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TECHNICAL REPORT

SKB

Evaluation of residual stress measurements. Effect of measured residual stresses on damage tolerance of cast iron PWR- and BWR-inserts

Report No.: 50018390-1

Revision No.: 2

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Inspecta

TECHNICAL REPORT

Report No.: 50018390-1 Revision No.: 2

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Approved by	**Organizational unit**
Annika Haglund	Inspecta Technology AB
Customer	**Customer reference**
SKB	Mikael Jonsson

Summary

SKB has commissioned Inspecta Technology AB to perform an assessment of residual stress measurements in PWR- and BWR-inserts. The aim with this assessment is to investigate the residual stress distribution measured at different locations and determine a typical (representative) residual stress profile for locations where the damage tolerance analyses for postulated cracks have previously been conducted [1]. The effect of measured residual stresses on the results from these damage tolerance analyses, for the isostatic load case, is also evaluated in this report.

The conclusion, from the damage tolerance analysis of the isostatic load case, is that including the residual stresses has no influence on the calculated acceptable defect sizes (both for BWR- and PWR-inserts).

Report title	Subject Group
Evaluation of residual stress measurements. Effect of residual stresses on damage tolerance of cast iron PWR- and BWR-inserts	
	Index terms
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Table of content ***Page***

1 INTRODUCTION

SKB has commissioned Inspecta Technology AB to perform an assessment of residual stress measurements in PWR- and BWR-inserts. The aim with this assessment is to investigate the residual stress distribution measured at different locations and determine a typical (representative) residual stress profile for locations where the damage tolerance analyses for postulated cracks have previously been conducted [1]. The effect of measured residual stresses on the results from these damage tolerance analyses is also evaluated in this report.

2 SUMMARY OF PERFORMED MEASUREMENTS

Residual stress measurements were performed by two companies, namely VEQTER Ltd (UK) and SP Technical Research Institute (Sweden). Both companies have measured residual stresses in PWR- and BWR-inserts. Two different techniques were used for measurements; the Deep-Hole Drilling (DHD) and the Incremental Centre-Hole Drilling (ICHD). VEQTER has used both techniques whereas SP performed measurements with ICHD only. All residual stress measurements are summarised in Table 2.1.

Table 2.1: Summary of residual stress measurements per PWR- and BWR-insert.

Measurement method	BWR inserts			PWR inserts	
	I63 [2]	I54 [5]	I56 [3]	IP25 [4]	IP8 [5]
ICHD	-	27 pos.	9 pos.	2 pos.	26 pos.
DHD	5 pos.	-	-	3 pos.	-

3 REVIEW OF MEASUREMENT TECHNIQUES

Residual stress measurement techniques are generally categorized as non-destructive, semi-invasive and fully destructive methods. Most of the non-destructive methods such as conventional X-ray and magnetic techniques are restricted to near surface measurements except for the neutron diffraction method penetrating up to depths of about 50 mm. Fully destructive methods such as layering or slotting techniques can measure through thickness residual stresses in a component, but as the name suggests the component is completely destroyed [6].

Semi-invasive methods imply that a component is locally “invaded” by removing a small amount of material to release stresses and hence disturb the state of residual stress equilibrium. However, the overall structural integrity of a component remains intact for further testing, repair and/or use. Two semi-invasive methods were used for the residual stress measurements in PWR- and BWR-inserts; the ICHD method providing near surface measurements up to depths of about 1mm and the DHD providing through-depth measurements to depths in excess of 750 mm. A short description of these methods is presented below.

3.1 Short description of the ICHD technique

The ICHD residual stress measurement technique is a semi-invasive, mechanical strain relief (MSR) technique (i.e. the strain of the component is measured during stress relief from the removal of a small amount of material). The ICHD procedure involves drilling a small hole into the surface of the component at the centre of a strain gauge rosette and measuring the relieved strains. A strain gauge rosette is bonded to the specimen with gauge elements aligned in the hoop, axial and in-plane shear directions.

Drilling is performed by a drilling rig equipped with a computer-controlled 3-axis motor and a microscope for exact alignment of the drill tip in the centre of the strain gauge and establishment of zero depth, see Figure 3.1. Drilling is performed in increments of about 12-16 µm down to final depths of 1-1.9 mm. Between each increment, the strains measured by all three elements of the strain gauge rosette are recorded by the controlling computer. Finally, the residual stresses are calculated from the recorded strains using the Integral Method (both VEQTER and SP used this method).

The ICHD technique is prone to many sources of uncertainty, e.g. surface condition and preparation (may affect proper bonding of a strain gauge), drilling factors (drill tip shape and condition, depth control and diameter measurements) and material properties (stresses are related to strains through the material elastic constants). The VEQTER report [4] demonstrates an awareness of these sources of uncertainty and also provides a quantitative assessment of measurement errors. The SP report [3] provides guidance that for residual stresses lower than 50% of R_p (i.e. the yield strength) the errors are small (within 2-5%), for residual stresses of 50-70% of R_p the errors are ±10%. For higher residual stresses the error is difficult to quantify [3].

It is important to underline that the ICHD technique is capable and suitable for measurements of residual stresses within 1 mm depth from the surface.

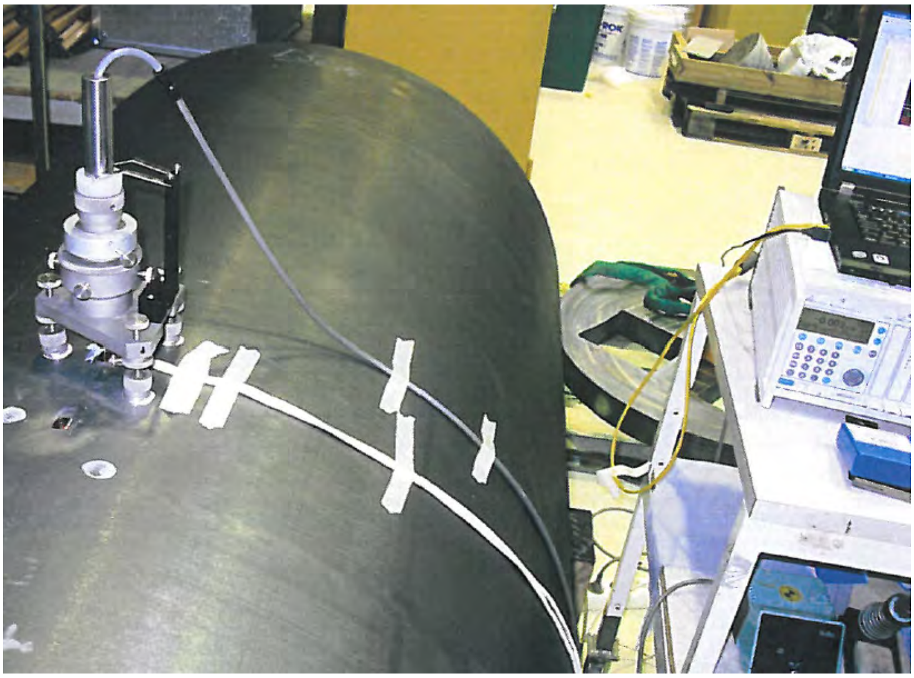


Figure 3.1: The ICHD measurement of residual stresses.

3.2 Short description of the DHD technique

The DHD residual stress measurement technique is also a semi-invasive, MSR technique. The procedure used for the DHD technique can be divided into 5 stages [5], as schematically shown in Figure 3.2 for a simple welded component:

1. Reference bushes are attached to the front and back surfaces of the component at the measurement location.
2. A reference hole is gun-drilled through the component and reference bushes.
3. The diameter, $Ø_0$, of the reference hole is measured through the entire thickness of the component and reference bushes using an air-probe. Diameter measurements are taken at 0.2mm increments in depth and at 22.5º increments in angle about the axis of the reference hole.

4. A cylinder (i.e. core) of material, containing the reference hole along its axis is cut from the component using electro-discharge machining (EDM).
5. The diameter, Ø, of the reference hole is re-measured through the entire thickness of the cylinder and reference bushes. Diameter measurements are taken at the same locations as those measured in Stage 3.

The diameter, $Ø_0$, of the reference hole measured in Stage 3 is the diameter when stresses are present. During Stage 4 the stresses are relieved, hence the diameter, Ø, of the reference hole measured in Stage 5 is the diameter when stresses are not present. The differences between the measured diameters in Stages 3 and 5 enable the original residual stresses to be calculated.

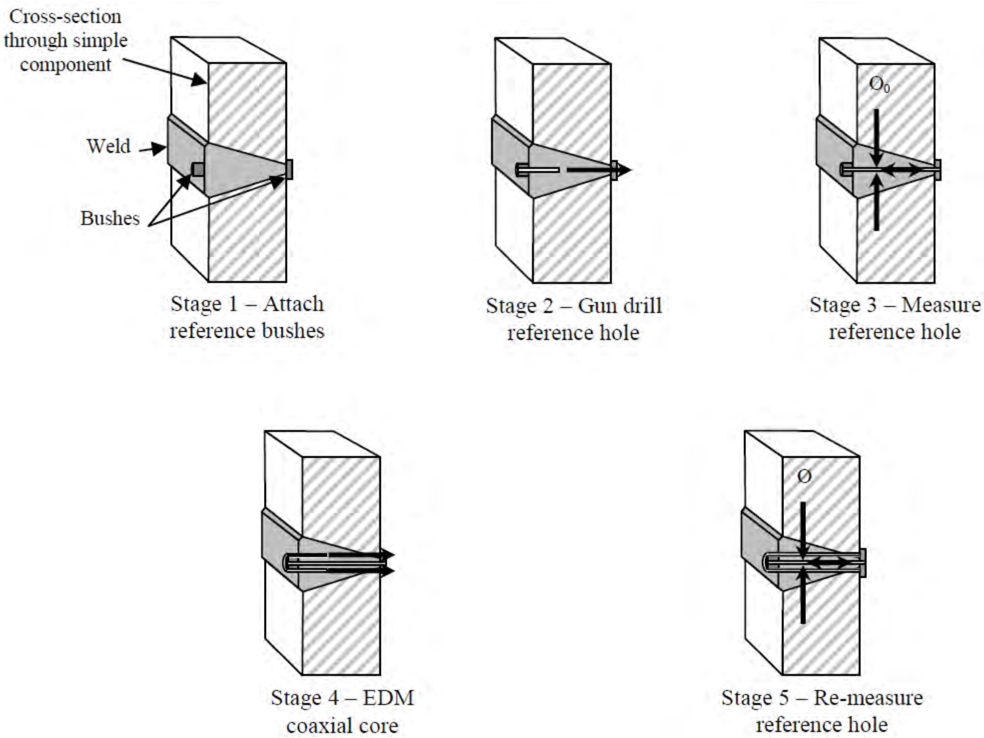


Figure 3.2: The DHD measurement of residual stresses.

Because the technique measures diameters at Stage 3 and Stage 5 through the thickness of the specimen, a stress profile can be generated without the need for material's elastic constants as with the ICHD technique. Therefore the measurement accuracy is independent of depth and specimen thickness.

Although the DHD technique is indifferent to the surface finish of the component, there are surface phenomena that affect the accuracy of shallow measurements, or measurements near a free surface. The overall accuracy of the DHD technique is assessed to be ±30 MPa assuming isotropic material properties and presence of residual stresses <60% of R_p. However, this accuracy cannot be assured for residual stresses at depth of 1 mm from a surface [2].

In general, the DHD technique is suitable and capable of residual stress measurement through the entire cross-section of a component, except for the near surface regions.

4 REVIEW OF RESIDUAL STRESS MEASUREMENTS

4.1 Residual stresses in BWR-inserts

4.1.1 BWR-insert I63

The bi-axial residual stress measurements were performed by VEQTER Ltd using the DHD technique on a section of the I63 insert measuring 960 mm in diameter and 980 mm in length. The section was cut from about 1310-2290 mm from the bottom and thereby represents a middle part of the insert [2].

Residual stresses were measured in 5 locations, all drilled from the circumferential surface inward towards the insert axis, see Figure 4.1. The locations DHD1, DHD2 and DHD3 were drilled radially towards the insert axis allowing the measurement of true axial and hoop stresses. The locations DHD4 and DHD5 were not drilled radially inwards and the measurements gave the axial residual stresses as well as a combination of the hoop and radial stress directions, which were referred to as 'hoop' stresses.

The measured stress profiles from the 5 prescribed locations showed similar results where the locations are comparable. The axial and hoop residual stresses were shown to be very similar at all locations, except for the DHD5 measurement. For the DHD5 measurement, the hoop stresses were tensile and distinctly higher than the axial stress. The tensile stresses in hoop direction in the DHD5 location demonstrated a uniform profile with slight increase towards the steel channel tube in the centre of the I63 insert. Similar local peak in tensile hoop stresses (about 25 MPa) was even observed for the DHD3 measurement at the distance of about 270 mm from the surface. These features of measured residual stresses are marked in green colour in Figure 4.1. It can be observed that both indications of higher tensile hoop stresses are located at about the same distance from the surface, in the nodular cast iron between the outer and inner steel tubes. The residual stress profiles for the DHD3 and DHD5 locations are presented in Figure 4.2.

In general, all measured residual stresses were within a nominal accuracy of approximately ±30MPa. Therefore, VEQTER makes the following judgement which appear to be reasonable: "…*Based on this error bound, many of the 'features' in the residual stress profiles were considered to be measurement fluctuations and were not necessarily due to a changing stress field, but more likely a result of the errors and inaccuracies of the measurement technique*" [2].

Within 1-2 mm distance from the surface all measurements demonstrated the compressive stresses, except for the DHD1 measurement. For this location, the maximum tensile stress levels in the nodular cast iron for both the axial and hoop directions were 58 MPa and 57 MPa respectively, both found at approximately 2 mm from the surface.

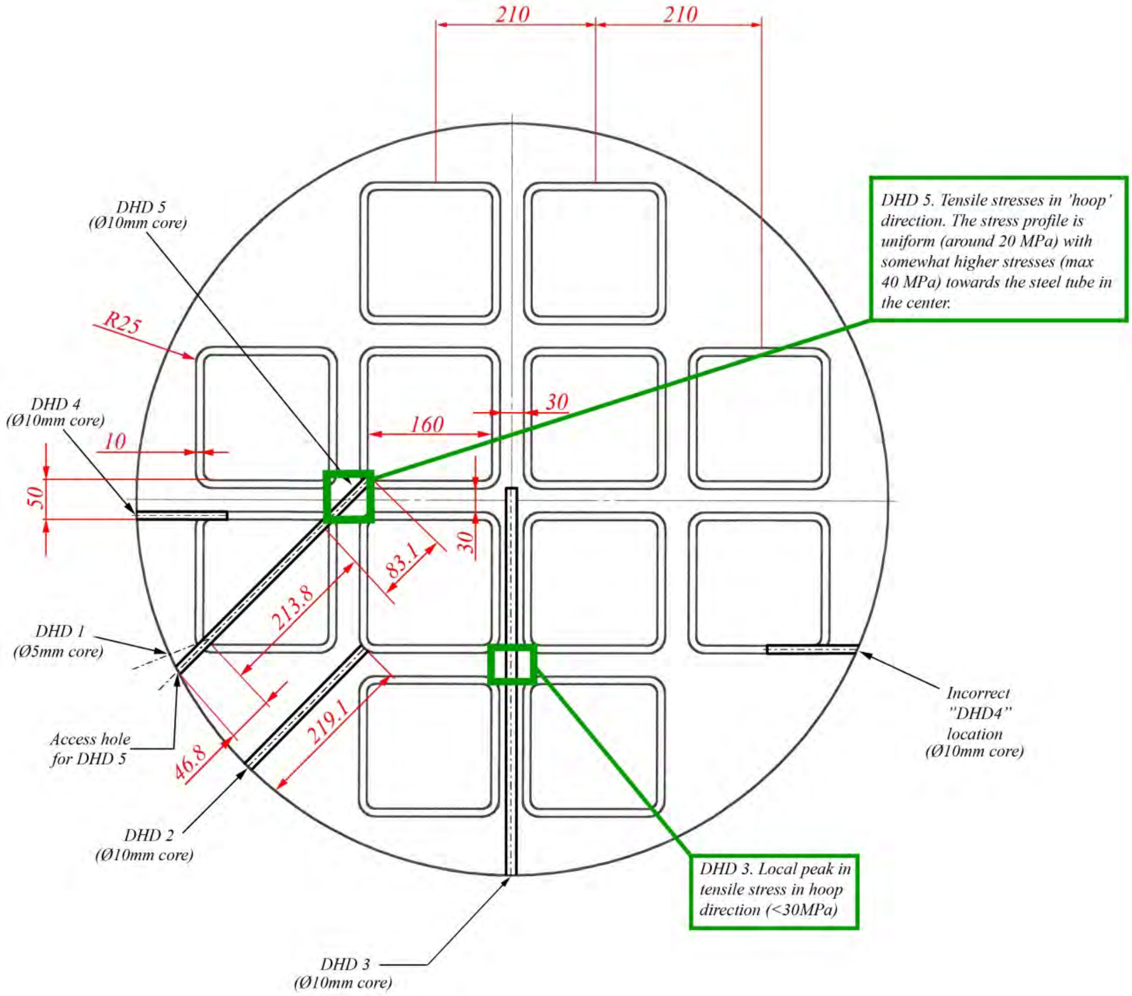
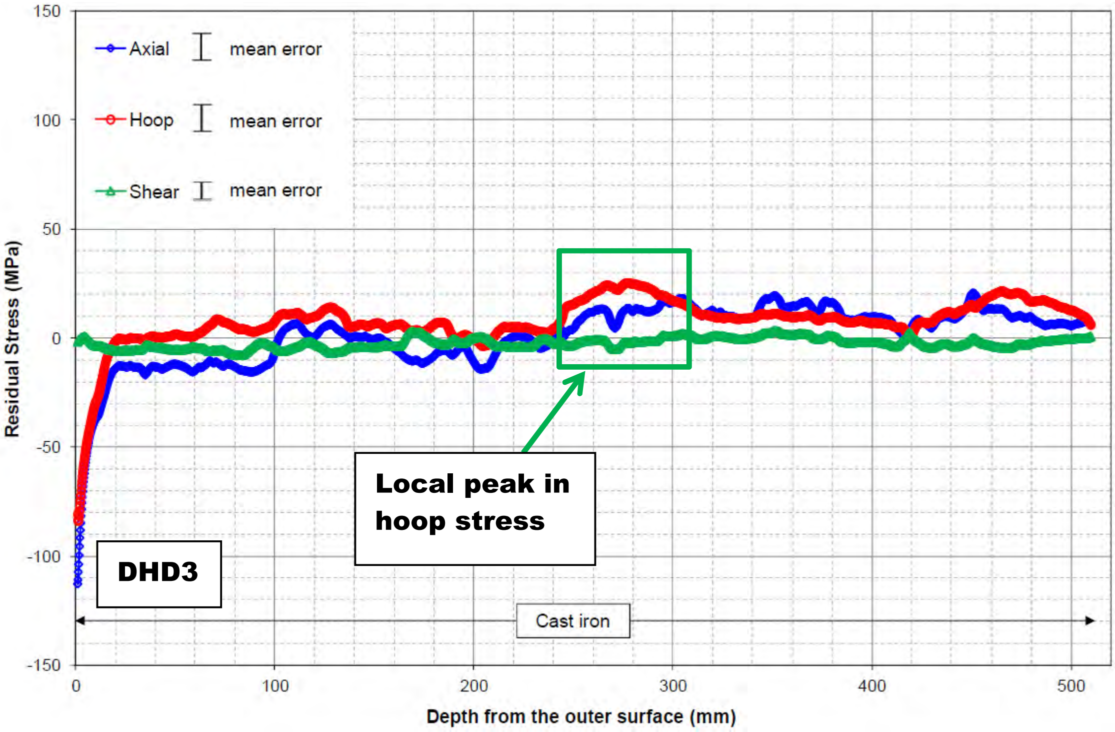


Figure 4.1: DHD measurement locations in the BWR I63 insert.



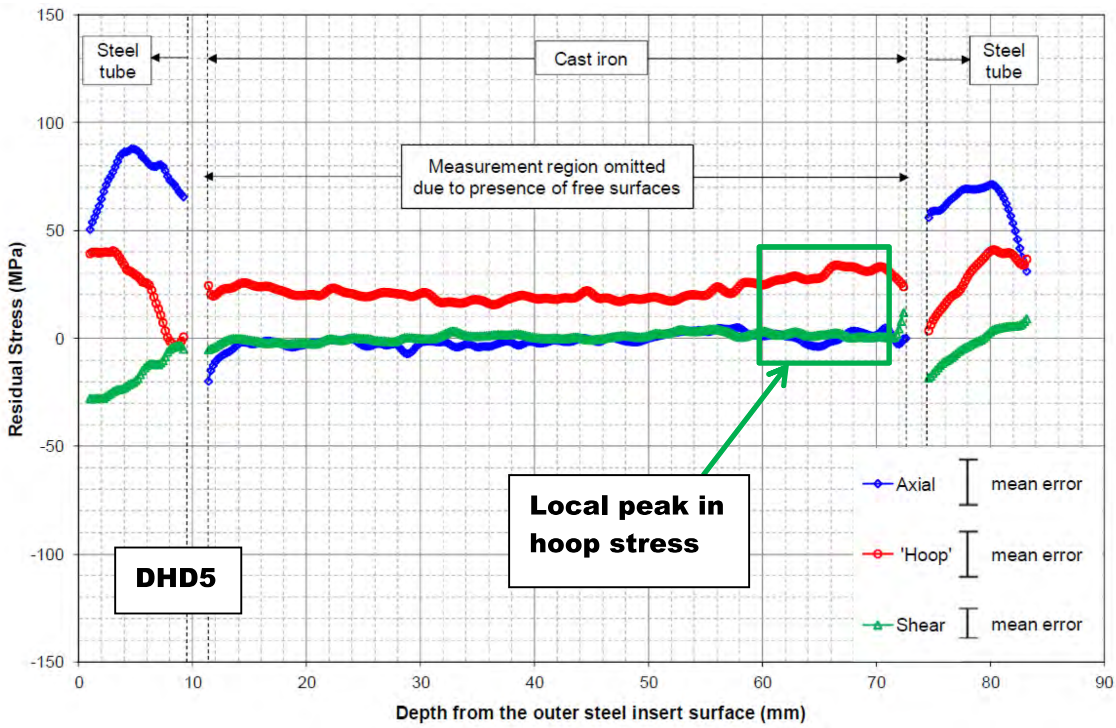


Figure 4.2: The residual stress profiles from the DHD3 and DHD5 measurements.

4.1.2 BWR-insert I54

The bi-axial residual stress measurements were performed by SP using the ICHD technique. The test object was a 75 mm thick section of the BWR I54 insert of 950 mm in diameter [5]. It remains unclear from the SP report [5] from which position along the insert axis the provided section was cut.

In-plane residual stresses were measured on both sides of the insert section (the front side and the back side) as shown in Figure 4.3. In the front side the measurements were performed at two reference locations marked as R1 and R2 and at 6 locations along the shortest ligament between the circumferential surface towards the corners of the steel tubes (3 measurements along each ligament). After these measurements were completed, the I54 section was heat-treated and additional measurements marked with “T” were done, including 3 locations in the back side of the section. In total, 27 measurements of the residual stresses were conducted.

The measured in-plane residual stresses were calculated in the local coordinate system (relative to strain gauge orientation). In order to allow for a comparison with measurements from VEQTER the stresses were transformed into the global coordinate system of the insert used by VEQTER. The measurements from SP [5] provide hoop and radial stresses whereas VEQTER measurements [2] give hoop and axial stresses. Therefore, only the hoop stresses measured by SP are relevant for comparison with the measurements from VEQTER.

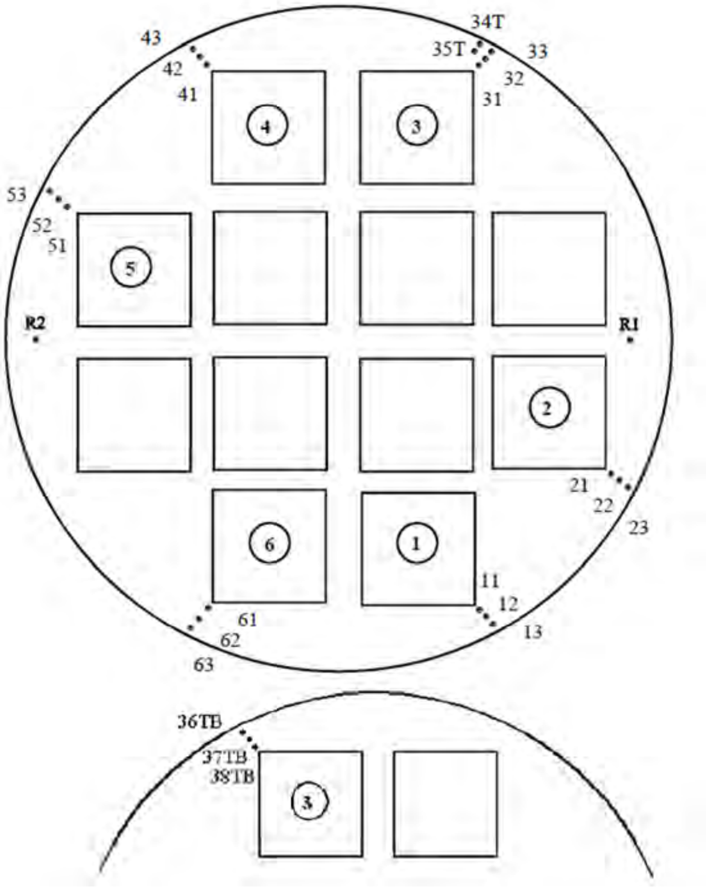


Figure 4.3: Locations for the residual stress measurements in the BWR-insert I54.

The length of a shortest ligament between the insert circumference and the corner of the steel pipe is about 35 mm (as judged from the I63 insert in Figure 4.1). The SP report [5] provides neither the ligament length nor the exact coordinates along the ligaments where the ICHD measurements are performed. It is reasonable to assume that the measuring points, e.g. 11 and 13 (Fig. 4.3) were located within a few millimetres from the free surface and the point 12 was equidistant.

In the SP report [5] the values of hoop stresses at each location are provided for different depth increments starting from just near the surface (typical depth for the first increment is 0.04 mm) and down to 1 mm. The stress value at the first depth increment of 0.04 mm was almost in all locations very high (> 70% of R_p) so the accuracy could not be determined. Even if the first value was within 70% of R_p, it was standing out from the values measured at other depth increments.

In this report, the values of hoop stress at each location, except the value from the first depth increment, are used to calculate the mean hoop stress. The results of this assessment are plotted for three measuring locations along the ligament starting from the location at the circumferential surface of the insert and moving towards the corner of a steel channel tube, see Figure 4.4. This provides a way to analyse the hoop stress profile along the ligaments.

For all locations, except the locations 3 and 4, the residual hoop stresses are close to zero or tend to be compressive. For the locations 3 and 4, the residual stresses were tensile and of significant magnitude. In location 3, the measurement before and after heat-treatment were compared. It appears that heat-treatment significantly reduces the residual stresses. It is unclear whether the reduction of residual stresses could solely be attributed to heat treatment and not affected by previous measurements (before heat treatment). The distance between measuring points before and after heat treatment is not provided in [5] but it is reasonable to expect that the residual stress field is disturbed within several hole diameters away from a measuring point.

In general, the ICHD measurements of hoop stresses in the SP report [5] confirm findings from the DHD measurements for the I63 insert performed by VEQTER (the DHD1 location) [2]. The VEQTER measurements demonstrated the hoop stress profile varying from tensile stress of 60 MPa at the circumferential surface to compressive stresses of about -60 MPa at the corner of a steel channel tube.

Based on the findings in [5] and [2] it is reasonable to make a pessimistic assumption that the residual hoop stress along the ligament between the outer surface and the corner of the steel tube is 60 MPa.

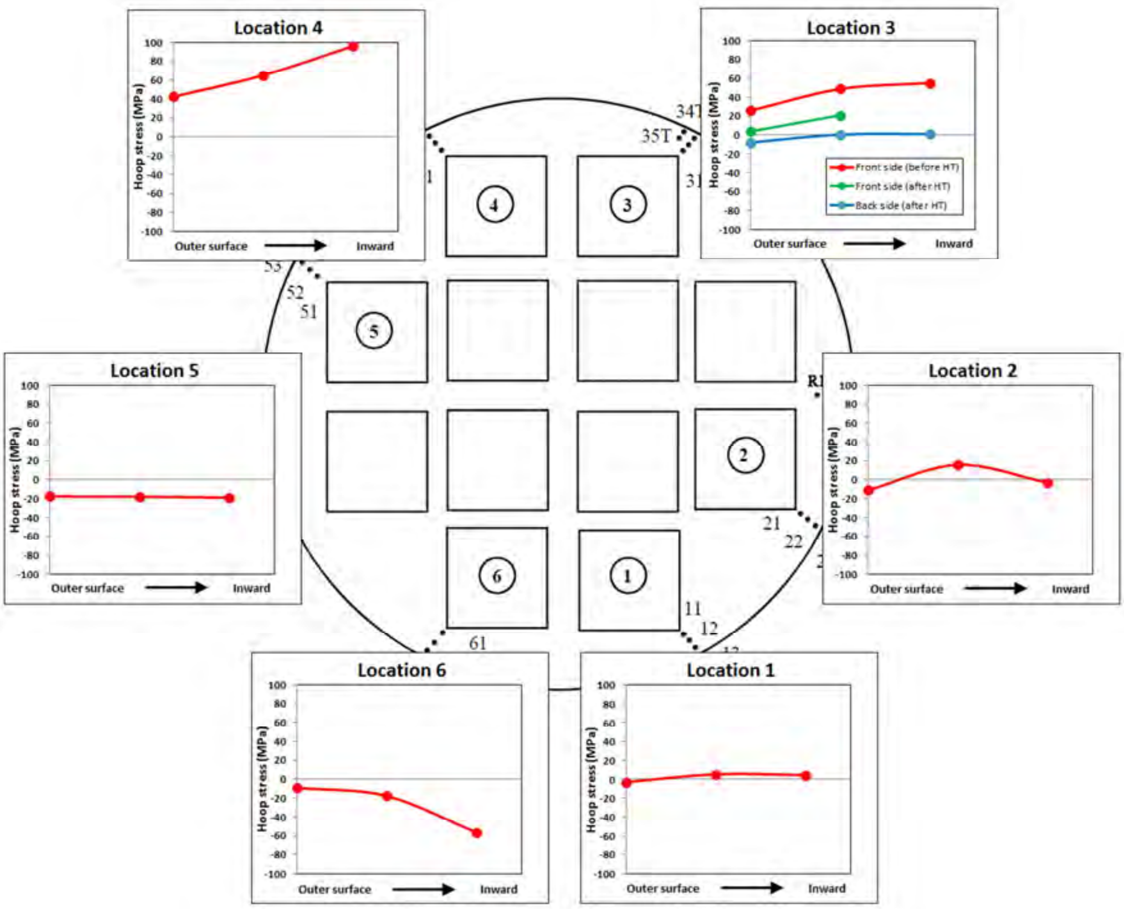


Figure 4.4: A sketch of the I54 insert with measured hoop stresses.

4.1.3 BWR-insert I56

The bi-axial residual stress measurements were performed by SP using the ICHD technique on a section of the I56 insert measuring 950 mm in diameter and 2000 mm in length [3]. It remains unclear from the SP report [3] from which position along the insert axis the provided section was cut.

Residual stresses were measured at 9 locations, all drilled in the circumferential surface, see Figure 4.5. At the location 5 the measurements were disturbed by a sudden increase in measured strains due to unclarified reason. The measurement was aborted and resumed at the location 5a positioned 15 mm to the left from the location 5. Even this measurement was disturbed and resumed at the location 5b positioned 15 mm to the right from the location 5.

It can be noted that the locations 7-9 and the locations 4-6 correspond to the DHD2 and DHD1 measurements performed for the BWR insert I63 [2]. The ICHD measurements can be used for verification and confirmation of the DHD measurements near the surface where the DHD technique fails to provide reliable results. However, the exact position of the locations 1-3 (Fig. 4.5) is unclear but it appears to conform to the DHD3 measurement.

The ICHD measurements are performed at the circumference of the insert so the hoop and axial stresses were resolved from the measurements. For comparison with the results from VEQTER measurements, the measured in-plane residual stresses were transformed into the global coordinate system.

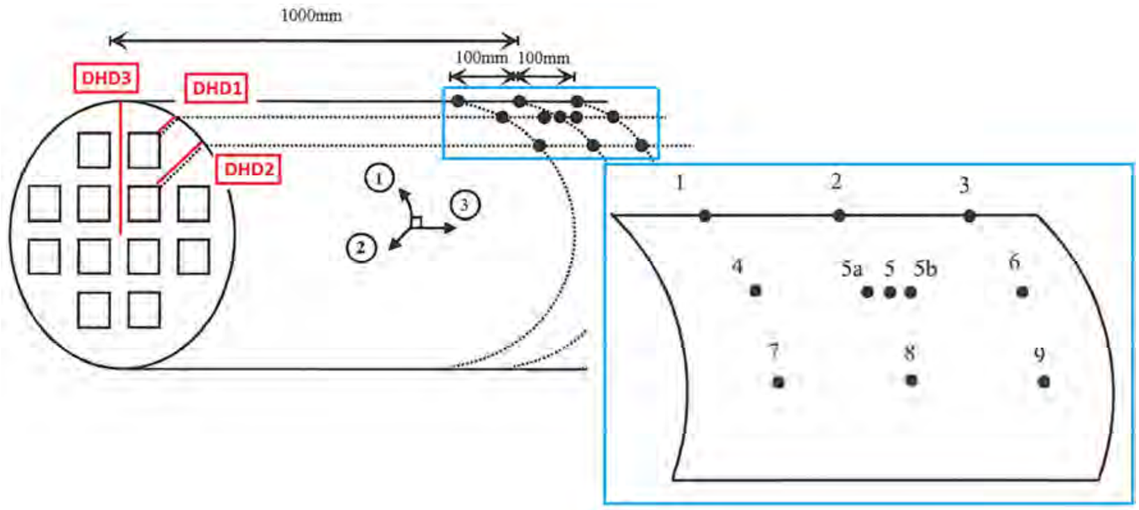
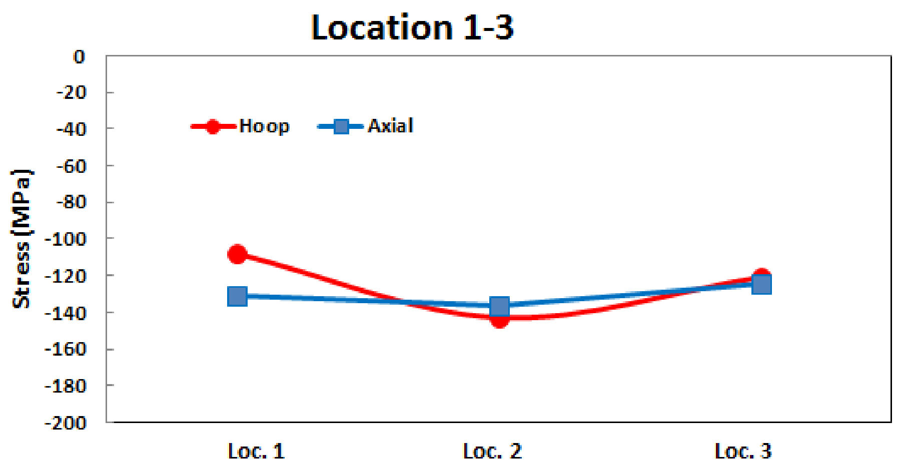


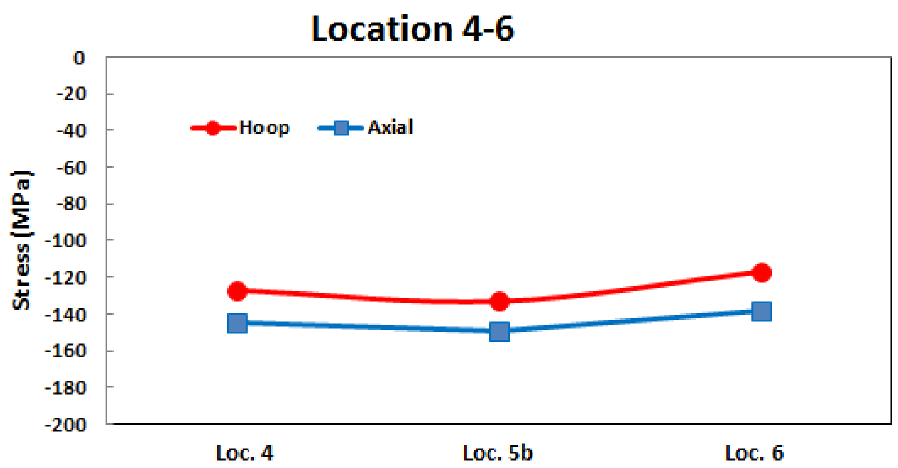
Figure 4.5: Locations for the residual stress measurements in the BWR-insert I56.

In the SP report [3] the values of hoop and axial stresses at each location are provided for different depth increments starting from just near the surface (typical depth for the first increment is 0.04 mm) and down to 1 mm. At some depth increments the stress values were very high (> 70% of R_p) so the accuracy could not be determined. These values were greyed in the result tables in the SP report [3].

In this report, we calculate the mean values of hoop and axial stress at each location based on provided measurements [3]. The greyed stresses were excluded from the calculation of the mean values. The mean values of hoop and axial stresses are plotted along the paths running through locations 1-3, 4-6 and 7-9, see Figure 4.6.

The ICHD measurements show consistent results at all locations. Both the hoop and axial stresses are compressive and show uniform distribution along the measured paths 1-3, 4-6 and 7-9. Similar findings were obtained by DHD measurements in the BWR-insert I63 [2], although VEQTER emphasized that the results near the surface should be treated with caution due to deficiency of the DHD technique. The SP results confirm that the near surface stresses are compressive.





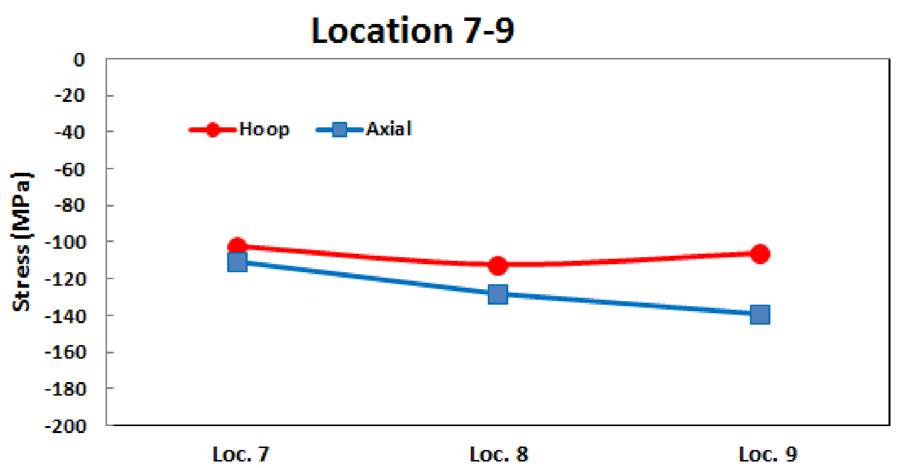


Figure 4.6: Mean values of hoop and axial residual stresses (in MPa) at the measurement locations for the BWR-insert I56.

4.1.4 PWR-insert IP8

The bi-axial residual stress measurements were performed by SP using the ICHD technique. The test object was a 75 mm thick section of the PWR IP8 insert of 950 mm in diameter [5]. It remains unclear from the SP report [5] from which position along the insert axis the provided section was cut.

In-plane residual stresses were measured on both sides of the insert section (the front side and the back side) as shown in Figure 4.7. In the front side the measurements were performed at three reference locations marked as R1, R2 and R3 and at 4 locations along the shortest ligament between the circumferential surface towards the corners of the steel tubes (3 measurements along each ligament). Also, five (5) measurements were performed in the centre of the insert section, marked as C1-C5. After these measurements were completed, the IP8 section was heat-treated and additional measurements marked with “T” were done, including 4 locations in the back side of the section. In total, 26 measurements of the residual stresses were conducted.

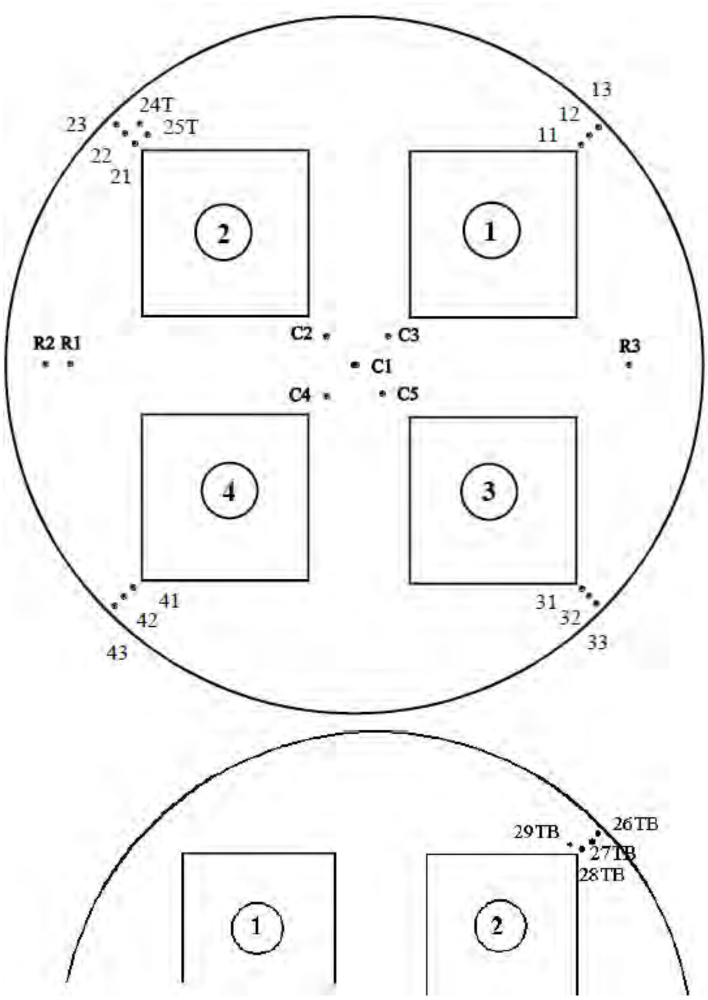


Figure 4.7: Locations for the ICHD residual stress measurements in the IP8 insert.

The measured in-plane residual stresses were calculated in the local coordinate system (relative to strain gauge orientation). In order to allow for a comparison with measurements from VEQTER the stresses were transformed into the global coordinate system of the insert used by VEQTER. Only the hoop stresses measured by SP are relevant for comparison with the measurements from VEQTER.

The length of a shortest ligament between the insert circumference and the corner of the steel tube is about 40 mm (as judged from the DHD measurements in the PWR insert IP25 [4]). The SP report [5] provides neither the ligament length nor the exact coordinates along the ligaments where the ICHD measurements are performed. It is reasonable to assume that the measuring points, e.g. 11 and 13 (Fig. 4.7) were located within a few millimetres from the free surface and the point 12 was equidistant.

In this report, the values of hoop stress at each location, except the value from the first depth increment, are used to calculate the mean hoop stress. The results of this assessment are plotted for three measuring locations along the ligament starting from the location at the circumferential surface of the insert and moving towards the corner of a steel channel tube, see Figure 4.8. It is observed that the residual stresses for location 4 (the measuring point 41) were not presented in SP report [5]. For central locations C1-C5, two profiles along the measuring points C5-C1-C2 and C4-C1-C3 are also plotted in Figure 4.8.

For locations 1-4 the residual hoop stresses are close to zero or tend to be compressive. For location 2, a comparison of the residual stresses before and after heat-treatment is presented indicating that the heat-treatment reduces the stress magnitudes. For all central locations the residual stresses are compressive except for the location C2 where tensile stress of about 60 MPa was measured. Stresses of a similar magnitude were expected to be measured in locations C2-C5 due to symmetry. Reasons for deviation in the stress value for the point C2 are unknown.

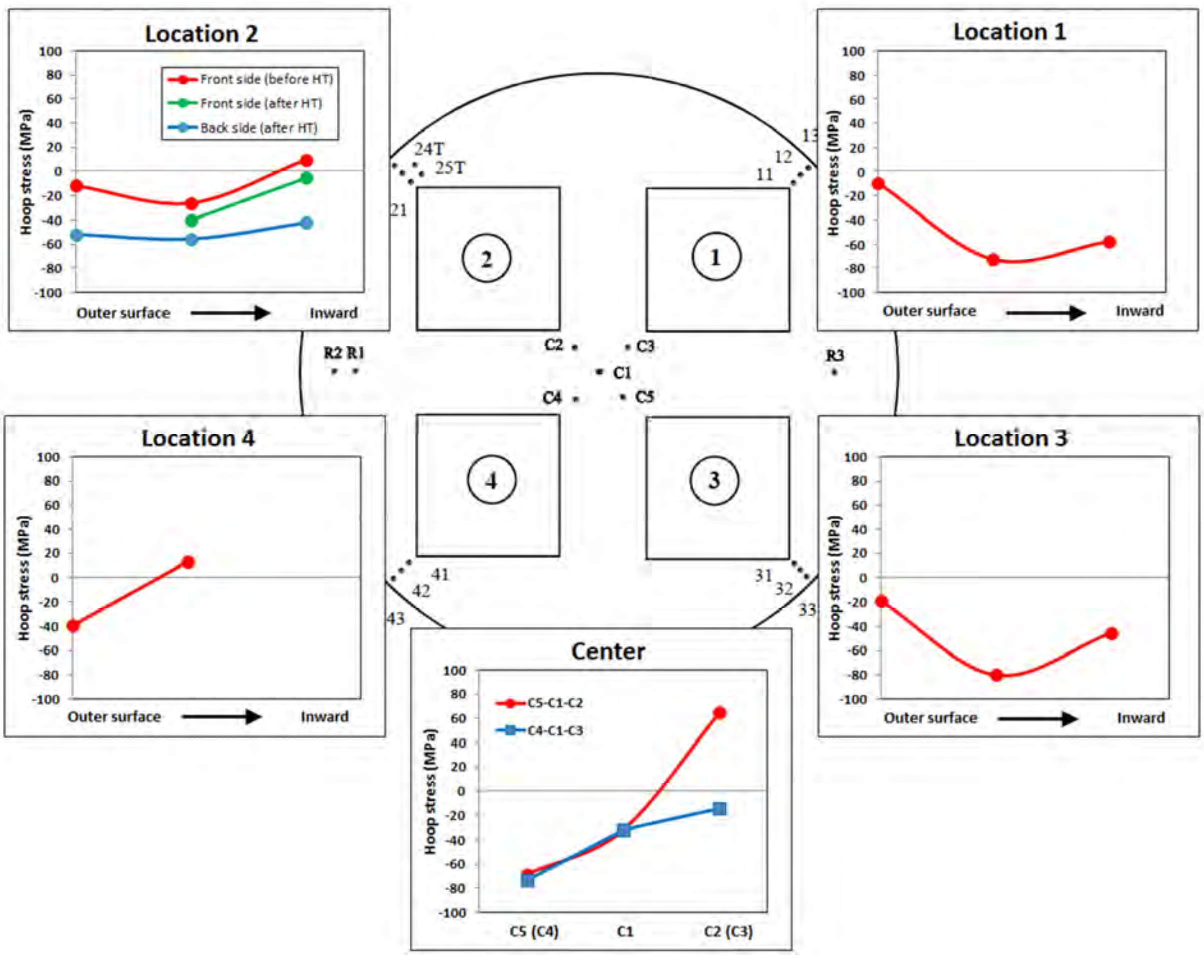


Figure 4.8: A sketch of the PWR-insert IP8 with measured hoop stresses (in MPa).

4.1.5 PWR-insert IP25

The bi-axial residual stress measurements were performed by VEQTER Ltd on a section of the IP25 insert measuring 960 mm in diameter and 750 mm in length. The section was cut from about 1455-2205 mm from the bottom of the steel tubes and thereby represents a middle part of the insert [4]. The residual stress measurements were performed by using the ICHD and DHD techniques. There were two ICHD and three DHD measurements carried out in the positions as shown in Figure 4.9.

At the position 1 and 3 the ICHD measurements were performed prior to the DHD measurements. In these positions the DHD drilling was carried out radially towards the insert axis allowing the measurement of true axial and hoop stresses. The location DHD2 was drilled axially along the insert axis allowing the measurement of the hoop and radial stresses.

Compressive residual stresses were found at the surface of the insert specimen using the ICHD technique. For the DHD1 measurement from the circumferential surface towards the steel tube corner the axial and hoop residual stresses were found to be compressive and approximately constant at roughly -24 MPa and -35 MPa respectively.

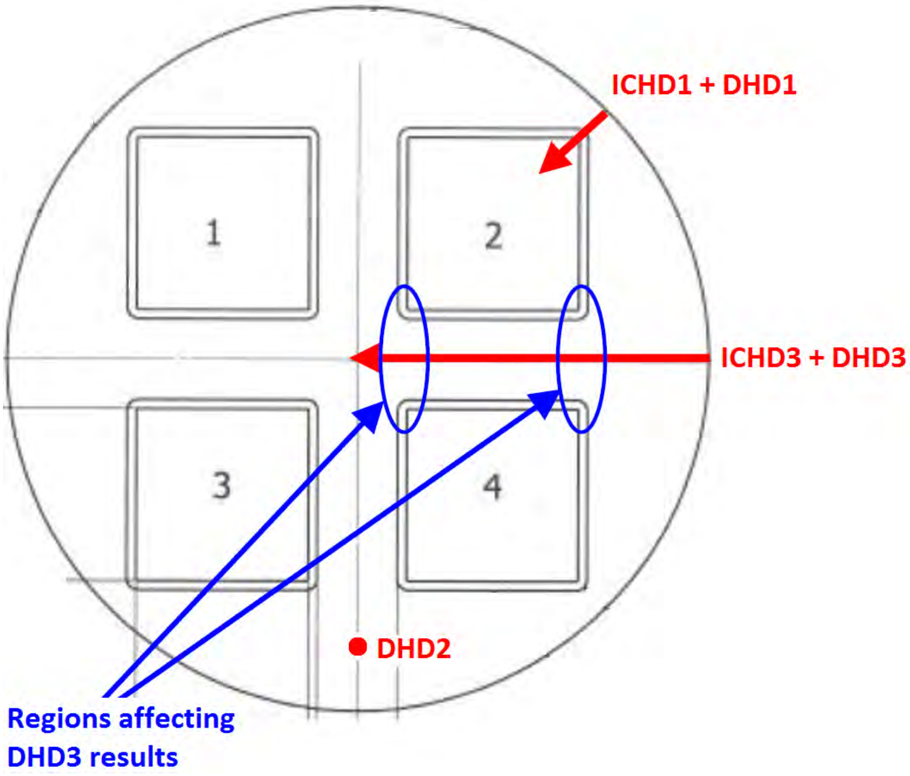


Figure 4.9: Locations for the ICHD and DHD residual stress measurements in the IP25 insert.

For the DHD2 measurement along the insert axis the radial and hoop residual stresses were found to be predominantly equi-biaxial, varying between -30 MPa and 20 MPa.

For the DHD3 measurement drilled radially between the steel tubes 2 and 4 the axial and hoop residual stresses were low in magnitude within ±10 MPa, apart from the two regions adjacent to the steel tube walls. Within these regions (as marked in Figure 4.9) the axial and hoop residual stresses reach distinct tensile peaks from 40 MPa to 90 MPa with the hoop residual stresses being the most tensile. The residual stress profile for the DHD3 measurement is presented in Figure 4.10.

Based on this finding the constant residual stress of 90 MPa in the hoop direction can pessimistically be assumed for the DHD3 location.

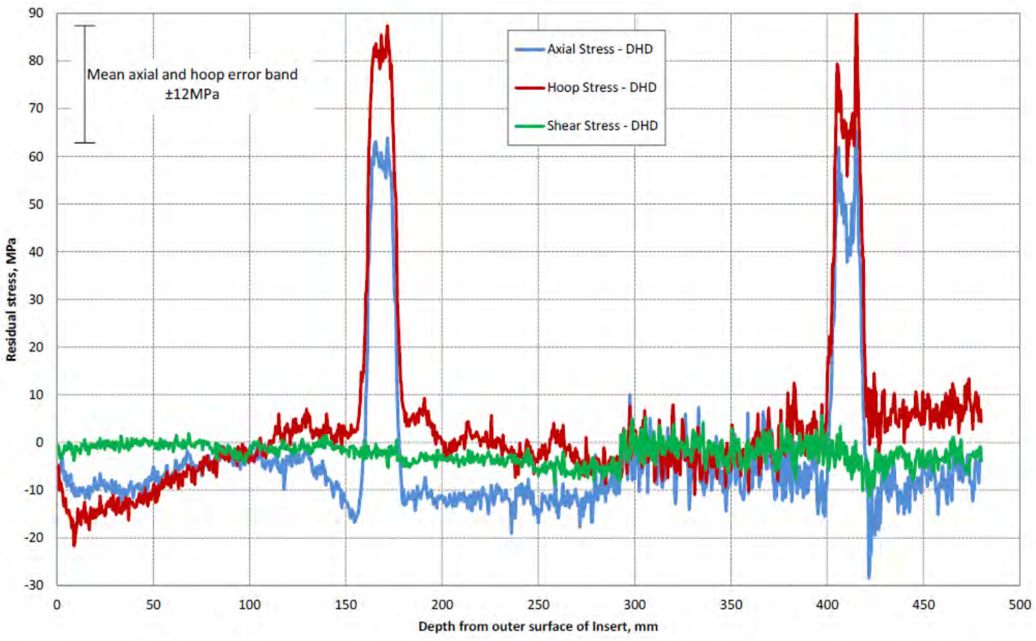


Figure 4.10: The residual stress measurements at the DHD3 position for the IP25 insert.

5 DAMAGE TOLERANCE ANALYSIS

Damage tolerance analyses of BWR- and PWR-inserts with postulated crack defects have previously been carried out [1]. The positions for postulated cracks are shown in Figure 5.1. Based on the residual stress measurements [2-5] and the findings presented above in this report, the damage tolerance analyses are reproduced taking into account the residual stress distribution.

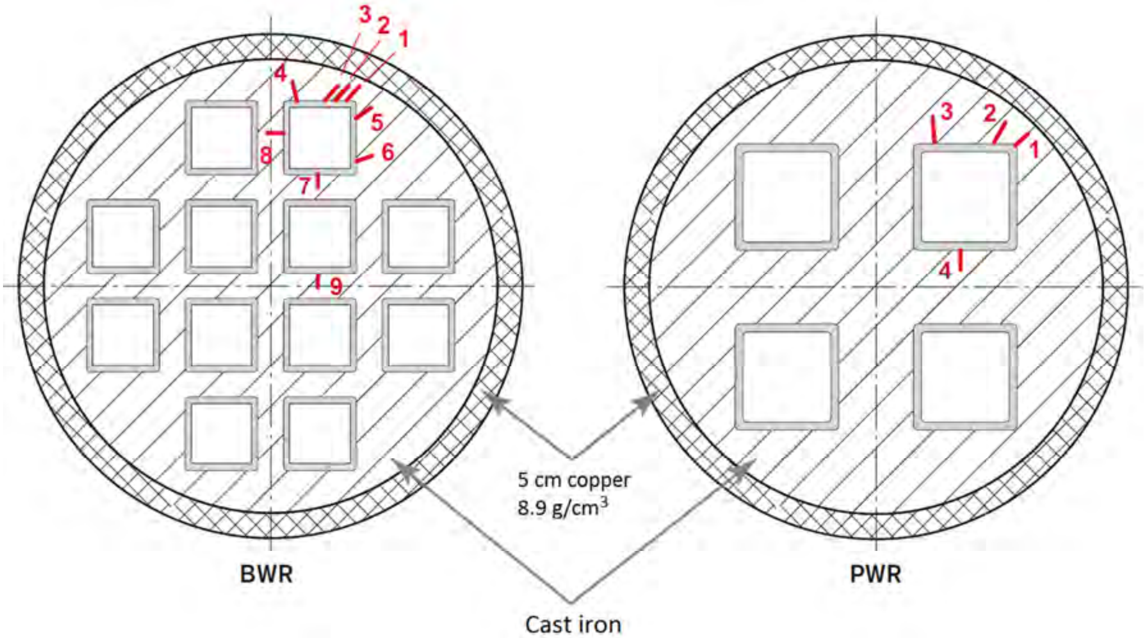


Figure 5.1: Locations for postulated cracks in damage tolerance analyses [1].

Tables 5.1 and 5.2 summarize the residual stress distributions used in the analysis at each defect location based on the discussion in Section 4 of this report. All defects depicted in Figure 5.1 lie in the hoop-radial plane. The postulated cracks at the locations 1-6 for the BWR-insert and at the locations 1-3 for the PWR-insert are governed by the residual hoop stress. The cracks in the location 7-9 for the BWR-insert and at the location 4 for the PWR-insert are governed by the residual radial stress.

It should be observed that no measurements for radial stresses in the BWR-inserts were present in the reviewed reports [2-5].

Table 5.1: Residual hoop and radial stresses used in the analysis at defect positions in the BWR-inserts.

Defect position	Residual stress (MPa)	
	Hoop	Radial
1, 2, 3, 4, 5, 6	60	-*
7, 8, 9	-*	Not available

*) Residual stress is not relevant for the defect position and orientation

Table 5.2: Residual hoop and radial stresses used in the analysis at defect positions in the PWR-inserts.

Defect position	**Residual stress (MPa)**	
	Hoop	**Radial**
1, 2, 3	90	-*
4	-*	20

*) Residual stress is not relevant for the defect position and orientation

Damage tolerance analyses with residual stress fields according to Tables 5.1 and 5.2 were carried out using the software ProSACC version 2.0, revision 1. The applied residual stresses had no influence on previously reported results [1]. The results are shown in Tables 5.3 and 5.4 which are identical with the results in Tables 7.1 and 7.2 in the SKB report [1].

Table 5.3: Acceptable defect size for BWR-insert.

Position of defect	l_{acc} [mm]	a_{acc} [mm]
1	> 196.3	> 32.7
2	> 208.3	> 34.7
3	> 222.2	> 37.0
4	> 305.3	> 50.9
5	> 393.1	> 65.5
6	> 915.3	> 152.5
7	> 144.0	> 24.0
8	> 144.0	> 24.0
9	> 144.0	> 24.0

Table 5.4: Acceptable defect size for PWR-insert.

Position of defect	l_{acc} [mm]	a_{acc} [mm]
1	> 189.1	> 31.5
2	> 319.3	> 53.2
3	> 672.9	> 112.2
4	> 624.0	> 104.0

6 CONCLUSIONS

SKB has commissioned Inspecta Technology AB to perform an assessment of residual stress measurements in PWR- and BWR-inserts. The aim with this assessment was to investigate the residual stress distribution measured at different locations and determine a typical (representative) residual stress profile for locations where the damage tolerance analyses for postulated cracks have previously been conducted [1]. The effect of measured residual stresses on the results from these damage tolerance analyses, for the isostatic load case, is also evaluated in this report.

The conclusion, from the damage tolerance analysis of the isostatic load case, is that including the residual stresses has no influence on the calculated acceptable defect sizes (both for BWR- and PWR-inserts).

7 REFERENCES

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8 TABLE OF REVISIONS

Rev.	Activity / Purpose of this revision	Handled by	Date
0	—	Andrey Shipsha	2013-12-03
1	The report is revised according to the review comments (SKBDoc 1416697) The value of postulated residual hoop stress in Table 5.2 (locations 1,2,3) is changed to 90 MPa. This value was suggested in Section 4.1.5 but the incorrect value was typed in Table 5.2 in revision 0 of this report. This change has no impact on the results in Tables 5.3 and 5.4.	Andrey Shipsha	2014-01-22
2	The report is revised according to the review comments (SKBDoc 1425328)	Andrey Shipsha	2014-02-03