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PRESSURIZED THERMAL SHOCK (PTS) ANALYSIS IN NUCLEAR POWER PLANTS

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ABSTRACT

For more than 40 years TÜV NORD has provided services as a competent consultant in nuclear safety issues giving expert third party opinion to our clients.
According to German regulations the safety against brittle fracture of the reactor pressure vessel (RPV) has to be proven according to the state-of-the-art. Hence, new knowledge has to be regularly incorporated into the proof with the development in international codes and standards like ASME, BS and RCC-M and with the gain of new operating experience, as the detection of hydrogen flakes in the RPV walls of Belgian nuclear power plants.
The transient load of the RPV results from very complex pressure and temperature effects. Nowadays, these loading conditions can be modelled by thermal hydraulic calculations and on the basis of new experimental results much more detailed than in the construction phase of German nuclear power plants in the 1980s. Therefore, the proof against brittle fracture from the construction phase had to be updated for all German Nuclear Power Plants with new findings of the loading conditions. The fracture mechanics assessment is performed for normal and abnormal operating conditions and for accidents like Loss of Coolant Accident (LOCA).
With the non-destructive finding of several regions with a high concentration of hydrogen flakes (micro-cracks) in Belgian RPVs (Tihange 2 and Doel 3) these studies are of great interest for the current international reactor safety assessment.
In this paper the German approach to fracture mechanics assessment to brittle fracture will be discussed from the point of view of a third party organization. It will also be outlined what influence such findings as for the Belgian RPVs would have on this approach.

INTRODUCTION

In Germany there were 17 Nuclear Power Plants (NPP) for many years in operation. As a consequence of the Fukushima event German politics decided to shut down 8 NPPs in 2011. 9 NPPs were allowed to remain in operation with staggered shutdown dates until 2022.

The task for TÜV NORD is to supervise the utilities in the safety procedures of the remaining German NPPs for their lifetime. In this business TÜV NORD is commissioned by the federal state governments. In Germany, TÜV NORD as a third party expert must have the knowledge to make own independent calculations and examinations to verify the operators statements and informations.
In addition to the national projects, over the last 15 years TÜV NORD was successful in receiving international orders in the nuclear business from NPP operating companies or government authorities in Argentina, Brazil, South Africa, South Korea, Sweden and Switzerland.

The international development of assessment methods for the thermo-mechanical stresses and strains of the Reactor Pressure Vessel (RPV) has made significant progress since the construction of the German

Nuclear Power Plants. The starting point was a transient in the Rancho Seco nuclear power plant in California and the subsequent research. A strong downcooling of the reactor coolant occurred in this transient in the reactor coolant system with a simultaneous pressure recovery. This effect induced thermal stresses in the RPV wall in an unfavourable way and additional tension was caused by the high pressure, Iyer, K., Nourbakhsh, H.P., and Theofanous, T.G., (1986).

This resulted in a load case which caused a combined Pressurized Thermal Shock (PTS) for the RPV different from the previously considered isolated Thermal Shock (TS). Due to the increasing radiation embrittlement of the RPV during plant operation such a pressure-temperature induced stress can lead to the instability of near-surface cracks in the RPV wall. Due to the existing internal pressure during PTS transients there will be a higher probability that this results in crack instability. This results in the possibility of further crack propagation through the RPV wall followed by a total failure of the RPV.

The international codes and standards describe two different methods for evaluating the brittle fracture of RPV's. These are the probabilistic analysis method preferably used in the U.S. and the deterministic method preferred especially in Germany and France, see GRS (1999). In Germany the fracture mechanics calculations are performed with precise crack geometry, which is an input from nondestructive testing (NDT) experience.

The application of the probabilistic method requires an investigation of the entire spectrum of transients. First, the probability of occurrence of these transients by using a fault tree analysis and afterwards the probability of an RPV failure are determined (e. g. with a Monte Carlo simulation). The Monte Carlo simulation takes into account the RPV material properties, the initial error distribution, the crack propagation for the stresses of the transients and the probability distribution of the detected errors of a certain size during recurring tests.

Brittle fracture safety is accepted if the failure probability of the RPV is below a maximum permissible value.

Applying the deterministic method, the transient with the highest loading is determined. For this, a fracture mechanics analysis with pessimistic calculation assumptions is carried out. It has to be ensured that small imperfections in the RPV wall in the size of the NDT detection limits cannot lead to a failure of the RPV for the transient with the highest load.

The American authority U.S. Nuclear Regulatory Commission (NRC) argues in its set of rules (i.e., "Fracture Toughness Requirements for Protection against Pressurized Thermal Shock Events" of the Code of Federal Regulations 10 CFR 50.61) that the PTS risk is the sum of small risks, each resulting from a large number of possible (but less probable) PTS events. In order to get the entire PTS Risk, the NRC-Regulatory Guide 1.154 describes a method to identify as many potential PTS events as possible, divide them into groups, calculate the frequencies and consequences, determine the risk for each group and add up the results, see NRC (1987). The deterministic method is classified by the NRC as only conditional suitable for plant-specific PTS analyses.

The NRC argues that the overall risk of all PTS loads can be significant, although the individual events lead to significantly less stress than the event with the highest loading selected for a deterministic analysis. However, a detailed plant-specific PTS analysis is only necessary if it is to be expected that the screening criterion is reached during the operating time of the plant.

Advancements in the state of knowledge since the U.S. Nuclear Regulatory Commission (NRC) promulgated its PTS Rule suggest that the embrittlement screening limits imposed by 10 CFR 50.61 are overly conservative. Therefore the NRC conducted a study to develop the technical basis for a revision of

the PTS-Rule consistent with the NRC's current guidelines on risk-informed regulation, see NRC (2007). In early 2005, the Advisory Committee on Reactor Safeguards (ACRS) endorsed the approach and its proposed technical basis. The technical basis was documented in a lot of reports, which were then reviewed. Based on these reviews, the probabilistic calculations were modified in certain aspects to refine and improve the model, see NRC (2010).

For the assessment of the brittle fracture safety of the German RPV according to the state of the art, rules and practice, we have taken into account not only the application of the German rules, but also the NRC position regarding the probabilistic assessment of the PTS risk. The consideration of the US PTS regulations for a German nuclear system demands for an examination of the plant engineering and material requirements. We previously transferred our own investigations for older German pressurized water reactors (PWRs) to the latest generation of German PWRs, the so-called Konvoi plants. In a second step, we compared the calculations for the Konvoi plants with the American calculations. The results show that the American screening criterion is not reached by the Konvoi plants. Therefore, there is no need for a system-specific probabilistic assessment of the PTS risk for the Konvoi RPV.

For the application of the deterministic method, the transient with the maximum load is identified, which is used with pessimistic assumptions for a fracture mechanics analysis. The result must show that small defects in the RPV wall, which grow below the detection limit, cannot lead to a failure of the RPV for the transient with the maximum load.

The deterministic fracture mechanics assessment of the RPV has the purpose to prevent the catastrophic failure of the vessel with a postulated defect. A leakage, critical crack propagation and brittle failure of the component have to be absolutely excluded (Damage Tolerance).

FLAW INDICATIONS IN THE REACTOR PRESSURE VESSELS OF BELGIAN RPV

In June 2012 specific ultrasonic (UT) in-service inspections were performed to check for underclad cracking in the RPV of the Belgian Nuclear Power Plant (NPP) Doel 3. There were no indications of underclad cracks, but several thousands of quasi-laminar flaw indications were detected in the base metal of the Doel 3 RPV, located mainly in the upper and lower core shells, see figure 1. A second inspection was performed in July 2012 with UT probes able to inspect the whole thickness of the vessel. This inspection confirmed a large number of the same type of indications deeper in the material. Similar inspections were planned on the Belgian Tihange 2 NPP, whose RPV is of identical design and construction, and were conducted in September 2012. Similar quasi-laminar flaw indications were detected as well, but to a lesser extent. The most likely origin of the flaw indications identified in the Doel 3 and Tihange 2 reactor pressure vessels is hydrogen flaking due to the manufacturing process.

There is now the question, whether such flaws have to be considered in the 3D PTS analysis. At the end of this publication we will evaluate the results of the PTS analyses for the German plants in this regard. We will investigate whether the stresses due to the temperature transient and temperature distribution at the RPV wall lead to more severe loads on the flaws as would arise by an axisymmetric calculation.

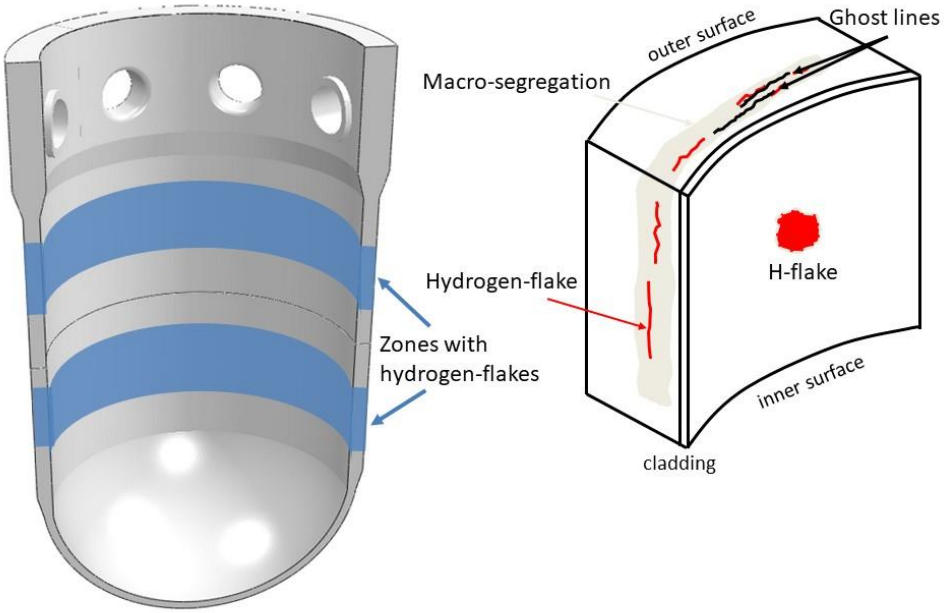

Figure 1: RPVof Doel 2 with hydrogen flakes

THERMAL-HYDRAULIC CALCULATION

The concept for the PTS-Safety analysis especially for LOCA is based on thermal-hydraulic analyses. These computations are divided in two steps. First, the calculations for the determination of the global system behaviour are performed with system codes like RELAP or ATHLET. The current versions of these thermal hydraulic analysis programs are not able to simulate the three-dimensional flow, especially the description of flow layers, water streams with heat transfer into the vapour phase and the thermal buoyancy mixing in the downcomer is not possible. Therefore in a second step, additional detailed analyses with the CFD method (CFD = Computational Fluid Dynamics) or engineering models derived from large-scale tests are carried out.

CFD programs like ANSYS CFX are based on the numerical solution of the general equations governing fluid dynamics, such as the Navier-Stokes equations, the energy equation, and several turbulence model equations. In this context, the finite-volume or finite element approaches are often used.

The engineering models are based on similarity of correlations that have been adapted to measurements on large-scale facilities. In comparison with CFD programs the engineering models currently provide still better solutions for cases where the test rigs used for deriving these models are representing the analysed plants well, see Changheui, J., Ill-Seok, J., Sung-Yull, H. (2000).

In the thermal hydraulic analysis the temperature field and the heat transfer coefficient field are determined at the RPV inner wall. These fields are described with the medium temperature of the plumes, the plume width and the plume displacement over the height of the RPV wall. Based on these data the fracture mechanics Finite Element Model (FEM) calculates first azimuthal temperature distributions for several heights using a Gaussian distribution and then from this temperature field the stress-strain field in the RPV.

FRACTURE MECHANICS

The technical rules for the fracture mechanics assessment of the RPV (Fig. 2) did not change so much from the construction phase until today. What changed the situation for fracture mechanics assessment are the current tremendous possibilities and improvements in thermal-hydraulic, structural and fracture mechanics calculations. The ASME-Code (Section III – "Rules for Construction" and Section XI – "Rules for In-service Inspection") and the KTA nuclear safety standard are assuming a specified defect size geometry (We distinguish between a postulated not really existing "defect" and a really existing "crack"). So it should first be said that in all the following PTS analyses we look at a postulated defect. There was never found any mentionable crack in German RPVs!

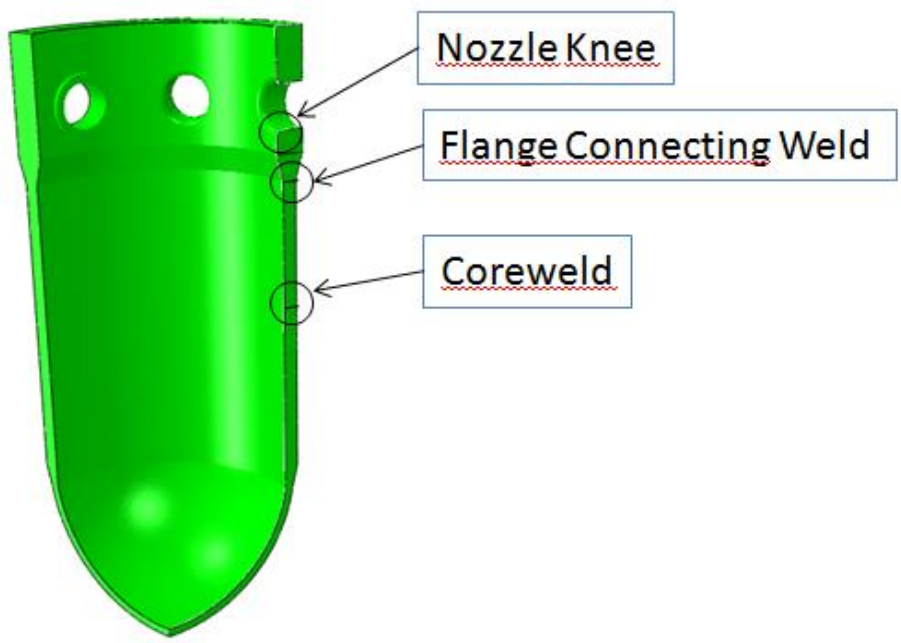

Figure 2: RPV – Critical locations for Brittle Fracture Assessment (Pressurized Water Reactor (PWR)

The assessment concept is the RT_{NDT}- or the RT_{T0}-concept: Experimental fracture toughness values are estimated for the RT_{NDT}-concept from Charpy specimen (RT_{NDT}, and with the radiation embrittlement the value RT_{NDTj}) and then compared with numerical or analytical calculated stress intensity values KI (KTA-Rule 3201.2).
For the RT_{T0}-concept or rather Mastercurve-concept, see IAEA (2005), specific fracture mechanics specimen (for example C(T)-specimen) are tested according to ASTM-E-1921 at different temperatures resulting in a T_0-Value. With this temperature and the ASME-Code-Cases N-629 and N-631 the RT_{T0} can be assessed also considering the radiation-embrittlement. From this RT_{T0} value the master curve can be designed and is compared with stress intensities from the numerical or analytical solution.
The fracture toughness K_{IC} and stress intensities K_I are shown in a diagram over the crack tip temperature (K_{IC} and K_I over T-RT_{NDT} or RT_{T0} - Figure 3).

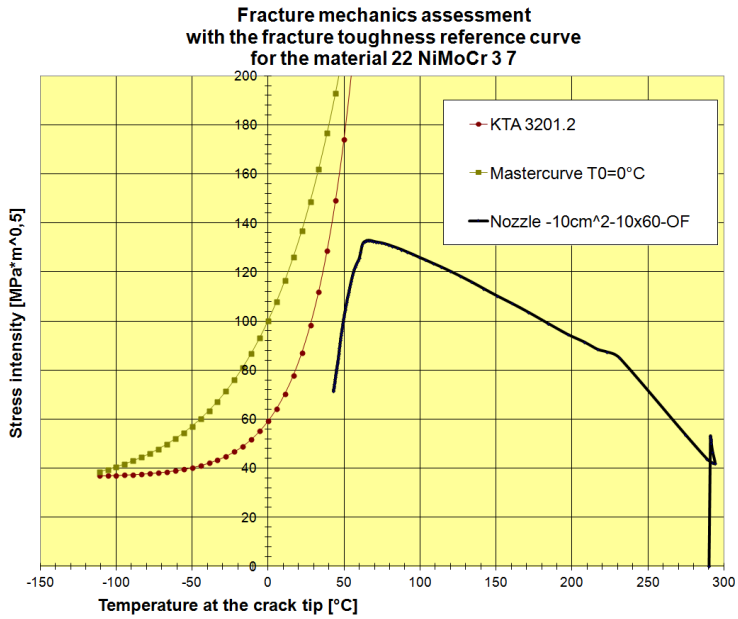

Figure 3: Fracture mechanics assessment with Mastercurve and KTA-curve
(here exemplary for the numerically evaluated curve from the nozzle knee)

Some particularities in the assessment concept are the Warm-Pre-Stress-Effect and the Constraint-Effect; but the conditions of acceptance of these effects are still in discussion or accepted on an international level (for example: IAEA) and in Germany at the Nuclear Safety Standards Commission (KTA).

The RPV is a bimetallic component consisting of ferritic base material and austenitic cladding (Figure 2). The different physical properties of these materials and the weld zone can be modeled nearly exactly with modern FEM software.
The material can be modeled in its elastic-plastic behaviour, so a significant realistic plastic zone results at the crack tip zone.

The residual stresses of the cladding process and in the welds of the component can also be modeled realistically.

From nondestructive testing the detectable crack size is multiplied by 2 (KTA-Rule 3201.2) and so we have a postulated semielliptical defect size for the RPV of 10 mm crack depth and 60 mm crack length.

We look at two different types of postulated defects:

1. Surface cracks with the cracked cladding and cracked base material
2. Sub-Surface crack with uncracked load bearing cladding (the crack is just in the base material)

Three crack positions in the RPV are of high interest, the Core Weld, the Flange Connecting Weld and the Nozzle In- and Outlet (Figure 1).

The fracture mechanics assessment is performed for normal and abnormal operation, pressure and leak tightness test and the Loss of Coolant Accident conditions (Figures 4 & 5).

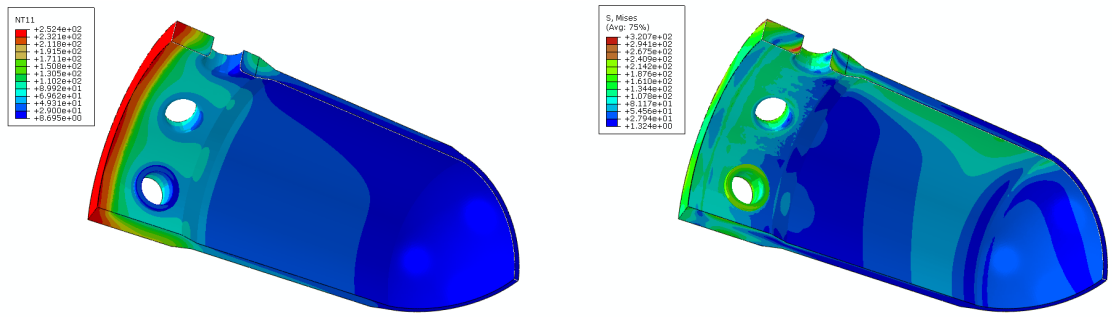

Figure 4: Contour plot of the temperature (left) and Mises stress (right) at the end of the transient loading (Cut in the middle of the cooling plume)

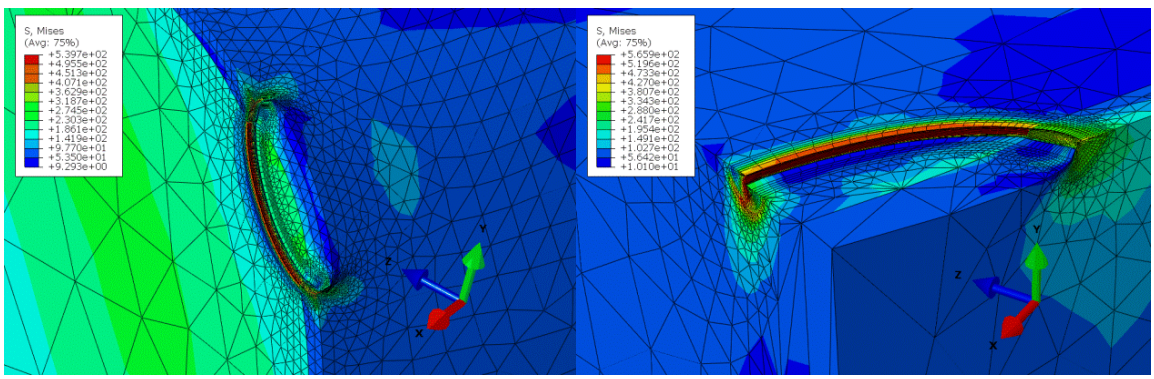

Figure 5: Mises stress contour plots for two submodels – semielliptical surface crack area at the nozzle knee (left) and core weld (right) - deformed structure with cracked area

As a result of this study the calculated K_I values are below the material K_{IC} curve (Figure 3 for LOCA – 10 cm^2 transient) and so the safety for all relevant loading conditions can be proven.

For the above mentioned problems in the Belgian nuclear power plants Tihange 2 and Doel 3 (hydrogen flakes or areas of micro crack fields in a certain depth of the base material of the RPV) there were performed numerical studies with an axisymmetric assumption for thermal-hydraulics and the crack opening stresses (FANC-AFCN 12-11-2015). Under these circumstances we can see a good conformity of these results presented by Belgian authorities with our numerical calculations for German RPVs.

To evaluate further, whether the tangential cracks should be considered in a 3D-analysis of the PTS transient we analyzed our results in depth. For various points in time we plotted the stress distributions in the RPV wall, see examples in Figure 6, showing the tangential (left) and radial (right) stresses in the RPV wall at the critical time of t = 1500 s in the transient. As can be seen, the azimutal stress variation is rather small inside the wall at the depth of the flaws. The highest stresses are identified close to the inner surface. The radial stresses in the wall at core height, which would lead to an opening of the flaws, are in the order of few N/mm^2 and so are negligible. This is in line with previous results of 3D PTS analyses which show that 3D-analyses to take into account local effects are primarily important to assess the nozzle knee area.

Hence, we conclude that for the assessment of hydrogen flakes as detected in the RPV walls of Belgian NPPs axisymmetric simplifications of the thermal-hydraulic and mechanical model are permissible in connection with conservative assumptions, see Figure 6.

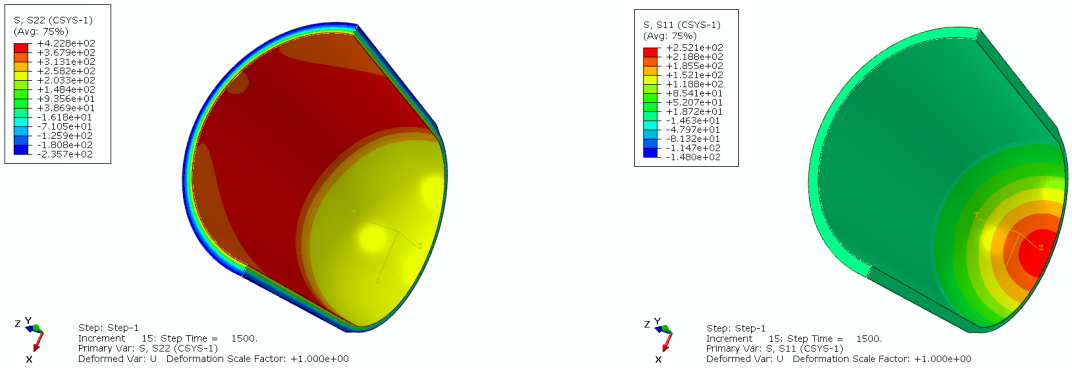

Figure 6: Base material of the RPV (cladding is hidden) – Nearly axisymmetric stress results for tangential (left) and radial (right) stress in some depth of the RPV (cut in the height of hydrogen flakes), transient time t = 1500 s

CONCLUSION

It can be shown with new methods and findings in thermal-hydraulic simulation and new assessment possibilities in fracture mechanics that German Reactor Pressure Vessels are brittle safe for their remaining lifetime.
With some modifications this procedures can be adapted to the situation of the Belgian RPVs with areas of hydrogen flakes in some deeper regions of the ferritic base material.

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