



## Parametric studies in the frame work of RPV integrity assessment

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### INTRODUCTION

Due to neutron irradiation, the reactor pressure vessel (RPV) especially the weldment near the core experiences an embrittlement which increases the brittle fracture transition temperature of the material and reduces the safety margin of the RPV against cleavage especially in case of thermo-mechanical loading due to emergency cooling transients. This issue is therefore relevant in the regulatory safety review of the plants in operation. To ensure the safe operation, fracture mechanics based integrity analysis of the RPV is applied to determine the crack loading which is then compared to the degraded toughness of the embrittled RPV material to assess the integrity of the vessel. According to the verification of the procedures fracture analyses of large scale experiments have been performed in the framework of an international comparative assessment study [1]. Furthermore fracture analyses of Western type RPVs as well as VVER type RPVs have been performed in the framework of studies concerning the integrity assessment [2, 3]. The loading of postulated cracks is affected by various parameters related to the thermo-mechanical loading assumption, the crack configuration, the material properties and the details of the analysis model. To identify as well as to quantify the influence of the key parameters, parametric studies have been carried out on VVER type RPVs loaded by emergency core cooling transients due to primary or secondary leaks. The 3D Finite Element (FE) Method has been applied to investigate the effects of changes in some input parameters on results of the integrity analysis.

First, the cooling width and the number of cooling stripes have been chosen as parameters to reflect asymmetric effect of the emergency core cooling process. Then, the 3D effects both on cooling conditions and crack configuration have been investigated. For simplicity, RPV integrity assessment is often performed by assuming axisymmetrical cooling and fully circumferential cracks in order to apply 2D axisymmetrical models for the analysis. Whether such conservative assumption of the crack ensures the conservative integrity assessment is to be investigated. To quantify the influence of plasticity, both thermo-elastic and thermo-plastic

material models have been applied to surface and underclad cracks. Furthermore, the crack loading of surface and underclad cracks have been compared.

## LOADING AND FE MODEL

A pressurized thermal shock (PTS) transient was chosen for the parametric studies, which was calculated by ATHLET [4] code under the assumptions that a leak DN50 occurs in the cold leg of a VVER 1000 plant and the emergency core cooling water of 55 °C is injected by two high pressure pumps. The fluid temperature inside the cooling region of the downcomer was assumed to be 55 °C after 165 sec. while outside the cooling region calculated values were taken (Figure 1). Mixing in the downcomer as well as the heating up of injection water before reaching the downcomer are not taken into account so the loading is considered as conservative. Internal pressure is also shown in Figure 1, which quickly drops from 16.8 MPa to 7.5 MPa within 165 sec. then goes further down to 2.0 MPa and stabilises at 2.4 MPa to the end of the transient. Heat transfer coefficient (htc) between fluid and RPV wall is demonstrated in Figure 2. A constant high htc value of 10 kW/(m<sup>2</sup>K) is taken within the cooling region and variable htc from 10 kW/(m<sup>2</sup>K) to 1 kW/(m<sup>2</sup>K) is applied outside cooling region.

Circumferential cracks are postulated in the weldment near the core of the VVER-1000 type RPV where the embrittlement is expected to be strongest due to neutron irradiation. The underclad crack is assumed as semi-elliptic shape of 6 mm in depth and 50 mm in length. The surface crack has the same configuration inside the weldment and a straight line through the 9 mm thick cladding is additionally assumed so that the crack size is  $a \times 2c = 15 \text{ mm} \times 50 \text{ mm}$ . The cylindrical part of the RPV below the crack has been modelled with the postulated crack. Due to symmetrical condition, only half of the cylinder in circumference (180°) has been taken into the FE model which consists of 1232 3D continuous elements and 6005 nodes. To count for the heat transfer between RPV wall and the fluid, additional 120 2-D convection elements were created on the innersurface of the vessel. In the crack front, the mid-nodes were placed in the half way position of the degenerated elements so that 1/r type of singularity has been achieved in the stress and strain fields. On the bottom plane of the cylindrical FE models, constraint equations were applied to keep all nodes on a movable plane during the entire transient.

## PARAMETRIC STUDIES

Numerical analyses have been carried out with the structure mechanics program chain of GRS based on the finite element program ADINA [5]. The local crack loadings in terms of J-integral were determined through virtual crack extension method [3] with consideration of thermal and pressure correction terms. Three virtual shifts at each crack front position were applied to check path independency. The FE determined J-integral values were then transformed to stress intensity factor  $K_I$  under the plane strain assumption for all crack front positions except the points near the inner surface. Parameters related to different aspects like cooling conditions, crack configurations, plasticity and so forth have been selected for the investigations. However, the scope of the parameters is limited and the PTS transient was fixed. Studies on large scope parameters are going on in the form of uncertainty and sensitivity analyses which take the advantage of statistical methods to quantitatively identify the influences of the parameters. The deterministic parametric studies yield basic knowledge and experience for the probabilistic uncertainty and sensitivity analyses.

#### - Influence of the cooling stripe width

Under one stripe cooling assumption, the cooling width is obviously a parameter which may effect the crack loading. To quantify the influence, cooling stripe width has been varied from 160 mm (4.4°) to 12981 mm (360°, axisymmetrical cooling). The stress intensity factor ( $K_I$ ) curves at the deepest point of the surface crack, where the local crack loading is the highest along the crack front, are shown in Figure 3 versus the crack tip temperatures. The maximal  $K_I$  value occurs after about 15 min in the transient in the case of a 950 mm wide stripe. However, insignificant change of crack loading is demonstrated for the stripe width from 400 mm to 2000 mm which is 8-40 times of the crack length. By the narrow cooling width 160 mm, 5% lower peak crack loading at deepest point is reached at 13 °C higher crack tip temperature. Substantial shift of crack loading path is displayed under axisymmetric cooling condition which decreases 15% maximal  $K_I$  value and increases almost 40 °C of crack tip temperature corresponding to the peak crack loading. Furthermore the peak value is reached already after about 7 min of the transient. The crack loading path is assessed by comparison with fracture toughness curves characterized by the critical brittle fracture temperature  $T_k$  according to Russian rules. The maximum allowable  $T_k$  value under axisymmetrical cooling is about 135 °C while for the 400-2000 mm wide stripe cooling it is 100 °C, if it is taken into account, that no cleavage occurs on a decreasing loading path. Therefore, a 35 °C shift of critical brittle fracture temperature can be resulted from cooling width assumption under the assumed transient and crack size.

#### - Influence of the number of cooling stripes

By an emergency core cooling injection different numbers of cold water stripes may appear in the downcomer of the RPV. To find the influence of the number of cooling stripes on the crack loading four cooling cases with 1,2,4 and 6 stripes have been postulated and applied to the FE models. All cooling stripes were assumed to have the same cooling conditions, the same width of 400 mm and being evenly located in the circumference of the RPV. The case of 6 cooling stripes is fictive for VVER-1000 but possible in VVER-440. The FE determined crack loading versus crack tip temperature diagram is shown in Figure 4. The  $K_I$  paths coincide together at the beginning of the transient then differ from each other slightly with elevation of crack loading as the number of the cooling stripes decreases. The maximal stress intensity factor values only change a small amount of about 5%. In terms of critical  $T_k$  value, the difference is assessed as about 10 °C.

#### - Influence of 3-D effects

To limit the calculation effort, fracture analysis of RPV under PTS loading is often performed under the simplified axisymmetrical cooling and fully circumferential crack assumptions so that a two dimensional axisymmetric model can be applied to the analysis. By such simplifications it needs to be investigated whether the analysis is conservative compared to a realistic 3D model with stripe cooling and semi-elliptic circumferential crack. To resolve this issue, two axisymmetrical cooling models with fully circumferential crack (15 mm deep, model 1) and semi-elliptic crack ( $a \times 2c = 15 \text{ mm} \times 50 \text{ mm}$ , model 2) have been calculated. Additionally as a stripe cooling model (model 3) with 400 mm cooling width and the same semi-elliptic crack as model 2 has been analyzed. By comparing model 1 and model 2 (Figure 5), it can be seen that the maximal crack loading of the fully circumferential crack is about 40% bigger than that of

the semi-elliptic crack. Hence the two dimensional model is conservative under axisymmetrical cooling conditions. When model 2 and model 3 are compared together, it is obvious that stripe cooling not only enhances the crack loading but also shifts the maximal value to a lower crack tip temperature. The contraction of the cooling stripe area of the RPV is restricted by the less cooled rest region, which enhances the crack loading as well as keeps it at high values for a longer time period. From the  $K_I$ -T diagram, the critical  $T_K$  value of model 3 is estimated as about 100 °C while the models 1 and 2 show  $T_K=110$  °C and 135 °C respectively. Therefore, a 2D model with axisymmetrical cooling and conservative 360° crack assumptions does not ensure the conservative assessment although the crack loading is enhanced. The 3D model with stripe cooling and semi-elliptic surface crack shows the critical loading path.

#### - Influence of plastification

In many simplified methods, the formulas for the evaluation of stresses as well as the crack loading are based on the assumption of the elastic material behaviour. Under pressurized thermal shock load, the RPV generally demonstrates some plastification especially in the cladding and the vicinity of the front of postulated cracks. Therefore, it is necessary to evaluate the influence of the plastification to the crack loading in order to assess the validity of the simplified method. Two cases with semi-elliptic surface as well as underclad crack have been calculated with thermo-elastic and thermo-elasto-plastic material models respectively. The local stress intensity factor values at deepest point are demonstrated in Figure 6. For the surface crack, elastic analysis overestimates the crack loading by about 15% at the peak loading. The high cladding stress in the elastic analysis, which is limited to much lower level in the plastic analysis due to the low yield stress of the austenitic cladding, contributes to the overestimation. On the contrary, the crack driving forces for the underclad crack are underestimated by the elastic material model. Plastification in the cladding increases the crack mouth opening so that the crack loading is also enhanced compared with the elastic assessment.

#### - Influence of crack form

In Figure 7, the crack loading paths of both the clad-through and the underclad crack are displayed with toughness curves. The surface and the underclad crack have the same configuration in the weldment and differ from each other only concerning the integrity of the cladding. The local stress intensity factor curves at deepest point as well as near cladding position show the similar behaviour for both cracks. However, the absolute  $K_I$  values of the surface crack are much higher than those of the underclad crack. At the deepest point more than doubled maximal  $K_I$  is demonstrated in the surface crack and tripled crack loading is shown in the near cladding position S6. Hence, when cladding integrity can be ensured, the crack loading may substantially be decreased so that the safety margins against brittle fracture can be significantly enhanced.

## CONCLUSION

Parametric studies have been carried out with 3D FE-models including postulated cracks of a VVER-1000 type RPV loaded with a partly simplified pressurized thermal shock transient due to an assumed leak DN50 in a cold leg. The crack loading has been demonstrated insensitive to the cooling width assumption in the range of 400 to 2000 mm, but significant lower crack loading has also been shown if the width is assumed smaller or bigger. The one cooling stripe

case has yielded the highest crack loading, but no substantial change has been demonstrated in the analysis for different numbers of cooling stripes with 400 mm width. An axisymmetrical cooling with fully circumferential crack gives higher crack loading compared to a semi-elliptical crack of the same depth. However, stripe cooling with semi-elliptical crack is the more critical case because the peak crack loading is reached at later time and lower crack tip temperature. Besides, consideration of plastification may substantially change the local crack loading. By an elastic approach the stress intensity factor can be significantly overestimated in case of a surface crack but underestimated in case of an underclad crack. Furthermore, the assumption on the crack form largely varies the crack loadings which show much enhanced values in the surface crack compared with those of the underclad crack. Therefore, the integrity of the cladding can be beneficial to increase the safety margins against brittle fracture.

In order to obtain a comprehensive survey of the sensitivity and uncertainty in the integrity assessment of RPVs, the parameters, which characterize an analysis, should be considered as stochastic variables. Based on the sampled value sets of parameters, deterministic fracture analyses are carried out. Then, the uncertainty of the integrity analysis can be directly estimated. The sensitivity of the analysis to the input parameters can be evaluated quantitatively through correlation coefficients. The main uncertainty sources can be identified. Therefore, further improvement on the different steps of the RPV integrity approach can be guided to the issues which have demonstrated high sensitivities. This work is going on in GRS.

#### ACKNOWLEDGEMENT

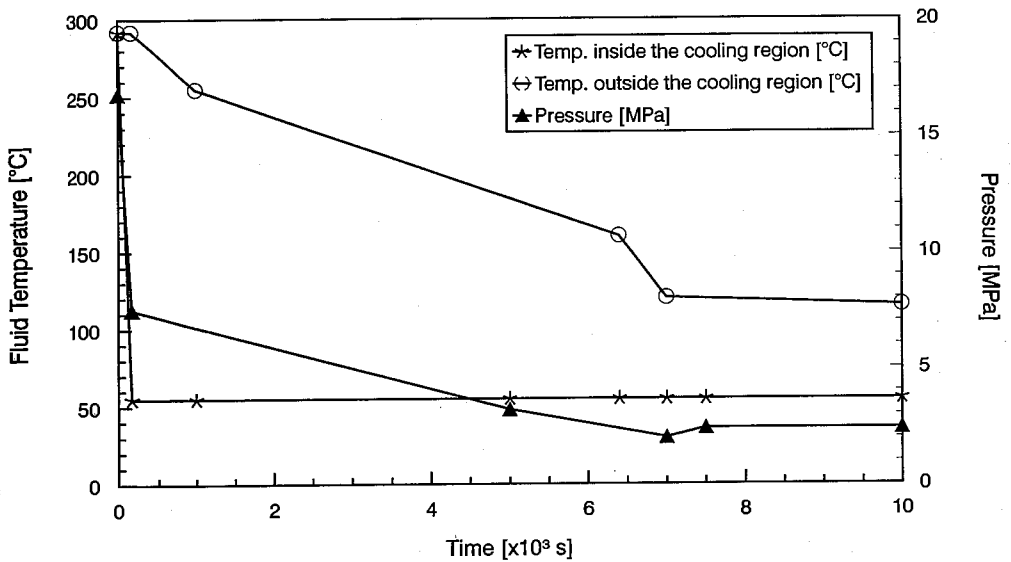
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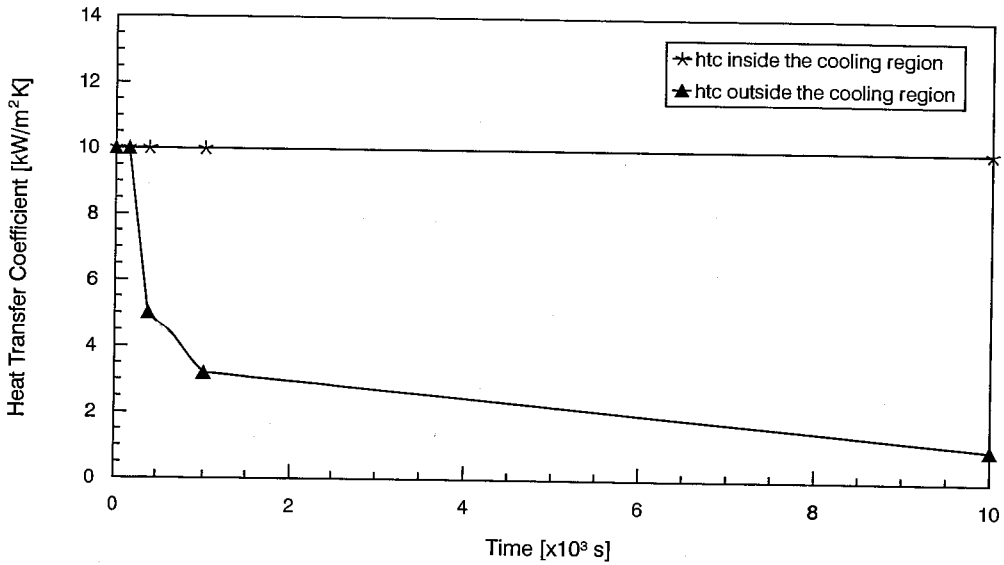
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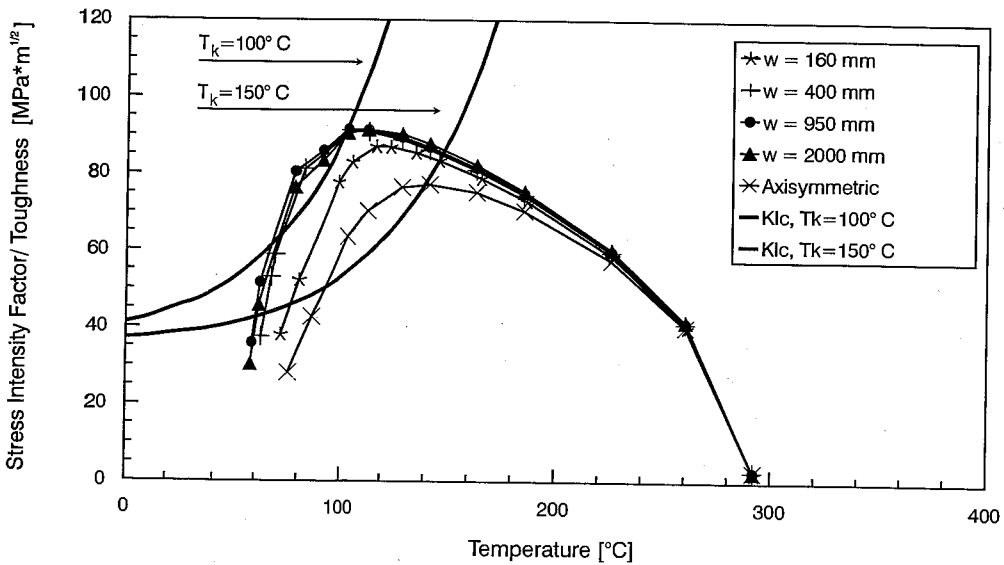
FIGURES



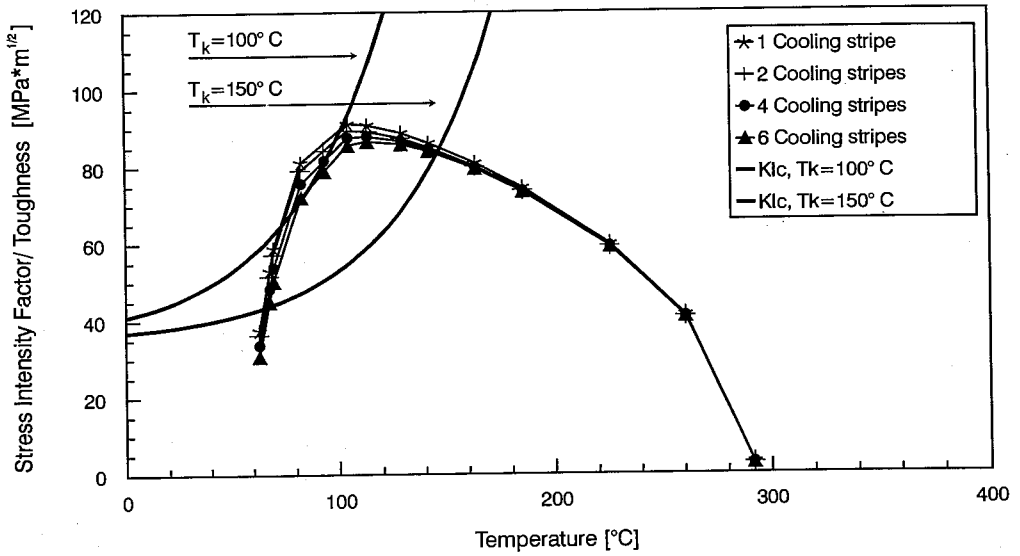
**Figure 1:** Fluid temperature and pressure in the RPV downcomer due to the emergency core cooling transient "Station blackout and leak DN50 in a cold leg of a VVER 1000 plant"



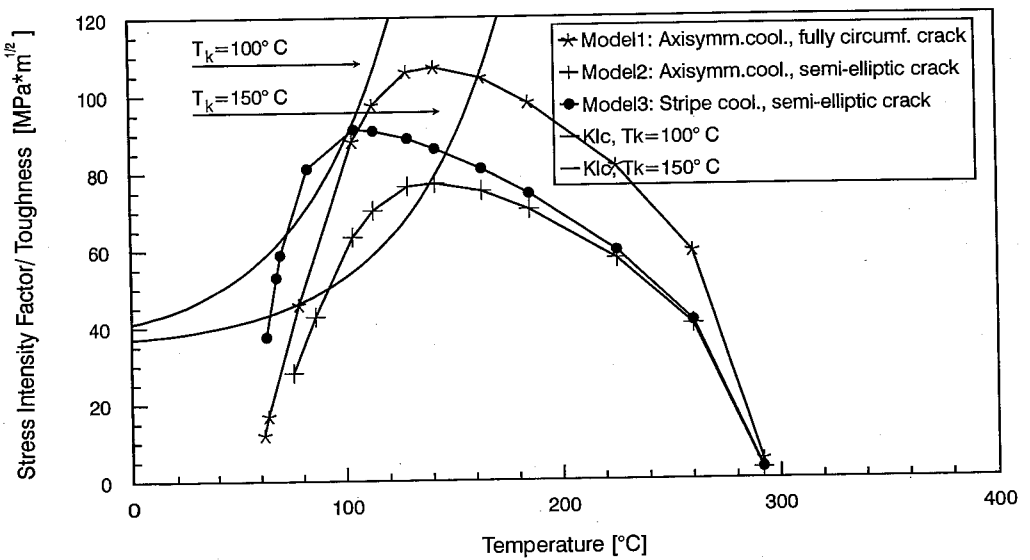
**Figure 2:** Heat transfer coefficient in the RPV downcomer due to emergency core cooling transient "Station blackout and leak DN50 in a cold leg of a VVER 1000 plant"



**Figure 3:** RPV-VVER1000, fracture assessment of the deepest point of a surface crack (depth 15 mm, length 50 mm), variation of the width(w) of the assumed cooling stripe

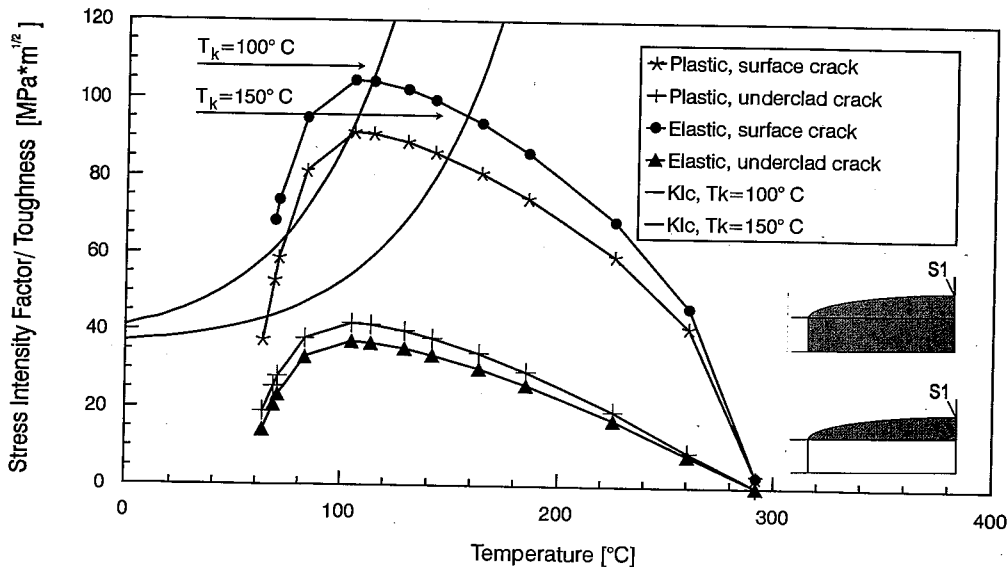


**Figure 4:** RPV-VVER1000, fracture assessment of the deepest point of a surface crack (depth 15 mm, length 50 mm), variation of the number of cooling stripes

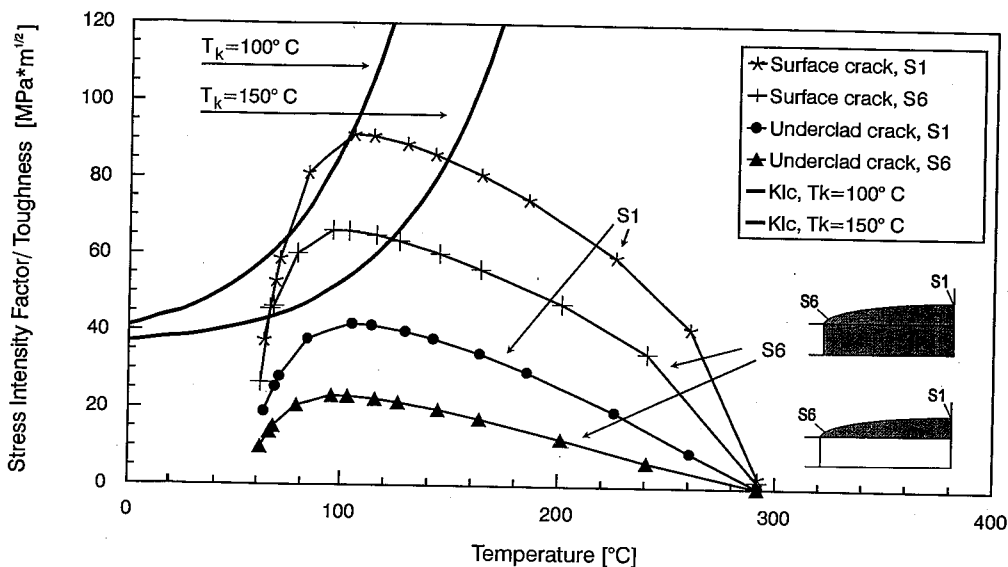


**Figure 5:** RPV-VVER1000, fracture assessment of the deepest point of a semi-elliptic and a fully circumferential surface crack under axisymmetric or stripe cooling





**Figure 6:** RPV-VVER1000, fracture assessment of the deepest points of a surface crack (depth 15 mm, length 50 mm) and an underclad crack (depth 6 mm, length 50 mm) by elastic and elasto-plastic analyses



**Figure 7:** RPV-VVER1000, fracture assessment of a surface crack (depth 15 mm, length 50 mm) and an underclad crack (depth 6 mm, length 50 mm)

