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Safety Analysis of the Reactor Pressure Vessel of NHR-200

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The safety features of the reactor pressure vessel (RPV) of the 200MW Nuclear Heating Reactor (NHR-200), which has been developed by the Institute of Nuclear Energy Technology of Tsinghua University of China, are investigated in this paper. The stress distribution, fatigue crack propagation and leak-before-break (LBB) of the RPV are analyzed. In comparison with RPVs of pressurized water reactors (PWRs) or boiling water reactors (BWRs), the stress level and the fatigue crack growth rate of the RPV of NHR-200 are very low. It is concluded from an LBB analysis that postulated cracks will not fracture in an unstable fashion before they are detected. These features are very beneficial for the inherent and passive safety of the reactor.

1 Introduction

In order to mitigate the problems of energy shortage, environmental pollution and overburdened transportation system, the research and development of nuclear district heating reactors (NHR) has been attracting much attention of scientists. During the past decade, a commercial size NHR with a thermal output of 200MW (NHR-200) has been developed by the Institute of Nuclear Energy Technology (INET) of Tsinghua University in China. Such an NHR-200 demonstration plant will be built in Daqing in northeast China.

In the design of NHR-200, some special considerations related to safety features are reflected. A number of experimental and theoretical analyses with the aid of numerical computation were carried out to gain or demonstrate the safety features of NHR-200. The NHR developed by INET is a vessel type, light water reactor with an integrated arrangement, natural circulation, self-pressurized performance and dual vessel structure. Due to its important role in NHR-200, the safety features of the reactor pressure vessel (RPV) were examined strictly. In this paper, some problems of deformation, fatigue and fracture, which are crucial for the characteristic features of the RPV, are analyzed, including stress distribution, fatigue crack propagation and leak-before-break (LBB) behavior. The reported results may be useful for the research and design of other nuclear reactors. For clarity, the RPV of NHR-200 is compared with that of Biblis B, another typical reactor.

2 Structure and Materials of the RPV

The NHR-200 adopts an integrated arrangement of the primary loop components and a natural circulation of the primary coolant. Its primary heat exchangers are arranged on the periphery in the upper part of the RPV, and its core at the bottom. A containment vessel fits tightly around the RPV so that the core will not become uncovered under any postulated leakage in the reactor coolant pressure boundary. As one of the most important components of NHR-200, the RPV has a small wall thickness and a big inner diameter, as shown in Figure 1. It consists of the cylindrical shell and a closure head, which is connected to the shell with 84 main bolts of $M\,80 \times 4$. The main flange is sealed with 2 metallic O-shaped rings. The inner surface of the vessel wall is a layer of stainless steel cladding, which prevents the RPV from corrosion. The main design parameters of the RPV of NHR-200 are shown in Table 1. Some of these aspects concerning its safety characteristics are reviewed in what follows. By comparing with PWRs and BWRs, it is easily seen that in some important aspects the RPV of NHR-200 is quite different from those of PWRs or BWRs.

The RPV considered is fabricated with two carbon steels, SA516-70 and SA508-1a due to its low operating parameters. These two materials are with low strength, high ductility and high toughness. Some of their basic mechanical properties are listed in Table 2, together with those of the materials used for the RPVs in PWRs and BWRs. During the whole service period, the neutron irradiation damage to the materials of the RPV of NHR-200 could be negligible because of the very low neutron flux (Table 1). The materials will always keep good toughness in all life time of the reactor.

The RPV of NHR-200 has a wide margin of safety to ensure its excellent performance. Its wall thickness of different parts is primarily determined based on the requirements of deformation, stiffness, diameter of main bolts and manufacturing. The stress distributions in the shell and in the closure head are calculated by the finite element program, NASTRAN. The numerous figures and tables of stress distributions are omitted here. It was proved that the stress level in the vessel wall is quite low. The maximal equivalent stress is lower than 100 MPa.

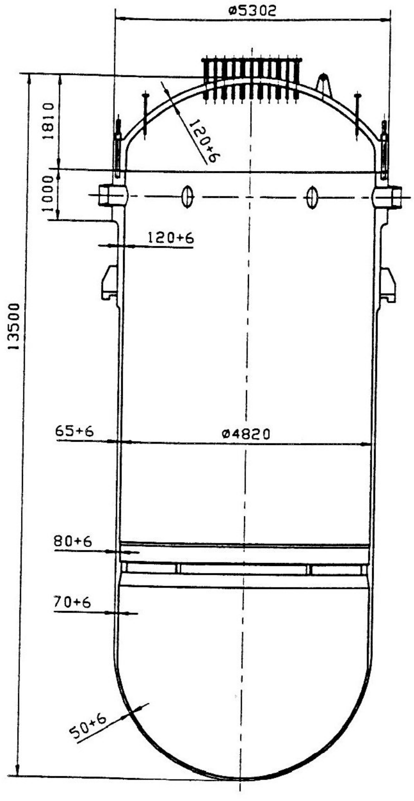

Figure 1. The RPV of NHR-200

Inner diameter (mm)	4820
Wall thickness (mm)	65
Total height (mm)	13500
Total weight (Mg)	190
Material	SA516-70 (plate) and SA508-1a (forging)
Cladding material	SA309-L and SA308-L
Cladding thickness (mm)	6
Maximal neutron flux (n/cm^2)	$< 1 \times 10^{16}$
Design pressure (MPa)	3.1
Design temperature ($^\circ$ C)	250
Operating pressure (MPa)	2.5
Operating temperature ($^\circ$ C)	213

Table 1. Design Parameters of the RPV of NHR-200

Reactor	Material of the RPV	σ_y (MPa)	σ_b (MPa)	σ_y/σ_b
NHR-200	SA516-70 SA508-1a	262	483	0.542
PWR and BWR	SA508-3 SA533-3	345	552	0.625

Table 2. Materials of RPVs

The low design parameters lead to the small wall thickness of the RPV of NHR-200. According to the fatigue theory of surface cracks, defects tend to adopt preferred shapes as they propagate through the wall of a vessel or a pipe. Due to the large diameter of the RPV discussed here, the bulging effect on surface crack growth can be neglected. A surface crack tends towards an equilibrium aspect ratio of crack depth b to half-length a, $0.7 \le b / a \le 0.9$ provided that its initial aspect ratio is not too small (Gilchrist, et al., 1992; Feng and He, 1997). This means that the length of a crack at through-thickness is about 2.2~3.0 times the wall thickness. Therefore, it follows that when a surface crack penetrates through the thickness of the vessel its size will be still very small, and that the wall-through crack will be found before it reaches a size big enough to danger the safety of the RPV. In other words, the size of a wall-through crack at penetration is bigger for a thicker vessel. Furthermore, it will be shown in the coming section that the possibility of penetration of a postulated surface crack is very low.

In summary, the high toughness, the low stress level and the small wall thickness are very beneficial to the safety properties of the RPV of NHR-200.

3 Analysis of Fatigue Crack Growth

It follows from the foregoing analysis that the size of a wall-through crack at penetration from a postulated surface flaw in the wall usually increases with the increase in the thickness of the vessel wall. It is also well known that the fatigue crack growth rate (FCGR) under varying loads increases with the increase in crack sizes. Because the wall thickness of the RPV in NHR-200 is only about 1/3 of that in PWRs with the same output power, the sizes of possible flaws at penetration in the wall of RPV of NHR-200 will be much smaller than those in PWRs. In this article, Biblis B is taken as a typical example of PWRs for the comparison the FCGRs of NHR-200 and PWRs. Some main parameters of Biblis B are given in Table 3 (Provan and Wellein, 1987).

Wall thickness (mm)	250
Inner diameter (mm)	5,000
Material	22MnMoNi37
Operating pressure (MPa)	15.8
Operating temperature ($^{\circ}$C)	292.5~329.6
Design pressure (MPa)	17.5
Design temperature ($^{\circ}$C)	350

Table 3. Design Parameters of the RPV of Biblis B (Provan and Wellein, 1987)

The FCGR of a mode-I crack can be calculated by the familiar Paris' formula

$$\frac{da}{dN} = C_0(\Delta K_{\text{I}})^n \tag{1}$$

where n and C_0 are material constants, a is the depth of the surface crack, N is the number of loading cycles, $\Delta K_{\text{I}} = K_{\text{I}\max} - K_{\text{I}\min}$, $K_{\text{I}\max}$ and $K_{\text{I}\min}$ are the maximal and the minimal values of mode-I stress intensity factor during a load cycle, respectively. For some carbon steels, the exponential and coefficient, n and C_0, can be determined approximately from the FCGR curves in Figure A-4300-1 in Ref. (ASME, 1983a). The stress intensity factor K_{I} for a crack in the wall of a pressure vessel can be calculated by (ASME, 1983a)

$$K_{\text{I}} = \left(\sigma_{\text{m}} M_{\text{m}} + \sigma_{\text{b}} M_{\text{b}}\right)\sqrt{\pi a / Q} \tag{2}$$

where σ_{m} and σ_{b} are the membrane stress and the bending stress normal to the crack plane, respectively, Q is the modification factor depending upon the defect shape, M_{m} and M_{b} are modification coefficients of membrane stress and bending stress respectively. For a surface crack, the parameters Q, M_{m} and M_{b} can be found in Figs. A-4300-1, A-4300-3, A-4300-5 in Ref. (ASME, 1983a), respectively.

Although the possible size of a postulated crack at penetration in Biblis B is larger than those in NHR-200, for easy comparison, assume that there exists a semi-elliptic, circumferential surface crack of the same size and shape in both the internal walls of RPVs of NHR-200 and of Biblis B. Such an assumption is conservative for the RPV of NHR-200. This case of cracks is designated as case 1 in Table 4. The surface cracks are assumed to be 10 mm deep and 50 mm long. Three fluctuation magnitudes of cyclic pressure, i.e., from 0 to the operating pressure P_0, from $0.5\,P_0$ to P_0, and from $0.95\,P_0$ to $1.05\,P_0$, are considered in our analysis. The stress intensity factors K_I and the FCGRs da/dN for the RPVs of NHR-200 and of Biblis B are calculated and given in Table 4. Under the three pressure fluctuations, the FCGRs of the RPV of Biblis B are about 6, 31 and 43 times of those of NHR-200, respectively.

For further comparison, cracks with different sizes in the RPVs of NHR-200 and of Biblis B are also considered. This case of cracks is referred to as case 2 in Table 4. The crack depth and length are taken as 25 mm and 150 mm in the NHR-200, and 62.5 mm and 375 mm in Biblis B, respectively. This is based on the correlation between minimum crack size and wall thickness in vessels and pipes (ASME, 1983b). The FCGRs of these two cracks under the pressure fluctuation from $0.9\,P_0$ to $1.1\,P_0$ are given in Table 4. In this case, da/dN of Biblis B is more than 100 times larger than that of NHR-200.

It follows from the above analysis that the FCGRs of the RPV in NHR-200 are much lower than those in PWRs or BWRs under all conditions. Hence, it is expected that the RPV of NHR-200 has an excellent characteristic safety to guarantee its safe operation in a much longer period.

Crack case	Reactor	Pressure fluctuation	σ_m (MPa)	σ_L (MPa)	K_I (MPa$\sqrt{m}$)	ΔK_I (MPa$\sqrt{m}$)	da/dN (mm/cycle)
1	NHR-200	0 P_0	0 92.32	0 1.20	0 16.23	16.23	2.36×10^{-4}
	Biblis B	0 P_0	0 158.4	0 7.90	0 28.76	28.76	1.49×10^{-3}
	NHR-200	$0.5\,P_0$ P_0	46.16 92.32	0.60 1.20	8.10 16.23	8.21	4.08×10^{-6}
	Biblis B	$0.5\,P_0$ P_0	79.18 158.4	3.45 7.90	14.13 28.76	14.63	1.27×10^{-4}
	NHR-200	$0.95\,P_0$ $1.05\,P_0$	87.70 96.94	1.14 1.26	15.36 17.01	1.65	2.92×10^{-10}
	Biblis B	$0.95\,P_0$ $1.05\,P_0$	150.4 166.3	7.50 8.29	27.22 30.33	3.11	1.26×10^{-8}
2	NHR-200	$0.9\,P_0$ $1.1\,P_0$	83.09 101.56	1.08 1.32	28.03 34.61	6.58	1.29×10^{-5}
	Biblis B	$0.9\,P_0$ $1.1\,P_0$	142.56 174.24	7.11 8.69	71.15 87.91	16.76	1.34×10^{-3}

Table 4. Fatigue Crack Propagation Rate of RPVs

4 Leak-before-Break Analysis

The leak-before-break (LBB) design for pressure vessels, high pressure pipes and tanks has recently been attracting much attention from the standpoint of improved safety and economy. The LBB design aims to ensure that postulated cracks will cause a detectable leakage rate before they propagate in an unstable fashion, even in emergencies. An application of the LBB concept to protect the RPV of NHR-200 from a postulated break has been reviewed in INET to achieve the rationalization of structural design in the context of design improvements.

Up to now, the LBB theory and its application in reactor pressure vessels and pipes have been investigated in many countries. However, a unified criterion and methodology for LBB design have not been achieved. In our study, the LBB program developed by U. S. Nuclear Regulatory Commission (USNRC, 1984, 1988) and one simplified program (Feng and He, 1998) based on linear elastic fracture mechanics and plasticity theory have been adopted. Also, a detailed analysis based on elastic-plastic fracture mechanics has been performed with the aid of a computer program developed by INET. The results from the theoretical and numerical methods show that the RPV of NHR-200 meets the LBB conditions in a wide margin. Only the main procedure of the second method, which is developed on the basis of the first one (USNRC, 1984, 1988), is described in this section. The detail LBB analysis method based on a *J*-integral method and some relevant experiments will be published in another paper.

4.1 Validity of LBB Design

Before the LBB concept is introduced into the safety analysis of a pressure vessel or pipe, its validity must be assured first. Material selection, design, fabrication, inspection and detection should be performed in accordance with the applicable regulations, codes and standards. The LBB methodology is not usually applied to components that have a history or possibility of excessive or unusual loads or degradation mechanisms. The excessive or unusual loads or degradation mechanisms of concern mainly include water hammer, corrosion, erosion, creep, fatigue and brittle fracture. In the LBB analysis of the RPV of NHR-200, it is concluded from our review that all these potential failure mechanisms can be avoided by proper design, fabrication, installation and operating condition. Therefore, it is appropriate to apply the LBB analysis in the structural design and safety assessment of the RPV discussed here.

Considering the stress distributions and the mechanical properties of materials, and accounting for the effects of welds, some critical positions for LBB evaluation are determined. All these positions have to be demonstrated to meet the LBB criterion. In what follows, for conciseness, a postulated circumferential or longitudinal crack in the RPV is assumed to illustrate the basic procedure adopted for the evaluation of its LBB behavior.

4.2 Calculation of Leakage Rate

A calculation of leakage rate is essential for the determination of the crack length, $2a_{\text{leak}}$, which is defined as the minimal crack length detectable for the leakage monitoring system of the reactor primary coolant. It is well accepted that the leakage rate of 1 gallon/minute in a reactor primary pressure boundary should be detected within one hour by the monitoring system. The margin on leakage detection is often chosen to be 10. Therefore, the leakage rate of 10 gallon/minute is used to determine the detectable crack length $2a_{\text{leak}}$.

Introducing the damage of materials into the analysis of fatigue crack growth, Feng and He (1997) presented a theoretical method based on continuum damage mechanics to simulate crack shape development. According to their results, it should be noticed that the crack length that will be used in the fracture mechanics evaluation in the sequel should also be larger than 3~4 times of wall thickness, depending upon the initial aspect ratio of the surface crack and the loading conditions.

It is important but difficult to clarify the relation of leakage rate with respect to internal temperature and pressure, geometric dimension of the structure, crack shape, crack surface roughness and varying bending moment. Up to now, many theoretical or empirical models have been developed to solve the problem of calculating the leakage rate from a crack (Bahandari, 1993; Feng et al., 1998; Moody, 1966; Swarmy, 1986). Under different conditions of temperature, pressure, and properties of the liquid, different methods can be adopted in order to have a high accuracy. After some numerical comparison, the present authors adopt a two-phase critical flow model (Xu et al., 1995) to obtain the leakage rate for a through-wall crack in the RPV of NHR-200. This two-phase critical flow is rather simple to be applied and is accurate enough for our LBB analysis, although its shortcoming and limitations are also noticed. For the considered problems, the leakage rate through a crack, *m*, can be calculated by (Xu et al., 1995)

$$m = GA = A \times 0.61\sqrt{2p\rho(1-\eta)} \qquad \eta = p_{\text{sat}}(T)/p \tag{3}$$

where G is the leakage rate per unit flow area, A is the crack opening area, p and T are respectively the pressure and temperature in the vessel, ρ is the density of liquid, η is the critical pressure ratio, p_{sat} is the saturated pressure at temperature T. p_{sat} and η can be obtained from tables of physical properties of water in many textbooks on fluids.

For comparison, the Moody's two-phase flow model (Moody, 1966) is also used to calculate the leakage rate. The results of many examples from the two methods are in a good accordance under the operating condition of the RPV of NHR-200.

4.3 Calculation of Stresses and Stress Intensity Factors

In the LBB analysis, the most dangerous loading state to which the RPV may be exposed should be considered. Therefore, it is necessary to specify the types and magnitudes of all possible loads, which include the static forces and moments due to normal operation and those associated with the safe shutdown earthquake. Then, the total force and moment can be obtained by adding all the components according to the following equations

$$F_{\text{total}} = |F_{\text{DW}}| + |F_{\text{T}}| + |F_{\text{P}}| + |F_{\text{SSE}}| + |F_{\text{other}}|$$
$$(M_i)_{\text{total}} = |(M_i)_{\text{DW}}| + |(M_i)_{\text{T}}| + |(M_i)_{\text{P}}| + |(M_i)_{\text{SSE}}| + |(M_i)_{\text{other}}|$$
$$M_{\text{total}} = \left[(M_1)^2_{\text{total}} + (M_2)^2_{\text{total}} + (M_3)^2_{\text{total}}\right]^{1/2} \tag{4}$$

where F denotes the axial force, M the moment. The subscripts i (i=1,2,3) denote the three components of moment, the subscripts „total", „DW", „p", „T", „SSE" and „other" denote the total loads and its components due to dead-weight, internal pressure, temperature, safe shutdown earthquake and other reasons, respectively.

To obtain the stress distribution in an elastic-plastic structure, a complete three-dimensional constitutive relation of the material and an analysis of elastic-plastic mechanics are often needed. As aforementioned, the finite element program package, NASTRAN, is adopted in our analysis. For pressure pipes and vessels in LBB analysis, wide margins are required to ensure their safety and stability. Hence, the mechanical response of the pipes and vessels is often elastic. Under such cases, only an elastic analysis is necessary, and the constitutive relation and the stress computation become much simpler.

Longitudinal and circumferential through-wall cracks are two typical cases in LBB analysis of pressure pipes or vessels. Herein, the stress intensity factor is taken as the control parameter of unstable crack growth. Assume that a circumferential or longitudinal crack with half length a exists in a vessel with average radius R and thickness t. If the vessel is subjected to axial force N, bending moment M and internal pressure p, the mode-I stress intensity factor can be expressed as

$$K^{\text{I}}_{\alpha} = \sum_{\beta} K^{\text{I}}_{\alpha\beta} = \sum_{\beta} M_{\alpha\beta} K^{\text{I}}_{\beta 0} \qquad (\alpha = 1,2, \quad \beta = 1,2,3) \tag{5}$$

where $K^{\text{I}}_{\beta 0}$ denote the stress intensity factors of a crack with the same size in a plate subjected to the same loads, $M_{\alpha\beta}$ modification coefficients. The subscripts $\alpha = 1$ and 2 correspond to the circumferential and longitudinal crack cases, and β=1, 2 and 3 correspond to the loading cases of axial tension, bending and internal pressure, respectively. For example, M_{12} denotes the modification coefficient of stress intensity factor of a circumferential crack under bending, and K^{I}_{10} the stress intensity factor in a plate under tension.

Some other factors (for example, the ellipticity and ovalization of pipes, welds and transformation geometry) should also be accounted for in the calculation of stresses and stress intensity factors (Feng et al., 1998). These factors may exert an evident influence on the magnitudes of stresses and stress intensity factors.

4.4 Crack Instability Analysis

To demonstrate the LBB behavior of a component, both the global and the local stability evaluations are required. A simple effective method of global plastic instability analysis is the plastic instability method, based on traditional plastic limit load concepts, but accounting for strain-hardening effects and taking into account the presence of a crack (Swarmy, 1986). A widely adopted method of local instability analysis, which is also used in the LBB analysis of NHR-200, is based on the concept of J-integral in elastic-plastic fracture mechanics. The corresponding crack instability criterion can be found in many textbooks on fracture mechanics. Due to the complexity in the calculation of J-integral and in the measurement of J-resistance curve, however, some methods based on linear elastic fracture mechanics are often adopted to make an estimation of LBB characteristics of a component.

According to the Regulations of Chinese Vessel Defect Assessment (CVDA, 1984), the concept of stress intensity factor can be used to review the stability of crack growth in pressure vessels and pipes provided that the equivalent tensile stress is lower than the yield stress of material. The low stresses in the RPV of NHR-200 meet this condition. Then, it is thought that unstable brittle fracture will not occur in a crack provided that its stress intensity factor satisfies the inequality

$$K^{\mathrm{I}} < 0.6\, K_{\mathrm{c}}^{\mathrm{I}} \tag{6}$$

where $K_{\mathrm{c}}^{\mathrm{I}}$ is the critical value of stress intensity factor of the material.

For comparison, the R6 method is also adopted, in which the interaction between brittle fracture and plastic collapse is accounted for. A non-dimensional stress intensity factor K_{r} and a non-dimensional plastic load factor L_{r} are defined by

$$K_{\mathrm{r}} = \frac{K^{\mathrm{I}}}{K_{\mathrm{c}}^{\mathrm{I}}} \qquad L_{\mathrm{r}} = \frac{P}{P_{\mathrm{L}}} \tag{7}$$

respectively, where P is the applied load, and P_{L} the plastic collapse load. If an assessment point (K_{r}, L_{r}) for a component lies inside the curve of the failure assessment diagram, the crack will not lead to failure under the applied loads.

4.5 Calculation of Crack Opening Area

The crack opening area of a component is another important parameter in LBB analysis. Its importance includes two aspects. First, the leakage rate of a through-wall crack is directly related to its crack opening area. The leakage can be detected more quickly for a larger crack opening area. Second, the jet force of coolant acting on the vessel or pipe is also related to the crack opening area. The crack opening area can be calculated from several theoretical approaches on the basis of elastic or elastic-plastic fracture mechanics (Bahandari, 1993; Feng et al., 1998). Here, the crack opening area is evaluated approximately by

$$A = 2\pi\sigma a^2(1+0.1\lambda+0.16\lambda^2)/E \tag{8}$$

for a postulated through-wall longitudinal crack or by

$$A = 2\pi\sigma a^2(1+0.117\lambda^2)^{1/2}/E \tag{9}$$

for a postulated through-wall circumferential crack (Wüthrich, 1983). In equations (8) and (9),

$$\lambda^4 = 12(1-\nu^2)a^4/(R^2t^2) \tag{10}$$

E is Young's modulus, ν is Poisson's ratio, σ is the tensile stress normal to the crack surfaces, a is the half-length of the crack, and R and t are the average radius and the thickness of the vessel, respectively.

4.6 Results

In the LBB evaluation of the RPV of NHR-200, some used parameters are as follows: $K_{\mathrm{c}}^{\mathrm{I}}$=220 MPam$^{1/2}$, σ_{y}=262 MPa, σ_{b}=483 MPa, p=3.1 MPa, T=213 °C, P_{sat}=2.031 MPa, R=2426.3 mm, t=65 mm, and ρ=848.7 Kg/m^3, E= 2.1×10^5 MPa and ν=0.28. Among them, the material parameters are conservatively obtained from our experiments or related handbooks. The results of the LBB analysis of the RPV of NHR-200 are given in Table 5. In this table, A and a_{leak} correspond to the leakage rate of 10 gallon/minute, while K^{I}, K_{r} and L_{r} correspond to the crack with the half length $2a_{\mathrm{leak}}$. Apparently, the RPV has the LBB property, and hence the possibility of brittle failure can be excluded from it. This stems mainly from its small wall thickness and low stress intensity. In the authors' opinion, it is often difficult for the RPVs of PWRs or BWRs to meet the LBB conditions due to their big wall thickness and high stress level.

Crack	A (m^2)	a_{leak} (mm)	K^I (MPam$^{1/2}$)	K_r	L_r
Longitudinal crack	2.06×10^{-5}	73.7	133.0	0.397	0.454
Circumferential crack	2.06×10^{-5}	106.0	76.82	0.223	0.242

Table 5. Results of LBB Analysis of the RPV of NHR-200.

5 Conclusions

Some safety features of the RPV of NHR-200 designed by INET of China are analyzed. Theoretical analysis and numerical computation show that both the stress level and the FCGR in the RPV are very low, and that it can operate safely during the whole life of the reactor. The LBB evaluation demonstrates that postulated cracks in the RPV will cause a detectable leakage rate before they propagate in an unstable fashion, even in emergencies. Therefore, the possibility of brittle fracture can be excluded from the RPV. It is expected that the RPV of NHR-200 have a much lower probability of failure than those of PWRs and BWRs.

Acknowledgment

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