CONSTRAINT EFFECTS OF SHALLOW FLAWS ASSUMED IN RPV UNDER ASYMMETRIC THERMO-MECHANICAL TRANSIENT LOADING

J. Sievers* and X. Liu*

With a detailed 3d-Finite Element (FE) model of a six loop RPV with assumed partly circumferential crack a thermo-mechanical loading transient due to a loss of coolant with high pressure injection characterized by an axisymmetric followed by an asymmetric strip like cooling period has been analyzed. For the fracture assessment based on the J-integral constraint evaluations have been taken into account and compared with experience from specimen calculations.

INTRODUCTION

In the integrity assessment of reactor pressure vessels (RPV) the emergency core cooling system injection is one of the main load cases to be analyzed. For safety assessment analysis methods based on Finite Elements and estimation schemes are applied. The used FE- analysis technique has been verified by several analyses of large scale thermal shock experiments , e.g. reference (1). The loading transient, which is investigated in this paper concerning the influence of constraint effects on fracture toughness, has been analyzed in a comparative manner by IVO Intern. (Finland), VTT (Finland) and GRS (see reference (2)). It has been shown that with different FE-programs and -meshes the crack loading can be calculated within a 10% scatter.

* Gesellschaft für Anlagen- und Reaktorsicherheit (GRS)mbh, Köln (Germany)

RPV BOUNDARY CONDITIONS AND LOADING

In this paper the loading of a cladded six loop VVER-440 RPV with assumed clad-through partly circumferential crack (15 mm deep, 50 mm long) in the circumferential weld near the core mid-height is investigated.The thermo-mechanical transient loading due to an assumed stuck-open pressurizer safety valve is based on thermohydraulic calculations done at IVO International Ltd. Finland. Mixing effects between the injected cold water and the water reservoir in the vessel have been taken into account. Figure 1 shows that in the first 25 min the fluid temperature in the RPV decreases from 257 to 127 °C without asymmetry, i. e. the RPV is loaded by axisymmetric cooling. After that a stagnation of the fluid circulation in the primary circuit takes place and an asymmetric strip like cooling of the RPV-wall with axial variation of the fluid temperature (T_1 -T_{15} in Figure 1) due to high pressure injection is assumed. As worst case conditions the pressure during the transient has been set constant at the level of opening pressure of pressurizer safety valve.

STRUCTURE ANALYSIS

Figure 2 shows the RPV-FE model generated with PATRAN (reference (3)) to calculate the temperature distribution in the structure, the deformation, stresses, strains and the J-integral for fracture assessment with the FE-programs ADINAT and ADINA (reference (4)). With the global model (about 45000 degrees of freedom) the boundary conditions for the detail model (about 30000 degrees of freedom) with partly circumferential crack (15 mm deep and 50 mm long) have been calculated . The 9 mm thick cladding is taken into account. In Table 1 the used material data of the base metal, the weld material and the cladding are summarized. They characterize an irradiated VVER-440 RPV (type 213) . In this calculation the weld material has the same material properties as the base metal. The calculated wall temperature distribution in the middle of the cooling strip at the position of the weld is presented in Figure 3 for different time steps during the loading transient described in the previous section. The temperature gradient in the cladding is much larger than in the base/weld material. Compared with PTS thermal shock experiments the temperature gradients are much smaller because the temperature of the cooling fluid changes in a much longer period here from 257 °C to 140 °C in about 17 min and to 70 °C in further 34 min (see Figure 1). The maximum crack mouth opening of 0.12 mm is reached after 30 min when the maximum difference between fluid temperature in the cooled strip and outside the strip at the position of the weld of only 7 °C is reached (see Figure 1: T_M - T_8) .

FRACTURE ANALYSIS

The crack loading is calculated based on the local J-integral due to virtual crack extension at different locations on the crack front. Figure 4 shows the time dependence of the J-integral at the deepest point of the crack (S1) and at some points on the crack front in the cladding, which show higher values. In each point on the crack front the largest value is reached after 30 min , i.e. about 4 min after start of the high pressure injection. At this time the temperature distribution in the wall (see Figure 3) has the strongest gradients at the different depths of the crack front. Then the crack loading decreases and goes into a warm prestress (WPS) state. For fracture assessment the diagram stress intensity factor K_I as function of crack tip temperature is usually used. The K_I -values are calculated from the J-integral with the plane strain relation

$$K_I = \sqrt{(JE/(1-\nu^2))} \qquad (1).$$

In the calculated load path curves of Figure 5 the temperatures of the different crack front points S1, S8 and S10 decrease with increasing transient time. The tendency of the crack to initiate is dependent on the fracture toughness. For demonstration a fracture toughness curve based on the Russian rules for a brittle to ductile transition temperature of 135 °C is given in the diagram. For fracture assessment the distance between toughness curve and load curve is representative. Thermal shock experiments show that a crack will not initiate in a period with decreasing crack loading (WPS-effect) , e. g. position S1 after 30 min when the crack tip temperature becomes lower than 130 °C.

CONSTRAINT EFFECTS

It is well known that the crack resistance and the fracture toughness especially in the transition region are not material constants but are dependent on the crack size and the stress state at the crack front , i. e. the loading. Therefore the fracture assessment can be improved by consideration of a parameter which describes the load and geometry dependence of the fracture toughness by representing the stress triaxiality and constraint on the ligament of a crack. Especially for thermal mechanical loading different parameters have been tested in reference (5) and it has been shown that the parameter Q proposed by O'Dowd and Shih (6) seems to be suitable. Q is the difference between the crack opening stress component calculated in the FE-vessel model and that of a reference state of stress . A plane strain small scale yielding (SSY) model as reference state gives best results because the stress-strain curve can be approximated as in the vessel calculation, while HRR[1] is based on a deformation plasticity material with Ramberg-Osgood approximation, which effects in our investigations that Q on the ligament shows stronger dependence on the distance from the crack tip, i.e. finding a representative Q- value becomes more

[1] HRR : Hutchinson, Rice, Rosengreen

difficult. Negative Q-values indicate increased fracture toughness relative to the reference state (Q=0).

Figure 6 shows the calculated loss of constraint due to shallow cracks in Three-Point-Bending specimens, which show an increase of the crack initiation value. Oscillations in Q due to numerical effects very close to the crack tip have been cut. The two ratios a/w = 0.18 and 0.51 of crack depth to specimen thickness have been investigated. In the load cases L20 and L18 crack initiation takes place together with strong plasticity and the constraint parameter shows much smaller values for the shallow crack. In load case L6 the plasticity is very limited and the loss of constraint is much smaller.

Figure 7 shows the Q- results of the partly circumferential crack (ratio of maximum crack depth to wall thickness: 0.10) in the RPV under thermal-mechanical transient loading as described in the previous sections for the transient time 30 min. The time dependence of the curves can be neglected. The low loading effects only small plasticity and therefore a little loss of constraint which is biggest at the deepest point of the crack (S1). Therefore only a very small increase of fracture toughness is expected in that special case. Furthermore the evaluated region of 4 mm on the ligament together with J-values lower than 20 N/mm shown in Figure 4 is equivalent to a region up to 250 in terms of the dimensionsless parameter $r/(J/\sigma_{0.2})$. It has to be proved in future calculations whether further mesh refinements in the vessel detail model which effect a better resolution in the region $r/(J/\sigma_{0.2})$ of about 2 to 5 proposed from specimen calculations are necessary and will change the conclusions.

CONCLUSION

Objective of this work was to apply a proposed analysis technique for the calculation of most accurate crack loading in a RPV as a basis for improved fracture assessment and not to perform a RPV-safety analysis . Therefore with a complex FE-model of a six loop VVER-440-RPV the structure mechanical loading due to a thermo-mechanical transient loading with mixing effects and strip like cooling has been analyzed. The transient due to a stuck-open pressurizer valve followed by a high pressure safety injection is based on thermal hydraulics calculations . The variations of the fluid temperature near the RPV-wall in axial and circumferential direction due to mixing effects in the RPV have been taken into account.

The accuracy of fracture assessment based on the J-integral can be increased if the dependence of fracture toughness and crack resistance on the stress triaxiality in the vicinity of the crack front can be taken into account. In the case of thermal-mechanical loading the constraint parameter Q proposed by O'Dowd and Shih (6) seems to be suitable to extend the J-integral based fracture assessment of cracks in components. Investigations on Three-Point-Bending specimens show that the loss of constraint of a shallow crack is correlated to the amount of plasticity. In the vessel calculation under thermal-mechanical transient loading the plasticity has been very limited and therefore the loss of constraint has been found to be very small. The RPV studies compared with fracture specimen calculations show that the constraint effects are strongly dependent on the loading and the crack geometry considered.

Further work has to be done to verify the J-Q concept by application to large scale thermal shock experiments and tests under controlled biaxial loading especially to develop a suitable procedure of evaluating a characteristic constraint value. By this the accuracy of fracture assessment for cracks in components can be improved.

ACKNOWLEDGMENT

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REFERENCES

(1) Sievers, J., Nuclear Eng. and Design Vol 130 , 1991, pp. 13-19

(2) Sievers, J., X. Liu, P. Rajamäki, H. Talja, H. Raiko, "Comparative analyses concerning integrity of a VVER-440 reactor pressure vessel", 19. MPA-Seminar, Stuttgart, October 1993, submitted to Nuclear Eng. and Design

(3) PATRAN Plus, User Manual, PDA Engineering Report PIN-2191001, 1989

(4) ADINA R&D, Inc., Reports ARD 92-5 and 92-8, 1992

(5) Sievers, J., and X. Liu, Transactions of the 12th SMiRT Conference, Elsevier, Vol. G, pp. 313-319 , submitted to Nuclear Eng. and Design

(6) O'Dowd, N. P., and C. F. Shih, J. Mech. and Physics of Solids, Vol. 39, No. 8, 1991, pp.989-1015

TABLE 1 - VVER 440 (Type 213) Material data of Base Metal (BM), Weld (W) and Cladding (CL), Heat Transfer Coefficients

Material		BM / W	CL	BM / W	CL
Temperature [° C]		20	20	325	325
λ	[N/(sK)]	40.2	15.1	37.9	18.8
α_{20}	[10^{-6}/K]	11.3	16.3	13.1	17.4
ρ*c	[N/(mm^2 K)]	3.92	3.6	3.92	4.18
E	[GPa]	210	205	195	180
ν		0.3	0.3	0.3	0.3
$R_{p0.2}$	[MPa]	625	426	555	326
E_T	[MPa]	8 682	876	8 682	676

with :

λ	Thermal Conductivity
α_{20}	Coefficient of Thermal Expansion
ρ*c	Specific Heat per unit volume
E	Elastic Modulus
ν	Poisson´s Ratio
$\sigma_{0.2} = R_{p0.2}$	Yield Stress
E_T	Hardening Modulus

Heat transfer coefficients:

2000 W/(m^2 K)	(inner surface out of the cooling strip)
2000 W/(m^2 K)	(inner surface in the cooling strip for t < 1550 s)
5000 W/(m^2 K)	(inner surface in the cooling strip for t > 1550 s)
8 W/(m^2 K)	(outer surface)

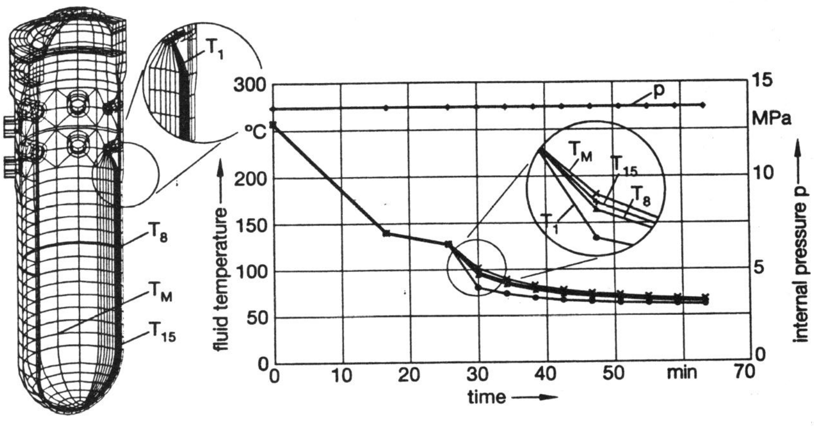


Figure 1 VVER 440-RPV, loading assumptions for intermediate loss of coolant due to a stuck-open pressurizer valve followed by high pressure injection

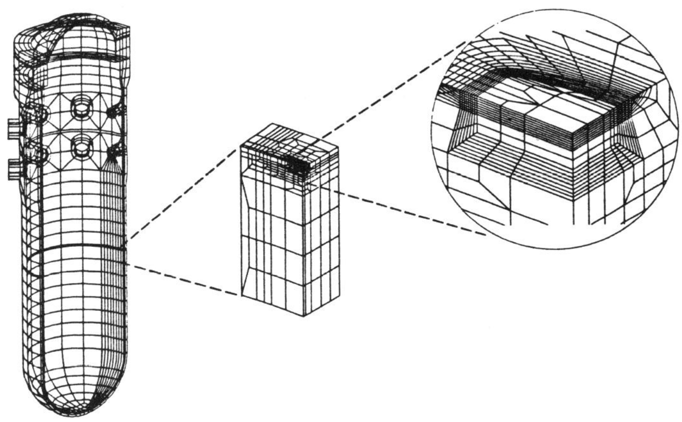


Figure 2 VVER 440-RPV, FE-Model (3D-180°) with one cooling strip and a detail model with partly circumferential crack (15 mm deep, 50 mm long)

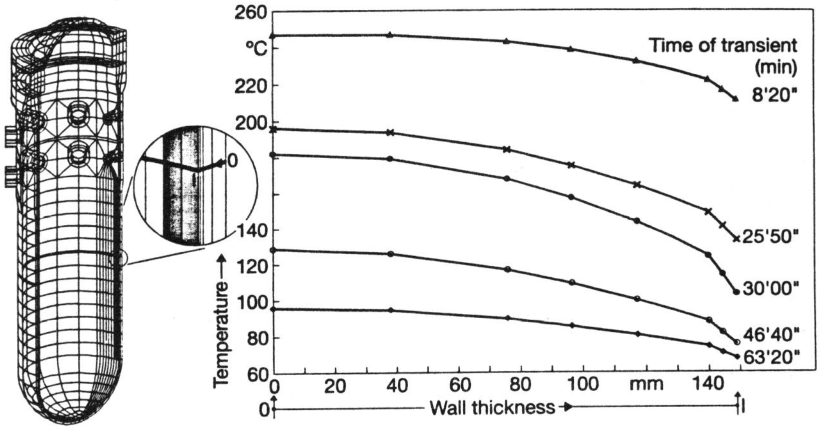


Figure 3 VVER 440-RPV, wall temperature distribution in the middle of the cooling strip at the position of the weld for loss of coolant transient with mixing

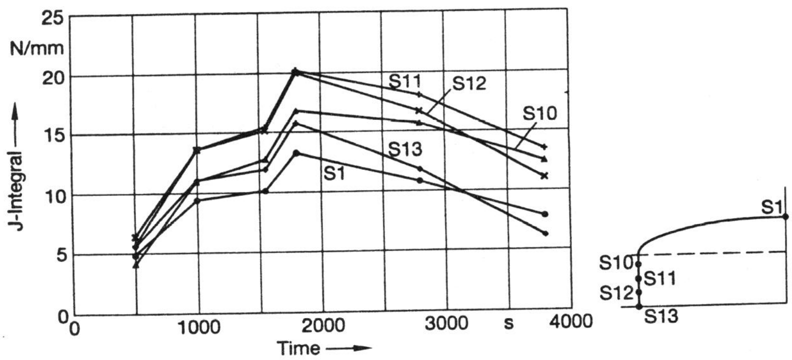


Figure 4 VVER 440-RPV, crack loading (local J-integral) of partly circumferential crack (15 mm deep, 50 mm long) for loss of coolant transient with mixing

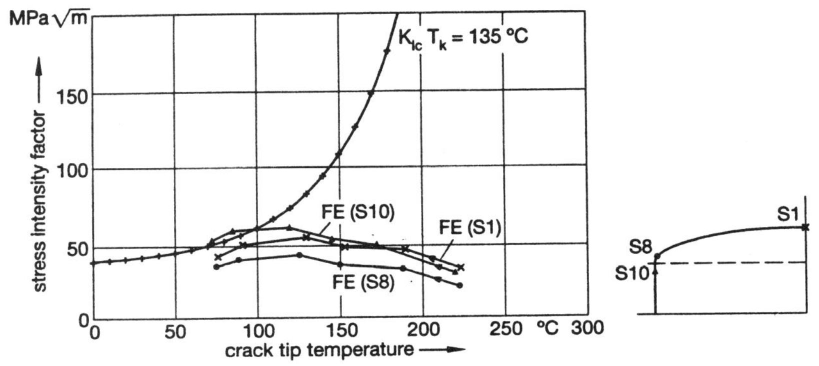
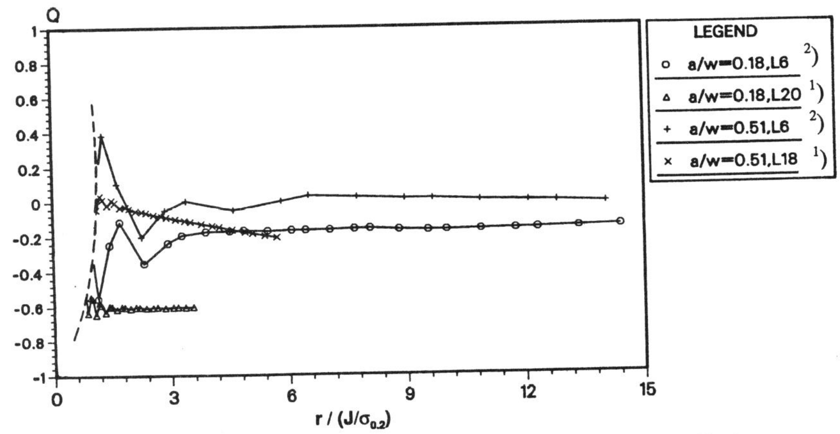


Figure 5 VVER 440-RPV, crack loading (stress intensity factor) of partly circumferential crack (15 mm deep, 50 mm long) for loss of coolant transient with mixing



[1]) crack initiation load with about 1.0 mm prescribed displacements

[2]) loadcase with 0.2 mm prescribed displacement

Figure 6 Three-Point-Bending-specimen with different crack depth ratio a/w , Constraint parameter Q on 1.2 mm of the ligament calculated from plane strain analysis

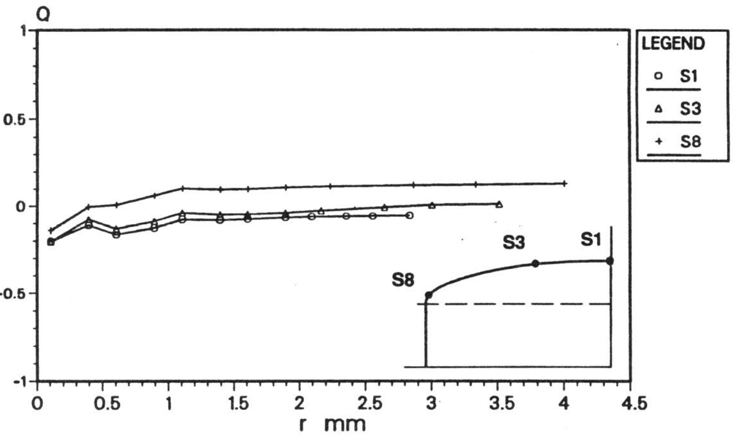


Figure 7 VVER 440-RPV with partly circumf. crack (15mm/50 mm depth/length), Constraint parameter Q on the ligament for different positions on the crack front