 + \frac{E_{steel}}{E_c}\rho_{total}\right]t_c \tag{5}$$

Then, the cylinder hoop cracking pressure is obtained by equation 6:

$$P_{hc} = \frac{t'_{eq}E_c\varepsilon_{cr}}{R} + P_0 \tag{6}$$

Pressure at Rebar Yield, Ply,Pry

Assuming the tendons have not yielded, the hoop stiffness after cracking is approximately that of elastic rebar, liner and tendons acting alone. Therefore,

$$\begin{aligned} P_{ly} &= \frac{\varepsilon_{ly}(\rho_{total})t_c E_s}{R} + P_0 \\ P_{ry} &= \frac{\varepsilon_{ry}(\rho_{total})t_c E_s}{R} + P_0 \end{aligned} \tag{7}$$

Ultimate Barrel Failure Based on Ultimate Strengths of Steel Components, Pult

The ultimate barrel failure based on ultimate strengths of steel components is obtained as

$$P_{ult} = \frac{\sigma_{bar,ult}\rho_{hr}t_c}{R} + \frac{\sigma_{tendon,ult}\rho_{ht}t_c}{R} + \frac{\sigma_{liner,ult}\rho_{liner}t_c}{R} \tag{8}$$

According to the method above, the results is obtained as follows:

1) Pressure at Which Cylinder Stress Overcomes Prestress, Po is 0.6275MPa(g)

2) Cylinder Hoop Cracking Pressure, Phc is 0.7855MPa(g)

3) Pressure at Rebar Yield, Ply, Pry is 1.0325MPa(g),1.1338MPa(g)

4) Ultimate barrel failure based on ultimate strengths of steel components, Pult is 1.3640MPa(g)

According to the researchs of SNL, the ultimate strength of rebar, tendon and liner obey lognormal distribution. The type of ultimate load is calculated and then the fragility curve is obtained. The distribution of failure probability density versus the containment pressure is shown in figure 1 and the overpressure fragility curve of CPR1000 containment is drawn in figure 2. We can see from figure2, the failure pressure at which has a 5% failure probability is 0.7936MPa(g). Taking 10% margin into account, the opening pressure for the EUF of CPR1000 can be 0.71MPa(g).

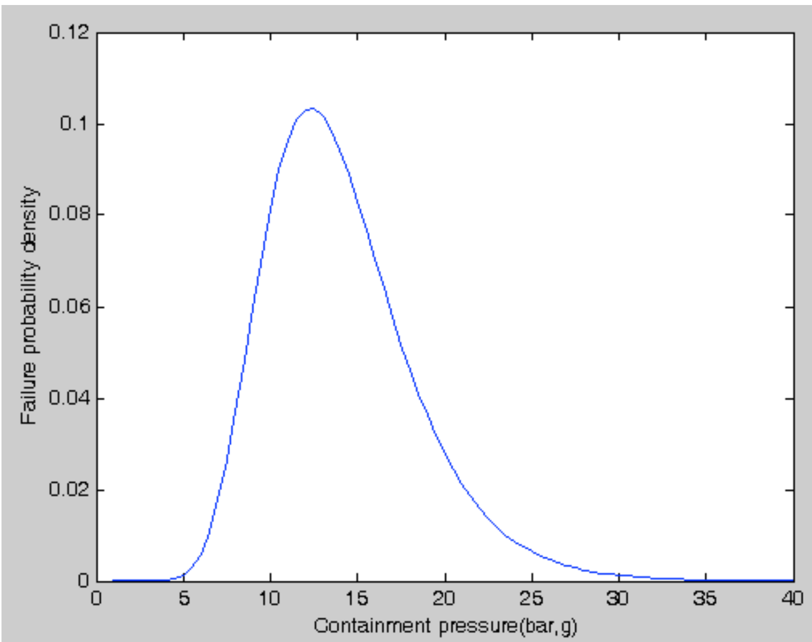

Figure 1 The distribution of failure probability density of CPR1000 containment

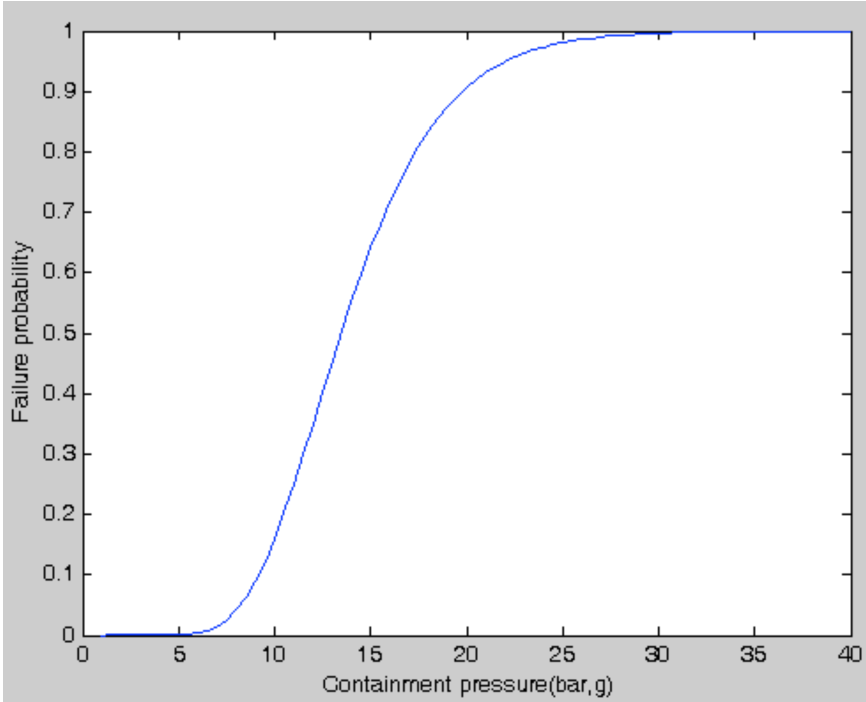

Figure 2 CPR1000 containment failure probability

4. FINITE ELEMENT ANALYSIS RESULTS

The finite element model of CPR1000 containment is built by ABAQUS including cylinder, dome, hoop, basement, buttress, equipment hatch, personal airlock hatch, steel liner, etc. By conservative assumption, the tension of the prestress tendons is kept as the initial value during the structure response.

With different internal pressure, the analysis of containment structure response has been done, the results of stress distribution of the containment with $0P_{design}$ and $1.7P_{design}$ internal pressures have been shown in figure 3 and 4. (P_{design} is the design pressure of CPR1000 containment, which is 0.42MPa)

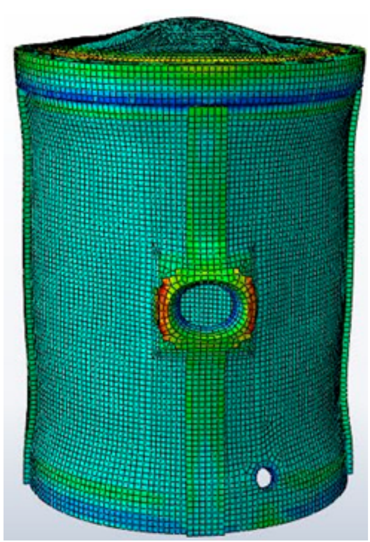

Figure 3 Stress distribution($0P_{design}$)

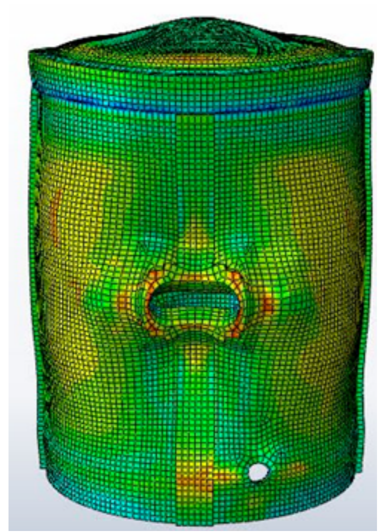

Figure 4 Stress distribution($1.7P_{design}$)

According to the analysis, with $1.7P_{design}$ internal pressures, the stress is beyond the yielding limit for about 10% percents of points in the region, but the steel liner and rebar are still elastic, the integrity of the containment is kept intact. The pressure threshold for EUF operation can increase to 0.71MPa(g).

5. IMPROVEMENT OF CONTAINMENT FILTRATION AND EXHAUST SYSTEM

The current operation condition for CPR1000 EUF system is: at least 24 hours after the beginning of the accident, when containment design pressure is reached (0.42MPa(g)). As discussed in chapter 2, the pressure threshold for EUF operation can increase to 0.71MPa(g) with low failure probability. This chapter will make radiological consequence analysis with different opening pressure for EUF, and make some comparison.

5.1 Assumption and sequences selection

Taking account of different fuel management of CPR1000(12months fuel cycle, 18month fuel cycle, 1/4 reload), the core activity inventory, decay power have been calculated by ORIGEN-S. The filtering efficiency of EUF is 100(except noble gas) and the assumed venting flowrate inside containment atmosphere is shown in Figure 5.

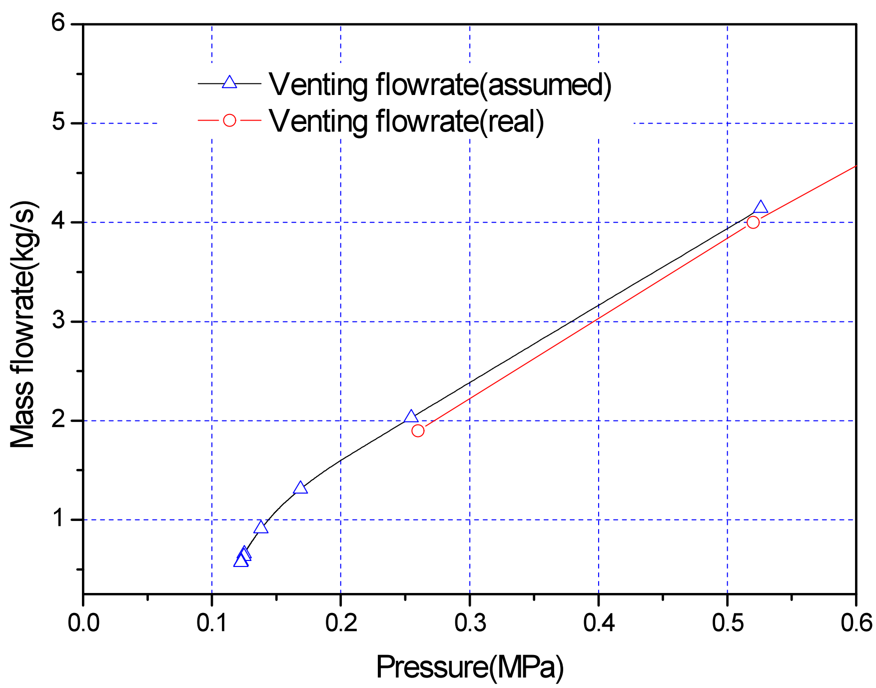

Figure5 Venting flowrate setting

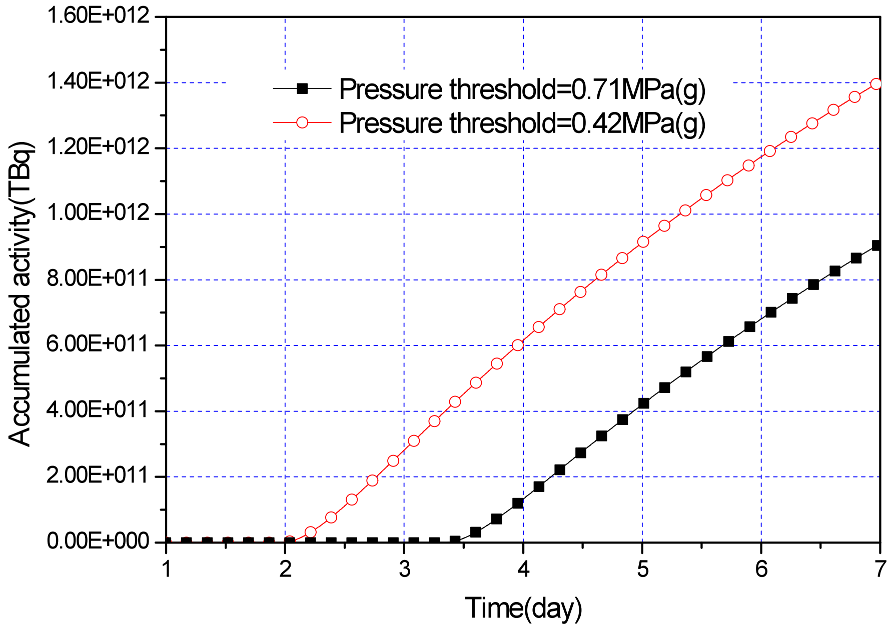

Figure6 Accumulated activity to the environment in LLOCA

5.2 Radiological consequence analysis

Five typical(LLOCA, MLOCA, SLOCA, ATWS, SBO) severe accidents has been analyzed, the results show that the opening time of the EUF is delayed about 1day and the accumulated activity to the environment is also decreased definitely with higher opening pressure. Table 2 shows the accumulated fraction of core radiological material to the environment in LLOCA(1~7days). Figure 6 shows the accumulated activity of Xe133 to the environment in LLOCA, we can see that with higher opening pressure the accumulated activity of Xe133 is about 35% lower.

Table 2 Accumulated fraction of core radiological material to the environment in LLOCA

	Xe 133(1)	Xe 133(2)	Percents	Cs 137(1)	Cs 137(2)	Percents	I 131(1)	I 131(2)	Percents
1day	0	0	-	0	0	-	0	0	-
2d	0.104421	0	0%	10^{-6}	0	0%	10^{-6}	0	0%
3d	0.958727	0	0%	$1.4*10^{-5}$	0	0%	$1.4*10^{-5}$	0	0%
4d	0.995191	0.894945	89.9%	$1.9*10^{-5}$	$3*10^{-6}$	15.79%	$1.9*10^{-5}$	$3*10^{-6}$	15.79%
5d	0.99911	0.992347	99.3%	$2.1*10^{-5}$	$4*10^{-6}$	19.0%	$2.1*10^{-5}$	$4*10^{-6}$	19.0%
6d	0.999671	0.998896	99.9%	$2.1*10^{-5}$	$4*10^{-6}$	19.0%	$2.1*10^{-5}$	$4*10^{-6}$	19.0%
7d	0.999729	0.999622	99.9%	$2.1*10^{-5}$	$4*10^{-6}$	19.0%	$2.1*10^{-5}$	$4*10^{-6}$	19.0%

(1) The opening pressure is 0.42MPa(g)
(2) The opening pressure is 0.71MPa(g)

6. CONCLUSION

1) Based on the design character of CPR1000 containment and hand calculation, the results show that the ultimate pressure of CPR1000 containment can be 1.3640MPa(g).

2) Selecting the pressure at steel liner yield as the best-estimated ultimate pressure, the Over-pressure Fragility Curve of CPR1000 containment is drawn based on some conservative assumption. Taking account of low failure probability(5%) and 10% margin, The pressure threshold for EUF operation can increase to 0.71MPa(g).

3) With the finite element method, the response behavior analysis of CPR1000 containment with different loads shows that the integrity of the containment can be kept intact with $1.7P_{design}$ internal pressure.

4) The comparison of radiological consequence with different pressure threshold of EUF shows that the opening time of the EUF is delayed about 1day and the accumulated activity to the environment is also decreased definitely with higher pressure threshold.

The Over-pressure Fragility Curve of CPR1000 containment given by this paper has a reference to the severe accident management research and PSA level 2, 3 analysis. The calculation shows that the ultimate pressure of CPR1000 containment is far beyond the design pressure. The pressure threshold for EUF operation can increase to 0.71MPa(g) with low failure probability about 5%. Prior to the engineering application of this improvement, the performance of valves and other equipments in high pressure should be established.

7. REFERENCES

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