Nuclear Engineering and Design 288 (2015) 130–140

Contents lists available at ScienceDirect

Nuclear Engineering and Design

journal homepage: www.elsevier.com/locate/nucengdes

The deterministic structural integrity assessment of reactor pressure vessels under pressurized thermal shock loading

Mingya Chen*, Feng Lu, Rongshan Wang, Ping Huang, Xiangbin Liu, Guodong Zhang, Chaoliang Xu

Suzhou Nuclear Power Research Institute, Jiangsu Province, Suzhou215004, PR China

HIGHLIGHTS

- The conservative and non-conservative assumptions in the codes were shown.
- The influence of different loads on the *SM* was given.
- The unloading effect of the cladding was studied.
- A concentrated reflection of the safety was shown based on 3-D FE analyses.

ARTICLE INFO

Article history:
Received 23 November 2014
Received in revised form 23 February 2015
Accepted 3 March 2015

ABSTRACT

The deterministic structural integrity of a reactor pressure vessel (RPV) related to pressurized thermal shocks (PTSs) has been extensively studied. While the nil-ductility-transition temperature (RT_{NDT}) parameter is widely used, the influence of fluence and temperature distributions along the thickness of the base metal wall cannot be reflected in the comparative analysis. This paper introduces the method using a structure safety margin (*SM*) parameter which is based on a comparison between the material toughness (the fracture initiation toughness K_{IC} or fracture arrest toughness K_{Ia}) and the stress intensity factor (SIF) along the crack front for the integrity analysis of a RPV subjected to PTS transients. A 3-D finite element model is used to perform fracture mechanics analyses considering both crack initiation assessment and arrest assessment. The results show that the critical part along the crack front is always the clad-base metal interface point (IP) rather than the deepest point (DP) for either crack initiation assessment or crack arrest assessment under the thermal load. It is shown that the requirement in Regulatory Guide 1.154 that 'axial flaws with depths less than 20% of the wall thickness and all circumferential flaws should be modeled in infinite length' may be non-conservative. As the assessment result is often poor universal for a given material, crack and transient, caution is recommended in the safety assessment, especially for the IP. The SIF reduces under the thermal or pressure load if the map cracking (MC) effect is considered. Therefore, the assumption in the ASME and RCCM codes that the cladding should be taken into account in determining the stress fields is conservative when there are small cracks in the cladding (considering MC effect).

1. Introduction

The dominant type of damage in the reactor pressure vessel (RPV) is embrittlement under neutron irradiation, especially in the beltline area. During the operation of a pressurized water reactor, a certain type of transients could initiate the emergency cooling system (pressure and temperature transients) leading to rapid cool-down of the RPV wall, so called Pressurized Thermal Shocks (PTS), which may induce a high tensile stress at the inner surface of the RPV. If an embrittled RPV were to have a flaw of critical size, the flaw could propagate very rapidly through the vessel during the PTS transient. Thus, the PTS event poses a potentially significant challenge to the structural integrity of the RPV (Qian et al., 2015; Coste et al., 2012). For each PTS transient of interest, a deterministic analysis that includes a set of crack depths corresponding to initiation and arrest events should be carried out (Jhung et al., 2009).

The PTS rule 10 CFR Part 50 (NRC, 1984) establishes a screening criterion based on a reactor vessel nil-ductility-transition temperature (RT_{NDT}). The screening criterion RT_{NDT} (called RT_{PTS} in the rule)

---

* Corresponding author. Tel.: +86 051268701169; fax: +86 051268602518.
E-mail addresses: chenmingya@cgnpc.com.cn, chenmingya200852@163.com (M. Chen).

http://dx.doi.org/10.1016/j.nucengdes.2015.03.008
0029-5493/© 2015 Published by Elsevier B.V.

were selected according to the studies that the risk due to PTS events is acceptable (NRC, 1987). The RT_{NDT} parameter is widely used since it considers directly the aging of the RPV. But as shown in the reference (IAEA, 2010; NEA, 1999), there are some limitations for this parameter. The influence of the distribution of fluence and temperature along the vessel thickness direction cannot be reflected in the comparative analysis. The PTS transients often produce both thermal and pressure stresses. Pressure stresses are almost constant through the thickness of the RPV wall, while thermal stresses are tensile on the inner diameter of the vessel, and are equilibrated by compressive stresses on its outer diameter during the cool-down process. Therefore, it is difficult to distinguish the effect of different loads in the integrated analysis. Also, the assessment result of single transient, material and defect size is often poor universal. On the other hand, the fracture often occurs around the time of the lowest coolant temperature rather than at the time of the maximum stress intensity factor (SIF) (IAEA, 2010; Chen et al., 2014). At this moment, the thermal stress has been in the unloading process, and the unloading effect of the cladding should be appreciated in the elastic–plastic analysis (few literatures have been reported on this effect).

In fact, there are many small cracks in the multi-layer cladding (NRC, 2013). Although the flaw that lies entirely in the cladding need not to be evaluated (ASME, 2013a), the cladding may only conduct heat flux but lose its strength to bear the loads when there are many small cracks. Therefore, the assumption in RCCM (RCCM, 2007) and ASME codes (ASME, 2013b) that the cladding should be taken into account in determining the stress fields may be nonconservative.

A typical analysis may show a number of initiation and arrest events during the PTS transient (Pennell et al., 1997). Actually, the safety margin (*SM*) of structure can be directly reflected by comparing the material fracture toughness (the fracture initiation toughness K_{IC} or fracture arrest toughness K_{Ia}) with the SIF along the crack front, and the influence of fluence and temperature distributions along the thickness of the base metal wall can be reflected in the contrastive analysis with this method (Chen et al., 2014). In this paper, the safety assessment is carried out on separation of pressure and thermal loads using the *SM* parameter considering both fracture initiation assessment and arrest assessment firstly, then the influence of transient information, material property and the crack size is analyzed. Lastly, the supplement analysis is carried out with the assumption that the cladding would be only able to conduct heat flux but lose its strength to bear the loads during PTS transients. The precise safety assessment is based on the finite element analyses.

2. Methodology

2.1. Fracture toughness

In the ASME Code Sec. XI (ASME, 2013c), the analytic expression of the lower bound K_{IC} and K_{Ia} versus temperature is as follows:

$$K_{IC} = 22.783e^{0.036(T-RT_{NDT})} + 36.5 \quad (1a)$$

$$K_{Ia} = 13.675e^{0.0126(T-RT_{NDT})} + 29.4 \quad (1b)$$

$$K_{IC}, K_{Ia} \le 220 \quad (1c)$$

where K_{IC} and K_{Ia} are expressed in $MP\sqrt{m}$, T (°C) is material temperature, and RT_{NDT} (°C) is the nil-ductility-transition temperature.

When the loading rate of SIF is less than $10^3(MP\sqrt{m})/s$, the effect of loading rate on fracture toughness can be ignored (Klepaczko, 1980). In fact, the loading rate of the SIF is always smaller than $10^3(MP\sqrt{m})/s$ during the whole PTS transient (IAEA, 2010; NEA, 1999), so the effect of loading rate on fracture toughness is ignored in this paper.

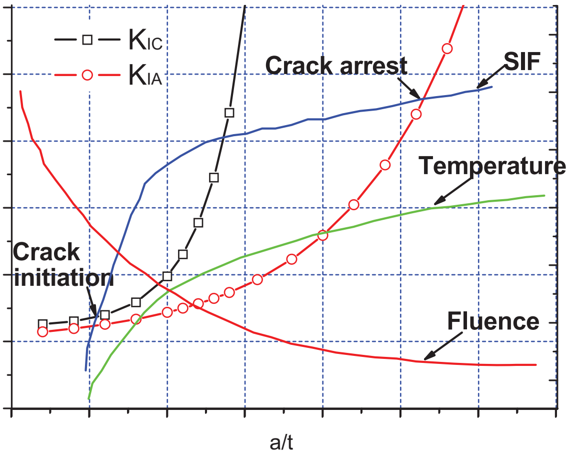

Fig. 1. The safety assessment of the PTS transient.

2.2. Embrittlement of the material

The material is likely embrittled, and the degree of embrittlement is quantified by the change in RT_{NDT}. In 10 CFR 50.61 (NRC, 1984), the analytic expression of the RT_{NDT} is as follow:

$$RT_{NDT} = RT_{NDT(U)} + M + \Delta RT_{NDT} \quad (2)$$

where $RT_{NDT(U)}$ means the reference temperature for a reactor vessel material in the pre-service condition, evaluated according to the procedure in the ASME Code, Paragraph NB-2331 or other approved methods. M means the margin to be added to account for uncertainties in the values of $RT_{NDT(U)}$. ΔRT_{NDT} is the mean change in RT_{NDT}, and can be calculated using Eq. (3).

$$\Delta RT_{NDT} = CF \cdot f_{surf}^{(0.28-0.10\log f_{surf})} \quad (3)$$

where CF (°F) is the chemistry factor, and f_{surf} is the best estimate neutron fluence, in units of 10^{19} n/cm^2 (E greater than 1 MeV), at the clad-base metal interface. The methodology to calculate the fluence at arbitrary depths of the reactor vessel wall is contained in Regulatory Guide1.99 Rev. 2 (NRC, 1988). And, it should be noted that the adjusted reference temperature (ART) in Regulatory Guide1.99 Rev. 2 is equivalent to the reference transition temperature in 10 CFR 50.61. The neutron fluence $f(x)$ at the depth in the vessel wall is determined as follows in Regulatory Guide 1.99 Rev. 2:

$$f(x) = f_{surf} \cdot e^{-0.24x} \quad (4)$$

where x (in inches) is the depth into the vessel wall measured from the clad-base metal interface.

2.3. Safety assessment

As shown in Fig. 1, the neutron fluence gradient in the vessel wall is produced in the operation, and thermal gradients are also generated in PTS events. At any point during a PTS transient, intersection of the applied SIF curve (stress and flaw geometry dependent) with the material fracture toughness curves (temperature, fluence and material dependent) defines the crack initiation and the intersection with the K_{Ia} curve defines crack arrest. Cracks which initiate in the cool inner region of the vessel may arrest in a region of the wall where temperature is much higher and neutron fluence is lower. The safety assessment of the PTS should contain crack initiation, crack arrest or reinitiation events.