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Focused on Fracture Mechanics in Central and East Europe

Review of pressurized thermal shock studies of large scale reactor pressure vessels in Hungary

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ABSTRACT. In Hungary, four nuclear power units were constructed more than 30 years ago; they are operating to this day. In every unit, VVER-440 V213-type light-water cooled, light-water moderated, pressurized water reactors are in operation. Since the mid-1980s, numerous researches in the field of Pressurized Thermal Shock (PTS) analyses of Reactor Pressure Vessels (RPVs) have been conducted in Hungary; in all of them, the concept of structural integrity was the basis of research and development. During this time, four large PTS studies with industrial relevance have been completed in Hungary. Each used different objectives and guides, and the analysis methodology was also changing. This paper gives a comparative review of the methodologies used in these large PTS Structural Integrity Analysis projects, presenting the latest results as well.

KEYWORDS. Structural Integrity Analyses; Reactor Pressure Vessels; Pressurized Thermal Shock.

INTRODUCTION

In a preceding paper [2], the concept and the general methodology of Pressurized Thermal Shock (PTS) Structural Integrity analyses of large scale Reactor Pressure Vessels (RPV) were presented. The PTS phenomenon was known to specialists earlier, but became widely known and consequently, subject to intensive research when in the late 1970's, two accidents occurred in the US. Those accidents showed that transients can occur in pressurized water reactors, resulting in a severe overcooling that causes thermal shock in the vessel, concurrent with or followed by re-pressurization. These are the transients generally known under the name of PTS. The very high tensile stress caused by thermal shock at the inner surface of the vessel wall can cause the cleavage initiation of a pre-existing flaw of a certain dimension to occur (i. e. crack-like defect). Concern about brittle crack initiation during PTS can arise because during operation the neutron irradiation exposure around the energy-generating core makes the material of the Reactor Pressure Vessel (RPV) increasingly susceptible to cleavage fracture initiation.

Although PTS calculations have been part of RPV safety evaluations since the first half of the 1980's, there are various approaches that are analogous in general, but have many differences in details. There exists no internationally recognized standard; there are guidelines in Europe that are recommended to use (e. g. specifically for VVER units [4] and [16]); various approaches are used at a national level in different countries. In Hungary, the HAEA Guide 3.18v3 [3] is currently in effect.

During the last three decades, four large PTS studies have been conducted in Hungary. Each used different objectives and guides, and the Analysis methodology has also been changing. In the preceding paper [2], the conceptual model of PTS Structural Integrity calculations was presented. It was shown that using the conceptual model –that is based on the notion of typed graph-transformation systems– the calculations and their evolution can be described on a theoretical level. Using the model, the structure and the key aspects of a more proper description of the PTS Calculation methodology were presented, as follows:

- Objective of the study;
- Codes and guides used during the project definition;
- Geometry definition:
    - Parts of the RPV modeled during the study and the geometric model,
        - locations selected for Fracture mechanics analyses;
    - Flaw-size and geometrical distribution at selected locations;
        - relation of postulated flaws vs. detected flaws;
- Description of neutron-transport calculations;
- Materials:
    - Description of materials;
    - Description of constitutive models:
        - thermo-mechanics model and its parameters
          description of ageing;
        - fracture model and its parameters;
          description of ageing;
    - Qualification of material test methods;
- Thermal-hydraulics:
    - Selection of overcooling sequences;
    - Thermal-hydraulic assessments;
- Modeling of physical fields:
    - Kinematical model;
    - Physical fields;
    - Fracture mechanics model;
- Integrity criteria.

Applying the results mentioned above, these points will be discussed in the course of this review concerning the evolution of PTS Calculation Methodologies in Hungary. Considering the changing context, the objectives of the study, as well as the codes and guides used during the problem definition and solution will also be presented.

PHASE 0.: DESIGNER'S AND MANUFACTURERS PTS STRUCTURAL INTEGRITY CALCULATIONS

Designer's and Manufacturers PTS Structural Integrity Calculations

The VVER-440 V213-type RPV design was developed by OKB Gidropress without PTS assessments in the first half of the 1970s; as at that time the PTS safety evaluations of the RPVs were not part of the design requirement. Normal operating events and anticipated emergency events were addressed in the loading specifications. Calculations of protection against brittle fracture were part of the original strength calculations, and followed the rules set by the Russian standard valid at the time. According to the rule, brittle fracture resistance was analyzed on the basis of the material's static strength properties, but did not use fracture mechanics criterion.

The Integrity of the RPV met the brittle fracture requirements if:

- $T_{wall} \geq T_k$, where T_{wall} is the component's wall temperature, T_k is the critical temperature of brittleness of the component's material, or
- when $T_{wall} < T_k$ and $\sigma^{red} < R_{p0,2}^T/n$, where σ^{red} denotes Mohr's reduced stress, $R_{p0,2}^T$ is yield stress of the material at the component's wall temperature, n is the safety factor; n=2 if the component is regularly examined by non-destructive tests (NDT), otherwise n=4 [14].

Later, starting in the mid-80s, several PTS calculations were performed by OKB Gidropress and by other institutes, but in most cases, these studies assumed a generic RPV; so plant-specific conditions were neglected.

The Manufacturer's PTS Structural Integrity Calculations

As part of the manufacturer's strength-calculation documentations, Škoda provided a PTS analysis for a few accidental situations chosen based on engineering judgments, using linear elastic fracture mechanics.

Concerning geometry definition, Weld N°5/6, and an ECCS nozzle were selected, taking the geometrical dimensions of the components into account, as it was given in the documentation. At both locations, embedded elliptical cracks were selected with $2a_0$= 5 mm, with fatigue crack growth of 1 mm, postulated up to End Of Life (EOL) conditions.
The thermo-mechanical material parameters of the base material type 15Ch2MFA were selected from the strength calculations documentation. For fracture mechanics calculation, the equation

$$K_{IR}\left(T,T_k\right)=\frac{86400}{86-(T-T_k)}\quad (kg\sqrt{m}) \tag{1}$$

described material fracture toughness.
Results of ageing evaluation gave T_k=136 °C for Weld N°5/6, and T_k=32 °C for the ECCS Nozzle.
Selection of overcooling sequences was based on empirical, engineering experience: the loss of coolant accident cases (LOCA) rupture of pipelines Ø135, Ø250 and Ø492 were analyzed.
The PTS calculations were performed by a code developed at Skoda.
The Integrity of the RPV was accepted for brittle fracture, if:

- $T_{wall} \geq T_k$, where T_{wall} is the component's wall temperature, T_k is the critical temperature of brittleness of the component's material, or
- when $T_{wall} < T_k$, then
    - $a_c/a_0 \geq 2$, where a_c is the critical crack size (where $K_I = K_{IR}$) and
    - $K_I(x=2c)/K_{IR}(x=2c) = n_k \geq \sqrt{}$;

Summary

The above-reviewed analyses –performed by the manufacturer in the early 1980s– were based on engineering models. They analyzed only a very limited set of thermal-hydraulic transients, and used linear-elastic material models (that is, a Linear Elastic Fracture Mechanics (LEFM) methodology); the results of the fracture mechanics evaluation were adequate.

PHASE 1: PTS STRUCTURAL INTEGRITY CALCULATIONS IN THE 1980S

Objective of the study:

The objective of the study was to provide results for the safety report that was necessary for the renewal of the operating license after each, 4-year inspection cycle.

Codes and guides used during problem definition:

The Interatomenergo rule 38.434.55-84 was used during the calculations.

Geometry definition:

- The RPV Beltline Region was selected for the study, with geometrical dimensions selected from the manufacturer's documentation,
    - in the beltline region, an axial, semielliptical shaped, through clad crack with depth a=35 mm and c=52,5 mm, and
    - in weld N° 5/6 a circumferential, semielliptical shaped, through clad crack with depth a=35 mm and c=52,5 mm was defined,

Description of neutron-transport calculations:

The fluence calculations were based on a semi-empirical approach. During generic studies, the lead factors for the critical beltline region and for the weld N° 5/6 were determined, and data from fluence-measurement results were used to assess factual neutron fluencies for EOL conditions at the selected locations.

Materials, constitutive models:

- Both the cladding and the ferritic materials (15Ch2MFA forging and the welding metal) were modeled during calculations. For thermal and strength calculations, the data were derived from the manufacturer's documentation.

- In thermal calculations, the thermo-physical parameters were independent from temperature; during calculations, averaged values of the manufacturer's documentation were used.
- In strength calculations, the Neumann-Duhamel constitutive model was used with temperature-independent, averaged values of the manufacturer's documentation.
- For the description of fracture toughness of the structural materials, the equation:

$$K_{Ic}\left(T,T_k\right)=26+36\cdot e^{0.02\left(T-T_k\right)} \tag{2}$$

  was used; the ageing was modeled by using the temperature-shift (ΔT_k) of the critical temperature of brittleness in the following form:

$$T_k=T_{k0}+\Delta T_k \qquad \Delta T_k=A\cdot\sqrt[3]{\Phi} \tag{3}$$

  where Φ is neutron fluence. ΔT_k values were evaluated from plant surveillance data.
- The above material parameters were based on experimental results, performed in a qualified laboratory.

Thermal-hydraulic assessments:

- The selection of overcooling sequences was based on engineering judgments.
  Loss of coolant accident cases (LOCA) rupture of pipelines Ø135, Ø250 and Ø492 were selected for calculations.
- The thermal-hydraulic assessments were performed by Relap 4 – Mode 6 version. During thermal-hydraulic assessments, a simplified model of the primary system was used; the model assumed that all primary loops are identical, the model was called 'One Loop model' of the primary system. For mixing calculations, a home-developed code was used.

Main features of the model used for PTS Structural Mechanics calculations:

- For Structural Mechanics calculations, an analytical code was used [10], which had been validated with a Finite Element Code [13] earlier. The model and the solution of the problems had the following features:
  - In the thermal problem solution, the code used a thick-plane model of the beltline area that touches the liquid-wall interface. The solution of the thermal problem was determined in terms of Fourier series. The boundary conditions of the problem were received from results of thermal-hydraulic assessments at selected points in the downcomer.
  - In the solution of the strength problem, the software used analytical stress-formulae to generate the solution.
  - In fracture mechanical calculations, the crack tip driving force was calculated using the method published by Westergaard [17].
  - The cladding residual stresses were taken into account, applying stress-free temperatures (T^{sf}), which were chosen equal to the operating temperature of the component.
  - The weld residual stresses were neglected.

Integrity Criterion:

The crack initiation condition in the form:

$$K_I\le K_{Ic} \tag{4}$$

was used during calculations.

Summary

The analyses shown above were based on an analytical approach of the underlying thermo-elastic problem. The overcooling sequences were selected based on engineering judgments; this resulted in a limited set of transients. The Structural Mechanics calculations were based on the 'force method' that had been widely used in mechanical engineering since the early days of the field of Strength of Materials. The fracture mechanics module worked with an LEFM methodology. The ageing characteristics of structural materials were derived from the experimental results of the surveillance program.

PHASE 2: PTS STRUCTURAL INTEGRITY CALCULATIONS IN THE 1990S

Objective of the study:

The main objective of the study was to reassess the safety of Paks NPP using internationally accepted design- and safety -codes and guidelines. Experiences from various international PTS-related projects were used in the elaboration of the methodology [1, 5, 9, 15].

Codes and guides used during problem definition:

The PNAE G-7-002–86 [8], the ASME BPVC XI, and the 10 CFR 50.61 were used during the project.

Geometry definition:

- The RPV Beltline Region was selected for the study, with geometrical dimensions selected from the manufacturer's documentation,
  - in the beltline region, axial, semielliptical shaped through clad cracks with depths a=13, 23 and 35 mm and shape factor a/c=2/3; and
  - in weld N° 5/6 a circumferential, semielliptical shaped through clad crack with depths a=13, 23 and 35 mm and shape factor a/c=2/3, were defined.

Description of neutron-transport calculations;

The fluence calculations were based on a semi-empirical approach. During generic studies, the lead factors for the critical beltline region and for the weld N° 5/6 were determined, and data from fluence-measurement results were used to assess factual neutron fluencies for EOL conditions at the selected locations.

Materials, constitutive models:

- Both the cladding and the ferritic materials (15Ch2MFA forging and the weld metal) were modeled during calculations. For thermal and strength calculations, the data were derived from the manufacturer's documentation.
- In thermal calculations, the thermo-physical parameters were independent from temperature; during calculations, averaged values of the manufacturer's documentation were used.
- In strength calculations, the Neumann-Duhamel constitutive model was used with temperature-independent, averaged values of the manufacturer's documentation.
- For describing the fracture toughness of the structural materials, the equation:

  $$K_{Ic}\left(T,T_k\right)=35+53\cdot e^{0.0217\left(T-T_k\right)} \tag{5}$$

  was used; the ageing was modeled by using the temperature-shift (ΔT_k) of the critical temperature of brittleness in the following form:

  $$T_k=T_{k0}+\Delta T_k \qquad \Delta T_k=A\cdot\sqrt[3]{\Phi} \tag{6}$$

  where Φ is neutron fluence.
- The above material parameters were based on experimental results, performed in a qualified laboratory.

Thermal-hydraulics:

- The selection of the overcooling sequences was based on engineering judgments integrated with conclusions of international experiences [15] as well.
  A broad spectrum of various overcooling sequences, various loss of coolant accident (LOCA) scenarios, e.g. rupture of various pipelines (e.g. Ø90, Ø135, Ø233 and Ø492) were selected for calculations.
- The thermal-hydraulic assessments were performed by the system thermal-hydraulic codes Relap 5 – Mode 2 and Athlet – mod 1.4.. During thermal-hydraulic assessments, a simplified 'One Loop model' of the primary system was used. For mixing calculations, the Remix code was used.

Main features of the models used for PTS Structural Mechanics calculations:

- For Structural Mechanics calculations, a Hungarian code (called ACIB-RPV) was used [11], which was validated to Finite Element Codes [12]. The model and the solution of the problems has the following features:
    - In the thermal problem solution, the code used a thick-plane model of the beltline area that touches the liquid wall interface. The solution of the thermal problem was determined in terms of Fourier series. The boundary conditions of the problem were received from results of thermal-hydraulic assessments at selected points in the downcomer.
    - In the solution of the strength problem, the software used analytical stress-formulae to generate the solution.
    - In fracture mechanical calculations, the crack tip driving force was calculated using the method published by Westergaard [17].
    - The cladding residual stresses were taken into account, applying stress free temperatures (T^{sf}), which were chosen equal to the operating temperature of the component.
    - The weld residual stresses were neglected.

Integrity Criterion:

The crack initiation condition in the form:

$$1.1 \cdot K_I \le K_{Ic} \tag{7}$$

was used during calculations.

Summary

The PTS project assessed above made a larger effort in selecting the overcooling sequences and their assessments. This led to a larger set of transients, so the reliability of results increased. The analysis methodology was based on an analytical approach of the underlying problem. The fracture mechanics module worked with LEFM methodology. The ageing characteristics of structural materials were derived from the experimental results of the surveillance program.

PHASE 3: PTS STRUCTURAL INTEGRITY CALCULATIONS IN THE NEW MILLENNIUM

Objective of the study:

The objective of the study was to reassess the safety of RPVs providing Time Limited Ageing Analysis (TLAA) results for Paks NPP for license-application beyond the designed service lifetime. Although the designed service lifetime of the RPVs was set to 40 years of operation, the analyses were conducted for the 30+ years of operation.

Codes and guides used during problem definition:

The HAEA Guide 3.18 [3], the IAEA PTS Guide for VVER units [4] and an earlier version of VERLIFE [16] were used during the project.

Research and developmental works before the study:

Beginning around the new Millennium, intensive research was initiated at KFKI AEKI in order to clarify the ageing properties of cladding materials, as well as to clarify the damage-mechanisms of various impurities in structural materials, with special emphasis on phosphorous segregation. AEKI joined a number of international projects. A full review of the activities would exceed the extent of the present paper. Many of the research results have been incorporated into the updated analysis methodology.

Geometry definition:

- The full RPV body was selected for the study, with geometrical dimensions derived from the manufacturer's documentation. Two main sub-models of the model were constructed, in order to reduce the costs of the project in terms of IT and human resources. The aim of the development was to make parametric studies on simpler models using conservative assumptions; and after the selection of the worst transient loading cases, perform a calculation on the more detailed model, if necessary. Two types of models have been worked out:

- a model designed for elastic calculations; the geometrical model is composed from two sub-models:

  1. a 3D Finite Element (FE) model of a lower-cylindrical part of the vessel with the bottom; the purpose of the model was the calculation of through wall temperature, stress and strain distributions occurring during PTS transients, and provide inputs to subsequent fracture mechanics calculations. The FE mesh models the welds, and includes quadratic, iso-parametric brick-type elements with 20 nodal points, but does not model the crack in the mesh. The developed model contains 58240 elements and 247405 nodal points. The geometrical model is presented on Fig. 1.

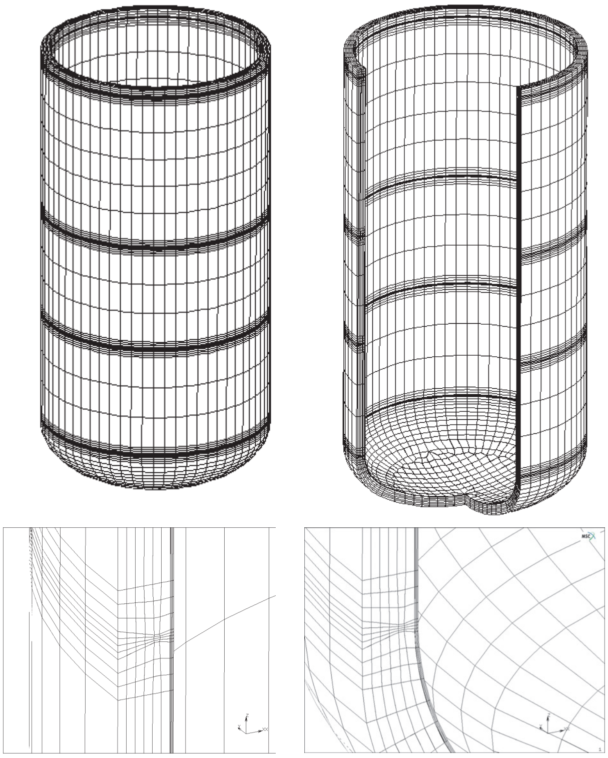

Figure 1: 3D Finite Element model of a lower cylindrical part, bottom and welds of a VVER-440 RPV.

  2. 3D models of the main coolant pipeline nozzles ∅492; the purpose of the models was to calculate through wall temperature, stress and strain distributions occurring during PTS transients, and provide inputs to subsequent fracture mechanics calculations. The FE mesh includes quadratic, iso-parametric brick-type elements with 20 nodal points. The developed model contains 7320 elements and 34144 nodal points. The geometrical model is presented on Fig. 2.

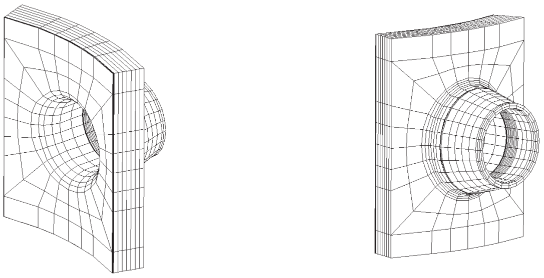

Figure 2: 3D Finite Element model of a main coolant pipeline nozzle ∅492.

3 For elastic calculations, a series of crack locations were selected for fracture mechanics calculations, as it is presented on Fig. 3. The aim of this development was to make the calculations suitable for an algorithmic evaluation of the crack locations in any transient case.

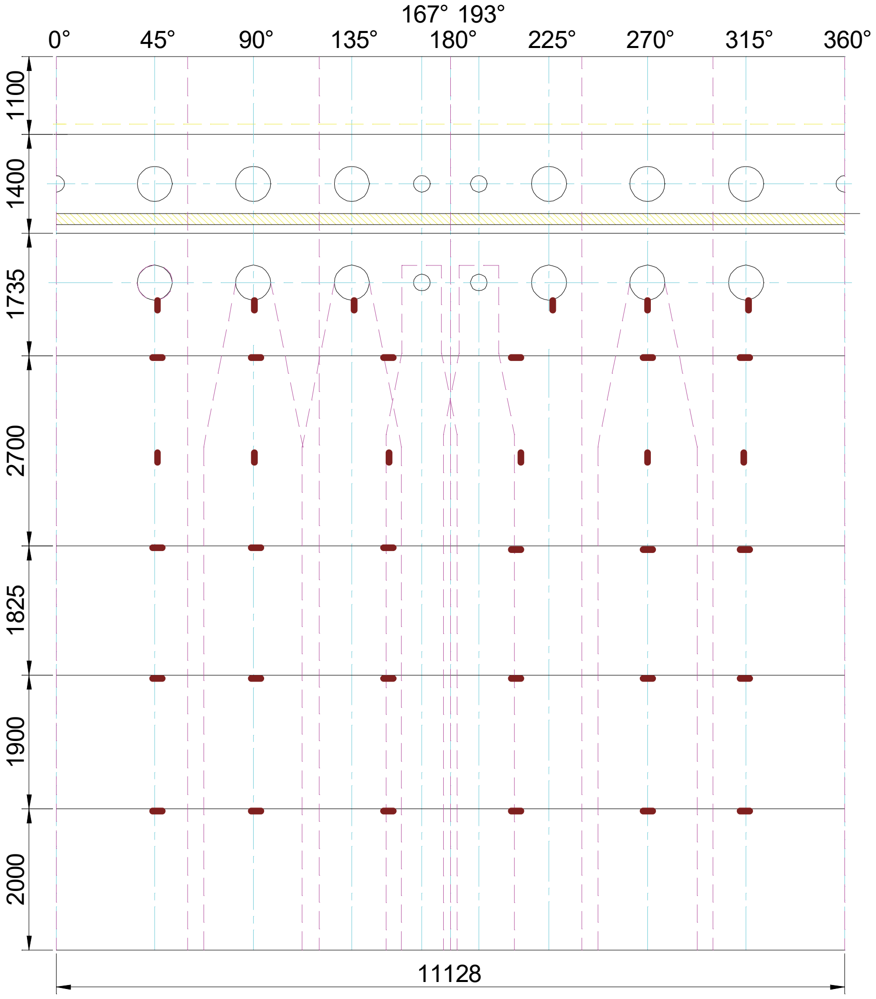

Figure 3: Locations selected for fracture mechanics calculations on a VVER-440 RPV.

At each location, two types of cracks have been defined, as follows: one type was a semi-elliptic, underclad crack; the other type was a through clad crack, both shown on Fig. 4. The a/c ratio was set to 1/3 [3]. The depth of the cracks varied between 2 and 14 mm from the cladding-base metal interface; the maximal crack-depth was *0,1s*. The use of this maximal postulated crack-depth parameter was allowed to calculate with because NDE tests were qualified according to international standards. NDE results also proved that the cladding could be seen free from critical defects, so the use of underclad cracks was also allowed. The through-clad cracks served for parametric studies.

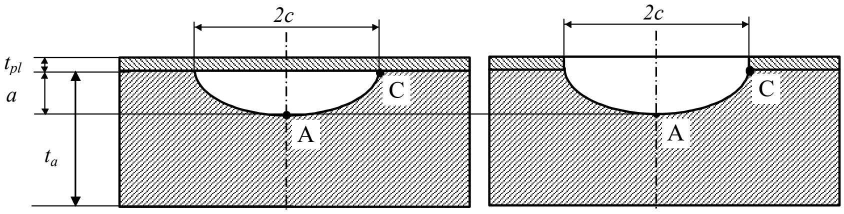

Figure 4: The two crack types defined for Fracture Mechanics analyses [6, 7].

- The other type of the model was designed for elastic or elastic-plastic calculations with a crack embedded into the mesh; it is the 3D FE model of the lower cylindrical part of the vessel with the bottom, including a crack embedded into the mesh. The model was developed with the purpose of simulating through wall temperature, stress and strain distributions occurring during PTS transients, and also performing subsequent fracture mechanics calculations on the embedded crack. The FE mesh models the welds, and includes quadratic, iso-parametric brick-type elements with 20 nodal points. The model was designed to study plasticity effects too. The developed model contains 160 540 elements and 709 826 nodal points. The geometrical model is presented on Fig. 5. The crack location was selected after long series of calculations performed on the simpler model, in order to reduce the time-consuming work of developing a mesh around the crack front. The crack model is an underclad, semi-elliptical crack with a=14 mm, a/c=1/3; the crack model is shown on Fig. 5 below.

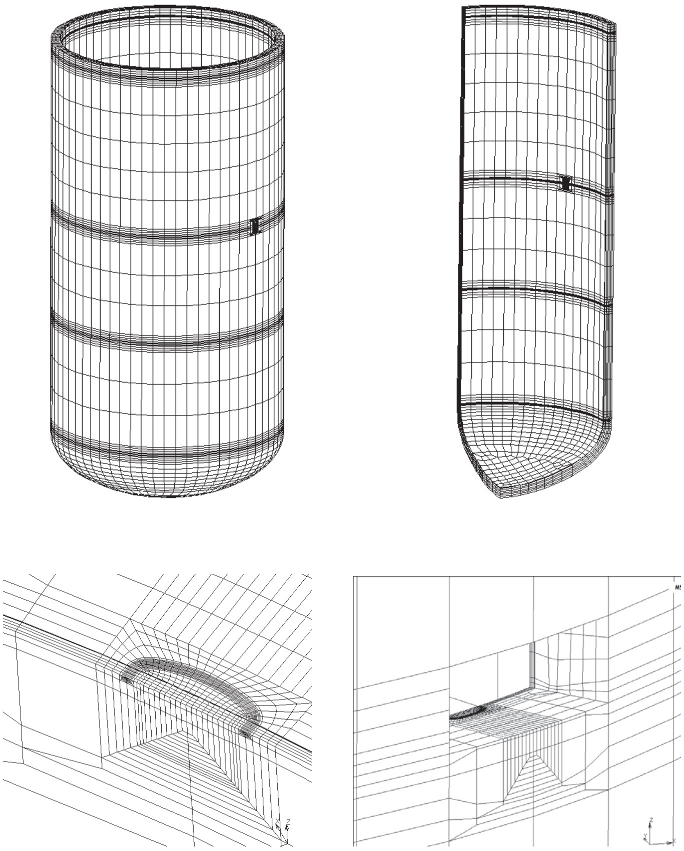

Figure 5: 3D Finite element model of a lower cylindrical part with embedded crack of a VVER-440 RPV.

Description of neutron-transport calculations:

The fluence data were provided by full 3D neutron-transport calculations that took the full loading-history of the energetic core into account. This fact made a complete re-evaluation of material ageing possible.

Materials, constitutive models:

- Both the cladding and the ferritic materials (15Ch2MFA forging and the weld metal) were modeled during calculations. For thermal and strength calculations, the data were derived from the manufacturer's documentation.
- In thermal calculations, the thermo-physical parameters were temperature-dependent.
- In thermo-mechanical strength calculations, the Neumann-Duhamel constitutive model was used with temperature-dependent parameters of the manufacturer's documentation. In the case of elastic-plastic calculations, plastic material properties were derived from the re-evaluation of the material tests performed in the frame of the manufacturer's surveillance program.
- For describing the fracture toughness of the structural materials, the equation:

$$K_{Ic}\left(T,T_k\right) = 26 + 36 \cdot e^{0.02\left(T-T_k\right)} \tag{8}$$

was used; the ageing was modeled by using the temperature-shift (ΔT_k) of the critical temperature of brittleness in the following form:

$$T_k^{age} = T_{k0} + \Delta T_k^{temp} + \Delta T_k^{fat} \Delta T_k^{irr} = A \cdot \Phi^n, \quad \Delta T_k^{fat} = F\left(T^{oper}\right) \tag{9}$$

where Φ is neutron fluence, a is fatigue damage, T^{oper} is the operational temperature, ΔT_k^{irr} is the temperature shift caused by neutron irradiation, ΔT_k^{temp} is the temperature shift caused by thermal activation and ΔT_k^{fat} is the temperature shift caused by fatigue.

- The above-described material parameters were evaluated on the basis of experimental results, performed in qualified laboratories.

Thermal-hydraulics:

- The deterministic selection of the PTS transients was based on engineering judgment using the design basis accident analysis approach combined with the operational experience accumulated at the plant. In this deterministic selection, only the individual initiating events were taken into account. A broad spectrum of various overcooling sequences was selected for calculations. Complementary to the deterministic analysis of the limiting scenarios, a selection of additional transients with the help of probabilistic event-tree methodology was also performed.
- The thermal-hydraulic assessments were performed by Relap 5 – Mode 3 and Athlet Ver 2.3. system codes. For mixing calculations, the Remix code was used. In the system's thermo hydraulic calculations, the six-loop model of VVER 440 systems were used. so inhomogenities of the temperature and the velocity fields occurring in the downcomer were taken into account in some approximation as well. The FE model has more refined structure at the coolant-solid interface than the TH system model, a sophisticated interface was developed for the generation of thermal boundary conditions from thermal-hydraulic calculation results. The relation of the points used in thermal-hydraulic analyses and the FE model solid interface is presented on Fig. 6.

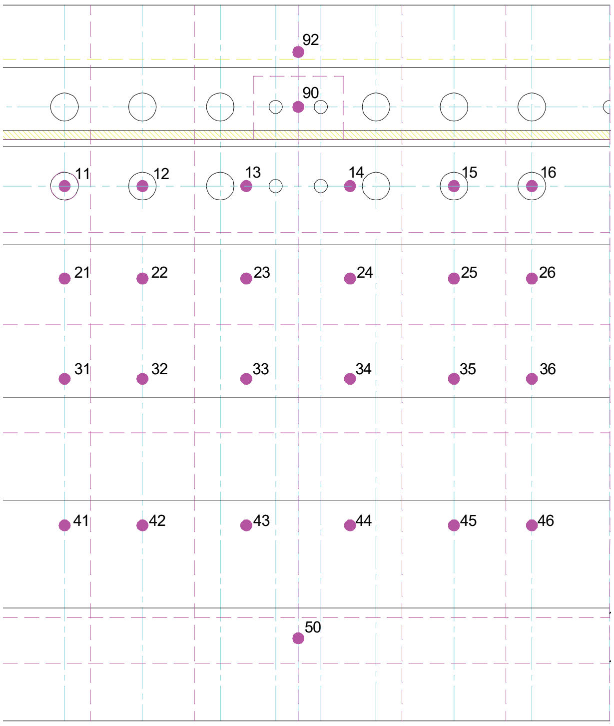

Figure 6: Locations of thermal-hydraulic data supplying points at the inner surface of the RPV.

Main features of the models used for PTS Structural Mechanics calculations:

- For Structural Mechanics Calculations, the MSC.Marc code was used which is a validated, general-purpose Finite Element Code, developed specifically for non-linear calculations. The model and the solution of the problems featured the followings:
    - In the case of thermal-elastic or thermal-elastic-plastic problems supplemented by fracture mechanics calculations, the problem-solving strategy was to solve the coupled physical problem in its coupled form. The coupling was manageable using a staggered scheme, but for future applications, the couplings could be made stronger.
    - While solving the strength problem, the software used the classical deformation-based FE approach.
    - In fracture mechanical calculations, in case of the simpler model (described above), the crack tip driving force was calculated using the method published by S. Marie and S. Chapuliot [6, 7], which was implemented into a home-developed software package.
    - In calculations integrating the crack into the FE model, the crack tip driving force was calculated along the crack-front using the J-integral.
    - The cladding residual stresses have been taken into account, applying stress-free temperatures (T^{sf}), which had been chosen equal to the operating temperature of the component.
    - The weld residual stresses were integrated into the model.

Integrity Criterion:

The crack initiation condition in the form:

$$K_I \le K_{Ic} \tag{10}$$

was used during calculations.

Summary

Within the frame of the PTS project presented above, a more detailed FE model has been developed and tested. Two models were developed: a simpler linear model of the RPV and a more detailed model for studying the plastic effects occurring during PTS transients. The number of overcooling sequences has increased significantly. The neutron-transport calculations provided more precise results concerning neutron-physics data. That made it possible for the ageing assessments to lower the uncertainty of results. The thermal-hydraulic system model was also considerably improved. The increasing number of selected transients and the more complex models together led to more resource-demanding calculations; however, they also made the deeper understanding of the problem domain possible.

CONCLUSIONS

Buildings, structures and systems of large scale and high value are designed for a certain, limited service lifetime, taking the standards and guidelines of the time into account. The standards applied during the design process of a large-scale structure reflect the scientific and technological level of the previous years or decades. However, the standards and guidelines are evolving over time, and the goals and requirements may also change during the service time of the equipment. That means that the context of safe operation is part of an advancing world, where the meaning of safety must remain unchanged.

During the last three decades, four large PTS studies have been conducted in Hungary. Each used different objectives and guides, and the Analysis methodology has also been changing. In the preceding paper, the conceptual model of PTS Structural Integrity calculations was presented. It was shown that using the conceptual model –that is based on the notion of typed graph-transformation systems– the calculations and their evolution can be described on a theoretical level. Using the model, the structure and the key aspects of a more proper description of the PTS Calculation methodology were presented, as follows: The main stages of this evolutionary process were:

- The analyses performed by the manufacturer in the early 1980s; these calculations were based on engineering models, analyzed only a very limited set of thermal-hydraulic transients, used linear-elastic material models a Linear Elastic Fracture Mechanics (LEFM) methodology; the results of fracture mechanics evaluation were adequate.

- The analyses performed in Hungary during the second half of the 1980s were based on an analytical solution of the underlying thermo-elastic problem. The overcooling sequences were selected based on engineering judgments, and this resulted in a limited set of transients. The Structural Mechanics calculations were based on the 'force method' that has been widely used in mechanical engineering since the early days of the field of strength of materials. The fracture mechanics module worked with LEFM methodology. The ageing characteristics of structural materials were derived from the experimental results of the surveillance program.
- The PTS project conducted in the first half of the 1990s made a larger effort in selecting the overcooling sequences and their assessments. This lead to a larger set of transients and results, so the reliability of results increased. The analysis methodology was based on analytical solutions of the underlying problem. The fracture mechanics module worked with LEFM methodology. The ageing characteristics of structural materials were derived from the experimental results of the surveillance program.
- After the Millennium, the numerical problem-solving methodology has been changed fundamentally, as higher-capacity IT infrastructure and large-scale FE software tools became available. A more detailed FE model has been developed and tested. The team developed a simpler linear model of the RPV and a more detailed model for studying the plastic effects occurring during PTS transients. The number of overcooling sequences has increased significantly. The neutron-transport calculations provided more precise results concerning neutron-physics data. That made it possible for the ageing assessments to lower the uncertainty of results. The increasing number of selected transients and the more complex models led to more resource-demanding calculations; however, they also made the deeper understanding of the problem domain possible. For lack of space, a more detailed presentation of results is left for future publications.

The main conclusion of the review of the various PTS projects carried out in Hungary during the last three decades is that in projects with industrial relevance, both the simplified engineering models and the highly sophisticated simulation tools have their own application domain; in each project it is the responsibility of the analysts to find a balance between the goals of the study; the complexity of the approach chosen for problem-solving; the available resources; and the time limits. The purpose of the research is to achieve a deeper understanding of the problem and develop robust engineering tools that can be used in later projects.

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