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Reactor pressure vessel embrittlement of NPP borssele: Design lifetime and lifetime extension

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Abstract

Embrittlement of the reactor pressure vessel of the Borssele nuclear power plant has been investigated taking account of the design lifetime of 40 years and considering 20 years subsequent lifetime extension. The paper presents the current licensing status based on considerations of material test data and of US nuclear regulatory standards. Embrittlement status is also evaluated against German and French nuclear safety standards. Results from previous fracture toughness and Charpy tests are investigated by means of the Master curve toughness transition approach. Finally, state of the art insights are investigated by means of literature research. Regarding the embrittlement status of the reactor pressure vessel of Borssele nuclear power plant it is concluded that there is a profound basis for the current license up to the original end of the design life in 2013. The embrittlement temperature changes only slightly with respect to the acceptance criterion adopted postulating further operation up to 2033. Continued safe operation and further lifetime extension are therefore not restricted by reactor pressure vessel embrittlement.

1. Introduction

The status of the reactor pressure vessel of the Borssele nuclear power plant shows no concern for operation to the design lifetime of 2013. The interest of this paper for Borssele is the possibility of lifetime extension beyond 2013. Therefore, the following goal is set for this study.

1.1. Goal

Review the state-of-the-art insights about reactor vessel irradiation embrittlement and safety standards concerning Borssele nuclear power plant. The review will result in an extensive multi-disciplinary irradiation embrittlement survey for long term operation of the Borssele reactor pressure vessel.

2. Current status

2.1. RT_{NDT}

The current status of the reactor pressure vessel with respect to irradiation embrittlement is based on the measured transition temperatures RT_{NDT} out of three material surveillance programs (“Staal Onderzoeks Programma’s”, SOP-0, SOP-1 and SOP-2). The transition temperatures are determined by Charpy energy measurements on the unirradiated material (SOP-0) and two sets of irradiated samples (SOP-1 and SOP-2) placed closer to the core than the actual vessel. These surveillance programs represent the irradiation embrittlement status of the vessel at a later stage by means of an elevated dose. The most irradiated parts of the vessel are ring 3, ring 4, weld W03 and the heat affected zone (HAZ) of this weld (see Fig. 1). The measured RT_{NDT} for

Abbreviations: AMES, Ageing of Materials and Evaluation Studies; ASME, American Society of Mechanical Engineers; ASTM, American Society for Testing and Materials; CF, Chemistry Factor given in tables in RG1.99 rev. 2 (1988); CFR, Code of Federal Regulations; Cu, copper content; EDF, Electricité de France; ϕ, Fluence given in 10^{19} n/cm^2; FIM, French Average Irradiation embrittlement prediction formula; FIS, French Upper Bound Irradiation embrittlement prediction formula; HAZ, Heat Affected Zone; IAEA, International Atomic Energy Agency; KTA, Kerntechnischer Ausschuss (German Nuclear Safety Standards Commission); Ni, nickel content; NPP, Nuclear Power Plant; NRC, Nuclear Regulatory Commission; NUREG, Report series from Nuclear Regulatory Commission (NRC); P, phosphorus content; PTS, pressurized thermal shock; RCC-M, Règles de Conception et de Construction relatif aux Matériels mécaniques (French nuclear material code); RG, Regulatory Guide; RSEM, Rules for in-service surveillance of mechanical equipment (French code); RT_{NDT}, Nil Ductility Reference Temperature; SOP, “Staal Onderzoeks Programma” (Material surveillance program); USE, Upper Shelf Energy; US, United States; WOL, wedge opening loading

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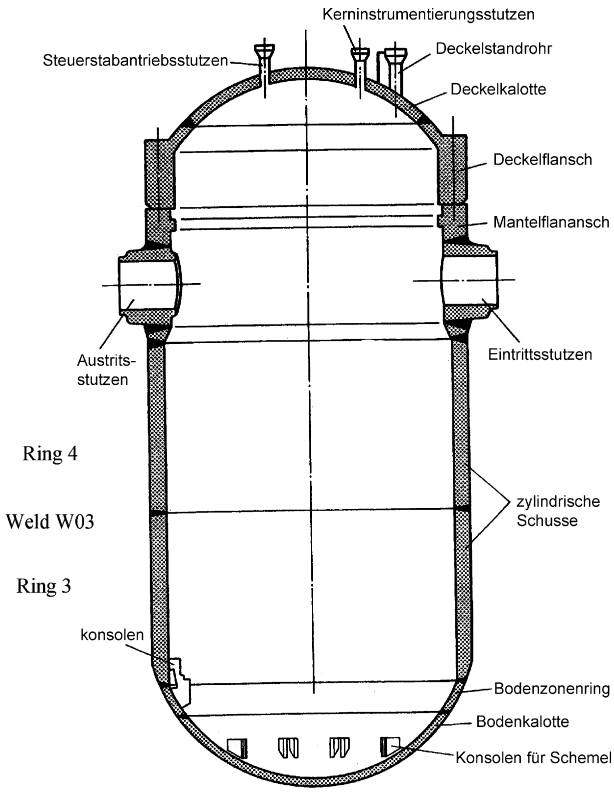

Fig. 1. Reactor pressure vessel of the Borssele nuclear power plant.

Table 1
RT_{NDT} (°C) SOP-0 to SOP-2 at different locations

Location	RT_{NDT} (SOP-0)	RT_{NDT} (SOP-1)	RT_{NDT} (SOP-2)
Ring 3	−10	−0.3	4.2
Ring 4	−20	−3.3	3.1
Weld W03	−45	−13.1	−4.1
HAZ	−5	7.5	27.4

the different zones are shown in Table 1. It can be seen that the highest RT_{NDT} is found in the HAZ and is equal to 27.4 °C.

Subsequently, the lead factors are determined for SOP-1 and SOP-2. These are used to determine the year, which is represented by both programs. These calculations are based on calculations using Point kernel methods and Twotran S2 (Oosterkamp and Dufour, 1983). The represented year is calculated using the actual load factor. The cumulative load factor is extrapolated to 2033 using a very high actual load factor of 97%. The transformation of the core to a low-leakage one after 10 years of operation is taken into account in order to determine the representative year for SOP-1 and SOP-2, which are shown in Table 2.

Table 2
Dating result for SOP-1 and SOP-2

	Year
SOP-1	2000
SOP-2	2012

2.2. Prediction equation RG1.99 rev. 2

From a conservative viewpoint, the licensing of Borssele nuclear power plant is based on the maximum RT_{NDT} from the US Regulatory Guide 1.99 rev. 1 (RG1.99 rev. 1, 1977) and 10CFR section 50.61 (10CFR 50.61, 1984). These standards conservatively predict the RT_{NDT} based on the initial RT_{NDT}, Cu and Ni content and fluence from correlation relations in large series of reactor pressure vessel test data. These prediction equations give a RT_{NDT} of 44 °C in the HAZ after 40 years of operation. The updated version of the prediction is given in RG1.99 rev. 2 (RG1.99 rev. 2, 1988) and 10CFR section 50.61 (10CFR 50.61, 2003).

The equation is given below,

$$RT_{NDT} = \text{Initial}\, RT_{NDT} + \Delta RT_{NDT} + \text{margin} \quad (1)$$

where InitialRT_{NDT} is the initial RT_{NDT} (see Table 1). Margin is equal to twice the standard deviation for the surveillance programs investigated (31 °C for welds and 19 °C for other materials). ΔRT_{NDT} is given below,

$$\Delta RT_{NDT} = (CF)\phi^{(0.28-0.10\log\phi)} \quad (2)$$

where CF is a 'Chemistry Factor', which is given in tables in RG1.99 rev. 2 (RG1.99 rev. 2, 1988) and 10CFR section 50.61 (10CFR 50.61, 2003) as a function of copper and nickel content. ϕ is the fluence given in 1019 n/cm^2 (>1 MeV). RT_{NDT} is given in °F due to the US background of the documents.

The RT_{NDT} for the different locations, calculated by these standards, is given in Fig. 2. The maximum RT_{NDT} is found in the HAZ and is equal to 45 °C in 2012 and 48 °C in 2033.

According to 10CFR section 50.61 (10CFR 50.61, 2003) there is a PTS screening criterion for the maximum RT_{NDT}, which has to remain below 149 °C in welds. The criterion is based on probabilistic PTS analyses performed on a database of US reactor pressure vessels (see RG1.154, 1987). If the PTS screening criterion is met, the probability of through wall fracture is lower than 5×10^{-6} per reactor year. Fig. 2 shows that the criterion is amply met. Therefore, it can be concluded that the RT_{NDT} criteria from (10CFR 50.61, 2003) do not pose a threat on further operation of the reactor pressure vessel until 2033.

2.3. Upper shelf energy

The upper shelf energy (USE) demand is determined by US NRC regulations in (10CFR 50.60, 1996) and (10CFR part 50 Appendix G, 2003b). These regulations state that the USE has to remain above 68J. The initial USE for the pressure vessel of Borssele is higher than 200 J for all locations. The decrease of the USE can be determined by means of a graph from (RG1.99 rev. 2, 1988) depending on the Cu and Ni content and fluence. This prediction is also based on a large series of reactor pressure vessel test data. Since the Cu content of the pressure vessel is low, the decrease of the USE is low and limited to 31% at a fluence of 3.5×10^{19} n/cm^2. The measured decrease of the USE is limited to 27%. It can be concluded that the USE criteria from (10CFR part 50 Appendix G, 2003b) do not limit the operation of the pressure vessel.