NENE 2020
September 7 - 10
PORTOROŽ
SLOVENIA
29th International Conference Nuclear Energy for New Europe

Preliminary Analysis of Creep and Ageing Influence During SBO Accident

Salvatore Angelo Cancemi
University of Pisa
Largo L. Lazzarino, 2
56126, Pisa, Italy
salvatore.cancemi@dici.unipi.it

Rosa Lo Frano, Riccardo Ciolini
University of Pisa
Largo L. Lazzarino, 2
56126, Pisa, Italy
rosa.lo.frano@unipi.it;
riccardo.ciolini@unipi.it;

Piotr Darnowski,
Warsaw University of Technology
Nowowiejska 21/25
00-665, Warsaw, Poland
piotr.darnowski@pw.edu.pl;

ABSTRACT

Severe accidents involve a set of difficult phenomena to understand and consequences to predict because of complex interactions occurring at high temperatures between materials. Complexity (of the heat transfer behaviour) increases further during the molten relocation of corium to the lower head of the reactor pressure vessel, such that the resulting thermal loads may threaten the strength of the vessel wall. In this framework and with reference to the SBO (Station Black Out) accident, the role played by the creep, and also the influence of ageing in terms of reduction of bearing capacity of the vessel lower head are studied. In doing that, an external coupling is performed between MELCOR and MARC codes: the output temperatures and pressures obtained from the first code represent the input for the thermo-mechanical simulations carried out with the latter one. Moreover, ageing phenomena are implemented through degraded mechanical material properties.

A suitable three-dimensional model allows to analyse the nonlinear behaviour of the reactor vessel undergoing thermo-mechanical creep in SBO conditions. The deformation in the structure is calculated using nonlinear material propriety, such as the reduction of Young' modulus and yield strength of carbon steel alloy.

The obtained results show that the thermo-mechanical loads are responsible of deformation of the vessel, which develops and increases as the transient progresses. They also highlight the creep deformation process appears where the maximum temperature is located.

1 INTRODUCTION

The Reactor Pressure Vessel (RPV) that is designed for 30 to 40 years operation could be inadequate for service far beyond the original design life or long-term operation (LTO). Two crucial and decisive factors to sustain nuclear equipment LTOs are their safety and profitability, which can be achieved through a combination of applying optimum management strategies with understanding of the ways in which safety-relevant systems, structures and components (SSCs) perform [1].

The paper deals with the investigation of the impact of thermal degradation and the creep effects on the performance of RPV during a severe accident (SA) with core meltdown [1][2][3]. For that reason, we propose a new methodology and its qualification that was carried out based on the FOREVER/C1 experimental activity [4][5].

It is worthy to note that very few studies on the effects/consequences of ageing and creep on RPV LTO are available in the open literature; they become almost rare when the object of the investigation refers to the simultaneous action of both of the long-term thermal ageing and creep [6]. On the one hand, this makes difficult to review the bibliographic and clearly identify issues affecting mostly the equipment performance, and identify suitable tools to be adopted predictive simulation. However, it makes new and interesting the developed (and described in what follows) methodological approach, which is "mechanistically based" on an integration between MELCOR 2.2 and Finite Element (FE) code [7][8][9].
Timofeev and Karzov [10][11] studied the effect of thermal ageing on mechanical properties of WWER reactors equipment steels although the testing conditions (temperature) resulted to differ considerably from plants operation conditions.
In this assessment, ageing and creep were investigated, as they are mainly responsible for degradation of structural / mechanical and physical properties (e.g. strength, σ (T), or Young modulus, E (T) under the extended influence of operating conditions [11]. Such time and/or temperature-dependent material degradation was taken into account to verify if RPV performance is still capable to fulfil the design safety requirements.

2 METHODOLOGICAL APPROACH

The behaviour of the RPV (safety class 1 component) of the 4500 MWth NPP described in [4] was analyzed numerically. Moreover, in this study, severe accident conditions and the actual properties of RPV material were taken into account for the purpose of safety requirement. The developed approach is based on the external coupling between the MELCOR code, for the assessment of severe accident scenario, and the MSC©MARC (Finite Element - FE) code, for investigating the “aged” component performance and its structural integrity.
The external coupling is based on the sequential exchange of data files: results, in terms of temperature and pressure, calculated by MELCOR in the lower plenum, are used as initial and boundary conditions in the thermo-mechanical analyses performed by MARC code. The NPP data were from [4], while the material properties were assumed varying gradually over time, with the use and depending on the operational environments.
Figure 1 illustrates the logic in which the methodology is articulated. Its most important steps are:

1. Identification of critical SSCs from the standpoint of the plant operation and safety (i.e. RPV in this study);
2. Identification of the operational loadings, stressors, and ageing mechanisms;
3. Development of methodology for performance prediction;
4. Identification and implementation of points 1) and 2) in the numerical codes;
5. FE assessment of the ageing and creep effects and consequences in order to verify the integrity of the structure or identify the design improvement actions.

In particular, with reference to point 5) the root causes of the ageing deterioration, which can be environmental and/or operational dependent, are underlined. Either the former (material degradation over the time) or the latter (e.g. temperature and pressure gradient produced by transient conditions) are considered in the FE simulations. Subsequently, the reliability of the implemented and set-up FE model was checked. The performed validation, carried out based on the FOREVER/C1 experiments, is presented in subsection 2.2.1.

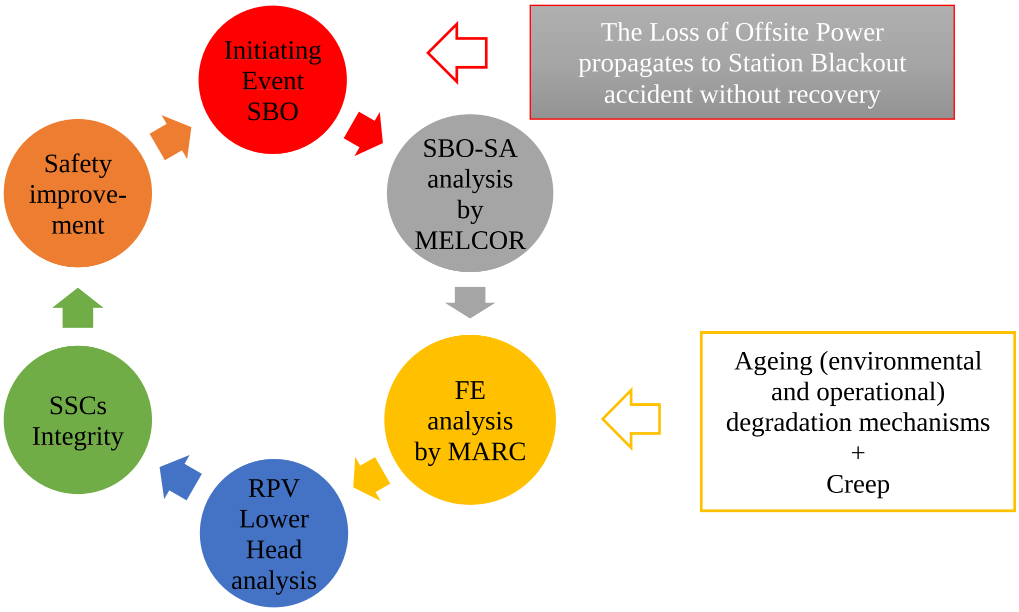


Figure 1: Methodology for structural integrity assessment

2.1 Description of the MELCOR model

As described in [4], a Reactor Coolant System (RCS) model under total Station Black Out (SBO) accident with a core meltdown was implemented by MELCOR 2.2 9541 The studied plant was a generic high-power Generation III Pressurized Water Reactor (PWR) developed in the frame of the EU NARSIS project[2].

Figure 2 shows specifically the nodalization of the RPV model of which the lower head is green coloured. Moreover, this model was made of thermal-hydraulics (CVH) package, core modelling (COR) package and heat structures package (HS). The core model has nineteen axial levels and six rings, and it was connected with five control volumes, one per ring and additional bypass volume.

Before to run MELCOR transient analysis, steady-state analysis was performed in order to reach the required stable thermo-mechanical conditions in the RPV lower head. Additionally, it was assumed that all the emergency diesel generators and the additional SBO dedicated diesel generators were not available due to combined failure (conservative approach). Accumulators were supposed available but without low- and high-head safety injections because of the lack of power. The heat removal from the primary side was negligible.

The temperature and pressure trends obtained as results of the SBO analysis (see Figure 3) were then used as input data for the thermal-mechanical simulations. From the analysis of these plots, it appears that massive core relocation occurred at 20000 s, while after 23000 s the RPV lower head integrity may not be guaranteed. It is worthy to note that the MELCOR analysis stopped at about 23.000 seconds as reflected in the trends of temperature and pressure of Figure 3. No ex-vessel phase of the accident was considered.

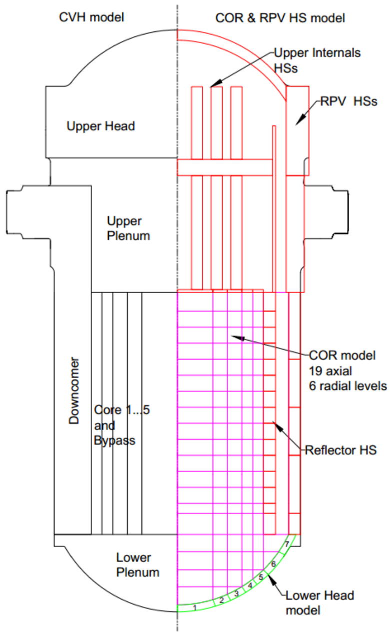


Figure 2: MELCOR RPV modelling. The lower head model is the hemispherical green coloured structure

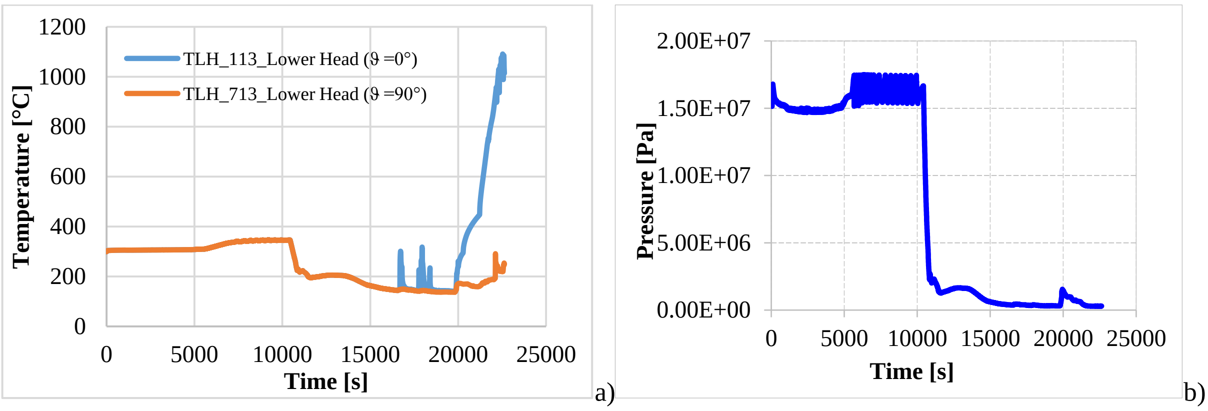


Figure 3: Plots of the temperature (a) and pressure (b) in the lower plenum obtained from MELCOR analysis [4]. In figure (a) the label TLH-ijj refers to the node jj of the segment i, where jj = 13 is the RPV inner surface, i = 1 and i= 7 are the first and last segment of the lower head, respectively, according to the azimuthal angular direction [4].

2.2 Description of the FE model

For the FE simulations, a 2D model representing the (real) RPV geometry, made of SA533B1 carbon steel, was implemented, as shown in Figure 4. It was made of a four-node, isoparametric, and arbitrary quadrilateral written for plane strain applications. As this element uses bilinear interpolation functions, strains tend to be constant throughout the element. The imposed boundary conditions are the temperature trend (called TLH-113 in Figure 3), which was applied at the RPV lower head and lower core plate, and the internal pressure, which was applied over the entire lower plenum surface (see previous Figure 3b). For conservative reason we assumed the lower head wall in adiabatic condition and no external cooling.

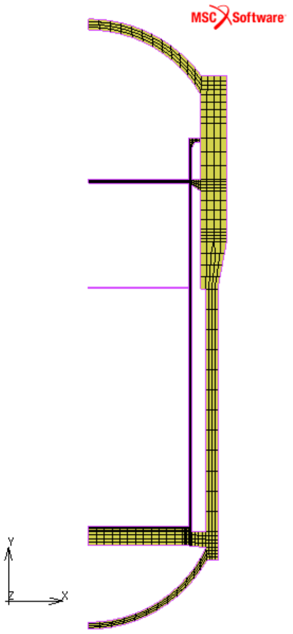


Figure 4: 2D FE-model of the RPV

In this study, the creep (accumulation damage) is the other important phenomenon considered. Creep is a slow and continuous plastic deformation of material over extended periods under mechanical stress; for this reason, the transient simulation has lasted up to 24 hours.

Creep behaviour can be split into three main stages, as represented in Figure 5 [6]. In the primary (or transient) creep the strain rate is a function of time, in the secondary (or steady-state) creep the strain rate is constant, and in the tertiary creep the strain rate increases exponentially.

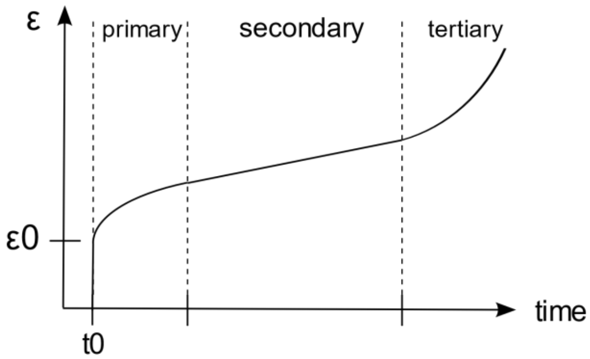


Figure 5: Creep curve under constant tensile load and constant temperature [6]

Although it is generally considered that, for metal, the creep becomes apparent at temperature above (0.3 - 0.5)T_m, where T_m is the melting temperature (often higher than roughly 0.4T_m), it may appear at various level of homological temperature [6].

Creep is implemented by means of an appropriate viscoplastic-model that allowed to solve the time-dependent gradual accumulation of plastic deformation. At temperature below 0.4T_m and after the initial deformation, the strain is virtually independent of time, while increasing stress and temperature:

- The instantaneous strain at the time of stress application increases;
- The steady state creep rate increases.
- The rupture lifetime reduces.

As before mentioned as of today, creep effects associated to SA event, e.g., the investigated SBO, have not been sufficiently studied. For this reason, the validation of FE model and, in particular, the application of power laws to describe the steel creep behaviour are felt necessary.

2.2.1 Modelling validation through FOREVER/C1 experiments

The FOREVER/C1 experimental campaign was used for verification and validation [5]. This facility employed 1/10-scaled 15Mo3-(German)-steel vessel of 400 mm diameter, 15 mm thick and 750 mm high (Figure 6 a). The high-temperature (up to 1300 °C) oxide melt is prepared in a SiC-crucible placed in a 50 kW induction furnace and is, then, poured into the test section. A $MoSi_2$ 50 kW electric heater in the melt pool allowed heat-up and keeping temperature in the range up to 1200 °C. For validation purpose, a suitable FE model of FOREVER/C1 experimental rig was implemented (Figure 6 b) and its testing conditions were simulated. SA533B1 temperature dependence properties (such as strength, σ(T), and Young modulus, E(T)) were assumed in the model.

The influence of the creep was investigated implementing a viscoplastic model expressed in terms of the following power law:

$$d\varepsilon/dt = \mathrm{A} * \sigma^{n} * T^{m} * k * t^{k-1} \quad (1)$$

Where: A = coefficient; ε = equivalent creep strain, σ = equivalent stress, N = stress dependence exponent, T = temperature, m = temperature dependence exponent, t = time and k = time dependence exponent.

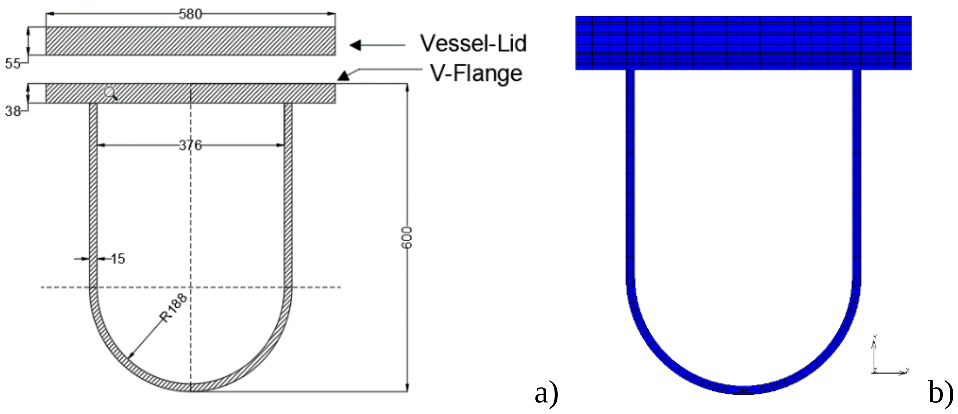
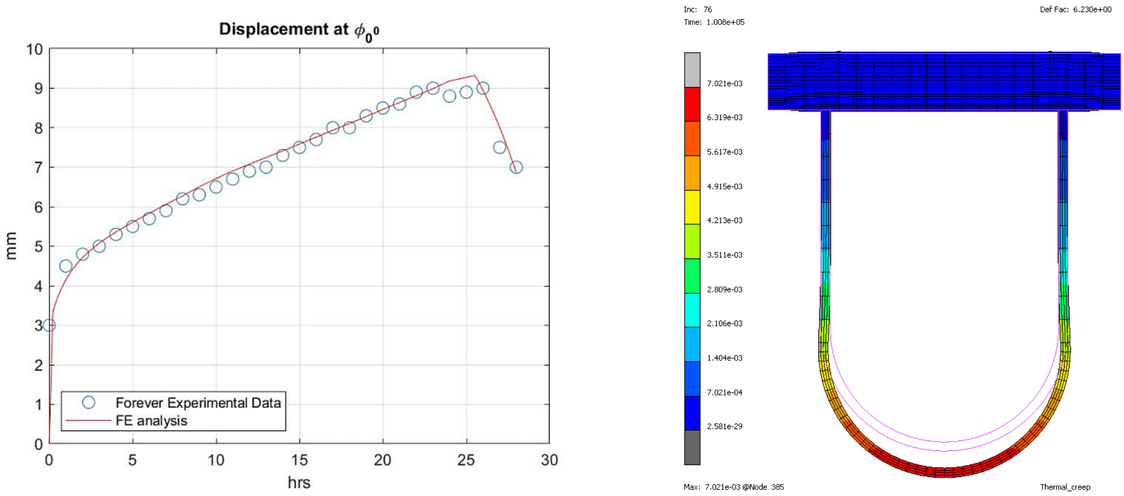


Figure 6: a) FOREVER/C1 vessel rig geometry (units are in mm) [5] and b) FE model

In what follows we present the results obtained from the simulation of FOREVER/C1 experiments. Figure 7 a shows the comparison between the displacement trend calculated numerically and the experimental one carried out at the polar coordinate $\phi_{0^{\circ}}$. Both the two trends appears almost superimposable, confirming the reliability of the proposed modelling and its capability to simulate/reproduce such a complex thermo-mechanical scenario. The maximum numerical displacement at $\phi_{0^{\circ}}$ was about 9.4 mm. The discrepancy between numerical and experimental values was less than 3 %. Figure 7 b shows also the contour plot of the wall displacement (“deformation scale factor” of 6.23); the maximum outwards displacement was at the bottom of the lower head of the RPV, in accordance with the experimental tests findings highlighted in [5].



a) b)

Figure 7: Experimental vs numerical displacements (a) and maximum displacement (b) over the model vertical section

3 RESULTS AND DISCUSSION

The performed simulations focused only on the "in-vessel phase" of the accident and described the vessel behaviour up to the occurrence of the failure of its lower-head (at failure time large displacement may occur and the structure is prone to collapse, for this reason limit/ analysis might be performed).

During the SBO event, the core melted. The corium mass relocated downwards to the lower bottom head of reactor vessel causing the wall overheating. This heat-up may induce in the long term the weakening and, at least, the collapse of the vessel wall. Indeed, the collapse or failure is due to the material degradation at elevated temperature and may become extremely severe when the plant is facing unprotected scenarios (i.e., absence of external cooling).

Figure 8 and Figure 9 show the simulation results for all four case studies analysed in in terms of displacement and Von Mises stress. It appeared that after 9.53 hr the displacement caused by creep (red curve) at ϕ_0° was about 148 mm. This represents the worst-case scenario characterised also by an earlier loss of structural integrity. Instead, in the cases where creep and thermal degradation were not accounted the displacement was about 136 mm after 9.92 hr from the start of the accident. Moreover, comparing the blue and the green curves of Figure 8, it emerges that:

- The RPV subjected to creep plasticises only before the end of transient, and is going to fail in about 10 hr;
- For the RPV unaffected by creep, the structural integrity is guaranteed.

The ageing and creep effects, as observed, strongly reduce the strength capacity, and their jeopardizing effects become even more relevant as long-term material ageing and creep progresses. This aspect may become even more critical in view of the life extension of the existing NPPs. To overcome this limitation, it is necessary to not only quantify the weight of degradation and creep but also have qualified predictive models that can be employed for the safety management (operation and maintenance) of the plant.

A validated FEM model may be used so to simulate both the normal and accidental operational behaviour of the safety relevant components in order to identify in advance the plant weaknesses and threats that ageing and/or creep may pose. Based on this, actions can be planned to counteract the degradation processes.

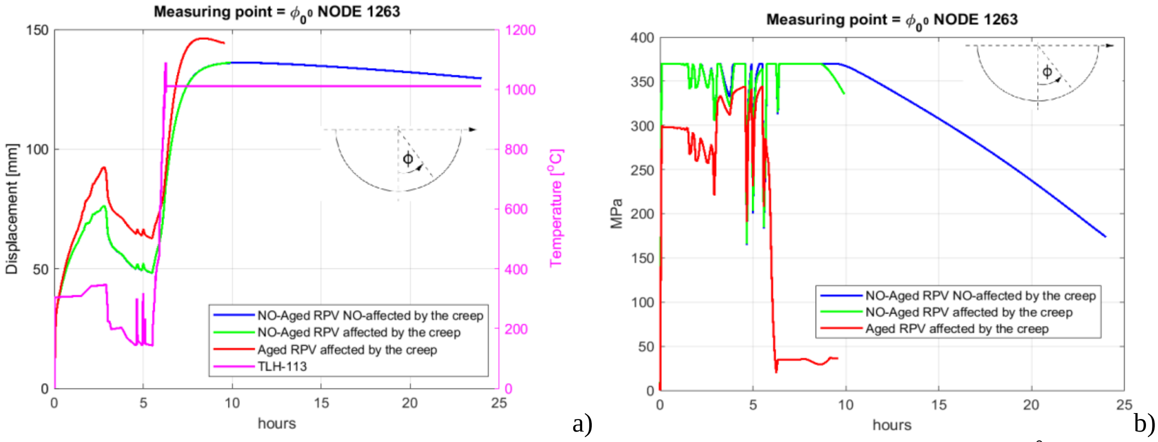


Figure 8: Trends of displacement (a) and Von Mises stress (b) at ϕ_0°

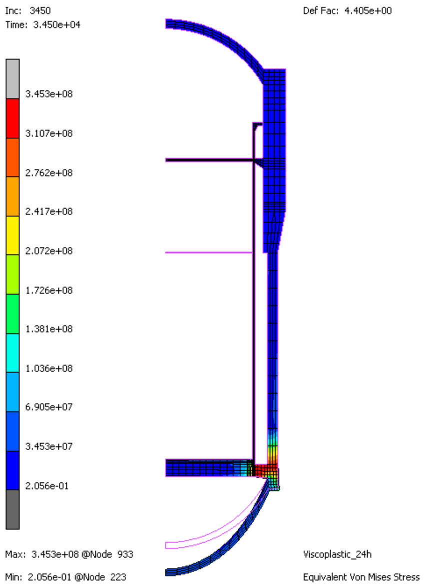


Figure 9: Contour plot of RPV Von Mises stress [Pa]: qualitative deformed vs undeformed (magenta contour) shape

4 CONCLUSION

This study investigated the influence and impact of the ageing and the creep phenomena on the behaviour of a 4500 MWth NPP RPV [4]. The occurrence and consequences of an SBO event were analysed preliminary by coupling MELCOR and MARC codes: results from former were the inputs of the latter.

The reliability of the FE modelling reproducing complex thermo-structural effects was demonstrated based on the FOREVER/C1 experiments. The comparison between experimental and numerical results highlighted a very good agreement.

The results of transient simulations performed considering the ageing and the creep acting alone or together highlighted:

- The vessel lower head bends downwards due to the applied thermo-mechanical loads, i.e. pressure and temperature.
- The lower head radially expands in the range from about 12.5 mm to 146 mm depending on the angular position due to the synergic effects of creep and ageing.
- The combined effect of ageing, creep and long heat-up strongly affect the resistance of whole vessel system till to severely compromise it in the absence of any delayed emergency intervention.

- Aged RPV system (end of life condition) may collapse earlier, and in less time, with the same accidental conditions.

Considering that most of the nuclear power plants are designed generally to operate about 40 years (plus the life extension period), an accurate knowledge of (not only thermal) ageing and creep performance is accordingly necessary in order to assure the plant safety operation.

The validated model based on the FOREVER/C1 experiments is able to predict the behaviour of the structure taking into account properly both the ageing and the creep phenomena.

Finally, it is worthy to remark that when the RPV temperature overcomes about 400 °C, creep phenomena can be triggered with RPV failure can get start occurring. For this reason, timely feedbacks coming from experience and assessment (implementation of effective management programmes) are essential to prevent unacceptable degradation that could jeopardise the plant integrity. In the future, we will also consider performing uncertainty analysis for MELCOR lower head failure and then we could assess the likelihood of given boundary conditions

ACKNOLEDGEMENT

The paper has been carried out in the framework of NARSIS (New Approach to Reactor Safety Improvements) H2020 EU Project (Grant Agreement No. 755439), which has received funding from the Euratom research and training programme 2014-2018.

REFERENCE

[1] IAEA, Assessment and management of ageing of major nuclear power plant components important to safety Primary piping in PWRs, IAEA-TECDOC-1361, 2003

[2] EU H2020 NARSIS Project, http://www.narsis.eu/

[3] Nuclear Safety in Light Water Reactors, Severe Accident Phenomenology, Chapter 2 - In-Vessel Core Degradation, pp. 89-183, 2012. ISBN: 9780123884466.

[4] R. Lo Frano, P. Darnowski et al., Study of the ageing effects on the lower head failure in a PWR reactor, Proceedings of the 2020 ICONE Virtual Conference: 4 -5 August, 2020

[5] B.R. Sehgal et al., Final report for the" Melt-Vessel Interactions" Project, 1999

[6] F. Abe et al., Creep-resistant steels, Woodhead Publishing, 2008

[7] IAEA, Deterministic Safety Analysis for Nuclear Power Plants, IAEA Safety Standards Series No. SSG-2 (Rev.1), 2019

[8] L. L. Humphries et al., (2017). "MELCOR 2.2 Computer Code Manuals - Vol. 1: Primer and Users' Guide", Sandia National Laboratories, United States.

[9] L. L. Humphries et al., (2017). "MELCOR 2.2 Computer Code Manuals - Vol. 2: Reference Manual", Sandia National Laboratories, United States.

[10] B.T., Timofeev, Assessment of the First Generation PV State after Designed Lifetime, Int. J. Pressure Vessel Piping, vol. 81, no. 8, pp. 703–712, 2004.

[11] G. Karzov, B. Timofeev, B. Ageing of RPV and primary circuit piping materials for NPP with WWER during a design operation time. Proceedings of the international topical meeting VVER-2004 - experience and perspectives, 2004