INSPECTA

TECHNICAL REPORT

SKB

Summary of important characteristic parameters for the BWR- and PWR-insert, based on performed strength and damage tolerance analyses

Report No.: 50017500-1

Revision No.: 4

PDF rendering: DokumentID 1288292, Version 1.0, Status Godkänt, Sekretessklass Öppen

Inspecta

TECHNICAL REPORT

Report No.: 50017500-1 Revision No.: 4

Date 2014-02-27	Our project No. 50017500
Approved by Keivan Ashhami	Organizational unit Inspecta Technology AB
Customer SKB	Customer reference Mikael Jonsson

Summary

Inspecta Technology has produced a summary, based on the performed analyses, of the insert characteristic parameters that are of significance to the design of the BWR and PWR inserts. Based on this summary, it is possible to determine different requirements for these parameters. These requirements are summarized in the table below. Also, requirements regarding the size of crack-like defects in BWR- and PWR-inserts that the NDT system to be used should detect are given in the report.

Parameters for BWR and PWR inserts	Min req.	Average req.	Max req.
Yield strength, compression at 20°C	240 MPa (1)	—	—
Ultimate strength, compression at 20°C	430 MPa (2)	—	—
Fracture toughness, at initiation (K_{Ic}), at 0-20°C	$4.1\ \mathrm{MPa}\sqrt{\mathrm{m}}$ (3)	—	—
Displacement of the steel cassette	—	—	10 mm
Yield strength, tension at 20°C	240 MPa (1)	—	—
Ultimate strength, tension at 20°C	410 MPa (2)	—	—
BWR Fracture toughness, including 2 mm stable crack growth ($J_{2\mathrm{mm}}$), at 0-20°C	88 kN/m	—	—
PWR Fracture toughness, including 2 mm stable crack growth ($J_{2\mathrm{mm}}$), at 0-20°C	78 kN/m	—	—
Elongation at failure, at 0°C or at 20°C	6.3% (4)	—	—

Note 1: The above mentioned yield strength values are true stress values, but because the strains are small it doesn't matter if they are given as engineering or true values.

Note 2: The above mentioned ultimate strength values are true stress values.

Note 3: It is "meaningless" to use a fracture toughness requirement for the isostatic load case because the tensile stress is so low in all parts of the insert.

Note 4: The above mentioned elongation value is an engineering strain value.

Report title Summary of important characteristic parameters for the BWR- and PWR-insert, based on performed strength and damage tolerance analyses	Index terms —
Work carried out by Peter Dillström	Distribution
Work verified by Lars Alverlind	☒ No distribution without permission from the customer or Inspecta Technology AB. ☐ Limited distribution in Inspecta Technology AB. ☐ Unrestricted distribution.
Date of this revision	

PDF rendering: DokumentID 1288292, Version 1.0, Status Godkänt, Sekretessklass Öppen

Table of content *Page*

PDF rendering: DokumentID 1288292, Version 1.0, Status Godkänt, Sekretessklass Öppen

1 INTRODUCTION

Inspecta Technology AB has performed a number of strength and damage tolerance analyses of the cast iron insert for the KBS-3 canister. While this has been going on, SKB has improved the insert casting process.

SKB has requested a summary, based on analyses carried out, of those insert material characteristic parameters that are of importance and those which are assumed to be significant to the design of the inserts. The summary should be based on those load cases that are used as a basis for already carried out design analysis of the insert [1]. SKB is also interested to get some requirements regarding the NDT (Non-destructive testing) system that should be used to inspect the outside of the insert. The requirements should be given for BWR- and PWR-inserts.

PDF rendering: DokumentID 1288292, Version 1.0, Status Godkänt, Sekretessklass Öppen

2 CHOICE OF CHARACTERISTIC PARAMETERS FOR THE INSERT

In order to provide this summary, Inspecta has used the failure modes defined in the design analysis [1] together with a number of underlying technical reports. For example, “Development of acceptance criteria and damage tolerance analyses of the nodular iron insert” [2], includes different analyses of the isostatic load case (both for BWR- and PWR-inserts) and ”Damage tolerance analysis of canister inserts for spent nuclear fuel in the case of an earthquake induced rock shear load” [3], which includes analyses of the rock shear load case (for BWR-inserts).

2.1 Choice of characteristic parameters in the isostatic load case

The canister is designed to resist all loads it can possibly be exposed to in the repository. The design analysis [1] describes loads affecting the canister in the isostatic case. The analysis also describes which damage mechanisms that are relevant given these loads. In conclusion, the following applies for the isostatic load case:

- Failure due to plastic collapse is possible for the insert, given the large primary stresses that are present in the isostatic case. To make sure that the margins are sufficient, an analysis with an increasing pressure load is applied to the insert [2] (in cases with/without cavity defects). The parameters with the largest impact are the stress-strain curve (via yield strength and ultimate strength in compression), and the geometry of the canister. The most important geometric parameter was shown to be the displacement of the steel cassette from an ideal location in the center.
- In case of existing crack like defects, the insert can also fail by a fracture mechanism. To make sure that margins to initiation of crack growth are large enough, cracks are postulated to exist in the insert [2]. The most important parameter in this case is the fracture toughness. The displacement of the steel cassette is of some importance here as well, but not to such an extent as for the plastic collapse case.

In the isostatic case, the canister is exposed to loads within the temperature limits of 0°C to 20°C [1]. Data regarding yield strength and ultimate strength in compression do not differ significantly within these temperature limits. For data regarding fracture toughness it is better to use values at 0°C to be conservative. However, since the performed testing at 0°C gives too conservative fracture toughness values (see section 4.3.3), it is more relevant to use data at 20°C. This means that the following characteristic parameters are of importance in the isostatic load case:

- Yield strength in compression, at 20°C.
- Ultimate strength in compression, at 20°C.
- Fracture toughness, at initiation, at 0-20°C.
- Displacement of the steel cassette.

2.2 Choice of characteristic parameters in the shear load case

The design analysis [1] describes the loads affecting the canister in the shear load case. It also describes which damage mechanisms that are relevant given these loads. In conclusion, the following applies for the shear load case:

- In case of crack like defects in the insert, the insert can fail by a fracture mechanism. To make sure there are enough margins to large amounts of stable crack growth, cracks are postulated to exist in the insert [3]. The most important parameter in this case is the fracture toughness (here with a value corresponding to 2 mm stable crack growth, which is relevant because the shear load case corresponds to a case with displacement controlled load [1]).

PDF rendering: DokumentID 1288292, Version 1.0, Status Godkänt, Sekretessklass Öppen

- In the shear load case, large bending stresses are present in the insert. A way to estimate the safety margins in the case of a displacement controlled load is to connect this margin to the elongation at failure of the material [1]. This means that the elongation at failure becomes an important parameter in the shear load case.
- Even though it is not clearly evident in [1], the stress strain curve (via yield strength and ultimate strength in tension) is of importance for the shear load case. This is partly because the stress strain data is used when estimating the elongation at failure [1], and partly because this data is used in the fracture mechanical analysis that is done prior to the damage tolerance analysis in [3]. Therefore, these parameters are included in this summary.

In the shear load case, the canister is exposed to loads within the temperature limits of 0°C to 20°C [1]. Data regarding yield strength and ultimate strength in tension do not differ significantly within these temperature limits. For data regarding fracture toughness, using values at 0°C is conservative. However, since the performed testing at 0°C gives too conservative fracture toughness values (see section 4.3.3), it is in this case more relevant to use data at 20°C. This is probably also relevant for the elongation at failure (but is has not yet been confirmed). This means that the following characteristic parameters are of importance in the shear load case:

- Yield strength in tension, at 20°C.
- Ultimate strength in tension, at 20°C.
- Fracture toughness, including 2 mm stable growth, at 0-20°C.
- Elongation at failure at 0°C or at 20°C.

PDF rendering: DokumentID 1288292, Version 1.0, Status Godkänt, Sekretessklass Öppen

3 CHARACTERISTIC PARAMETERS IN THE ISOSTATIC LOAD CASE

3.1 Yield strength in compression, at 20°C

To be able to give a recommendation, regarding the yield strength in compression, a number of sensitivity analyses have been conducted, where the yield point is varied between 240 MPa and 270 MPa (the value used in the analysis of the isostatic load case [1-2]) and the ultimate strength is varied between 428 MPa and 482 MPa.

3.1.1 Yield strength in compression, BWR-inserts

In [2] it is shown that the lowest calculated limit load allowed is 67.5 MPa. This should be compared to the limit load obtained with other yield strength values with/without cavity defects. The controlling cavity defect in the analysis of the isostatic load case [2] was cavity no 12 (Fig. 3.1 below), meaning that this cavity was chosen for the sensitivity analysis. To receive a similar stress strain curve to [2] the ultimate strength was scaled by a factor 240/270, meaning that the ultimate strength was set to 428 MPa. The results from the sensitivity analysis can be found in table 3.1.

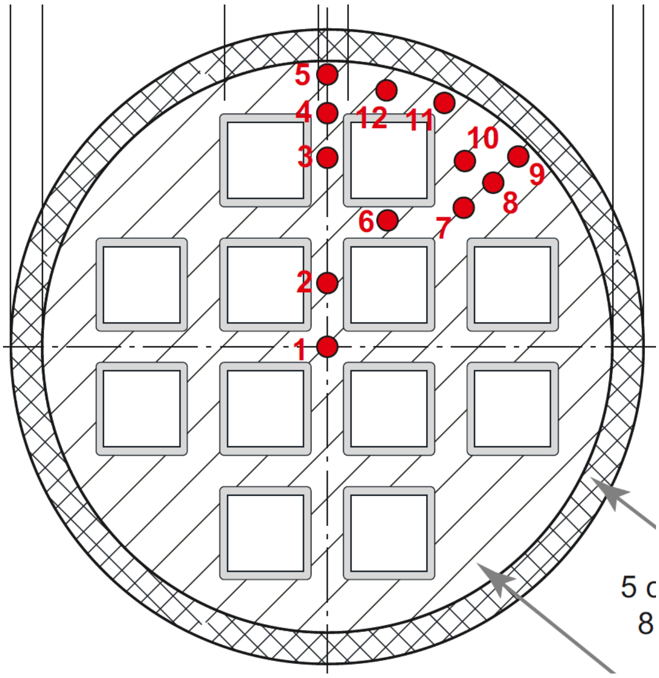

Figure 3.1. Positions for postulated cavity defects in BWR-inserts (cavity no 12 was chosen for the sensitivity analysis).

Table 3.1. Calculated collapse pressure in the sensitivity analysis (BWR-inserts).

Model	Collapse pressure with $R_{p0,2}$ = 240 MPa	Collapse pressure with $R_{p0,2}$ = 270 MPa
Nominal geometry	92.0 MPa	98.9 MPa
Cavity no 12 (Radius = 20mm)	63.6 MPa	67.8 MPa

PDF rendering: DokumentID 1288292, Version 1.0, Status Godkänt, Sekretessklass Öppen

As shown in table 3.1, the acceptable collapse pressure is obtained at yield strength 240 MPa. This applies to cases without cavity defects and surely also for most cavity defects given in Fig. 3.1. However, a lower collapse pressure is obtained for the combination of yield strength 240 MPa and cavity defect no 12 (the safety factor is 1.41 which is lower than 1.5 used as an acceptance criteria [2]). To push cavity no 12 into the acceptable region, the yield strength in compression must be increased to a value between 260 and 270 MPa.

In the analyses [2] a 2D-idealization of the canister has been used, which means that the postulated cavity defects are cylindrical with a height corresponding to the full length of the canister. This is a very pessimistic assumption. To check this assumption Inspecta has performed 3D-analyses with axial cavity defects limited in the axial direction [4] (the defects has a length of 50mm). The analyses show that these cavity defects have a very limited effect on the limit load. When this is translated to the analyses reported in table 3.1, it shows that collapse analyses with yield strength 240 MPa are acceptable even in the case of cavity no 12 (given that the defect has an axial length of 50 mm). It also shows that because the postulated cavity defects have such a small impact on the limit load, even lower yield strength in compression can be accepted. This conclusion is also valid for the bottom region of the insert [1]. However, we have chosen not to investigate this further, leaving the minimum requirement to 240 MPa.

3.1.2 Yield strength in compression, PWR-inserts

Also for PWR-inserts, the lowest calculated limit load allowed is 67.5 MPa. The controlling cavity defects in the analysis of the isostatic load case [2] was cavity no 5 and 7 (Fig. 3.2 below). The results for these defects are compared with an analysis without any defects, see Table 3.2.

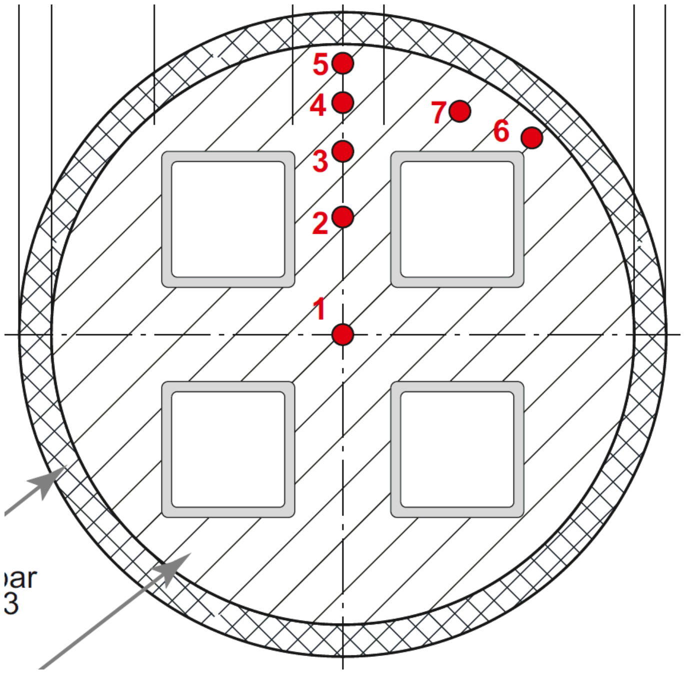

Figure 3.2. Positions for postulated cavity defects in PWR-inserts (cavity no 5 and 7 was chosen).

PDF rendering: DokumentID 1288292, Version 1.0, Status Godkänt, Sekretessklass Öppen

Table 3.2. Calculated collapse pressure from [2] (PWR-inserts).

Model	Collapse pressure with $R_{p0,2}$ = 270 MPa
Nominal geometry	127.9 MPa
Cavity no 5 (R = 50mm)	71.5 MPa
Cavity no 7 (R = 40mm)	71.3 MPa

The comparison shows that a PWR-insert is even more tolerant to very large cavities than BWR-inserts. Using a similar argument as for BWR-inserts (when comparing results using a yield strength of 240 MPa), the postulated cavity defects will have a small impact on the limit load, leaving the minimum requirement to 240 MPa.

3.2 Ultimate strength in compression, at 20°C

3.2.1 Ultimate strength in compression, BWR-inserts

To be able to develop a recommendation, regarding the ultimate strength in compression, a number of sensitivity analyses have been conducted, where the ultimate strength is varied between 428 MPa (scaled using a factor 240/270*482 MPa) up to 482 MPa (the same value used in the isostatic load case [1-2]). Notice that this scaling, related to the yield strength, means that this corresponds to those collapse analyses already reported in section 3.1. The conclusions already reported above therefore apply for this case as well and a minimum requirement of 428 MPa is obtained, simplified to 430 MPa (true stress). One should note that the minimum requirement is related to an elongation value of 10%, due to the fact that defining an ultimate strength limit during compressive testing is difficult.

3.2.2 Ultimate strength in compression, PWR-inserts

Since the PWR-inserts are more tolerant to very large cavities as compared to BWR-inserts, a similar argument as above gives a minimum requirement of 430 MPa (true stress).

3.3 Fracture toughness, at initiation, at 0-20°C

3.3.1 Fracture toughness, at initiation, BWR-inserts

To be able to give a recommendation, regarding the fracture toughness, a number of sensitivity analyses have been conducted, where the fracture toughness (given as K_{Ic}) is varied between 0 and 79.4 MPa$\sqrt{\mathrm{m}}$ (which also is the initiation value used in the analyses of the isostatic load case [2]).

In [2] it is shown that the insert is very resistant to defects in the isostatic load case. All postulated defect positions (see Fig. 3.3) presents acceptable defect sizes corresponding to 80% of the section thickness (this is a limit to the analysis in the used program ProSACC). This is because the tensile stresses are very low in the isostatic load case.

PDF rendering: DokumentID 1288292, Version 1.0, Status Godkänt, Sekretessklass Öppen

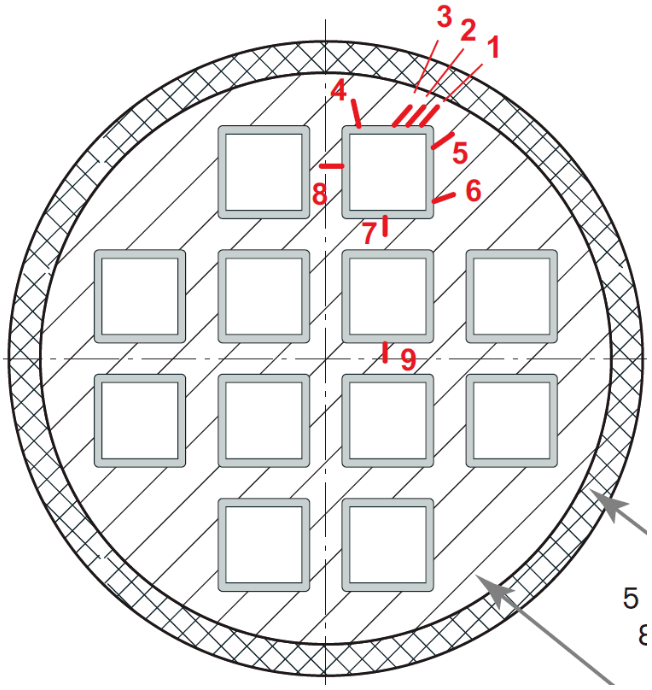

Figure 3.3. Postulated surface breaking crack like defects in BWR-inserts.

To check how the damage tolerance is affected by the assumed fracture toughness value, sensitivity analyses were conducted at all defect positions (see figure 3.3). The analyses show that it is “meaningless” to use a fracture toughness requirement for the isostatic load case because the tensile stress is so low in all parts of the insert. Defect position no 9 can be assumed to have the worst damage tolerance, but it takes fracture toughness levels lower than 1.4 MPa $\sqrt{m}$ to give acceptable defect sizes less than 80% of the section thickness. However, a requirement for fracture toughness is necessary for the shear load case as presented in section 4.3.

3.3.2 Fracture toughness, at initiation, PWR-inserts

Also, for PWR-inserts, sensitivity analyses have been conducted, where the fracture toughness is varied between 0 and the fracture toughness at initiation of crack growth.

In [2] it is shown that the PWR-inserts are very resistant to defects in the isostatic load case. All postulated defect positions (see Fig. 3.4) presents acceptable defect sizes corresponding to 80% of the section thickness (this is a limit to the analysis in the used program ProSACC). This is because the tensile stresses are very low in the isostatic load case.

PDF rendering: DokumentID 1288292, Version 1.0, Status Godkänt, Sekretessklass Öppen

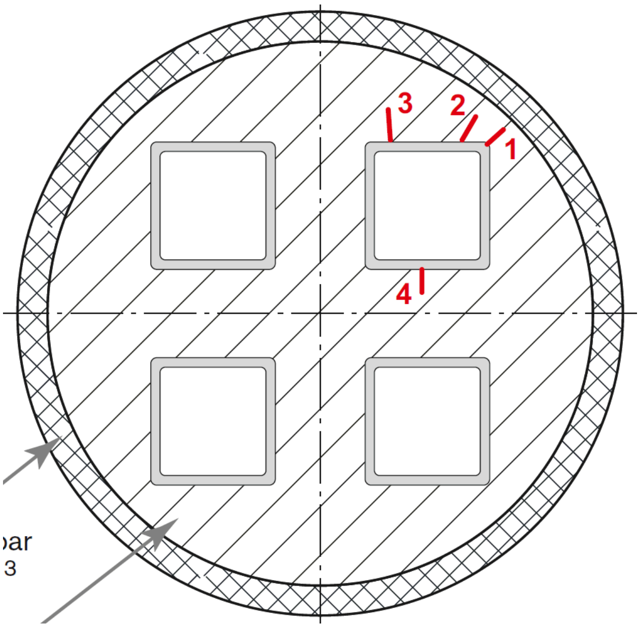

Figure 3.4. Postulated surface breaking crack like defects in PWR-inserts.

To check how the damage tolerance is affected by the assumed fracture toughness value, sensitivity analyses were conducted at all defect positions (see figure 3.4). The analyses show that it is “meaningless” to use a fracture toughness requirement for the isostatic load case because the tensile stress is so low in all parts of the insert. Defect position no 4 can be assumed to have the worst damage tolerance, but it takes fracture toughness (given as K_{Ic}) levels lower than 4.1 MPa$\sqrt{m}$ to give acceptable defect sizes less than 80% of the section thickness. However, a requirement for fracture toughness is necessary for the shear load case as presented in section 4.3.

3.4 Displacement of the steel cassette

3.4.1 Displacement of the steel cassette, BWR-inserts

To be able to give a recommendation, regarding the displacement of the steel cassette, a number of sensitivity analyses have previously been conducted and reported, where the displacement of the steel cassette is varied between 0 and 15 mm [2]. The results, for BWR-inserts, are shown in Table 3.3 below.

Table 3.3. Maximum principal stress in the BWR-insert, using different rigid body displacement of the steel cassette.

Rigid body displacement [mm]	Max principal stress [MPa]
0	2.8
5	3.3
10	3.6
15	21.9

PDF rendering: DokumentID 1288292, Version 1.0, Status Godkänt, Sekretessklass Öppen

The table above show that the maximum principal stress (which is a tensile stress) increases when the displacement of the body reaches 15 mm. One should notice however that a rigid body displacement of 15 mm still meets the conditions for plastic collapse (for the isostatic load case [2]). An acceptable size of displacement would be 10 mm.

3.4.2 Displacement of the steel cassette, PWR-inserts

The maximum principal stress is lower for PWR-inserts as compared to BWR-inserts (approximately 50% lower) and the safety margin related to plastic collapse are higher (approximately 30% higher). It is therefore reasonable to have the same acceptable size regarding the displacement of the steel cassette (i.e. 10 mm).

PDF rendering: DokumentID 1288292, Version 1.0, Status Godkänt, Sekretessklass Öppen

4 CHARACTERISTIC PARAMETERS IN THE SHEAR LOAD CASE

4.1 Yield strength in tension, at 20°C

4.1.1 Yield strength in tension, BWR-inserts

Inspecta has performed a number of analyses of the shear load case [5] where the yield strength was varied between 246.6 MPa and 314.2 MPa (using a bentonite density of 2050 kg/m^3 and a rock shear = 5 cm). These analyses did not have any purpose to connect specific failure mechanisms (for the shear load case) to a requirement of the yield strength.

Not even in the design analysis [1] can any direct connection be found to a mechanism depending of the yield strength, however the stress strain curve is used when evaluating the elongation at failure. By setting requirements on a certain elongation, requirements are also applied to the stress strain curve (for example via the yield strength and the ultimate strength).

As can be seen in section 4.4 below, the design analysis [1] has defined an acceptable elongation at failure of 6.3%. Using the results from the analyses presented in [5] it is possible to investigate the maximum effective strain as a function of the assumed yield strength in tension. This relation is presented in Table 4.1.

Table 4.1. Maximum effective total strain as a function of the assumed yield strength in tension (shear load case with shear = 5 cm and density = 2050 kg/m^3).

Yield strength in tension [MPa]	Maximum effective strain
246.6	0.76%
280.4	0.70%
314.2	0.63%

The presented results for the insert, from the shear load case, are the maximum effective bending strain (as can be seen in Fig. 4.1, it is almost a pure bending case). This means that there exists an additional margin to the acceptable elongation at failure (which is defined using tensile test specimens).

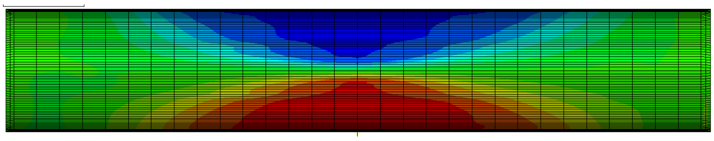

Figure 4.1. Maximum principal stress (or strain) for the shear load case, large tensile stresses/strains in red, large compressive stresses/strains in blue (from [5]).

This shows that a yield strength in tension of 247 MPa meets the elongation requirement in section 4.4. Because there is a very large margin to the acceptance criteria of 6.3%, a material with a worse stress strain curve (lower yield strength in tension) will also be acceptable. To simplify the presentation of the results, one can use the minimum requirement for the yield strength in compression, i.e. 240 MPa.

PDF rendering: DokumentID 1288292, Version 1.0, Status Godkänt, Sekretessklass Öppen

4.1.2 Yield strength in tension, PWR-inserts

For PWR-inserts, no extensive sensitivity analysis using different yield strength values in tension has been performed (as compared to the analysis of BWR-inserts in [5]). However, using a yield strength of 266 MPa, the maximum effective plastic strain is 0.58% (shear load case with shear = 5 cm and density = 2050 kg/m^3 [6]). This shows that the results for PWR-inserts are equivalent with the results for BWR-inserts, leaving the minimum requirement for the yield strength in tension to be 240 MPa.

4.2 Ultimate strength in tension, at 20°C

4.2.1 Ultimate strength in tension, BWR-inserts

Inspecta has performed a number of analyses of the shear load case [5] where the ultimate strength was varied between 416.8 MPa and 480.8 MPa (using a bentonite density of 2050 kg/m^3 and a rock shear = 5 cm). The results from these analyses were presented in section 4.1 (using yield strength as a parameter). This showed that an ultimate strength in tension of 417 MPa (equivalent to a yield strength of 247 MPa) meets the elongation requirement in section 4.4. Because there is a very large margin to the acceptance criteria of 6.3%, a material with a much worse stress strain curve (lower ultimate strength in tension) will also be acceptable. Therefore, the minimum requirement for the ultimate strength in tension would be 410 MPa (true stress).

The minimum requirement above could also be expressed as an engineering stress value using the same tensile test data as given in [5, 10]. The mean value using this data is 448.8 MPa (true stress) and 397.7 MPa (engineering stress). The chosen minimum requirement is 410 MPa (true stress), which is equivalent to 373 MPa (engineering stress).

4.2.2 Ultimate strength in tension, PWR-inserts

For PWR-inserts, no extensive sensitivity analysis using different ultimate strength values in tension has been performed (as compared to the analysis of BWR-inserts in [5]). However, using a ultimate strength of 425 MPa (true stress), the maximum effective plastic strain is 0.58% (shear load case with shear = 5 cm and density = 2050 kg/m^3 [6]). This shows that the results for PWR-inserts are equivalent with the results for BWR-inserts, leaving the minimum requirement for the ultimate strength in tension to be 410 MPa (true stress).

4.3 Fracture toughness, including 2 mm stable growth, at 0-20°C

4.3.1 Fracture toughness, including 2 mm stable growth, BWR-inserts

To be able to give a recommendation, regarding the fracture toughness, a number of sensitivity analyses have been conducted, where the fracture toughness is varied while the obtained acceptable defect sizes are controlled (for fracture toughness, a value of 2 mm stable growth is used, which is the most relevant value for the shear load case [3]).

In [3] a fracture toughness value is given (including 2 mm stable crack growth) in the form of $J_{2\text{mm}}$ = 88 kN/m (this being a value with 90% confidence, the average value is 91 kN/m). Using a pessimistic assumption regarding the postulated defect type (half elliptical surface defects with a defect length over depth ratio equal to 6) provided an acceptable defect depth of 4.5 mm (for the worst case bentonite density = 2050 kg/m^3). For fracture toughness, if one were to accept a deviation of 10% from the average value, $J_{2\text{mm}}$ = 82 kN/m is obtained. This corresponds to an acceptable defect depth of 4.2 mm, not that different from 4.5 mm, but if this can be qualified using a NDT system a lower

PDF rendering: DokumentID 1288292, Version 1.0, Status Godkänt, Sekretessklass Öppen

requirement with regards to J_{2mm} is obtained. Table 4.2 shows a sensitivity analysis where assumed fracture toughness is connected to acceptable defect depth.

Table 4.2. Acceptable defect depths for half elliptical surface defects (BWR-inserts, shear load case with shear = 5 cm and density = 2050 kg/m^3).

Fracture toughness including 2 mm stable growth [kN/m]	Acceptable defect depth [mm]
40	2.0
60	3.0
79	4.0
98	5.0
112	6.0

The table shows for example that if the NDT system can detect and size measure defects with a depth of 4 mm, the minimum requirement of fracture toughness would be 79 kN/m.

4.3.2 Fracture toughness, including 2 mm stable growth, PWR-inserts

Using a similar argument as above, a number of sensitivity analyses have been conducted, where the fracture toughness is varied while the obtained acceptable defect sizes are controlled (for fracture toughness, a value of 2 mm stable growth is used, which is the most relevant value for the shear load case [3]).

In [6] a fracture toughness value for PWR-inserts is given (including 2 mm stable crack growth) in the form of J_{2mm} = 78 kN/m (this being a value with 90% confidence, the average value is 86 kN/m). Using a pessimistic assumption regarding the postulated defect type (half elliptical surface defects with a defect length over depth ratio equal to 6) provided an acceptable defect depth of 4.1 mm (for the worst case bentonite density = 2050 kg/m^3). Table 4.3 shows a sensitivity analysis where assumed fracture toughness is connected to acceptable defect depth.

Table 4.3. Acceptable defect depths for half elliptical surface defects (PWR-inserts, shear load case with shear = 5 cm and density = 2050 kg/m^3).

Fracture toughness including 2 mm stable growth [kN/m]	Acceptable defect depth [mm]
38	2.0
76	4.0
108	6.0
134	8.0
160	10.0

The table shows for example that if the NDT system can detect and size measure defects with a depth of 4 mm, the minimum requirement of fracture toughness would be 76 kN/m.

PDF rendering: DokumentID 1288292, Version 1.0, Status Godkänt, Sekretessklass Öppen

4.3.3 Fracture toughness, comparison between BWR- and PWR-inserts

When comparing Table 4.2 and 4.3, one can see that the results are almost identical. This means that for an equivalent shear load the BWR- and PWR-inserts get almost identical *J*-values which are reasonable because the shear load is a displacement controlled load.

Recent fracture toughness data for PWR-inserts [7] is much better than the data for BWR- and PWR-inserts as given in Sect. 4.3.1-4.3.2. The reason for this is that earlier testing of BWR/PWR-inserts is conducted in water (at 0°C) and the more recent PWR-inserts are tested in air (at 20°C). This difference is mainly related to the testing conditions (water or air) and not the testing temperature. This has been shown in a study conducted in both water and air (at 20°C) which is summarized in Fig. 4.2 [8].

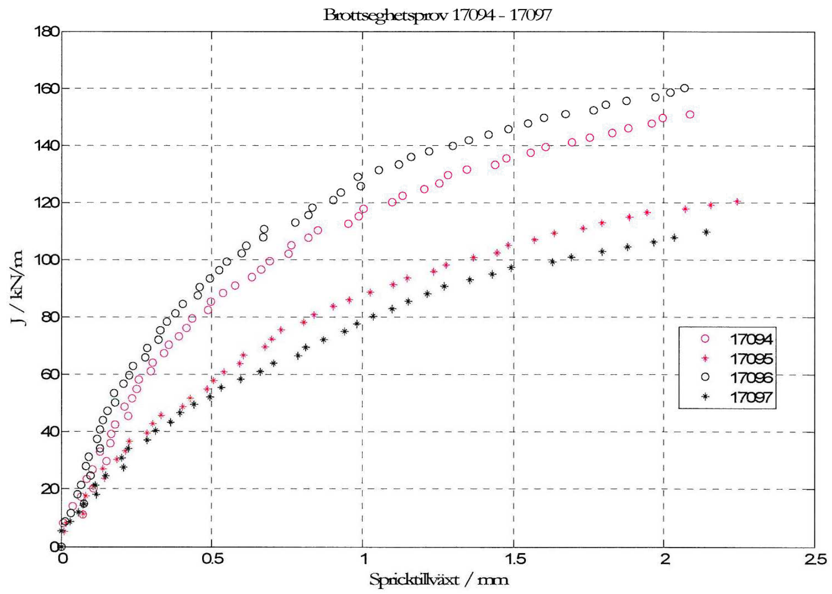

Figure 4.2. J_r-curvs for PWR-insert IP25 [8], a comparison between testing in water (the two lower curves) and air (the two upper curves) at 20°C.

This shows that the data from BWR/PWR-inserts (in water) is very conservative and PWR-data (in air) is more realistic to use in a damage tolerance analysis. However, since BWR/PWR-data (in water) has been used to calculate acceptable defect sizes for BWR/PWR-inserts, the minimum requirement will be given using data from fracture toughness testing conducted in water.

In order to show that it is reasonable to use fracture toughness data, including 2 mm stable crack growth, SKB has performed fracture toughness testing using very large test specimens (specimen length = 0.48 meter). These tests [9] can be summarized as follows:

- Two different test configurations were used (W = specimen width):
  - i) Specimens with a nominal crack depth $a = 0.15W$. For these specimens the crack extension was driven about 20 times longer than in a normal test.
  - ii) Specimens with a nominal crack depth $a = 0.6W$. For these specimens the crack extension was driven about 10 times longer than in a normal test.
- All test specimens had a significant amount of stable crack growth, up to approximately 33 mm.
- None of the test specimens experienced any unstable crack growth (globally).

The tests are also summarized in Fig. 4.3.

PDF rendering: DokumentID 1288292, Version 1.0, Status Godkänt, Sekretessklass Öppen

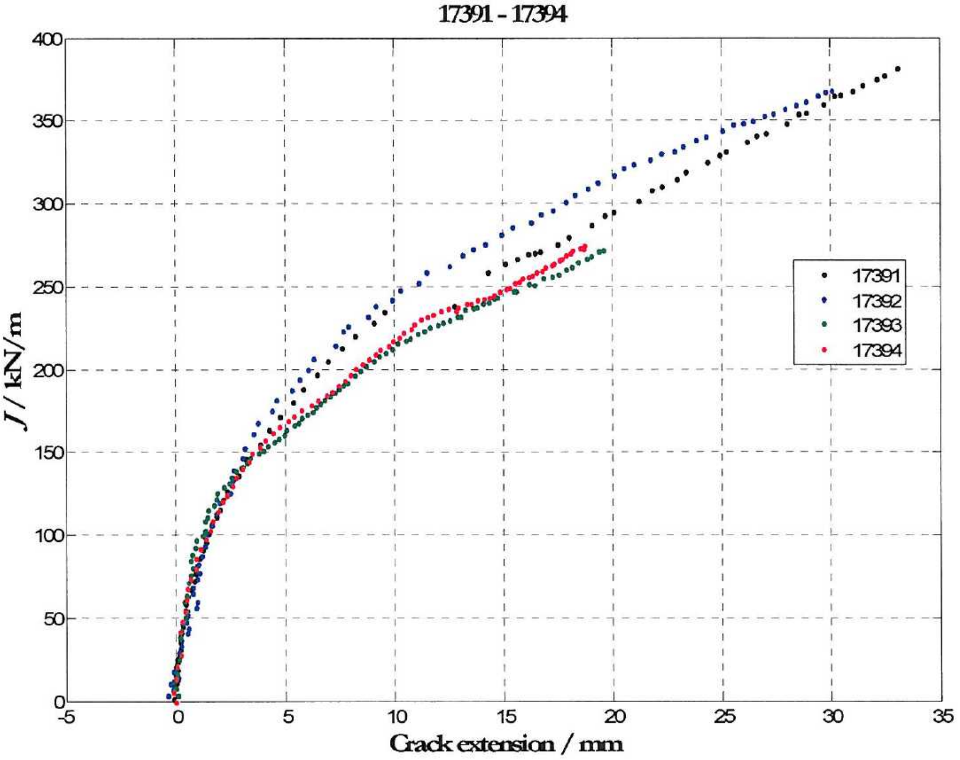

Figure 4.3. J_r-curvs using very large test specimens [9].

4.3.4 Relationship between stress strain data and *J*-values

As stated in Sect. 2.2, the stress strain curve (via yield strength and ultimate strength in tension) is of importance for the shear load case. This is because the stress strain data is used in the fracture mechanical analysis that is done prior to the damage tolerance analysis in [3]. It is therefore of interest to investigate the relationship between the assumed stress strain data and the *J*-values obtained in an FE-analysis. This has been performed as part of the analysis presented in [5]. Here the yield strength is varied between 247 and 314 MPa and the ultimate strength is varied between 417 and 481 MPa. Even though the variation in yield strength is ~27%, the largest variation in the *J*-values obtained is ~6% (using a crack depth of 10 mm).

4.4 Elongation at failure, at 0°C or at 20°C

4.4.1 Elongation at failure, BWR-inserts

When it comes to elongation at failure, no verifying analyses have been conducted [1]. There is however, an argument that connects testing in the form of elongation and stress strain curves to an acceptance criterion with regards to elongation at failure. This argument can be summarized in the following way:

- From testing an elongation at failure of 12.6% is obtained (using 90% confidence and defined as an engineering strain).
- A safety factor of 2 is used (with regards to the elongation, as defined and motivated in [1]), giving an acceptable elongation at failure of 6.3%.
- The design load case [1], using a bentonite density of 2050 kg/m^3 and a rock shear = 5 cm, has a maximum effective strain that is less than 1%.
- The worst combined shear load case (including ice load [1]) corresponds to an elongation (strain) of 2.55%.

PDF rendering: DokumentID 1288292, Version 1.0, Status Godkänt, Sekretessklass Öppen

The argument above indicates that there is a possibility to give a lower elongation requirement than 6.3%. It should be noted that a material which meets this (lower) requirement, will surely face problems with the above mentioned fracture toughness requirements. The reason being, that a material with low elongation values often has low fracture toughness values. There is a need to fulfill both requirements or the insert cannot be approved. Finally, it was not possible to decide if this testing should be performed at 0°C or at 20°C.

4.4.2 Elongation at failure, PWR-inserts

As mentioned earlier, using the results for an equivalent shear load, both the BWR- and PWR-inserts get almost identical strain values which are reasonable because the shear load is a displacement controlled load. This means that the results for PWR-inserts are equivalent with the results for BWR-inserts, leaving the minimum requirement for the elongation at failure to be 6.3%.

PDF rendering: DokumentID 1288292, Version 1.0, Status Godkänt, Sekretessklass Öppen

5 REQUIREMENTS REGARDING THE NDT SYSTEM

In this section, requirements regarding the NDT system are given related to the detection of crack like defects. These requirements are based on the calculated acceptable defect sizes given the measured fracture toughness data.

In section 3.3, it was shown that it is “meaningless” to use a fracture toughness requirement for the isostatic load case because the tensile stress is so low in all parts of the insert. Therefore, the requirements should be related to the shear load case only.

In section 4.3 one can see the results for the shear load case and its relation to acceptable defect sizes. For an equivalent shear load the BWR- and PWR-inserts get almost identical *J*-values which are reasonable because the shear load is a displacement controlled load (using a bentonite density of 2050 kg/m^3 and a rock shear = 5 cm). But, since the fracture toughness data for PWR-inserts (conducted in air) is much better than for BWR/PWR-inserts (conducted in water) it is better to present requirements separately. Fracture toughness values (including 2 mm stable crack growth) and acceptable defect sizes (using a pessimistic assumption with a postulated half elliptical surface defect with length/depth = 6 and oriented in the circumferential direction) are summarized in Table 5.1.

Table 5.1. Acceptable defect depths for postulated half elliptical surface defects (BWR- and PWR-inserts, shear load case with shear = 5 cm and density = 2050 kg/m^3).

Insert	Fracture toughness including 2 mm stable growth [kN/m]	Acceptable defect depth *a* [mm]
BWR	88	4.5
PWR	78	4.1
PWR (air data)	155	9.6

To better define requirements regarding the NDT system, data for internal cracks are also needed. These can be found in [3] (BWR-inserts) and in [6, 7] (PWR-inserts). Acceptable defect sizes (using circular and elliptical internal defects) are summarized in Table 5.2.

Table 5.2. Acceptable defect sizes for postulated circular and elliptical internal defects (BWR- and PWR-inserts, shear load case with shear = 5 cm and density = 2050 kg/m^3).

Insert	Defect geometry	Acceptable defect depth 2*a* [mm]	Distance from the surface (when an internal defect should be considered to be a surface defect) [mm]
BWR	circular internal defects	> 10.0	2
BWR	elliptical internal defects	> 10.0	2
PWR	circular internal defects	> 20.0	4
PWR	elliptical internal defects	> 10.0	2

Note: The acceptable defects depths is given as being larger than 10 mm or 20 mm. Larger defects would be acceptable but could not be analyzed because of restrictions in the FE-analysis [3, 6, 7].

PDF rendering: DokumentID 1288292, Version 1.0, Status Godkänt, Sekretessklass Öppen

The acceptable defect sizes given in Table 5.2 are calculated using postulated defect positions quite close to the surface of the insert [3, 6, 7]. These acceptable defect sizes are valid in all internal positions of the insert (a pessimistic assumption since the stresses are larger close to the surface). Also included in Table 5.2 is a definition when an internal defect should be considered to be a surface defect (using the rules in [11]).

Using the acceptable defect sizes given in Table 5.1 and 5.2 it is possible to give requirements regarding the size of crack-like defects in BWR- and PWR-inserts that the NDT system to be used should detect. The NDT system should be able to detect:

- Surface defects with a depth = 4.5 mm and a length = 27 mm (BWR-inserts).
- Surface defects with a depth = 4.1 mm and a length = 24.6 mm (PWR-inserts).
- Internal defects with a depth = 10 mm and a length = 60 mm (BWR- and PWR-inserts).
- Internal defects with a depth = 20 mm and a length = 20 mm (PWR-inserts).

The values given above are for a defect oriented in the circumferential direction of the insert (and perpendicular to the surface of the insert). If a defect is oriented in another direction, one will get larger acceptable defects.

- As an example, defects oriented 45° from the circumferential direction will get acceptable defects lengths which is multiplied by $\sqrt{2} = 1.4$ (same depth but larger length).
- Another example, defects oriented 45° from the surface will get acceptable defects depths which is multiplied by $\sqrt{2} = 1.4$ (same length but larger depth).

PDF rendering: DokumentID 1288292, Version 1.0, Status Godkänt, Sekretessklass Öppen

6 CONCLUSIONS

Inspecta Technology has produced a summary, based on the performed analyses, of the insert characteristic parameters that are of significance to the design of the BWR and PWR inserts. Based on this summary, it is possible to determine different requirements for these parameters. These requirements are summarized in the Table 6.1 below.

Table 6.1. Summary of different insert requirements (based on the performed analyses).

Parameters for BWR and PWR inserts	Min req.	Avarage req.	Max req.
Yield strength, compression at 20°C	240 MPa (1)	—	—
Ultimate strength, compression at 20°C	430 MPa (2)	—	—
Fracture toughness, at initiation (K_{Ic}), at 0-20°C	4.1 MPa $\sqrt{m}$ (3)	—	—
Displacement of the steel cassette	—	—	10 mm
Yield strength, tension at 20°C	240 MPa (1)	—	—
Ultimate strength, tension at 20°C	410 MPa (2)	—	—
Fracture toughness, BWR inserts, including 2 mm stable crack growth (J_{2mm}), at 0-20°C	88 kN/m	—	—
Fracture toughness, PWR inserts, including 2 mm stable crack growth (J_{2mm}), at 0-20°C	78 kN/m	—	—
Elongation at failure, at 0°C or at 20°C	6.3% (4)	—	—

Note 1: The above mentioned yield strength values are true stress values, but because the strains are small it doesn’t matter if they are given as engineering or true values.

Note 2: The above mentioned ultimate strength values are true stress values.

Note 3: It is “meaningless” to use a fracture toughness requirement for the isostatic load case because the tensile stress is so low in all parts of the insert.

Note 4: The above mentioned elongation value is an engineering strain value.

Also, requirements regarding the size of crack-like defects in BWR- and PWR-inserts that the NDT system to be used should detect are given in the report.

PDF rendering: DokumentID 1288292, Version 1.0, Status Godkänt, Sekretessklass Öppen

7 LIST OF REFERENCES

[1] RAIKO, H., SANDSTRÖM, R., RYDÉN, H. and JOHANSSON, M., (2010-04), “Design analysis report for the canister”, SKB Technical Report TR-10-28, Swedish Nuclear Fuel and Waste Management Co.

[2] DILLSTRÖM, P., ALVELIND, L. and ANDERSSON, M., (2010-01), “Framtagning av acceptanskriterier samt skadetålighetsanalyser för segjärnsinsatsen”, SKB Rapport R-10-11, Svensk Kärnbränslehantering AB.

[3] DILLSTRÖM, P. and BOLINDER, T., (2010-10), “Damage tolerance analysis of canister inserts for spent nuclear fuel in the case of an earthquake induced rock shear load”, SKB Technical Report TR-10-29, Swedish Nuclear Fuel and Waste Management Co.

[4] BOLINDER, T., (2011-03-21), ”Complementary damage tolerance analysis of the BWR iron insert subjected to an isostatic pressure load”, Technical Report 50010170-1, Rev. 0, Inspecta Technology AB, SKBdoc 1278258 - ver 1.0.

[5] DILLSTRÖM, P., and ALVERLIND, L., (2013-12), “Probabilistic analysis of BWR canister inserts for spent nuclear fuel in the case of an earthquake induced rock shear load”, Technical Report 50014130-1, Rev. 1, Inspecta Technology AB, SKBdoc 1412158 - ver 1.0

[6] DILLSTRÖM, P., BOLINDER, T., and E. BONNAUD., (2013-10-01), “Analysis of PWR canister inserts using data acquired from PWR material”, Technical Report 50010510-1, Rev. 3, Inspecta Technology AB, SKBdoc 1288288 - ver 2.0.

[7] SHIPSHA, A., (2013-12-03), “Statistical data analysis of cast iron properties for PWR-inserts from tension, compression and fracture toughness testing”, Technical Report 50017490-1, Rev. 1, Inspecta Technology AB, SKBdoc 1414800 - ver 1.0.

[8] ÖBERG, M., (2013-05-18), “Brottmekanisk provning av segjärn, IP25M”, Rapport SKB130518, KTH Hållfasthetslära, SKBdoc 1397931 - ver 3.0.

[9] ÖBERG, M., (2013-11-14), “Fracture toughness testing of cast iron, IP25”, Report SKB131109, Printed 131129, KTH Solid Mechanics, SKBdoc 1414796 - ver. 1.0.

[10] DILLSTRÖM, P., (2014-02-02), “Förstudie, Probabilistisk analys av skjuvlastfallet”, Inspecta PM 50011100-1, Rev. 2, Inspecta Technology AB, SKBdoc 1336557 - ver. 2.0.

[11] DILLSTRÖM, P., et. al., (2008), ”A combined deterministic and probabilistic procedure for safety assessment of components with cracks – Handbook”, SSM Research Report 2008:01, Swedish Radiation Safety Authority.

PDF rendering: DokumentID 1288292, Version 1.0, Status Godkänt, Sekretessklass Öppen

8 REVISIONS

Rev	Reason for change/Pages or sections	Our reference	Date
0	—	Peter Dillström	2013-11-29
1	Editorial comments. / All sections. Performed fracture toughness testing at 0°C is too conservative. / Summary and sections 2.1, 2.2, 3.3, 4.3 & 6. Use a fracture toughness requirement instead of a NDT system requirement / Summary and sections 4.3 & 6. Include fracture toughness testing using very large test specimens / Section 4.3.3. Investigate the relationship between the assumed stress strain data and the *J*-values obtained in an FE-analysis / New section 4.3.4. Reformulated the requirement regarding elongation at failure / Section 4.4.1. All references to SKBDoc 1064461 are removed / All sections.	Peter Dillström	2014-01-12
2	Revised according to comments made by SKB.	Peter Dillström	2014-02-04
3	The report is revised according to the review comments in SKBDoc 1425851, Ver. 0.8.	Peter Dillström	2014-02-22
4	Table 5.2 is revised to include a definition when an internal defect should be considered to be a surface defect.	Peter Dillström	2014-02-27

PDF rendering: DokumentID 1288292, Version 1.0, Status Godkänt, Sekretessklass Öppen