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Evaluation of Pressurised Thermal Shocks for VVER 440/213 Reactor Pressure Vessel in NPP Dukovany

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ABSTRACT

NPP Dukovany is one of two NPPs operated in the Czech Republic. It has 4 units with VVER 440 type 213 reactors. The NPP started its operation in 1985 - 1987.

PTS evaluation for this NPP was started in 1996 and the project is to be completed in 2004. Deterministic approach based on system thermal hydraulic analyses, detailed mixing analyses, and linear fracture mechanics is used. Evaluations are performed according to IAEA „Guidelines on PTS Analysis for WWER NPP“ and Czech standards. The following categories of PTS transients have been evaluated until now:

1) Large breaks in Main Steam System
2) Leak from primary circuit through the pressurizer safety valve
3) Spurious signals
4) LOCA
5) Primary to secondary circuit leaks

Thermal Hydraulic Analyses

System TH analyses are performed using the RELAP5 computer code with a detailed 6-loop input model of NPP Dukovany. Primary and secondary circuits are modelled in detail according to the actual NPP configuration, signals specific to NPP Dukovany are built into the model and operator actions are taken into account for some PTS transients.

The behaviour of the hermetic confinement, sumps and ECCS coolers is investigated by MELCOR code for LOCA accidents to determine ECCS water temperature in recirculation regime.

The detailed mixing analyses are performed for all non-symmetric cases using CATHARE (with 2-D model of reactor downcomer) or REMIX/NEWMIX codes.

Structural Analyses

All computations are focused on circumferential weld 0.1.4 in beltline zone.

Overall approach to the analyses:

Temperature and stress fields are computed by FEM on RPV model without crack. Linear elastic model is used. After that, the stress intensity factors K_I are computed for postulated defects based on calculated stresses and using formulae from Czech standards. The defects are postulated (according to the IAEA Guidelines) as semielliptical surface cracks, both axial and circumferential, with aspect ratios a/c = 0,3 and 0,7 and with the depth up to 1/4 of the wall thickness. Maximum allowable critical temperature of brittleness T_K^a is determined by comparison of K_I and $[K_{IC}]_3$ (the allowable value of stress intensity factor) curves using the tangent approach.

Some examples of results are presented.

KEY WORDS: pressurised thermal shock, reactor pressure vessel, nuclear power plant, integrity, thermal hydraulic analyses, mixing, fracture mechanics, stress intensity factor, postulated defect, crack, finite element method, temperature, stress, crack driving force, Dukovany, PTS, TH, VVER, RELAP5, MELCOR, CATHARE, REMIX, NEWMIX, COSMOS/M, SYSTUS.

INTRODUCTION

Nuclear power plant (NPP) Dukovany is the older one of the two NPPs operated in the Czech Republic. It has 4 units with VVER 440, type 213 reactors (i.e. PWR type reactors with electric output 440 MW). The NPP started its operation in 1985 – 1987, so now the first unit is approaching 20 years of operation and its licence renewal is necessary.

PTS evaluation for this NPP started in 1996 in NRI Řež. Deterministic approach is used for the evaluation. Evaluations are performed according to the Czech standards [1], [2] and the IAEA Guidelines [3].

Reactor pressure vessel (RPV) is the most important component of nuclear power plant. Its lifetime is a limiting factor for the lifetime of the entire NPP. To ensure its integrity is one of the key tasks of the nuclear safety. The evaluation of the RPV lifetime is therefore a high-priority objective. The RPV lifetime evaluation consists in the assessment of the RPV actual state and in the prediction of the future development of its properties, i.e. especially in the evaluation of material degradation resulting from various effects. First, neutron fluence causes radiation embrittlement.

This process is characterized by growth of RPV material critical temperature of brittleness T_K. These changes are identified using results of the surveillance programme, which is supported by determination of the neutron fluence on the RPV wall. A significant part of the lifetime assessment is defect identification in the RPV wall by means of qualified non-destructive testing.

For the assessment of the RPV lifetime it is necessary to know the limits that can be reached by the material degradation without endangering the RPV integrity even in cases of the most unfavourable accidents, i.e. during pressurised thermal shock (PTS) events. These are characterized by rapid cooldown of the primary coolant, particularly in the downcomer (DC), and by the subsequent cooldown of the RPV wall leading to thermal stresses in the RPV wall loaded at the same time by inner pressure. This cooldown is often nonuniform. So-called „cold plumes“, „cold stripes“ or „cold sectors“ (further simply called „cold plumes“ here) appear and consequently the thermal stresses in the RPV wall are increased. The nonuniformity of the RPV cooldown is caused in particular by Emergency Core Cooling System (ECCS) injection or by rapid asymmetric cooling down via steam generators. The high stress in the RPV wall causes high values of stress intensity factor in the potentially existing defect in the RPV wall (interpreted as a crack). This can at simultaneously low temperature and because of the embrittled material lead even to a fast fracture. The objective of the PTS analyses is to determine the maximum allowable RPV material critical temperature of brittleness (T_K^a) in such a way that if the real value of the RPV material critical temperature of brittleness T_K is bellow this value, even in the case of the most unfavourable PTS accident fast fracture will not be initiated from a defect potentially existing in the RPV wall which is smaller than the crack postulated in the PTS analyses.

PTS analysis is of multidisciplinary character. It consists of a closely consequential series of thermal hydraulic and structural analyses described in detail in the following sections.

LIST OF PTS TRANSIENTS FOR NPP DUKOVANY

Five categories of PTS transients were evaluated till now:

1) **Large Breaks in Main Steam System (MSS)**
   - Main steam header rupture (MSHR) with simultaneous break of 3 main steam lines. 6 variants were evaluated (full or hot zero power, high or low water level in pressurizer, old or modified signal MSHR“). All these cases were computed as axisymmetric. All the following cases were non-symmetric, i.e. with cold plumes.
   - Main steam header break with acting signal MSHR and possible failure of Main Steam Line Isolation Valve (MSLIV) closing. 3 variants were evaluated (failure of valve closing was supposed for none or one or six main steam lines).
   - Main Steam Line Break (MSLB) in the hermetic confinement. 1 variant was evaluated.
2) **Leaks from Primary Circuit through the Pressurizer Safety Valve**
   - Inadvertent opening of pressurizer safety valve (PRZ SV). 2 var. evaluated (with or without PRZ SV reclosure).
   - Total loss of feedwater (LOFW) accident mitigated by feed-and-bleed (F&B). 1 variant was evaluated.
3) **Spurious Signals**
   - Spurious signal „Large break LOCA“. 2 variants were evaluated (full or zero power).
   - Spurious signal „Main Steam Header Rupture“. 4 variants were evaluated (full or zero power, with or without loss of external power supply).
4) **Loss-of-Coolant Accidents (LOCA)**

   Operator actions were taken into account for LOCA 10 mm, 30 mm and 50 mm.
   - LOCA 10 mm, 4 variants (full or hot zero power, leak from hot or cold leg).
   - LOCA 30 mm, 4 variants.
   - LOCA 50 mm, 4 variants.
   - LOCA 90 mm, 4 variants.
   - LOCA 150 mm, 1 variant (full power, leak from hot leg).
   - LOCA 200 mm, 2 variants (full power, leak from hot leg. Additional analysis with heated-up low pressure injection system tanks).
   - LOCA 250 mm, 1 variant (full power, leak from hot leg).
   - LOCA 2x500 mm, 2 variants (full power, leak from hot or cold leg).
5) **Leaks from Primary to Secondary Circuit**
   - 3 steam generator (SG) tubes rupture without operator actions, 5 variants (full or hot zero power, different SG damaged, different number of operating ECCS trains).
   - 3 steam generator tubes rupture with operator actions, 4 variants (hot zero power, different SG damaged, different number of operating ECCS trains, different operator actions).

Total number of PTS analyses performed till now is 50 thermal hydraulic and 33 structural analyses (+ many auxiliary and sensitivity analyses).

Remaining Transients (to be Evaluated during 2003 year)

- Steam generator primary collector cover opening.
- Low temperature overpressure.
- Flooding of the reactor cavity.

THERMAL HYDRAULIC ANALYSES RELATED TO PTS EVALUATION

Specific thermal hydraulic (TH) analyses must be performed for the PTS evaluations with PTS-specific conservative assumptions (focused on maximum cooldown, maximum pressure and flow stagnation), which are different from those used in the standard safety analyses focusing mainly on the core cooling.

First analysis to be performed is system TH calculation. Its aim is to model both primary and secondary circuits including emergency core cooling systems. For system analyses the RELAP5/MOD3.x system TH code is used with a detailed 6-loop model of NPP Dukovany. Primary and secondary circuits are modelled in detail according to the actual NPP configuration (see Figs. 1, 2). Signals specific to NPP Dukovany are built into the model. The operator actions according to the Emergency Operating Procedures (EOP) are taken into account for some PTS transients. Conservative assumptions with respect to PTS are included according to IAEA Guidelines.

In selected cases we used already in the system TH calculation a model with 2D nodalization of the reactor downcomer (see Fig. 1). The aim of this non-standard approach was to improve prediction of flow coast down and stagnation onset in individual primary loops, because they are often associated with multi-dimensional velocity (and temperature) field in the reactor downcomer.

The behaviour of confinement, sumps and ECCS coolers was investigated by MELCOR 1.8.3 code for LOCA accidents to determine ECCS water temperature in recirculation regime.

The detailed mixing analyses were performed for all non-symmetric cases. The goal of these analyses is to determine the thermal loading of the RPV wall including detailed modelling of temperature, velocity and heat transfer coefficient fields in the downcomer.

In the cases with ideal mixing in cold legs and no radial stratification in the downcomer (“cold sectors”) or two-phase conditions in the downcomer (“cold stripes”), the CATHARE 2, ver. 1.3 code was used.

For the other transients with flow stagnation and thermal stratification in cold legs and predominantly single-phase conditions in the downcomer, the REMIX or NEWMIX code modified for NPP Dukovany was used. The detailed mixing calculation can be, in specified cases, substituted by system TH calculation with multidimensional model of the reactor downcomer.

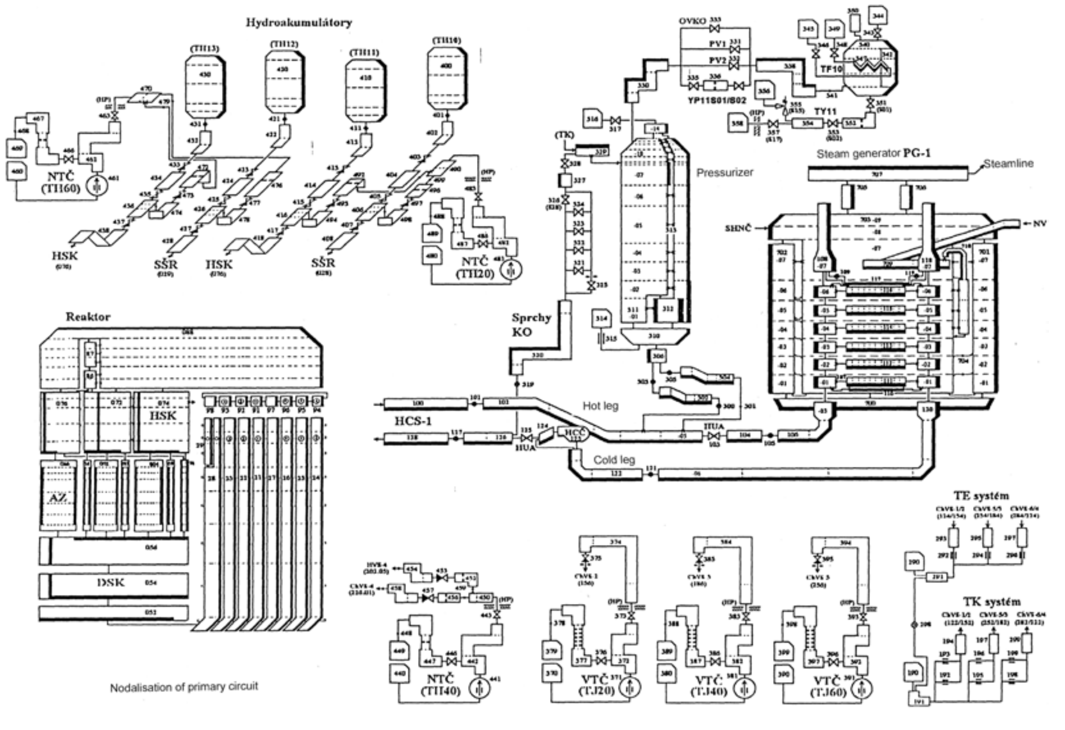

Fig. 1 Nodalisation of primary circuit

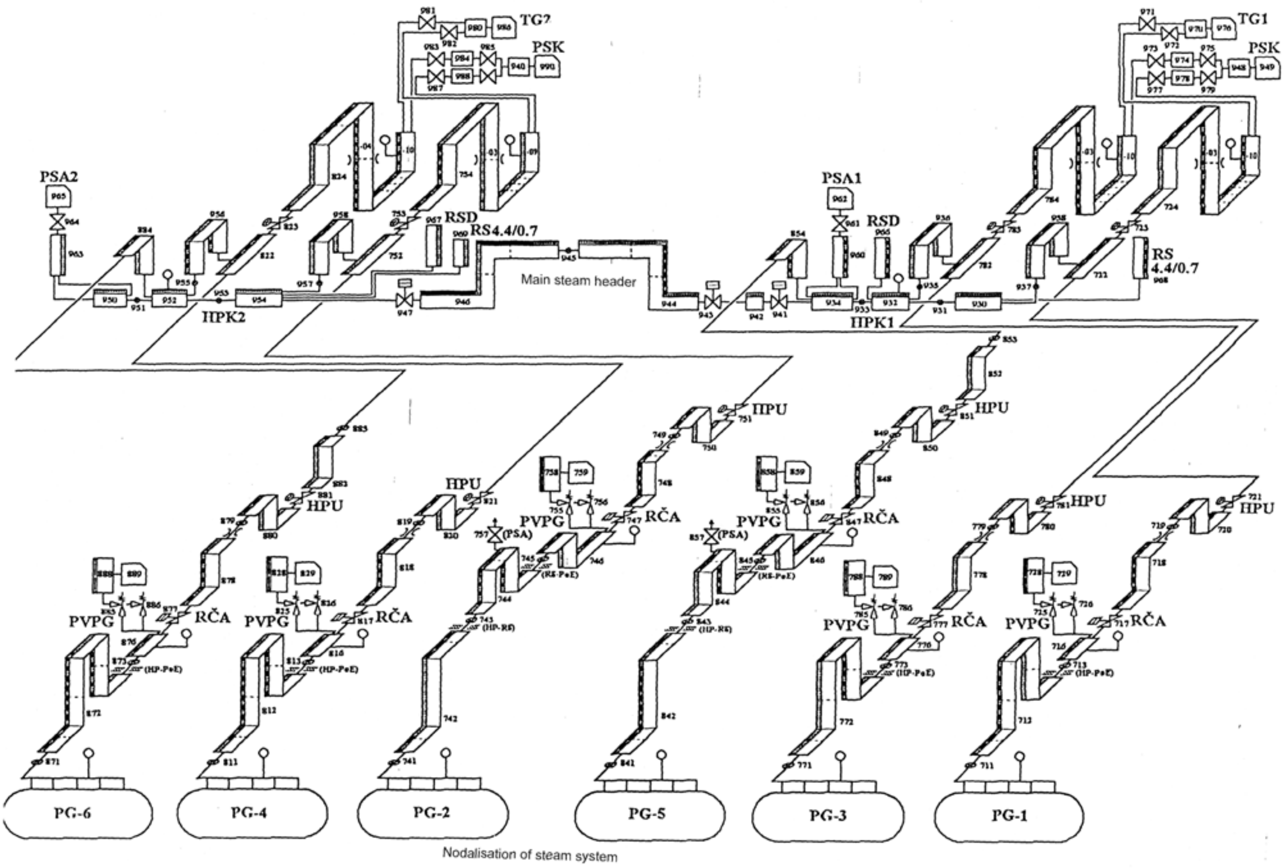

Fig. 2 Nodalisation of steam system

STRUCTURAL ANALYSES

All the computations were focused on the most embrittled circumferential weld 0.1.4 in the beltline zone.

General Approach to the Analyses

Temperature and stress fields are computed by the finite element method (FEM) on model without crack. Then, the stress intensity factors K_I are computed for postulated defects based on calculated stresses and using formulae from the standard. Linear fracture mechanics is used. Definition of the maximum allowable critical temperature of brittleness T_K^a is based on comparison of K_I and $[K_{IC}]_3$ curves using the tangent approach, i.e. the following inequality must be satisfied:

$$K_I\left(x,\sigma(x,t)\right) < \left[K_{IC}\left(T(x,t),T_K\right)\right]_3 \qquad (1)$$

Neither crack arrest nor warm prestressing approach is used.

FEM Model

For the symmetric cases the 2D axisymmetric model and the **SYSTUS** code were used. For non-symmetric cases with cold plumes, the 3D models of 1/4 of the RPV and of the whole circumference of the cylindrical part of the RPV were created (see Fig. 3) and the **COSMOS/M** code was used for the solution. In all models the austenitic cladding is included.

From TH results the following data are transferred to the FEM model as the boundary conditions: reactor coolant system pressure, coolant temperature in the downcomer and water-to-wall heat transfer coefficient or directly the RPV inner surface temperature, all values depending on time. The non-linear transient calculation of thermal fields and linear elastic calculation of stress fields are performed.

Postulated Flaws in Reactor Pressure Vessel Wall

The defects are postulated according to the IAEA Guidelines [3]. Semielliptical surface (i.e. through cladding) cracks, both axial and circumferential, with aspect ratios a/c = 0,3 and 0,7 and with the depth up to 1/4 of the wall thickness (i.e. up to 35 mm) are evaluated (see Fig. 4). In the case when the non-destructive testing (NDT) for the in-service inspections (ISI) of the RPV (i.e. the procedure, equipment and personnel) is qualified, the postulated crack depth can be reduced (according to standards) to 1/10 of the wall thickness (i.e. to 15 mm).

Both the deepest and the cladding/base material interface points are assessed.

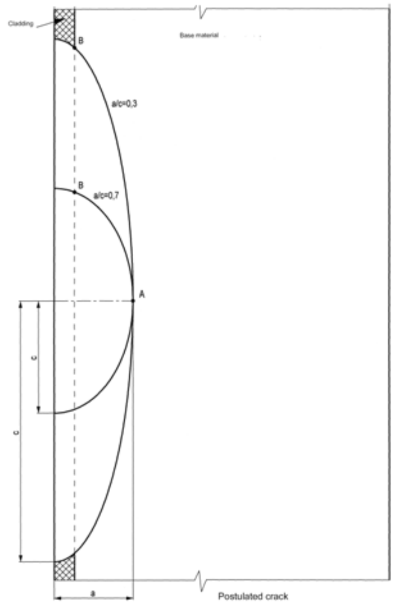

Fig. 3 Postulated defects

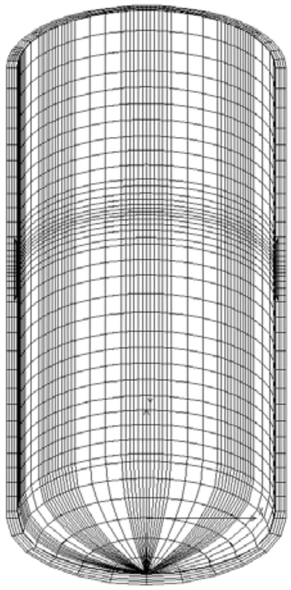

Fig. 4 FEM model of the whole circumference of RPV (1/2 of the model)

Stress Intensity Factor K_I Calculations

Linear fracture mechanics is used. For the K_I calculations the following formulae from the Czech standard [2] (which are of Russian origin - from CNIITMAS) are used:

$$K_I(A) = \sigma_{KA} \cdot Y_A \cdot \sqrt{a/1000} \qquad (2)$$

$$K_I(B) = \sigma_{KB} \cdot Y_B \cdot \sqrt{a/1000} \qquad (3)$$

where A is the deepest point, B is the surface point of the crack, equivalent stresses σ_K are defined as follows:

$$\sigma_{KA} = 0{,}111 \cdot (3\sigma_A + \sigma_B + 5\sigma_C) + 0{,}4 \cdot \frac{a}{c} \cdot (0{,}38\sigma_A - 0{,}17\sigma_B - 0{,}21\sigma_C) - 0.28 \cdot \frac{a}{s} \cdot \left(1 - \sqrt{a/c}\right)(\sigma_A - \sigma_B) \qquad (4)$$

$$\sigma_{KB} = 0{,}64\sigma_B + 0{,}36\sigma_C \qquad (5)$$

where σ_A, σ_B and σ_C are the stress components perpendicular to the crack plane in the deepest, surface and middle-depth points of the crack and where the shape factors Y_A, Y_B are:

$$Y_A = \frac{2 - 0{,}82 \cdot a/c}{\left[1 - \left(0{,}89 - 0{,}57\sqrt{a/c}\right)^3 \cdot (a/s)^{1{,}5}\right]^{3{,}25}} \qquad (6)$$

$$Y_B = \left[1{,}1 + 0{,}35(a/s)^2\right]\sqrt{a/c} \cdot Y_A \qquad (7)$$

Allowable Value of Stress Intensity Factor

Temperature dependency of the allowable value of stress intensity factor $[K_{IC}]_3$ is according to the standards:

$$[K_{IC}]_3 = \min\{26 + 36 \cdot \exp[0.02 \cdot (T - T_K)], 200\} \quad MPa \cdot m^{1/2} \qquad (8)$$

THE WORST CASES OF PTS FOR NPP DUKOVANY FOUND TILL NOW

The following list indicates the worst cases of PTS found for NPP Dukovany till now (beginning from the worst):

1) Inadvertent PRZ safety valve opening with its later reclosure (issue resolved in improved EOPs revision).
2) Medium-break LOCAs.
3) Steam generator tube rupture.
4) Large-break LOCA.

EXAMPLE OF RESULTS

As an example of the results of our PTS evaluation the LOCA event with equivalent diameter of leak 90 mm is chosen. The leak was postulated in the hot leg. As the initial state the nominal power was supposed. The primary pressure vs. time diagram resulting from RELAP5 computation is presented in Fig. 5. The coolant temperature vs. time curves in the downcomer (temperatures in the cold plume and in the ambient region in the level of the critical weld) obtained from the CATHARE code are presented in Fig. 6. The coolant temperature distribution in the downcomer for the critical time 1160 s from the CATHARE code is presented in Fig. 7.

Main System Events during the transient influencing the PTS evaluation (obtained from the TH system results):

25 s	start of high pressure safety injection (HPSI),
493 s	start of hydroaccumulators (HA) injection (2 HA connected to DC, 2 HA to upper plenum),
1250 s	first cold plume decay,
1561 s	stop of HA injection,
1663 s	start of low pressure safety injection (LPSI),
1737 s – 1840 s	switch of the high pressure safety injection (HPSI) pumps suction from the HPSI tanks (heated up to 55 °C) to the LPSI tanks (not heated),
3182 s – 3755 s	switch of HPSI and LPSI pumps suction to the sumps.

Main Results

The worst case was found as follows: circumferential crack of 35 mm depth, interface point, aspect ratio a/c=0,7. The critical time for the RPV integrity was the time before the first cold plume decay (1160 s). Resulting values of stress intensity factor K_I depending on the temperature together with the temperature dependency of the allowable value of stress intensity factor $[K_{IC}]_3$ are presented in Fig. 8 for the worst case.

The resulting value of maximum allowable critical temperature of brittleness T_K^a is 82 ºC, which is unfavourable from the point of view of the RPV lifetime (preliminary prediction of the end-of-life value of T_K based on design values of fluence and trend curves from standards is 100 ºC). NPP Dukovany has completed successfully the process of qualification of NDT for ISI of the RPV recently. So that reduction of the depth of postulated defect to 1/10 of wall thickness (i.e. to 15 mm) can be adopted in accordance to the standards. The resulting value of T_K^a for this case is 115 ºC, which is acceptable from the point of view of the RPV lifetime. The resulting graphs are presented in Fig. 9.

LESSONS LEARNED WITHIN THE NPP DUKOVANY PTS PROJECT

- Close connection between thermal-hydraulic and structural part of the analysis is necessary.
- Selection of minimal number of initiating events, which should be analysed to cover all PTS, is not an easy task.
- Conservative assumptions for TH calculations specific to PTS analyses have to be taken into account.
- Behaviour of ECCS significantly influences the PTS course and the results.
- In the ECCS injection phase, the coolant temperature in HPSI and LPSI tanks is of high importance.
- In the recirculation phase, the coolant temperature in sump and downsteam of ECCS cooler(s) can be important.
- In some regimes, the operator's actions can make the results more favourable.
- In some regimes, the multi-dimensional TH capability is needed already at system TH analysis level.
- Selection of the appropriate mixing codes with respect to their limitations is of high importance.
- The postulated crack depth influences significantly the results.
- Both crack orientations (axial and circumferential) have to be analysed.

CONCLUSION

The analyses of all PTS regimes relevant to NPP Dukovany will be finished this year. The results will serve as a basis for RPV lifetime assessment and for the licence renewal after 20 years of operation. For the 1st unit this has to be done in 2004.

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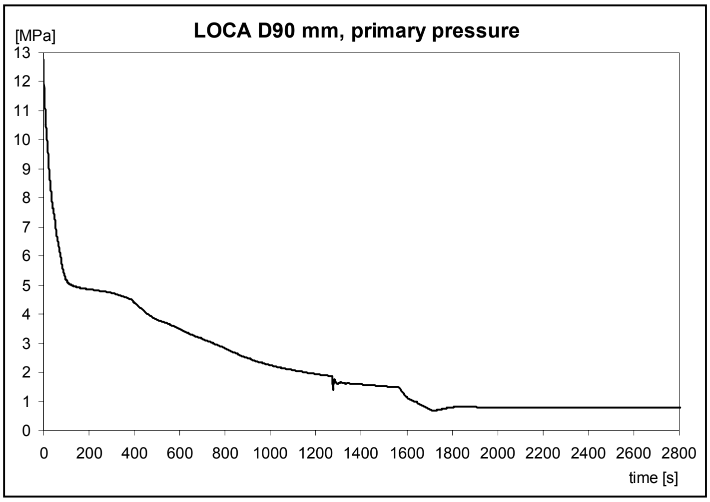

Fig. 5 Primary pressure vs. time

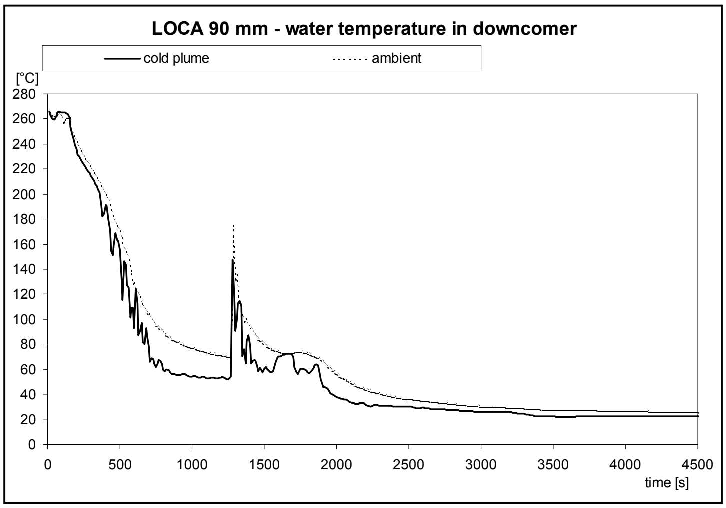

Fig. 6 Water temperature vs. time

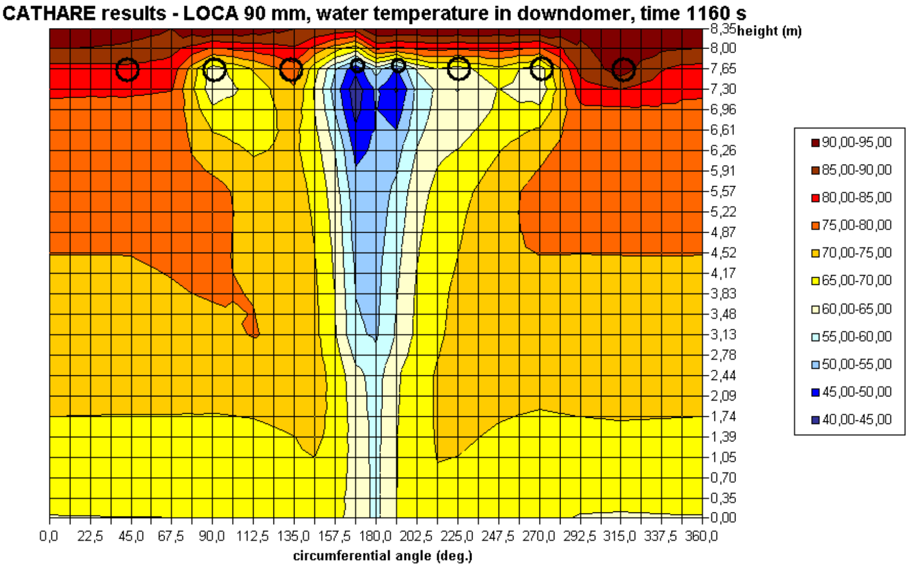

Fig. 7 Water temperature in downcomer in time 1160 s

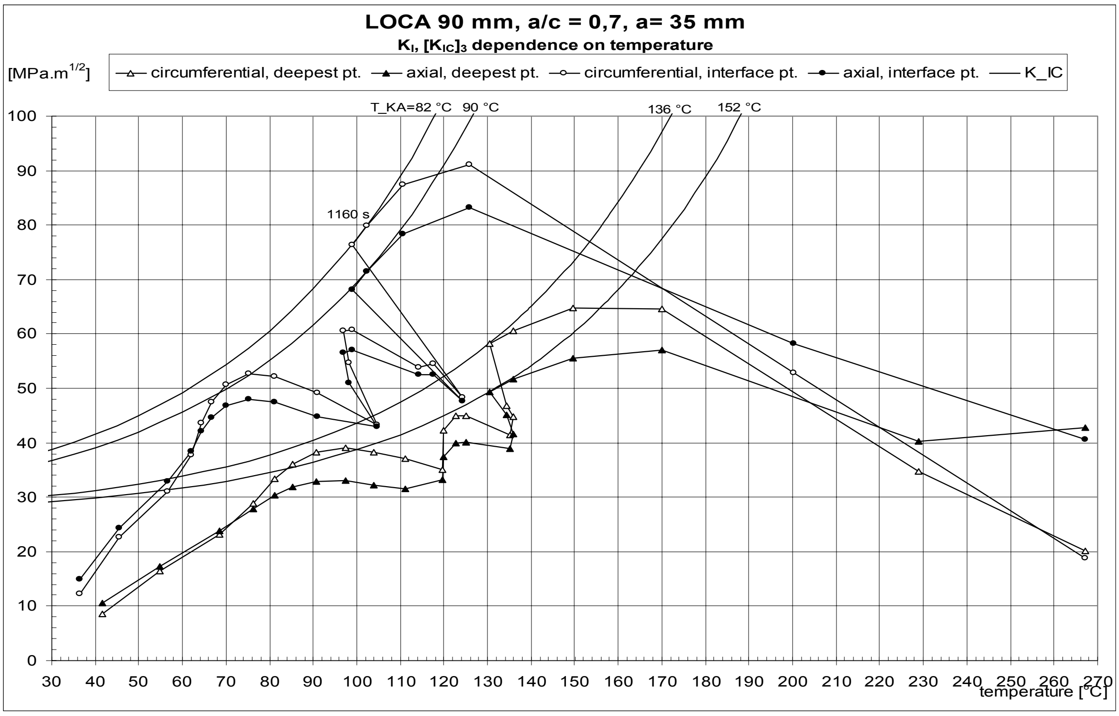

Fig. 8 Results for LOCA 90 mm, crack depth *a* = 35 mm

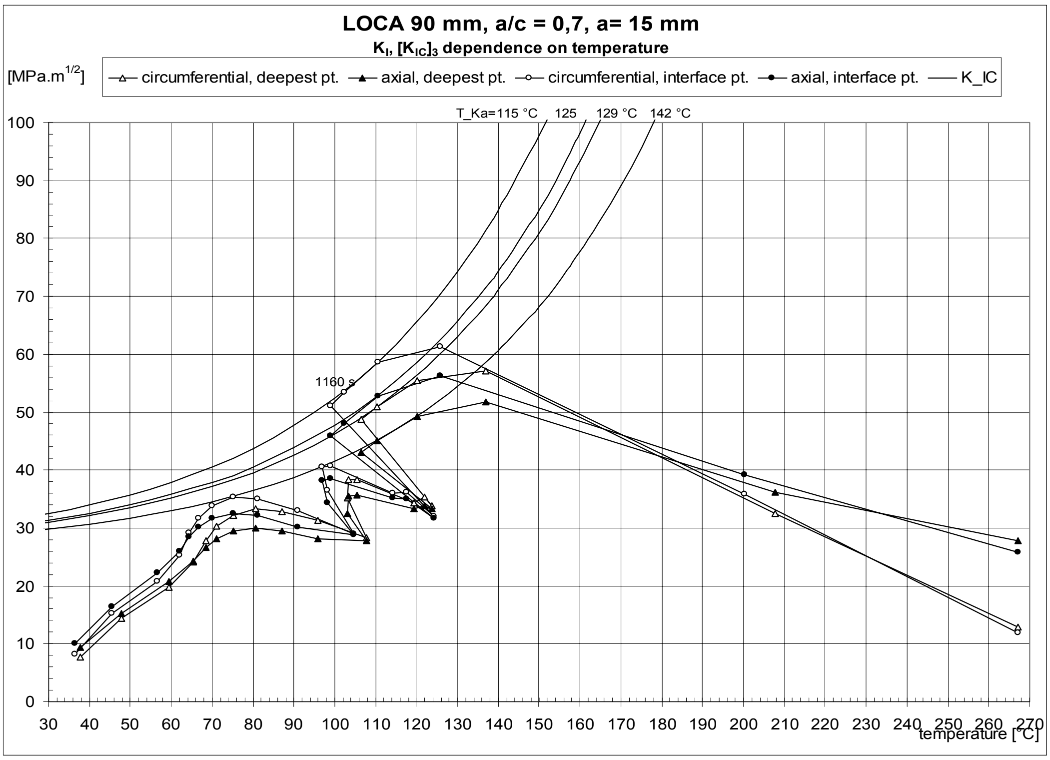

Fig. 9 Results for LOCA 90 mm, crack depth *a* = 15 mm