# Review of Research on the High Temperature Resistance of Concrete Structures in Chinese NPP

Jianzhuang Xiao, Wengang Xie, Qinghai Xie

*Journal of Advanced Concrete Technology,* volume 14 (2016 ), pp. 335-343



This paper will also be published as an electronic book together with other papers of the special issue, "Aging management of concrete structures in nuclear power plants" in 2016.

Journal of Advanced Concrete Technology Vol. 14, 335-343 July 2016 / Copyright © 2016 Japan Concrete Institute 

*Scientific paper*

# Review of Research on the High Temperature Resistance of Concrete Structures in Chinese NPP

Jianzhuang Xiao[1*], Wengang Xie[2] and Qinghai Xie[3]

Received 1 April 2016, accepted 27 June 2016

doi:10.3151/jact.14.335

## Abstract

In line with the strategic energy goals and sustainable development, considerable investment has been made on nuclear energy, leading to construction of a growing number of nuclear power plants (NPPs) across China. Concrete is the main structural materials applied in many key elements of a typical NPP including reactors. Among other stringent requirements, resistance to thermal loads both at early ages and during operating life is crucial for the concrete used in nuclear facilities. This paper provides an overview of high temperature resistance of concrete structures in Chinese NPP, including information on construction and operation. Early-age thermal cracking of mass concrete structures due to differential thermal stresses induced by hydration heat has been highlighted in literature as a major issue. The common approaches to tackling this issue are based on limiting the maximum temperature in the concrete and temperature difference between hotter interior and cooler exterior of the concrete. These approaches include the optimum mix ratio method and the reasonable design of the construction technology. During operation, the temperature control of containment under steady or accidental case is an important prerequisite to ensure the safety of NPP, especially after a loss of coolant accident (LOCA). In addition, various coatings used for thermal insulation in China's NPP are introduced and compared. Based on the existing literature, further studies involving longtime monitoring of temperature, strain and displacement are found necessary to obtain a better understanding of thermal resistance, long-term performance and safety of concrete containment used in NPP.

## 1. Introduction

As a new energy which is clean and efficient, nuclear power has gained worldwide attention and been widely used in Europe, America and other developed countries and regions. It is also the important strategic direction of China's energy in the future. By 1 July 2015, there are 30 countries and regions operating nuclear power plants (NPPs) in the world (Schneider and Froggatt 2015). **Table 1** shows 15 countries and regions with the largest amount of nuclear electricity generation in 2014. In addition, although no unit in Japan operated or generated power due to the Fukushima accident, the number of reactors is also presented to remind the readers about the Fukushima accident. Based on the evaluation of the Fukushima accident, the aging degradation has little influence on the loss of function in systems and components important to safety. Additional investigation needs to be launched to confirm the status of equipment in the future when the further understanding is gained (Sekimura 2012).

As seen in **Table 1**, despite the growing investment on nuclear energy and increasing number of NPPs in China, the share of nuclear power in China's total power generation is still small. Based on the *Medium- and Long-term Development Plan of the State on Nuclear Power* issued by the State Council in 2007, it plans to increase China's total nuclear power capacity to 40 million kW in 2020, making the under-construction capacity not less than 18 million kW. This is expected to lead to an increase proportion of China's nuclear power installed capacity from 1.7% in 2005 to about 4% in 2020 (Ye 2012). As shown in **Table 2**, the total capacity of 28 commercial nuclear power units operating in China mainland is 168.99 TWh, accounting for 3.01% of the national total power generation in 2015. However, the Chernobyl nuclear accident in the former USSR and the leak of Japan's Fukushima NPP have attracted attentive focus around the world on the safety of nuclear power.

During the process of construction and operation of NPP, the concrete structure and facility might be affected by exposure to elevated temperatures. From an engineering point of view, a number of measures have been investigated to guarantee the safety of NPP, including the application of a composite liner glued onto the inner side of the containment wall (Costaz and Danisch 1997; Wu *et al.* 2013). This paper begins with reviewing the measures adopted in Chinese NPP to control the temperature in the concrete structure during the construction phase. The paper then continues by analyzing the behavior of containment in the natural state as well as under the loss of coolant accident (LOCA). Furthermore, various high temperature coatings used in NPP are summarized.

[1]Professor, Department of Structural Engineering, Tongji University, Shanghai, China.
*Corresponding author, *E-mail*: jzx@tongji.edu.cn
[2]Master student, Department of Structural Engineering, Tongji University, Shanghai, China.
[3]PhD student, Department of Structural Engineering, Tongji University, Shanghai, China.

Table 1 Number of nuclear reactors and nuclear electricity generation.

| Country or Region | Nuclear reactors (1 July 2015) | | Nuclear electricity (2014) | |
|---|---|---|---|---|
| | Operating (units) | Constructing (units) | Generation (TWh) | Share in electricity mix |
| USA | 99 | 0 | 797 | 20.2% |
| France | 58 | 0 | 415.9 | 76.9% |
| Russia | 34 | 3 | 171 | 18.6% |
| South Korea | 24 | 5 | 150.4 | 30.1% |
| China | 27 | 18 | 130.5 | 2.39% |
| Canada | 19 | 0 | 100.9 | 16.0% |
| Germany | 8 | 0 | 91.7 | 15.8% |
| Ukraine | 15 | 0 | 82.0 | 48.6% |
| Sweden | 9 | 0 | 62.2 | 41.2% |
| UK | 16 | 0 | 57.8 | 16.6% |
| Spain | 7 | 0 | 54.8 | 20.4% |
| Taiwan, China | 6 | 0 | 40 | 18.8% |
| India | 20 | 7 | 33 | 3.40% |
| Belgium | 6 | 0 | 32 | 50.0% |
| Czech Rep. | 6 | 0 | 28.6 | 33.3% |
| Japan | 43* | 0 | - | - |

* All reactors in Japan had been shut down.

Table 2 Power production statistics of Chinese NPP in 2015*.

| NPP | Reactor type | Installed capacity (MWe) | Generation (TWh) |
|---|---|---|---|
| Qinshan NPP | CNP300 | 310 | 2.57 |
| The 2nd Qinshan NPP | CNP600 | 2620 | 20.29 |
| The 3rd Qinshan NPP | CANDU 6 | 1456 | 11.24 |
| Fang Jiashan NPP | CNP1000 | 2178 | 15.168 |
| Hongyanhe NPP | CPR1000 | 3356.37 | 14.47 |
| Tianwan NPP | VVER-1000 | 2120 | 16.62 |
| Changjiang NPP | CNP600 | 650 | 0.07 |
| Daya Bay NPP | M310 | 1968 | 15.43 |
| Lingao NPP phase I | M310 | 4152 | 32.28 |
| Lingao NPP phase II | CPR1000 | | |
| Yangjiang NPP | CPR1000 | 2172 | 12.95 |
| Ningde NPP | CPR1000 | 3267 | 19.59 |
| Fuqing NPP | CPR1000 | 2178 | 8.34 |
| Total | | 26427.37 | 168.99 |

*The data come from *http://www.china-nea.cn/html/2016-01/35018.html.*

## 2. Temperature control during construction

The hydration of Portland cement is an exothermic reaction. In mass concrete, (e.g., concrete containment and foundation), where the surface area of concrete is relatively small compared to its total volume, the hydration heat may result in considerable temperature difference between interior and exterior of concrete. The thermal stresses caused by such temperature gradients can readily induce the development of early-age thermal cracks in concrete, which is highly undesired from both aesthetic and durability points of view (Acker and Ulm 2001; Wang 2011). Temperature control of concrete after its casting is considered to be the key to limit the concrete thermal cracking (Ling *et al.* 2005; Schindler 2004). The delayed ettingite formation (DEF) because of high temperature and the resulting stresses generated by the expanding ettringite have been particularly identified as a cause of concrete cracking, especially in European pressurized-water reactor (EPR) nuclear power plants (NPPs) (Zhao and Zhou 2012). In order to limit the maximum temperature and the temperature difference between inside and outside of the concrete within the prescribed standard, the concrete temperature should be reduced from two aspects as the optimum mix design and the reasonable construction technology.

### 2.1 Concrete mix design

Hydration heat is the main reason that the volume of concrete grows larger when the temperature increases. Medium or low heat cement can be chosen to control the hydration heat of binding materials in concrete strictly. Meanwhile, adding mineral admixture and chemical additive should also be helpful (Xu 2010). The mineral admixture can partly replace the Portland cement to lower and delay the peak temperature of hydration. Furthermore, some chemical additive such as Polycarboxylate water-reducing agent (PCA) can retard cement hydration and increase the dosage of slag or fly ash in concrete. The concrete proportion of the reactor building

Table 3 The concrete proportion (Xu 2010; Wang *et al.* 2012).

| Material | The reactor building raft of Taishan NPP | | The 3rd reactor building raft of Yangjiang NPP | |
|---|---|---|---|---|
| | Specification quantity | Usage /(kg/ m$^3$) | Specification quantity | Usage /(kg/ m$^3$) |
| Sand | Medium sand | 780 | Medium sand | 785 |
| Coarse aggregate | 5~16 | 1050 | 5~16 | 1075 |
| | 16~31.5 | | 16~31.5 | |
| Cement | PII 42.5 | 240 | PII 42.5 | 280 |
| Slag powder | S95 | 50 | - | - |
| Fly ash | I | 100 | I | 100 |
| Additive | PCA* | 3.9 | PCA | 3.8 |
| Water | Potable water | 151 | Potable water | 148 |

*Polycarboxylate water-reducing agent.

Table 4 Examples of aggregates based on density (Kaplan 1989).

| Type aggregate | Density (kg/ m$^3$) | Examples | Concrete density (kg/ m$^3$) |
|---|---|---|---|
| Normal weight | 1520-1680 | Limestone, granite, sandstone | 2400 |
| Light weight | < 1120 | Volcanic pumice, blast furnace slag, cinder | < 1850 |
| Heavy weight | > 2080 | Magnetite, barytes, ferrophosphorus | > 4000 |

raft of Taishan and Yangjiang NPPs can be taken as a typical example, which is listed in **Table 3**. The concrete unit weights of both Taishan and Yangjiang NPPs meet the standard of normal-weight aggregates in **Table 4**, which have been used in the biological shields of pressurized-water reactors (PWRs) (Kaplan 1989; Willam *et al.* 2013).

## 2.2 Reasonable construction scheme

During the maintaining process of the mass concrete, temperature measurement is the main gist of temperature control to decide the maintenance time of concrete, and to adjust the layers of the proof material. This procedure can limit the temperature difference and cooling rate inside the concrete, and thereby can prevent the development and growth of cracks. During the construction of the foundation in Hongyanhe NPP, a temperature monitoring and controlling system was applied to avoid the negative influence of winter weather and to assure the program on schedule. In this strategy, 54 temperature sensors and 57 strain sensors were set to monitor the temperature and stress development, along with an alert system being triggered when stress got close to the tensile strength of concrete (Yang *et al.* 2009; Wei *et al.* 2008).

In the southern coastal area of China, the high temperature and humid environment brings many difficulties to the pouring and maintaining process of NPP foundation, such as overhigh central temperature and great temperature gradient, which are very difficult for controlling cracks. Gu *et al.* (2010) undertook an intensive research on controlling cracks during the maintaining period by taking some NPPs in south China as examples. A finite element numerical simulation model was built by ANSYS to compare with the monitoring data of temperature and strain during the pouring of concrete. According to the numerical calculation results, the control section of concrete and stress orientation in this section are determined to provide the guidance of the position design of sensors. The data from the sensors could provide useful information for the effective adjustment of maintaining measures. When the temperature in concrete is overhigh, some cooling measures can be adopted like ice bag cooling, rebar covering, spraying on pouring pipe during stratified slope concreting and adjusting the covering layer thickness based on the real-time monitoring data in the conservation process. The research shows that there can be no obvious cracks even when the temperature reaches 80 °C.

Considering the enormous pouring volume of containment of Taishan NPP with a height of 48.95 m, the area is divided into 16 layers, where the thickest one is 1.8 m. The outer containment has an inner diameter of 53 m and an outer diameter of 55.6 m, with the C45 massive concrete of 1237.6 m³ in all (Liu 2014). Through the numerical simulation, Liu (2014) found that the center of containment wall had the highest temperature over 70 °C while the surfaces were much cooler. The temperature of inside surface was the same as the outside surface, and they were symmetrical by the center. According to the existing construction layering arrangement, the thickness of construction layer rather than the height could have a significant influence on the temperature field. For a 1.8 m thick layer, the center temperature of containment wall could reach 75 °C, which was 5 °C higher than that of the 1.3 m one. The maximum vertical temperature gradient would reach 71.8 °C/m, and the maximum radial temperature gradient would reach 50.3 °C/m. These positions with the maximum temperature gradient in two directions should be the key point during the construction. It is advised that maintaining time should be increased to 10 days since increasing the maintaining time is one of the effective ways to reduce the temperature difference. The worse the insulation is, the much bigger the difference between the inside and outside surface before hardening will be. Because the thermal conductivity of concrete suddenly rises after hardening, the surface temperature reduces more rapidly with a higher temperature before hardening. The better the insulation material is, the much bigger the difference between the inside and outside surface after hardening will be (Liu 2014; Qian *et al.* 2014). Therefore, adopting proper insulation material can help to prevent the temperature difference from exceeding the limit in the China standards of GB 50496-2009.

As the temperature rises after pouring, it is necessary to cure the concrete by wet maintenance methods to guarantee the hydration reaction of binding material inside concrete. This can reduce the peak temperature inside the concrete and avoid the loss of strength in the later period. When concrete begins to cool down, the structure shrinks and the compression state of concrete turns into tension state. Penetrating cracks may generate due to the restraints, which can break the integrality and durability of structures (Ariyawardena *et al.* 1997). Therefore, heat and humidity preservation measures should be taken to avoid the occurrence of penetrating cracks during the cooling stage.

## 3. Thermal safety of containment

The containment is the retaining structure of a nuclear reactor, which is the third safety barrier in addition to fuel rod cladding and pressure vessel. According to the composition of materials, the containment structure system of nuclear reactor can be classified as steel containment, reinforced concrete containment and prestressed concrete containment. The function of containment is to restrict and eliminate the release of radioactive fission products to ensure the safety of NPP and the public when the loss of coolant accident (LOCA) caused by the rupture of primary coolant pipe happens (Zhao *et al.* 2003; Costaz and Danisch 1997). The temperature effect has great influence on overall mechanical properties of the containment structure, and calculation of the containment temperature field is an important prerequisite to ensure the safety of NPP under steady and accident situation.

### 3.1 Thermal response of containment in atmospheric environment

In the process of testing the overall performance of containment structures, the test results of deflection and strain can be intervened by the temperature effect due to the change of the atmospheric environment (Lin and Yan 2003). Xie *et al.* (1993) concluded that the thermal conduction of the containment was a three-dimensional problem according to the theory of heat transfer. While the containment was relatively thin and the environment was relatively uniform, therefore it could be simplified into a one-dimensional heat transfer problem. They also selected several representative parts of containment of Qinshan NPP and established the differential equations. The temperature field was established according to the calculated temperature at each time point. By comparison, the calculated temperature were consistent with the measured temperature. For example, both the measured temperature and the calculated temperature of 62.5 m elevation on the surface of containment fluctuated in the range of 20~45 °C.

According to weather records of several years in the local experiment place and the existing data of air temperature in the containment, Lin and Yan (2003) revealed the variation, distribution pattern and the magnitude of the effects of temperature field based on the finite difference method. When the maximum of temperature difference reached 20 °C on the surface, the temperature varied within 1 °C in the middle thickness. Due to the influence of projection angle, duration of sunlight and other factors, the surface temperature on the top of containment was higher than that of the tube wall, and the variation range was larger (**Fig. 1**). The calculation results of temperature field were then introduced to the structure analysis program, and results showed that the structure deflection was less than 0.3 ~ 0.5 mm under the atmospheric environment for less than 10 days. In the atmospheric environment, the containment temperature decreases rapidly and distributes nonlinearly along thickness. The temperature difference of containment surface has little effect on the temperature and thermal stress in the inner (Singh and Heller 1980).

With the increasing operation time of NPP, the concrete structure and facility are bound to deteriorate. Therefore, the reactor must undergo in-depth inspection and test at intervals while the containment is evaluated by monitoring and inspecting. In order to ensure the security and safety of NPP, the research on the behavior of containment after withstanding longtime radiation and temperature variation need to be conducted by measurements of temperature, strain, and displacement.

### 3.2 Thermal resistance of containment after LOCA

LOCA releases high temperature steam and water, inducing an equivalent pressure of fluid with 150 °C acting

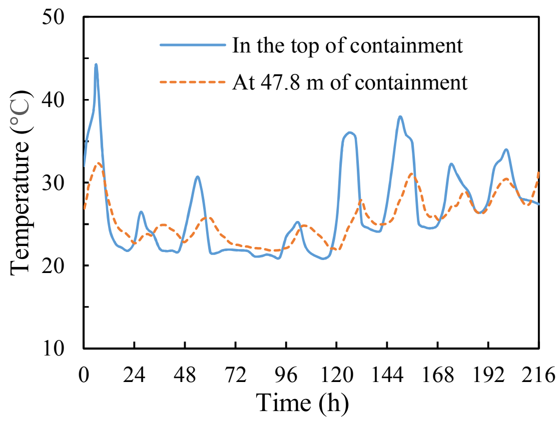


Fig. 1 Temperature-time curve at two places.

Table 5 Initial parameters of containment.

| Parameters | | Value | |
|---|---|---|---|
| | | Wu *et al.* (2010) | Sun *et al.* (2015) |
| Volume of containment ($m^3$) | | Approx. 300000 | Approx. 90000 |
| Height of containment (m) | | 76 | 58.5 |
| Concrete | Strength grade | C50 | |
| | Elastic modulus (MPa) | $3.45\times10^4$ | |
| | Poisson ratio | 0.2 | |
| | Thermal expansion coefficient (/ °C) | $1\times10^{-5}$ | |
| | Thermal conductivity (kJ/(m·h·°C)) | 8.28 | 10.6 |
| | Density ($kg/m^3$) | 2500 | |

on the containment surface. Then the temperature rises suddenly in the containment, resulting in a greater temperature difference between inside and outside, which brings about considerable temperature stress and influences the distribution of temperature and stress (Li and Wang 2010; Kanzleiter 1976). Therefore, the design of containment should take the effect of LOCA into consideration, especially in the type of PWR NPP which is applied widely in China.

Li and Wang (2010) from the Central Research Institute of Building and Construction of Metallurgical Corporation of China Group analyzed the temperature field and stress field of a 1.2 m-thick containment structure under the temperature effect of the LOCA by ANSYS. Assuming that the inner surface of containment was adiabatic and the heat transmits from the inner surface to the outer surface, the instantaneous temperature of 150 °C was applied to node on the inner wall of the containment. According to the analysis results, the temperature of each node at different distance from the inner wall is shown in **Fig. 2**. It can be found in **Fig. 2** that the temperature only influences a thin part of the tube wall. Affected by accidental instantaneous temperature, the high stress is mainly concentrated at the fixed bottom of the cylinder, at the top of the dome and around the opening, which does not reach the tensile strength of concrete. So the effect of accidental instantaneous temperature does not cause destructive damage to concrete structures.

The distribution of temperature field in the concrete containment becomes obviously nonlinear after LOCA. Based on the analysis by Zhao *et al.* (2003) about the containment temperature change for PWR, Wu *et al.* (2010) and Sun *et al.* (2015) respectively carried out the finite element simulation of concrete containment after LOCA. The parameters are listed in **Table 5** and the results are shown in **Fig. 3**. Due to the differences of factors including containment wall thickness, thermal conductivity of concrete and temperature difference inside and outside the containment, the extent of temperature increase in outer wall of containment is quite different when it is 6 h after the occurrence of LOCA, while the outside temperature of containment with thickness of 1.1 m does not obviously change. After obtaining the temperature field in containment, the inner force distribution and the deformation of containment in different time can be derived from theoretical analysis or numerical simulation:

(1) 6 h after the occurrence of LOCA, the bending moment reaches its maximum value according to the theory of elasticity, ignoring the confinement effect on structure bottom. Thus the temperature field at this time can act as a benchmark for internal force design. In practical engineering, a reduction coefficient ranging from 0.3 to 0.5 should be adopted for the calculation of thermal stress to consider the concrete cracking and creep effect (Wu *et al.* 2010).

(2) The temperature effect has a great influence on the

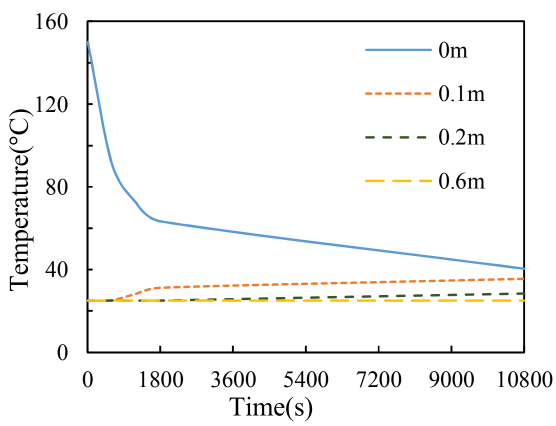


Fig. 2 Distance and temperature curve (Li and Wang 2010).

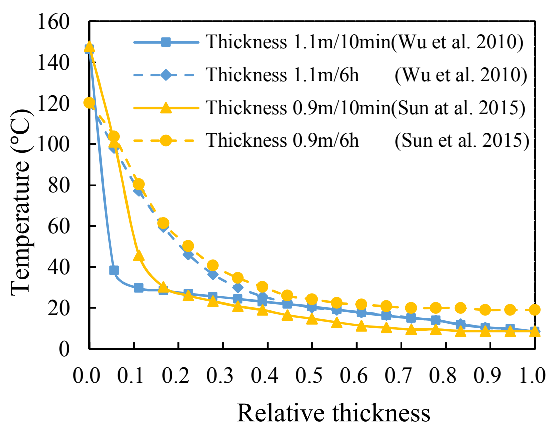


Fig. 3 Variation of temperature along relative thickness at different time after LOCA.

Table 6 Main types of coatings for Qinshan I NPP Project (Gong 2009).

| Category | Concrete structure | Steel structure | Steel equipment |
|---|---|---|---|
| Containment | Red polyurethane+ polyurethane | Inorganic zinc silicate + polyurethane | Inorganic zinc silicate + polyurethane |
| Radiation control area | Epoxy | alkyd | Epoxy primer + polyurethane |
| Security equipment | Epoxy, polyurethane | Epoxy zinc-rich + alloprene | Alkyd, epoxy asphalt etc. |

deformation pattern of the overall containment deformation. When a LOCA occurs, the maximum expansion displacement of containment structure increases nearly 14 mm and the overall expansion displacement also increases 6 ~ 10 mm under the combination of internal temperature and pressure (Sun *et al.* 2015).

If the pressure vessel fails, the integrity of containment will be jeopardized. The task of top priority is to cool down and seal the corium inside the pressure vessel. As an important material used in core catch, sacrificial concrete can melt and be mixed with the corium, which will bring the benefits of reducing solidus and liquids temperature of corium. Therefore, research on the preparation, function mechanism of nuclear sacrificial concrete is of great significance to ensure that containment remains intact. The sacrificial concrete designed by Southeast University in China has been applied in Taishan NPP (Chu *et al.* 2016).

## 4. High temperature resistant coating for NPP

Coating is a continuous film formed by spraying all paint at once to the surface of solid, usually referred to as the substrate, such as metal, fabric and plastic. It is a plastic thin layer for protection, thermal insulation, decoration etc. Coating of NPP is mainly used for steel and concrete structure, pipes and other components on the nuclear island and the conventional island. Although the corrosion resistance is one of the most basic requirements of the coating performance, strict process control has guaranteed the basic requirements of anticorrosion for the special nuclear power coating.

During the operation period, the temperature of the concrete containment is about 50 °C, and the radiation is 0.1 Gy/h. However, the temperature is likely to rise to more than 150 °C under accidental conditions with numerous of radiation particles generating. Therefore, the coating will experience a continuous aging process due to the high temperature and radiation, which may jeopardize its original function in the normal operation of NPP or accidental conditions (Chen 2013).

A great deal of research and development work have been done by the research institutes and suppliers in China. The coatings for Qinshan I NPP Project are provided by the Shanghai Kailin paint factory and the Changzhou Coating Chemical Research Institute (Ni *et al.* 2005). **Table 6** gives the main types of coatings for Qinshan I NPP Project. Based on the successful application of these coatings, corresponding standard of special coating for NPP is compiled referring to relevant contents in the American Society for Testing and Materials and Norme Française standards. At present, there are few researches on the aging and life prediction of the coating on the NPP in China, while the focus is placed on the production and application of the coating (Liu 2015).

In the test of the performance of the coating, simulated Design Basis Accident (DBA) is included as well as coating irradiation test and coating decontamination test. DBA simulates the effect of reactor on the coating for containment under the condition of design basis accident. The coating sample is placed in a high temperature and high pressure vessel sprayed with boric acid aqueous solution with pH=9 ~ 10. The temperature, pressure, period and other conditions can be determined according to different standards or specific design parameters. The typical condition is a 4 ~ 7 d period experiment under 153 °C with a certain pressure. After the test, the sample coating sample will be considered as not qualified if the cracking, delamination, bubble or breakage of the coating occurs (Zhang 2007).

Chi *et al.* (2006) made a comprehensive check and evaluation on the aging condition of No.1 reactor factory in Daya Bay NPP after an operation time of over 10 years. Through field test, the coating adhesion of steel structure, walls, floors and ceilings surface conformed to the requirement of the original design of the NPP. The coatings of the steel panels and concrete blocks had a poor condition with destructive defects caused by scratch, grind, hit, etc. Those test boards were prepared during the construction of Daya Bay NPP, which were later used as specimens for LOCA tests. Specimens were examined at 2 hours and 2 weeks after LOCA tests respectively, and the adhesion test were performed after 2 weeks. Excluding the effect of preexisting defects, the steel panels and concrete blocks reached the requirements for acceptance in **Table 7**.

The passive containment used in the third-generation NPP is composed of reinforced concrete structure and steel containment. The inner and outer surfaces of steel containment are covered by inorganic zinc coating with excellent heat transfer performance (Kindred and Wright 2014). Different from the aging characteristics of ordinary epoxy coatings, the inorganic zinc coating will generate zinc oxide during aging, and the oxidation substances can continue to fill pores in the coatings. Because the thermal conductivity of zinc oxide is better than that

Table 7 Results after LOCA tests.

<table>
<tr><th>Requirements for Acceptance</th><th>Specimens</th><th>Changes of coating</th><th>Adhesion</th><th>Conclusion</th></tr>
<tr><td rowspan="2">No spalling, peeling or powering;<br>Allow the coating to blister slightly, but each bubble is not broken and the diameter is less than 2 mm;<br>The crack length of specimen is not more than 10 mm;<br>The adhesion is not less than 0.2 MPa.</td><td>Steel panels</td><td rowspan="2">Except the existing pinhole and crack expansion, there were no spalling, bubble or new crack in the surfaces of specimens.</td><td>3.1 MPa</td><td rowspan="2">Excluding the preexisting defects, the specimens satisfied the requirements for acceptance.</td></tr>
<tr><td>Concrete blocks</td><td>1.2 MPa</td></tr>
</table>

Table 8 Results of adhesion test (Fan *et al.* 2015).

| *Location of Sample Points | Before accident | | After accident | |
|---|---|---|---|---|
| | Dry film thickness (μm) | Adhesion (MPa) | Dry film thickness (μm) | Adhesion (MPa) |
| Region A | 95 | 12.01 | 101 | 10.21 |
| | 85 | 13.24 | 93 | 11.2 |
| | 90 | 11.13 | 88 | 13.13 |
| Region B | 96 | 12.35 | 93 | 11.34 |
| | 90 | 10.09 | 90 | 12.78 |
| | 100 | 11.65 | 98 | 10.11 |
| Region C | 90 | 10.61 | 87 | 10.88 |
| | 100 | 9.21 | 100 | 8.79 |
| | 96 | 9.67 | 94 | 10.02 |

*The sample points are selected in region A, B, C (The specimen is rectangular, *A* and *B* are located on the same side of the specimen, bilateral symmetry; the *C* area is located on the other side, in the central area of the specimen). 3 sample points are selected from each region.

of coating pores, the heat transmission of inorganic zinc coating will not be affected adversely by aging (Liu *et al.* 2015). According to the physical environment that might form in the LOCA accident, Fan *et al.* (2015) conducted a simulation experiment on test panel with inorganic zinc coating. Dry film thickness and adhesion before and after the LOCA accident are shown in **Table 8**. A single simulation of the LOCA accident does not have a significant impact on the dry film thickness and adhesion of inorganic zinc coating, and the coating still meets the requirements of serviceable capacity, such as the integrity, heat transfer and radiation resistance.

## 5. Summary

This paper reviewed the researches and technical measures for minimizing the risk associated with concrete in Chinese NPP exposure to high temperatures. The main conclusions are summarized in the following:

(1) The concrete component should be optimized for the construction of foundation and main structure of NPP. While temperature and strain sensors are used for real-time monitoring of the temperature of each measuring point, appropriate insulation measures can be taken to prevent cracking due to excessively high temperature or excessive temperature gradient in concrete.

(2) Finite element analysis can be used to predict the temperature field of the containment vessel under the conditions of normal temperature and LOCA accident, which can provide reference for the internal force analysis and the structural design of the containment.

(3) To complete further analysis (such as the research on the whole life appraisal of containment), the longtime measurements of temperature, strain, and displacement are advised to adopt for the safety of containment.

(4) In China, some institutions already have the ability to research and produce the special coating for NPP. They have compiled the norms of NPP coating by referring to the norms of France and USA to provide technical support for the safe application of the NPP. Moreover, the damage of coating is inevitable and needs alleviation during the operation of generator units. Therefore it is necessary to compile the norms of coating maintenance and assessment based on the situation of the coating of NPP.

### Acknowledgements

The authors would like to gratefully acknowledge all the national and international investigators related to the references and the research grants from the Chinese National 973 Plan (2012CB719703).

### Reference

Acker, P. and Ulm, F., (2001). "Creep and shrinkage of concrete: physical origins and practical measurements." *Nuclear Engineering and Design*, 203(2), 143-158.

Ariyawardena, N., Ghali, A. and Elbadry, M., (1997). "Experimental study on thermal cracking in reinforced concrete members." *ACI Structural Journal*, 94(4), 432-441.

Chen, Z., (2013). "Study of aging and lifetime for the epoxy coatings in nuclear power plant." *Shanghai Jiao Tong University*. (in Chinese)

Chi, Z. H., Tang, M. L. and Cui, L., (2006). "Evaluation of aging of inner coating of containment vessel of Daya Bay nuclear power plant." *National Nuclear Material Academic Communication 2006*. (in Chinese)

Chu, H., Jiang, J., Sun, W., and Zhang, M., (2016). "Thermal behavior of siliceous and ferro-siliceous sacrificial concrete subjected to elevated temperatures." *Materials & Design*, 95, 470-480.

Costaz, J. L. and Danisch, R., (1997). "Discussion on recent concrete containment designs." *Nuclear Engineering and Design*, 174(2), 189-196.

Fan, H. C., (2015). "Study on the characteristic of inorganic zinc coating for passive containment." *Surface Technology*, 6, 7-10. (in Chinese)

GB 50496-2009, (2009). "*Code for construction of mass concrete*." Beijing: Standards Press of China. (in Chinese)

Gong, Y. Z., (2009). "Review on the research and development of China nuclear power coatings." *China Paint*, 24(6), 5-8. (in Chinese)

Gu, H. M., Cheng, D. Y. and Zhang, X. B., (2010). "Monitoring of temperature strain during pouring raft foundation for a nuclear island of a nuclear power plant in hot and humid environment." *Industrial Construction*, 40(1), 17-20. (in Chinese)

Kanzleiter, T. F., (1976). "Experimental investigations of pressure and temperature loads on a containment after a loss-of-coolant accident." *Nuclear Engineering and Design*, 38(1), 159-167.

Kaplan, M. F., (1989). "Concrete radiation shielding: nuclear physics, concrete properties, design and construction." *Essex: Longman Scientific & Technical*.

Kindred, T. A. and Wright, R. F., (2014). "Effects of aging on the thermal conductivity of the AP1000® containment vessel inorganic zinc coating." *2014 22nd International Conference on Nuclear Engineering, American Society of Mechanical Engineers*, V001T03A028-V001T03A028.

Li, J. W. and Wang, Y. H., (2010). "Calculation and analysis of temperature and stress fields for nuclear power plants under temperature effect of LOCA accident." *Industrial Construction*, S1, 300-305. (in Chinese)

Lin, Z. S. and Yan, J. H., (2003). "The temperature field of PCCV of nuclear power station under atmosphere circumstance." *Journal of Building Structures*, 36(6), 12-17. (in Chinese)

Ling, D. S., Xu, D. S. and Shen, Y. Y., (2005). "Model for hydration heat of cement in concrete and its application." *Journal of Zhejiang University*, 39(11), 1695-1698. (in Chinese)

Liu, G. Z., (2015). "Research on immersed thermal aging of coatings in nuclear power plant." *Shanghai Jiao Tong University*. (in Chinese)

Liu, S. H., (2014). "Research on construction temperature field characteristics and effect of nuclear island outer containment." *Harbin Institute of Technology*. (in Chinese)

Liu, X. Q., Xu, X. L. and Meng, F. J., (2015). "Reliability and design analysis of coatings used in passive containment vessel of nuclear power plant." *Paint & Coatings Industry*, 45(4), 74-78. (in Chinese)

Ni, A. B., Ding, W. Z. and Wang, L. F., (2005). "Development of heat-resistant coatings for nuclear facilities and equipment." *Paint & Coatings Industry*, 35(11), 7-9. (in Chinese)

Qian, H. L., Qin, F. and Fan, F., (2014). "Analysis on temperature filed of outer containment of the Taishan nuclear power plant." *Journal of Building Structures*, 35(7), 115-122. (in Chinese)

Schindler, A. K., (2004). "Effect of temperature on hydration of cementitious materials." *ACI Materials Journal*, 101(1), 72-81.

Schneider, M. and Froggatt, A., (2015). "*World nuclear industry status report 2015*."

Sekimura, N., (2012). "Securing the stability of ageing NPP considering Fukushima Dai-Ichi lessons learning: improving inspection system and ageing management and planning." *3rd International Conference on NPP Life Management (PLIM) for Long Term Operations (LTO)*, Salt Lake City, U.S.A.

Singh, M. P. and Heller, R. A., (1980). "Random thermal stress in concrete containments." *Journal of the Structural Division*, 106(7), 1481-1496.

Sun, F., Pan, R. and Chai, G. H., (2015). "Preliminary study on response law of prestressed concrete containment after LOCA in certain NPP." *Atomic Energy Science and Technology*, 10, 1815-1820. (in Chinese)

Wang, G. T., (2011). "Preparation of self-compacting concrete used in nuclear power plant and its application in cut-off cone structure." *South China University of Technology*. (in Chinese)

Wang, H. C., Chen, L. S. and Lv, G. Y., (2012). "Preparation and construction technology of nuclear power plant high-performance mass concrete." *Nuclear Power Engineering*, 32(z2), 47-50. (in Chinese)

Wei, J. G., Zhang, Z and Zhang, X. B., (2008). "Temperature-controlling monitoring and emulation analysis of mass-concrete of raft foundation of nuclear power plant." *Industrial Construction*, z1, 1033-1035. (in Chinese)

Willam, K., Xi, Y. and Naus, D., (2013). "A review of the effects of radiation on microstructure and properties of concrete used in nuclear power plants." *US NRC, NUREG/CR-7171*.

Wu, C., Meng, S. P. and Zhou, Z., (2010). "Analyses on temperature field distribution and internal force of concrete containment vessel after LOCA." *Engineering Mechanics*, 27(12), 206-212. (in Chinese)

Wu, Y., Shi, L. and Liu, J. Z., (2013). "Gas tightness evaluation of structural concrete applied to nuclear containment vessels." *Applied Mechanics & Material*s, 405, 19-23. (in Chinese)

Xie, Y. J., Xue, J. L. and Fu, B. L., (1993). "The study of the structural integrity test on security containment volumn of Qinshan nuclear power station." *Industrial Construction*, 3, 36-41. (in Chinese)

Xu, C., (2010). "Temperature control measure used in HRA reactor building of Taishan NPP." *Concrete*, 12, 114-117. (in Chinese)

Yang, Z. Y., Wei, J. G. and Ji, L. B., (2009). "Integral pouring construction technology of raft foundation A and B layers in Hongyanhe nuclear power station reactor workshop." *Construction Technology*, 38(8), 90-93. (in Chinese)

Ye, Q. Q., (2012). "China's nuclear power development after Fukushima nuclear power plant accident." *Chinese Society for Electrical Engineering*, 32(11), 1-8. (in Chinese)

Zhang, Y., (2007). "Analysis on application of special coating for nuclear power plant." *1st Symposium on Special Coating and Application*, 210-214. (in Chinese)

Zhao, J., Yu, H. X. and Li, F., (2003). "Calculation and analyses of containment pressure and temperature for PWR1000XL." *Nuclear Power Engineering*, 24(5), 409-411. (in Chinese)

Zhao, P. and Zhou, C. G., (2012). "Optimization of construction mix proportion based on raft foundation concrete of DEF nuclear power plant." *Henan Technology*, 17, 88-90. (in Chinese)

Zhao, S. M., Lin, S. T. and Wang, Y. H., (2003). "The structural integrity test of containment for Qinshan nuclear power plant." *Industrial Construction*, 33(9), 38-40. (in Chinese)