

First results related to the JRC Ispra PTS experiment: Nozzle corner crack behaviour

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1 INTRODUCTION

In the period since June 1985, the JRC (Joint Research Center) Ispra Pressurised Thermal Shock (PTS) experiment has passed the way from the feasibility study (Jovanović, 1985) to the start-up of the experimental work. The work performed, included a large number of activities, ranging from the procurement of the components and site preparation, up to the detailed pre-experimental analyses. Some preliminary results of these activities are briefly described further on.

The JRC PTS experiment represents a follow-up of the on-going JRC research and experiments on the scaled PWR vessel models (Lucia, 1982), so some results obtained in this research (Jovanović, Lucia, 1986) have been used when tackling the PTS problems. The experience has also been useful when dealing with the problem of extrapolation of results (Jovanović, Lucia, Volta, 1986).

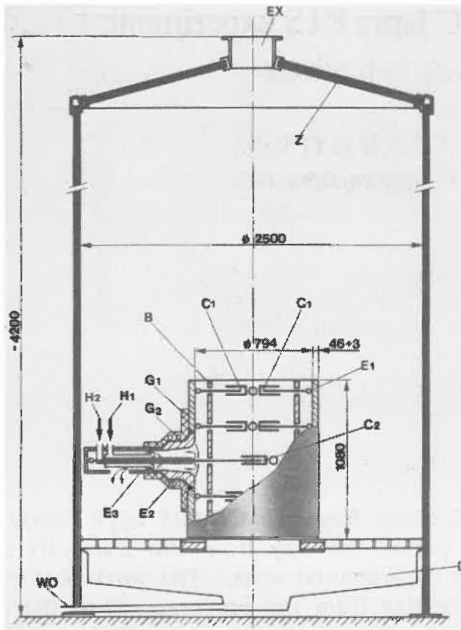
2 THE EXPERIMENT

The JRC Ispra experimental rig is aimed towards the examination of the problem of safety and reliability assessment of a pressure vessel (with cracks at the nozzle corner and safe-end), exposed to the repetitive PTS loads (Fig. 1). The pressure load is simulated by hydraulic actuators, heating of the test piece is obtained by the resistance and induction heaters, while the cooling medium is water. The test piece represents the cylindrical part of the PWR vessel, with a nozzle and the safe-end, in scale 1:5. Basic idea of the experimental design is to reproduce the local conditions around the supposed cracks, i.e. to create in the mentioned zones temperature and stress fields as those in a full-scale vessel.

3 SCOPE OF THE ANALYSIS

The scope of the planned analytical work is shown in Table 1. The types of the analyses performed, make part of the applied structural reliability assessment procedure described in the work of Jovanović, Lucia and Arman (1986). The results obtained regard in particular:

- the temperature distribution analysis,
- the stress analysis (mechanical and thermal stresses),
- the micro-crack nucleation analysis,
- the fracture mechanics analysis,
- the application of the advanced concepts in the data acquisition,
- the application of the artificial intelligence tools, and
- the pre-experiments related to the initial crack production.



- Z = containment vessel
- C₁ = hydraulic actuators for pressure simulation
- E₁ = test piece - vessel
- E₂ = test piece - nozzle
- E₃ = test piece - safe-end
- G₁ = resistance heaters
- G₂ = induction heaters
- WO = water outlet (forced)
- D = dump
- H₁ = cooling water - safe-end zone
- H₂ = cooling water - nozzle corner
- B = core barrel
- EX = air/steam exhaust (forced)

Fig. 1 - JRC Ispra PTS experimental facility

4 HEAT TRANSFER AND STRESS ANALYSIS

The heat transfer coefficient (HTC) analysis has shown that the peak value (at the very nozzle corner) should be between 5000 and 10000 W/m^2K , locally changing down to 1000 W/m^2K in the directly cooled zone, and down to 100 W/m^2K in the zones not cooled directly. The construction of the cooling device should allow regulation of the peak values. An example of results of the performed calculations is given in Fig. 2.

The stress analysis shows that during the the first 30 seconds of the cooling, a thermal stress (equivalent, elastic) of over 500 MPa would appear. The (superposed) mechanical stress induced by the hydraulic actuators is (in the regions of interest) identical to the one due to the internal pressure (Jovanović, Lucia, Volta, 1986).

5 FRACTURE MECHANICS ANALYSIS

First obtained results (pre-experimental) are, so far, based on LEFM (Fig. 3), while more complex and more adequate concepts are going to be applied further on. The concepts based both on the deformation theory and on the incremental theory of plasticity have been examined. The first group of solutions presents the parameters like J integral with the "thermal term" added, J^* integral (Muscati and Lee, 1984) and \hat{J} integral (Kikuchi and Shindo, 1984).

In the second group, the attention has been focussed on the T^* integrals (Atluri, Nishioka, Nakagaki, 1984), defined for the incremental potential ΔV over an arbitrary closed contour Γ^* (and the enclosed volume), not enclosing the crack-tip, as:

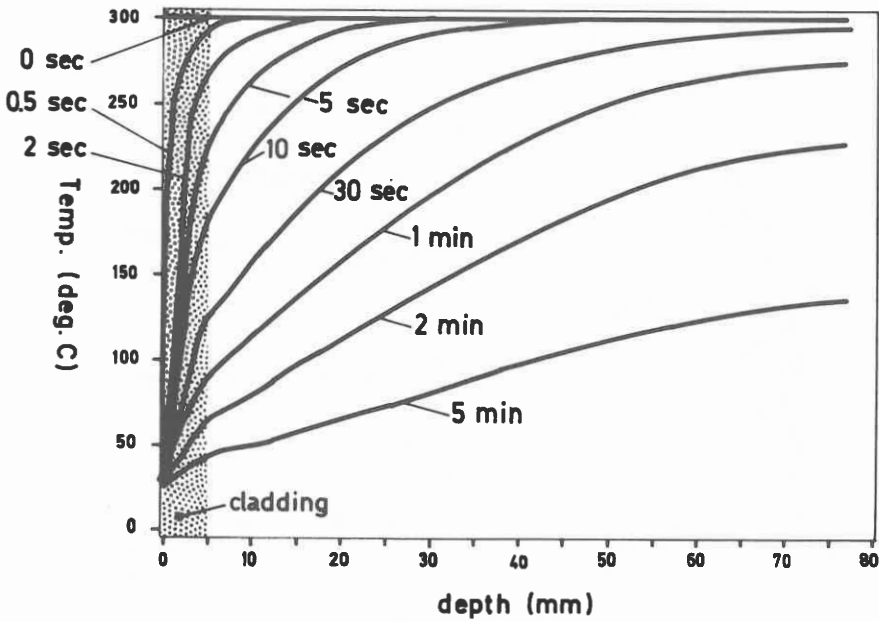


Fig. 2 - Section through the 3-D transient temperature field in the nozzle corner region

$$\begin{aligned}
 (\Delta T^*_p)_1 = & \int_{\Gamma_e} [\Delta W n_1 - (t_i + \Delta t_i) \Delta u_{i,1} - \Delta t_i u_{i,1}] dS = \int_{\Gamma + S_e \Gamma} [\Delta W n_1 - (t_i + \Delta t_i) \Delta u_{i,1} - \Delta t_i u_{i,1}] dS + \\
 & + \int_{V_r - V_e} [\Delta \sigma_{ij} (\epsilon_{ij,1} + \frac{1}{2} \Delta \epsilon_{ij,1}) - \Delta \epsilon_{ij} (\sigma_{ij,1} + \frac{1}{2} \Delta \sigma_{ij,1})] dV \quad (1)
 \end{aligned}$$

Recently, further improvements of T^* integral have been proposed and interesting comparisons with J integral and COD criteria made (Brust, McGowan, Atluri, 1986). Shih, Moran and Nakamura (1986), however, expressed doubts about the usefulness of the T^* integrals, but experiences regarding other PTS experiments (Sauter, 1986), seems to be encouraging.

6 CRACK NUCLEATION PROBLEM

Examination of the nozzle corner cracks, implies the research of the problem of crack nucleation (Jovanović, 1986, to be published). The analysis based on $\epsilon-N$ curves could not offer a solution, so the cumulative damage mechanics has been applied, leading to development of an analytical model and the corresponding computer code (MIC). The model has two parts: the one based on the single void growth and the one based on the volumetric void fraction.

The model takes the input from the finite element, three dimensional non-linear stress analysis (the 3-D strain field in the examined zone). The model has been developed by extending the works and models developed for creep and ductile rupture. For the single void growth analysis, the works of Rice and Tracey (1969) and of Shockey and co-workers (1980), are used. The volumetric void fraction option of the code is based on the work Rousselier and co-workers (1986):

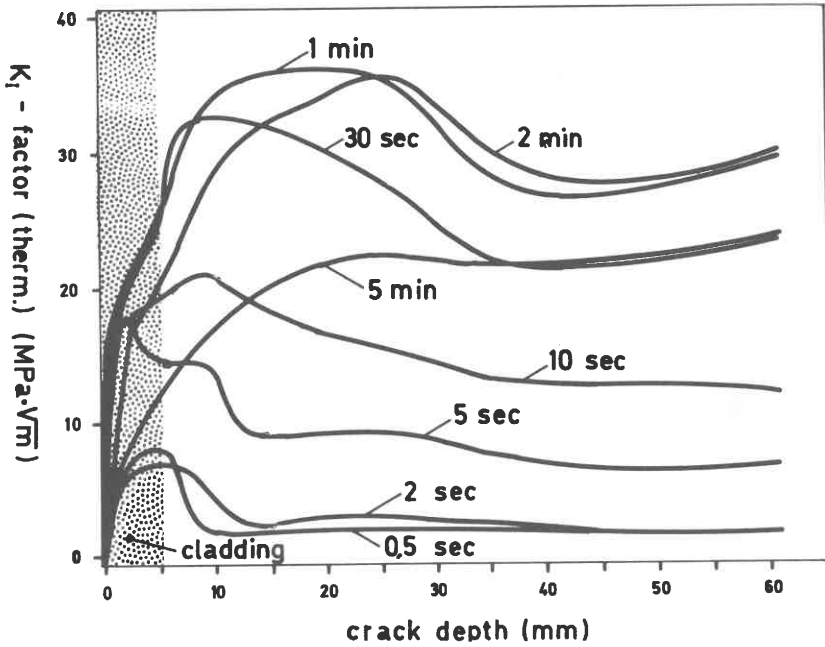


Fig. 3 - $K_{I \text{ therm.}}$ values for the nozzle corner crack

$$\frac{\dot{v}}{v} = - \left[\frac{\rho'}{\rho (1 - \rho - \rho f_o)} \right] D \dot{\epsilon}_{eq}^p \exp \left(\frac{\sigma_m}{\rho \sigma_1} \right) \quad (2)$$

(f_o - constant related to the volume fraction of inclusions f_v , $\sigma_m = \sigma_{ii} / 3$, σ_{eq} and $\dot{\epsilon}_{eq}^p$ - equivalent stress and plastic strain rate, ρ - relative density, v - average volume of voids). Both models (and the code) are applied to the case of repetitive loading conditions, assuming:

$$\epsilon_{total}^p = \sum_1^N \epsilon_{single \text{ loading}}^p \approx N \cdot \epsilon_{single \text{ loading}}^p \quad (3)$$

The MIC code (in C language), allows to calculate the probability of a macro crack of the given dimensions at various stages of the repeated loading.

7 APPLICATION OF THE ARTIFICIAL INTELLIGENCE TOOLS

The use of artificial intelligence (AI) tools is foreseen at three main levels (Fig. 4):

- qualitative modelling of the experimental installation,
- treatment of fuzziness in the input data, including the propagation of fuzziness through the structural reliability analysis, and
- man-machine interaction modelling.

The application is supported by the use of KEE-3 system (shell), in which a PTS experimenter knowledge base has been created. The "units" of the KB contain the necessary information ("slots" and "atributes") linked through the adequate types of "parent" or "child" links and "inheritances". The implementation of the qualitative model and of the rules, in the knowledge base, is in course.

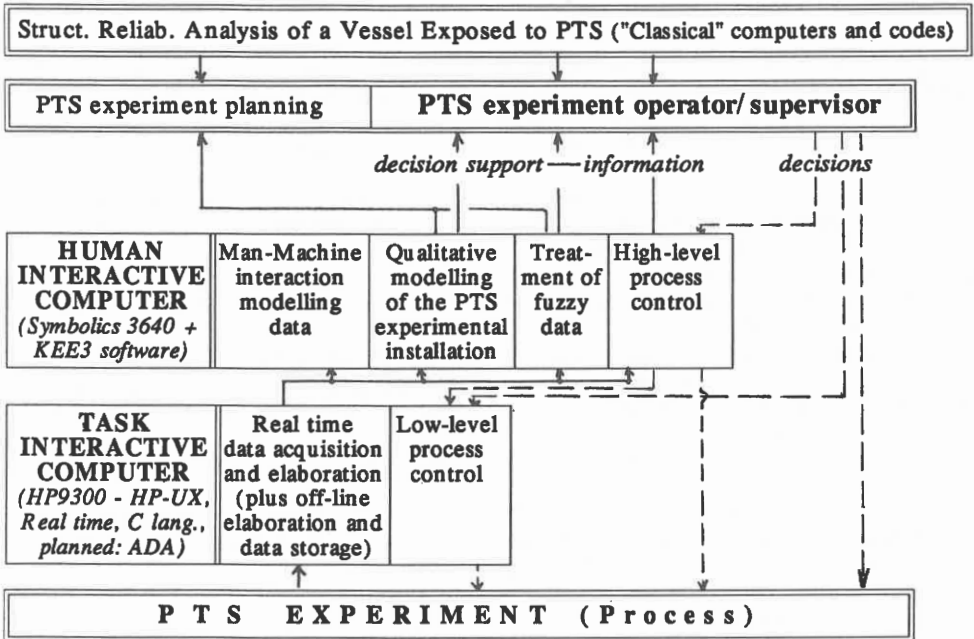


Fig. 4 - Application of the artificial intelligence in the JRC PTS experiment

8 FIRST EXPERIMENTS

The programme of the experimental work (Jovanović, Lucia 1986), foresees a series of experiments, starting with the Crack Production Experiment (CPE). The scope of the performed CPE was to examine the possibility of the initial crack production, in the cladding of the PTS test piece on the nozzle corner, by a sudden cooling by liquid N_2 . First experiments have shown the general feasibility, leaving the problems regarding the control of the produced crack dimensions, expected to be solved further on.

9 CONCLUSIONS

First results of the JRC PTS experiment indicate the importance of cracks in the nozzle corner region, whose nucleation and propagation is a result of the structural damage accumulation process, which cannot be easily modelled and is hardly detectable. Analytical modelling of the nozzle corner crack behaviour in the vessel exposed to the combined mechanical and thermal loads and the application of the new experimental concepts (use of AI tools, for instance) are the issues of the major efforts in the phases to follow.

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Table 1

JRC Ispra PTS Analytical Research Programme	
Phase	Main research goals
0. feasibility study phase	<ul style="list-style-type: none"> - preliminary HTC estimation - temperature field analysis - thermal stress field analysis - simulation of the internal pressure feasibility analysis - EPFM analysis of the nozzle corner crack behaviour under the combined thermal and mechanical loading
1. pre-experimental phase	<ul style="list-style-type: none"> - parametric analyses with constant and variable HTC (HTC variable in space and time) - temperature field analysis - thermal stress field analysis - mechanical loads stress analysis - combined loads stress analysis - EPFM analysis (nozzle corner and safe-end cracks under combined loads - (J integral) - Study and development of the T* integral post-processor
2. experimental phase	<ul style="list-style-type: none"> - as above, with measured input values - verification of assumptions - comparison between the J and T* integral approaches
3. post-experimental phase	<ul style="list-style-type: none"> - detailed analysis based on NDE and metallography results - final comparison: experimental vs. analytical results
4. conclusion phase	<ul style="list-style-type: none"> - summary of the research results - matching of PTS experiment results with results of the 1:5 scale experiment - proposal for the further research