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THERMAL AND CREEP ANALYSIS OF VVER-1000 REACTOR PRESSURE VESSEL AT HIGH TEMPERATURES CAUSED BY FUEL MELTING DURING SEVERE ACCIDENT

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Abstract: *Thermal and creep analysis of the VVER-1000 reactor pressure vessel (RPV) was performed at high temperatures caused by fuel melting during severe accident. First, the integral code ASTEC was applied simulating severe accident evolution since an initiating event up to a hypothetical radioactive release into the environment. The ASTEC outputs including the remaining RPV wall thickness, the heat flux achieved and the temperature profile in the ablated vessel wall served as boundary conditions for the consequent assessment of RPV integrity carried out with the aid of finite element method (FEM). The FEM analysis was performed including the creep behaviour of RPV material using a complex creep probabilistic exponential model with damage. The objective of the analysis was to computationally assess emergency condition and, on this basis, to propose a general methodology for evaluating the integrity of RPV at high temperatures due to fuel melting during severe accident.*

Keywords: Integrity of reactor pressure vessel, Severe accident, ASTEC, Creep, FEM.

1. Introduction

The subject of this work is the numerical analysis of the VVER-1000 reactor pressure vessel (RPV) in a hypothetical severe accident (SA), which assumes that due to insufficient cooling of the reactor core, the RPV internals, including the fuel elements, melt down. The objective of the analysis is to computationally assess this emergency condition, taking into account the creep of the RPV material, and, on this basis, to propose a general methodology for evaluating the integrity of RPV at high temperatures due to fuel melting during SA.

2. Thermal analysis using ASTEC code

In order to obtain boundary conditions for consequent structural analyses, the integral code for SA analyses ASTEC (developed by IRSN, France) was used. The ASTEC code is of type "lumped parameter" (LP), which means that the spatial discretization of the computational domain is rather rough - large nodes are used to represent parts of the core and RPV internals, of the primary/secondary circuit and of the containment. Thanks to this relatively coarse plant representation, the ASTEC code is able of simulating a SA evolution since an initiating event up to a hypothetical radioactive release into the environment.

Two SA scenarios, initiated, respectively, with large break loss of coolant (LOCA) and with station blackout (SBO), were analysed with the ASTEC code. The reference plant considered was the Czech Temelin NPP, equipped with 2 VVER-1000/320 units. Both SA sequences were launched with and without consideration of the in-vessel melt retention (IVMR) strategy, which consists of external RPV cooling. Thus, in total, 4 qualitatively different SA sequences were evaluated.

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Example of characteristic results, obtained from the ASTEC analysis of the LOCA-initiated SA scenario with the IVMR strategy applied, is shown in Fig. 1. The left picture shows a late-phase of the accident progression, with most of the reactor core being relocated into the lower plenum where it forms a 2-layer molten pool, consisting of an oxidic and a metallic layer. The heavily ablated RPV wall is also visible in the figure. The graph to the right shows the obtained axial heat flux profile. The lowest elevation (-1.756 [m]) corresponds to the RPV lower head bottom. Both plots correspond to the instant of reaching the peak heat flux (nearing the value of 930 [kW/m^2]) at $23\,600$ [s] from the initiating event.

The remaining RPV wall thickness, the heat flux achieved and the temperature profile in the ablated vessel wall serve as boundary conditions for the consequent assessment of RPV integrity, carried out with the aid of structural analysis methods, such as finite element method (FEM).

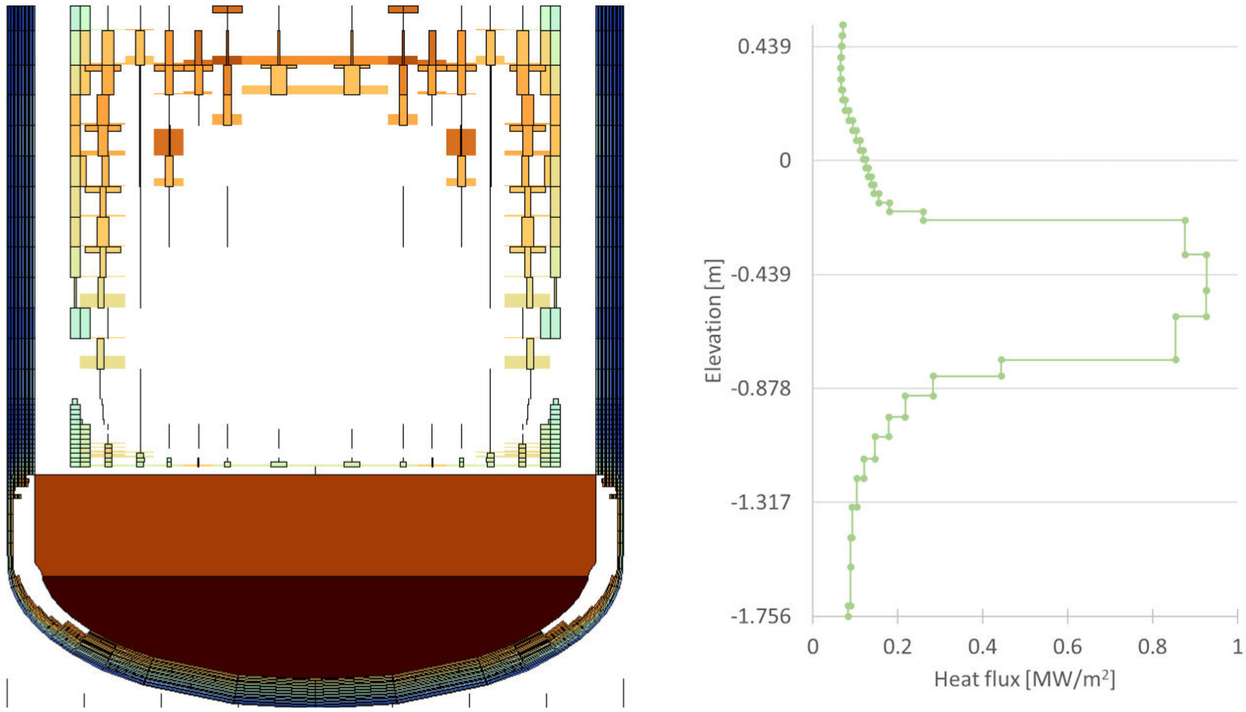

Fig. 1: State of the core and RPV wall shape (left) and heat flux profile as a function of axial elevation (right), respectively, at $t = 23\,600$ [s] into the accident. Outcomes of an ASTEC code analysis

3. Finite element analysis including the creep behaviour of RPV material

The FEM problem has been treated in a simplified way as an axisymmetric one which enables a detailed modelling of RPV wall melting and determination of local deformations at critical points of RPV. First, non-stationary heating analysis was performed, where the time-dependent heat flux density adopted from ASTEC code was considered as a boundary condition. Next, a creep analysis followed. The behaviour of the RPV material during SA is expected to be significantly influenced by the fact that high temperatures and stresses will be reached in a relatively short time instant. Thus, it seems appropriate to use a combined creep model that considers mainly the secondary and tertiary creep phases of the material. This is fulfilled by a well-established complex up to 19-parameter creep probabilistic exponential model with damage developed by Bína and Hakl (1994).

The governing equation furnishing the dependence of the total strain ϵ_c on initial strain ϵ_0, limit strain ϵ_m and damage $\pi(t) = t/t_r$ at time t is

$$\epsilon_c(\sigma_e, T, t) = \epsilon_0 \left(\frac{\epsilon_m}{\epsilon_0}\right)^{g[\pi(t)]} \tag{1}$$

where σ_e is the effective stress in [MPa], T is the thermodynamic temperature in [K], t the time in [hours]. The initial strain ϵ_0 can be calculated from the elastic solution

$$\epsilon_0 = 100\frac{\sigma_e}{E(T)} \tag{2}$$

where the dependence of the Young modulus on temperature is supposed to have the form

$$E(T) = E_1 + E_2 \exp^{-(E_3/T)} \tag{3}$$

The limit strain ϵ_m can be expressed by

$$\epsilon_m = \exp\left[M_1 + M_2 \tanh\left(\frac{\ln(t_r) - M_3 - M_4 T}{M_5}\right)\right] + 100\frac{\sigma_e}{E(T)} \tag{4}$$

The time elapsed at rupture t_r in [hours] is estimated by the empiric formula

$$\begin{aligned} \log t_r &= A_1 + A_2 \log\left|\frac{1}{T} - \frac{1}{A_5}\right| + A_3 \log\left|\frac{1}{T} - \frac{1}{A_5}\right| \log\Big(\sinh(A_6\sigma_e T)\Big) + \\ &+ A_4 \log\Big(\sinh(A_6\sigma_e T)\Big) \end{aligned} \tag{5}$$

The hardening function $g[\pi(t)]$ can be expressed as

$$g[\pi(t)] = [\pi(t)]^N \left[\frac{1+\exp^{-2\pi^K(t)}}{1+\exp^{-2}}\right]^M \tag{6}$$

Material data are given by parameters for the initial strain E_1–E_3, rupture strain M_1–M_5, creep strength A_1–A_6 and hardening function N, M, K. A careful calibration of parameters of complex model was performed based on measurement of creep properties of RPV steel 15Ch2NMFA-A, see Dymáček et al. (2022). Fig. 2 shows the comparison of the calibrated creep curves with experimental data for a selected temperature $T = 900\,^\circ$ [C] and stresses $\sigma = \{10, 15, 20, 30\}$ [MPa]. Note that recently proposed complex model describing creep behaviour under variable stress conditions can be alternatively used in the creep analysis of the RPV material, see Kloc et al. (2018a,b). The model can handle transient effects on the stress changes, as well as low-stress creep behaviour.

Generalized constitutive equations for creep follow from the Prandtl-Reuss equations

$$\dot\epsilon^c_{ij} = \frac{3}{2}\frac{\dot\epsilon_c}{\sigma_e} S_{ij} \tag{7}$$

where S_{ij} is the deviatoric stress

$$S_{ij} = \sigma_{ij} - \frac{1}{3}\delta_{ij}\sigma_{kk} \tag{8}$$

The effective stress σ_e is given by von Mises' function

$$\sigma_e = \sqrt{\frac{3}{2} S_{ij} S_{ij}} \tag{9}$$

The effective creep strain ϵ_c can be expressed as

$$\epsilon_c = \int_0^t \sqrt{\frac{2}{3}\dot\epsilon^c_{ij}\dot\epsilon^c_{ij}}\,\mathrm{d}\tau \tag{10}$$

assuming that the damage softening method is used

$$\dot\epsilon_c = \phi(\pi, \sigma_e, T) \tag{11}$$

Isotropic hardening function ϕ can be obtained from equations (1)-(6) by elimination of time t. Constitutive equations (7)-(11) are integrated by the Euler forward scheme with automatic subincrementation, see Plešek and Korouš (2002).

A computer implementation of the model in the finite element code PMD–Package for Machine Design (2013) is currently being verified by means of uniaxial stress loadings. The detailed results of creep FEM analysis of RPV will be presented at the conference.

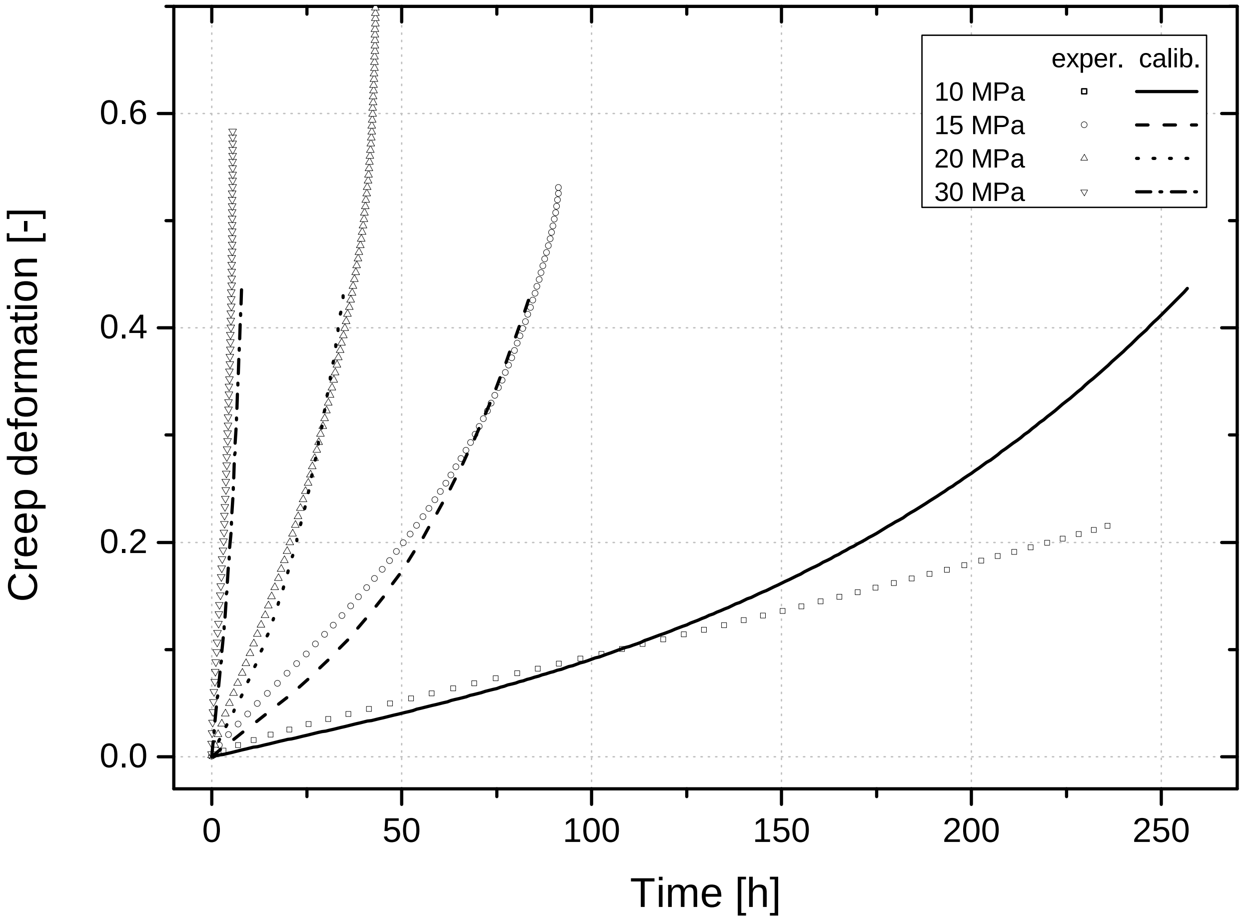

Fig. 2: Comparison of the calibrated creep curves with experimental data for a selected temperature $T = 900\,°$*[C] and stresses* $\sigma = \{10, 15, 20, 30\}$ *[MPa]*

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