SMiRT-12 / K. Kussmaul (Editor)

GF02/5

ANALYSIS OF REACTOR PRESSURE VESSEL NOZZLE CRACKS SUBJECTED TO CYCLIC PRESSURE AND TRANSIENT THERMAL STRESS LOADS USING THE P-EXTENDED FINITE ELEMENT SYSTEM PEXFE-3D

Z. Pammer and G. Szabolcs

PaB Company Ltd., Somogyi u. 28/A, H-1115 Budapest, Hungary

ABSTRACT

This paper presents a WWER 440 reactor vessel nozzle crack analysis. The main purpose of the analysis was to estimate the safety against two different failure modes as a function of the postulated crack depth: 1) brittle fracture; 2) fatigue crack growth. Besides internal pressure load, the structure was subjected to transient thermal effect due to operation of the high pressure emergency cooling system.

The problem was solved using the p-extended finite element software called PEXFE-3D specially designed to the requirements in reliability for the analysis of nuclear power plant components. All computed quantities (heat flux, temperatures, stresses, strain energy, stress intensity factors, etc.) are validated by error estimations.

1. INTRODUCTION

The cold inlet nozzle (ID 500 mm) to the WWER-440 reactor pressure vessel is one of the most important part that can influence the lifetime of the primary cooling system. Besides comparatively high stress concentration under internal pressure load, operation of the high pressure emergency cooling system can generate considerable thermal stresses.

A recent finite element analysis [1] aimed to determine the stress field in the nozzle-to-vessel intersection area due to hydrostatic test pressure load. Comparison of the computed peak stress data to experimental results showed good agreement (3 % difference only).
A test problem 'Surface crack in a cladded steel brick subjected to thermal shock conditions' was also solved to compare the finite element solution to the analytical result [1]. The difference was within 1 % in the stress intensity factor computation.
The above-mentioned results were obtained by the p-extended finite element software **PEXFE-3D**. Special technology, called 'p-extension' provides this system the capability to estimate the modelling and approximation error in those usual cases, when there are no other sources to compare the results with. Reference [1] provides more details about p-extension.
This paper presents a nozzle crack propagation analysis due to cyclic pressure load and due to the transient effect of the high pressure emergency cooling system, using PEXFE-3D. The crack is postulated at the inner fillet of the vessel-nozzle junction.

2. POSTULATED CRACK PROPAGATION

2.1. The crack is initiated at the inner fillet of the nozzle, where the internal pressure causes the highest stress concentration.

2.2. The shape of the crack is nearly semi-elliptic (surface crack), the ratio of the minor/major axis :

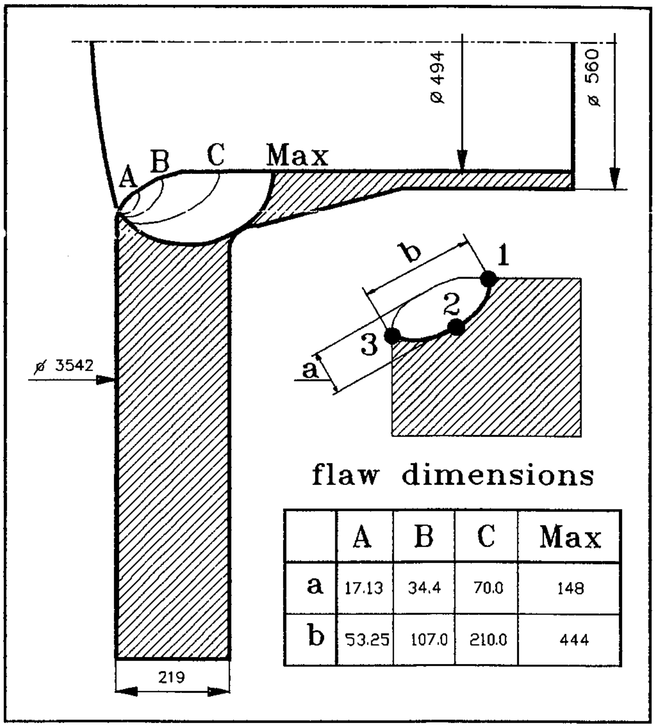
$$2\,a\,/\,b = 2\,/\,3$$

2.3. The crack propagation path was designed to hold the following conditions:

2.3.1. The crack should propagate towards to the most intensively cooled area.

2.3.2. The crack assumed to reach the stage marked by '**Max**' in Figure 1., which is the smallest flaw that causes leakage and satisfies the previous conditions as well. The crack is assumed to go through the stages denoted by **A**, **B** and **C** in Fig.1.

Three finite element geometrical models were built to include one of the crack stages in the nozzle intersection area. These geometrical models are simply identified by the letters A, B and C in the following text.



	A	B	C	Max
a	17.13	34.4	70.0	148
b	53.25	107.0	210.0	444

Fig.1. Stages of the crack propagation. Dimensions in mm.

3. THERMAL CONDITIONS DURING THE TRANSIENT PERIOD

The effect of the high pressure emergency cooling system (HPCS) injects cold water (30 °C) to the cold leg of the primary circuit that was initially at the temperature of 265°C. The injection to the main pipe (ID 500 mm) is located approx. at a distance of 3 m from the pressure vessel nozzle. The cold water, flowing to the vessel nozzle, suddenly cools down this region.

Fluid flow conditions could be considerably different, first of all, because of different ratios of mass flows. Mass flow rate of the cold high pressure injection (HPI) water is approximately 10 kg/s. However, mass flow rate in the cold leg of the primary circuit can be different when the HPCS is activated. Therefore we distinguished two extreme conditions.

3.1. Stagnant loop flow (JET SEPARATION)

The stagnant loop flow condition is the limiting case for overcooling transient in a PWR since it gives the highest rate of overcooling. When the primary loop flow is at (or nearly at) a stagnant condition, the cold HPI water settles down to the bottom of the cold leg forming a stratified layer. For this process, we evaluated the temperature distribution of the fluid discussed in the report of B. K. H. Sun et al. [2], which is based on existing data from mixing tests at EPRI/CREARE and EPRI/SAI facilities. The most important governing parameters for the phenomena are the HPI jet Froude number and the Froude number for the cold leg channel.

3.2. Perfect mixing (MIXED JET)

The primary mass flow rate in the cold leg amounts to 20 kg/s. The temperature of the mixed flow near to the nozzle is determined by the ratio of loop flow to HPI flow. The evaluated mixed - mean temperature is 187 °C in good agreement with the measured value.

4. THERMAL BOUNDARY CONDITIONS

The effect of the HPI operation (detailed in sect. 2) is considered by convective boundary conditions in the finite element model for the transient heat transfer analysis. Thermal boundary conditions are approximated by uniform distribution over a face of a finite element.

The transient time interval was considered from the beginning to 2000 s. This time interval was divided into 10 (non-uniform) time steps. Proper time step selection to obtain oscillation-free temperature vs. time functions is provided by PEXFE-3D based on the theory and practice detailed in reference [3]. This method has become a part of the KTA Nuclear Safety Standard [4].

5. RESULTS OF THE FINITE ELEMENT ANALYSIS

5.1. Transient temperature distribution

The temperature distributions are shown in Fig.2.(Jet Separation) and Fig.3. (Mixed Jet).

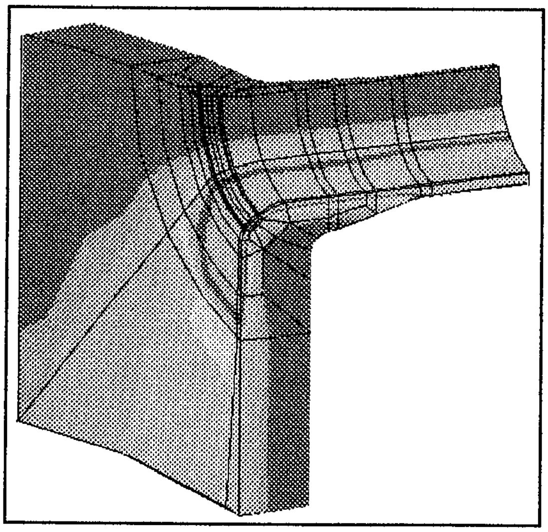


Fig.2. Temperature at time = 100 s.
Jet separation conditions.

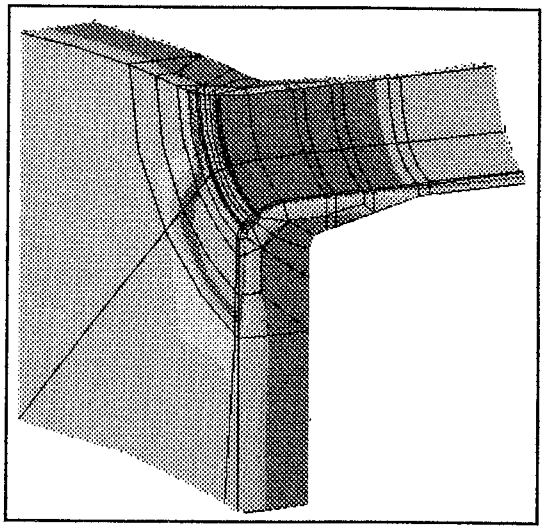


Fig. 3. Temperature at time = 100 s.
Mixed Jet conditions.

5.2. Stress and fracture analysis

5.2.1. Internal pressure load

Principal Stress 1 distribution under hydrostatic test conditions and the crack opening in case of the crack model **C** are shown in Fig. 4. and Fig.5. Computed Stress Intensity Factor is plotted in Fig.6.

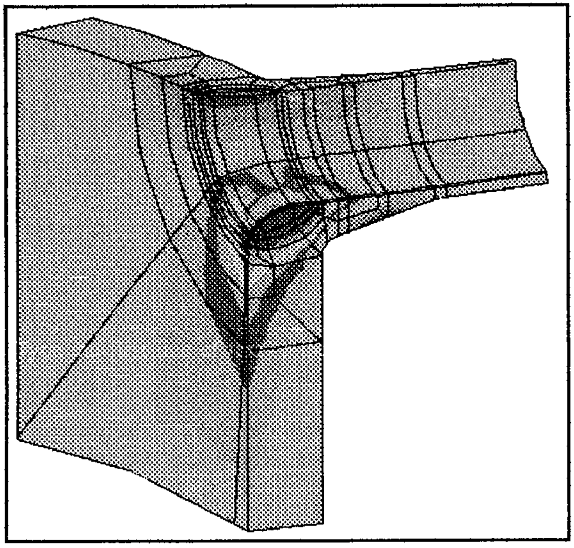


Fig. 4. Principal-1 stress contour plot.

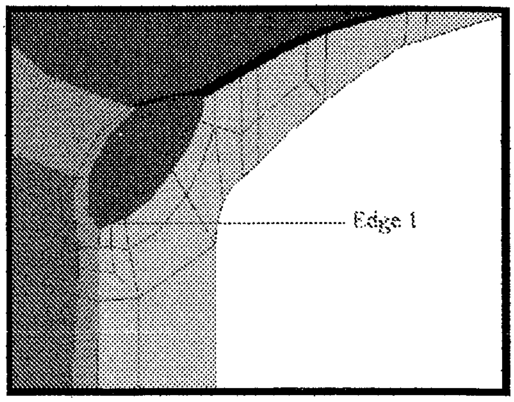


Fig.5. Crack opening displacement (magnified).

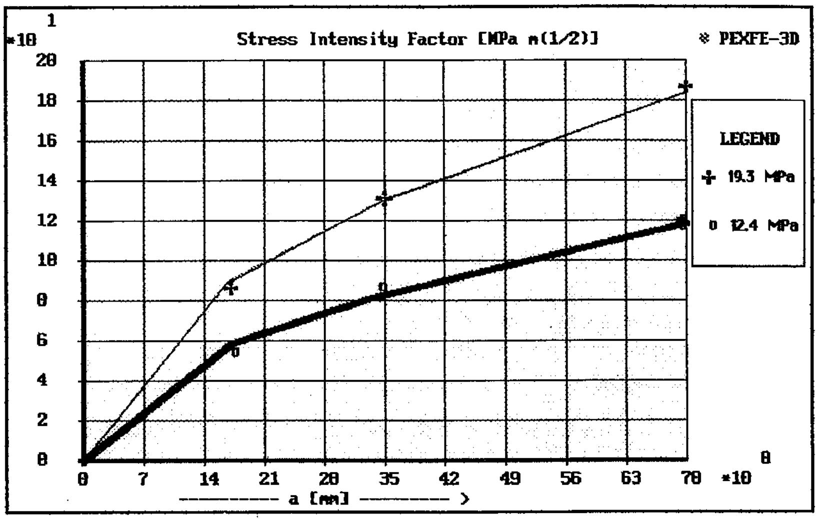


Fig. 6. Maximum Stress Intesity Factors vs. crack depth

Continuous lines in Fig. 6. denotes the following functions :

For normal operating pressure(12.4 MPa) load: $K_I = 450 \sqrt{a}$ [MPa $\sqrt{m}$]

For hydrostatic test pressure(19.3 MPa) load: $K_I = 700 \sqrt{a}$ [MPa $\sqrt{m}$]

where 'a' is the crack depth (see in Fig.1.).

These simple functions, being good approximations to the computed data, are used in the following.

5.2.2. Transient thermal stress load (due to HPI)

Thermal stress and fracture analysis were carried out at the end of each time steps. The maximum SIF values, occurred during the transient process, were determined. Results are summarized in Fig.7. PEXFE-3D indicated that the maximum percentage error in the computed SIF data were below 6 % both in space and time.

Comparing the SIF results for Jet *Separation* and *Mixed* Jet fluid flow models, small difference is visible. While thermal stress distribution due to Jet Separation has a local nature, the Mixed Jet causes smaller stresses but in a full circumferential range. The tangential stress has concentration effect on the cracked zone.

Continuous line in Fig. 7. denotes the following function :

For HPI thermal effect: KI = 260 √a [MPa √m]

where 'a' is the crack depth (Fig.1.). This simple function, as a good approximation to the computed data, is used in the following.

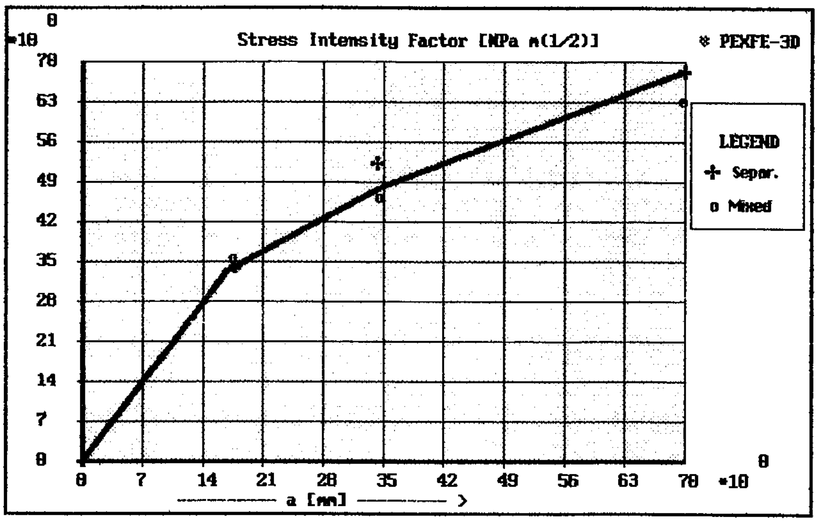


Fig. 7. Maximum SIF values vs. crack depth.

6. EVALUATION OF CRITICAL FLAW SIZES AND EXPECTED LIFETIME

6.1. Safety against brittle fracture

The safety factor against brittle fracture is defined as SF = K_{Ic} / K_I

The acceptance criteria against brittle fracture of *postulated* cracks in reactor vessels: SF ≥ 1. The fracture toughness K_{Ic} value is available from the rules of Interatomenergo. As the criteria is satisfied in all cases : CRT - TTKV ≥ 80 °C,

the fracture toughness is :

K_{Ic} = 200 MPa √m for emergency conditions.

To compare the different load conditions above, the safety factor is related to the same fracture toughness (200 MPa √m) in Fig. 8. Under hydrostatic pressure test condition or under the conditions (HPI operation + normal pressure) the safety factors are almost the same.

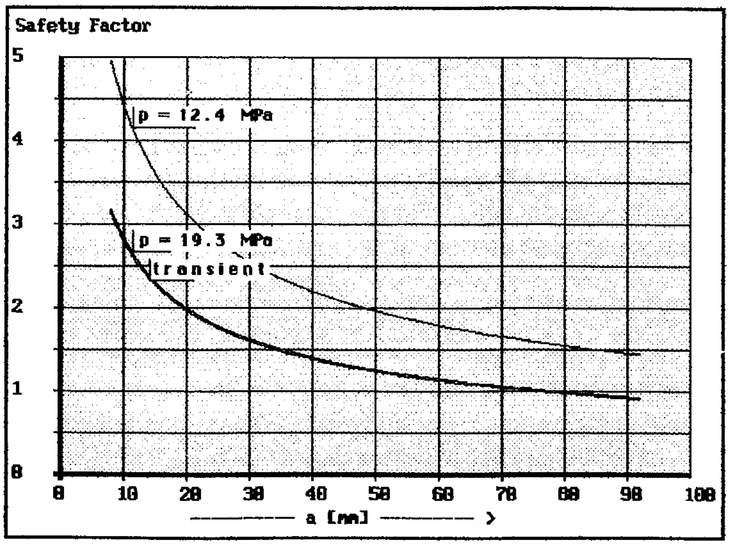


Fig. 8. Safety Factor against brittle fracture vs. crack depth.

6.2. Residual life estimation of detected nozzle cracks

The fatigue crack growth rate is approximated by the Paris-Erdogan form: $da/dn = C \; \Delta K^n$ [m/cycle], where the properties of the material 15H2MFA are obtained from Interatomenergo codes: $C= 5.8 \; 10^{-10}$ and $n = 2.66$, for cracks contacting reactor water. Subdivision follows the ASME XI. code.

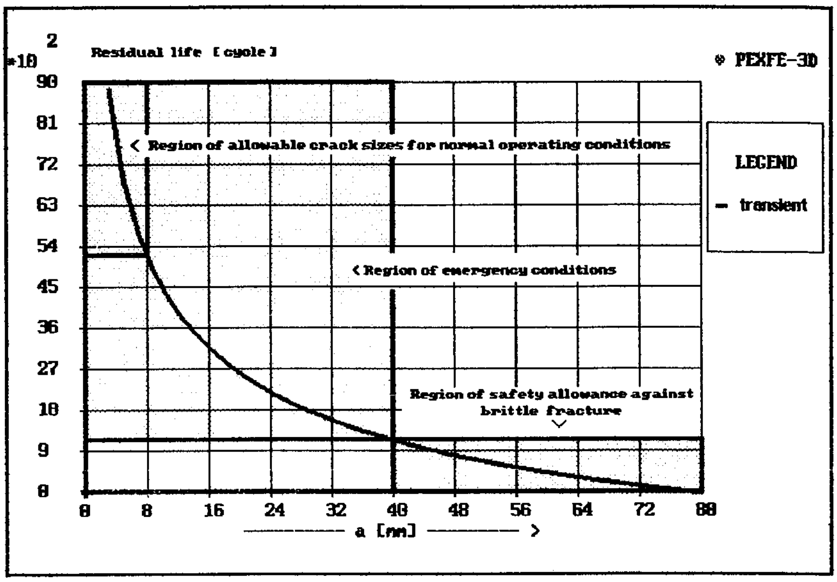


Fig. 9. Residual life versus crack depth. Load cycle: HPI operation

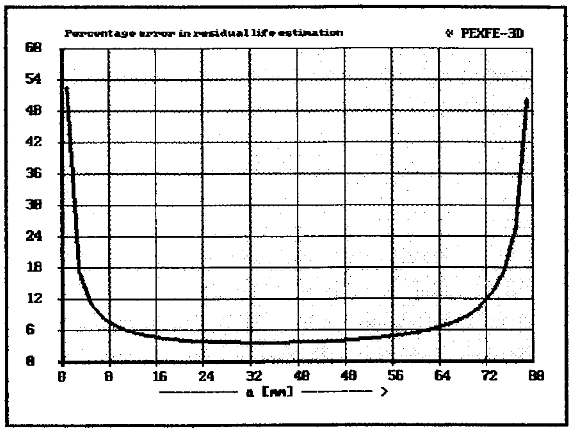


Fig. 10. Percentage error in residual life due to the error of 1 mm in the flaw size measurement vs. crack depth. End of life size of the crack is 79 mm in this sample.

CONCLUSIONS

i) Nozzle cracks at well detectable range of sizes can resist the cyclic loads. according to the rules of Interatomenergo and ASME XI. ii) The hydrostatic test pressure seems to be too high. A reduction to the factor 1.25 of the normal operating pressure were more reasonable. iii) Results of this analysis can serve the reliable safety evaluation of data obtained by ultrasonic flaw detection.

ACKNOWLEDGEMENTS

This paper is devoted in honour of Dr. F.Stelzer, KFA Jülich and Dr. P.Trampus, Paks NPP

REFERENCES

[1] Pammer, Z. (1992) *The p-version of the finite element method.* International Journal of Computer Applications in Technology. Special Issue on the Industrial use of Finite-element Analysis. Vol. 5. Nos. 2/3. pp 208-215

[2] Sun, B. K. H. et al.,(1984) *Transit Time of Mixed High Pressure Injection Water and Primary loop Water in Pressurized Water Reactor Cold Legs.* Nucl. Techn. Vol. 64.

[3] Pammer, Z.,(1980) *A mesh refinement method for transient heat conduction problems solved by finite elements.* Int. J. Num. Meth. in Engng., Vol. 15, pp 495-505.

[4] KTA Safety Standard 3413, Appendix B. Issue 6/89. Carl Heymanns Verlag KG, Köln.