DETECTION AND SIZING SURFACE BREAKING DEFECTS IN NODULAR CAST IRON INSERT

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ABSTRACT

The planned disposal depth is about 420 m below ground surface in the bedrock. The nodular cast iron insert will be used as the inner component of the nuclear fuel disposal canister. The outer cover of the canister is a copper tube of 50 mm nominal thickness. The nodular cast iron insert is cast around several steel channels. The insert is the load carrying part of the canister structure. The basic dimensioning calculations are performed for normal operating conditions and in some upset conditions. The basic mechanical design load for the canister is 45MPa external pressure. The design load consists of the hydrostatic pressure of the groundwater, the swelling pressure of the bentonite buffer around the canister and of the pressure of glaciations of 2 to 3 km. The cast iron insert is checked in design pressure load cases to have a reasonable margin in general membrane stresses when comparing to the material design strength (yield strength) in the design temperature. Secondly, the structure is checked in postulated upset load conditions - 5 cm rock shear through the canister position - to have a reasonable margin against failure. This rock shear is setting requirement for the most critical defect size for the surface breaking cracks having dimensions of 4.5 mm (depth) x 27 mm (length) in circumference direction.
For surface inspection are used 70° TRL (Transmission-receiving-longitudinal, 2MHz) probes.
This measurement is carried out in direct contact using water as a couplant between the inspection specimen and probe. Probes are focused from 5 mm until 40 mm in depth. The focus point is in 20 mm depth. Four main directions for the inspection are used (2 in axial and 2 in circumference directions). This technique is a simple method for evaluating the surface volume until the nearest corner of the steel cassettes. The method is time consuming but can be accelerated by increasing the probes and its construction. The detectability of the 70° TRL probes has been tested against to thermally induced artificial cracks made by Trueflaw ltd. The depth of cracks varied between 1 to 6 mm which around the critical defect size. Also other ultrasonic techniques (TOFD, shear and longitudinal angle probes, creeping wave probes) have been tested to evaluate the size of the cracks. The results of the measurement have been reported.

1. INTRODUCTION

Design loads for the canister structure are mechanical loads (pressure, local forces or forced displacements), thermal loads (varying temperature in time or position), chemical loads (chemical around the canister environment, including bacteria-induced chemical loads) and radiation load (radiation embrittlement).

Loading phenomena are grouped into the following sets:

- Handling loads
- Incidents and accidents in the operation phase
- Internal loads
- External mechanical loads
- External chemical loads.

From the mechanical point of view, the most severe load cases are the isostatic pressure under the glacial period and the rock shear deformation. The strength values are mainly based on either tension or compression tests depending on the load case type. The only load case that may locally lead to significant yielding and plasticity of the insert is the rock shear case. Rock shear is, however, a “displacement-controlled load” that causes secondary stresses only, according to ASME nomenclature. If the load is secondary, the possible local yielding or cracking leads to decreasing stiffness and increasing deformation in the structure and, consequently, the load would decrease. That is why additional safety factors are not needed in displacement-controlled load cases. The maximum allowable surface defect size on the cylinder surface is a 4.5 mm deep and 27 mm long reference defect laying in a circumferential orientation. This damage tolerance analysis is the design basis load case for the canister insert for close-to-surface volumes, Raiko et al. 2010 /1/. The reference canister withstands the specified loads with an applicable safety margin even if the material has the allowable size defects mentioned above. The rock shear scenarios are shown in Figure 1 /2/.

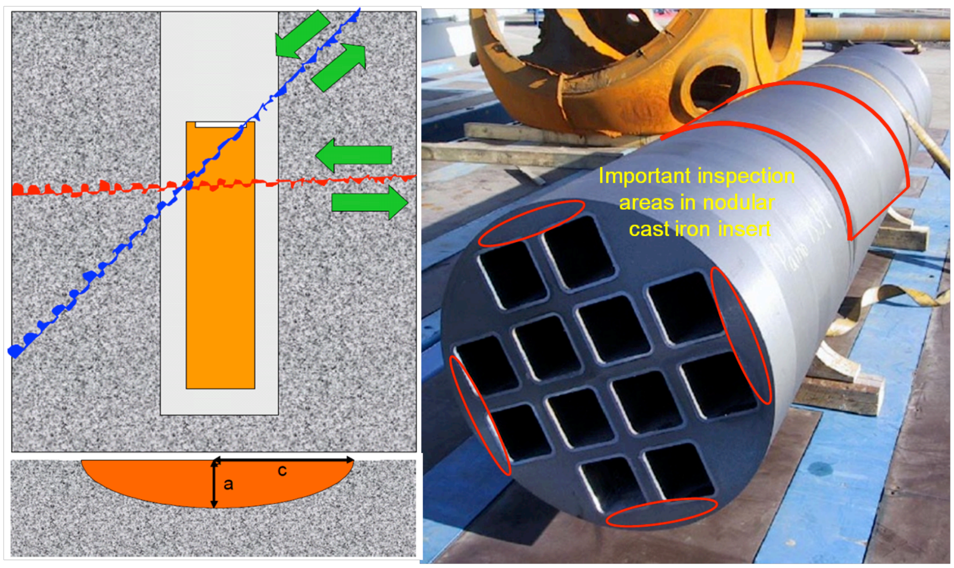


Figure 1. Rock shear is a “displacement-controlled load and the maximum allowable surface defect size on the cylinder surface is a 4.5 mm deep and 27 mm long reference defect laying in a circumferential orientation based on the fracture mechanics computations. Possible sensitive area on the surface is surrounded with the red line area. There are also in the insert one another near surface area, where can exist larger defect area - consisting of several pores forming a larger area.

The surface and near surface area will be inspected with TRL70-2MHz probes using typical 4 directions (0°, 90°, 180°, 270°), Figure 2. The acceptance -rejection process of the NDT-inspections for the insert is shown in Figure 2 on the right. According to this process the defect will be detected and sized as shown in Figure 2 in three phases: raw evaluation, advanced evaluation and evaluation deviation. This is the base when the detectability was studied in a real situation. This time the defects were real cracks which were manufactured on the surface. The surface is in typical condition as it has been until now. This is the object of this study.

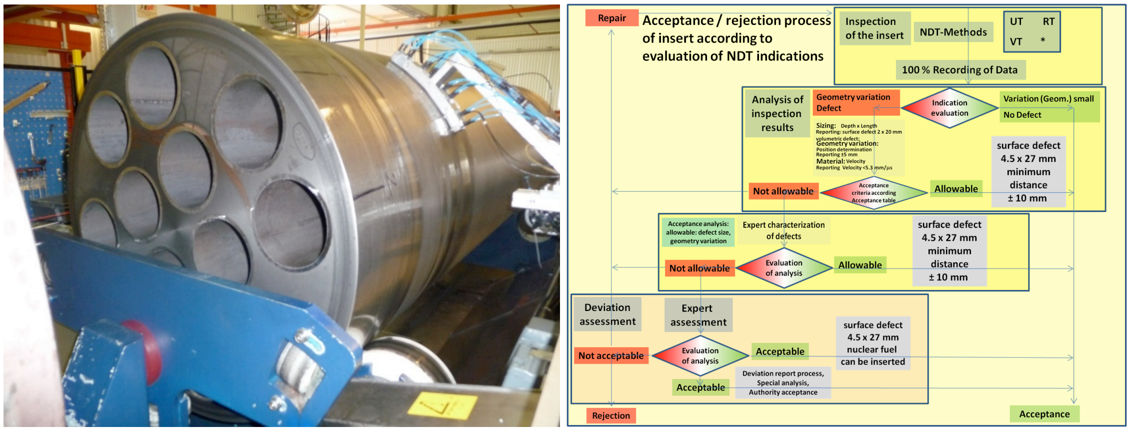


Figure 2. Surface and near surface inspection of VVER type of insert using TRL70-2MHz probes (left) and the acceptance and rejection process based on the NDT measurements (right)

2 DEFECT MANUFACTURING BY THERMAL FATIGUE

Controlled thermal fatigue cracks have been available since early 2000's from Trueflaw. In recent years the technology has matured, tried and tested. Capability of the technique to produce realistic, representative flaws has been analyzed by comparing the crack characteristics to the characteristics measured from service-induced cracks. This comparison has been made against measured values from service-induced flaws reported by Wåle /3/. The comparison indicated the flaws produced by the new technique are representative of several types of service-induced cracks. Current project represents the first instance of crack production to nodular cast iron. Due to it's two-phase microstructure, nodular cast iron presents new challenges for crack manufacturing. The nodules made crack initiation particularly easy and thus secondary cracking could not be avoided, especially for the larger cracks.

As always, to ensure reliable crack production and to know the depth of the produced cracks, each different crack produced is first validated destructively. That is, a crack is grown with a predetermined set of parameters and destructively examined to reveal the depth. Then, the same process can be repeated any number of times to produce number of similar cracks with known depth. This process is followed specifically for each material and flaw size. In this case, several validation trials were required to produce the desired cracking. Figure 3 shows example fracture surface image from a validation crack.

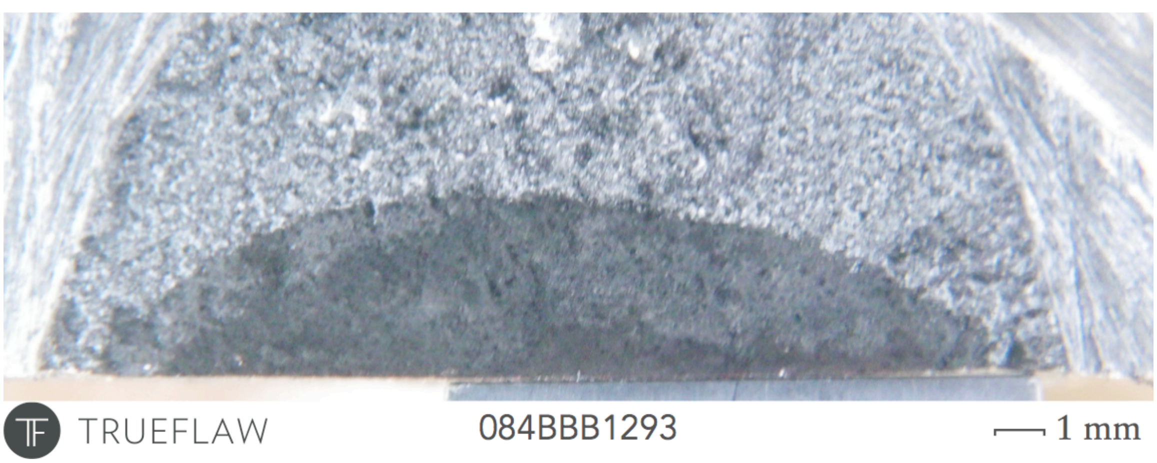


Figure 3. Example fracture surface image from a validation crack.

After validation, the actual cracks to the component were manufactured. Figures 4 – 5 show example surface image and PT image from a produced crack.

Figure 4. Example surface image from a produced crack. Graphite nodules are readily observable in the surface and seen to affect the crack growth.

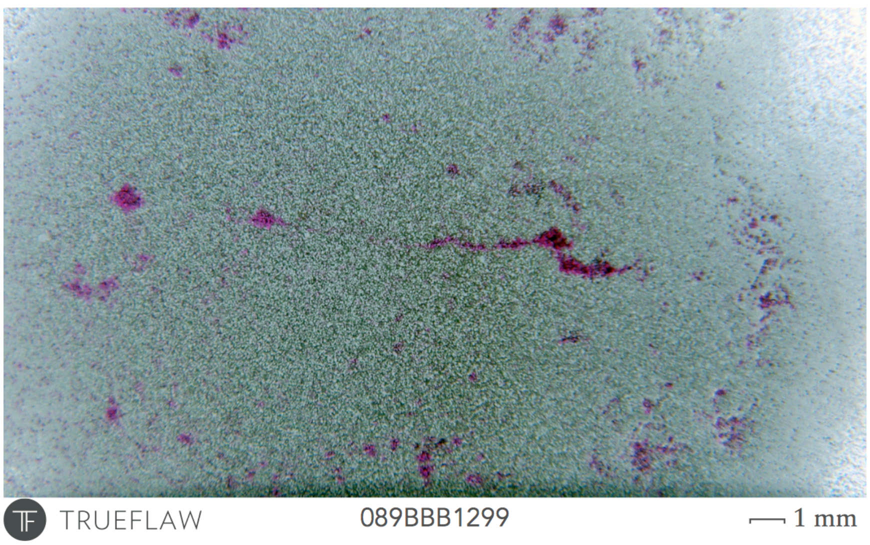


Figure 5. Example PT image from a produced crack.

For all the cracks, the sufrace opening was measured. Figure 6 shows example measurement graph. The mean opening for the crack in question was measured to be 46.6 µm. Altogether five cracks were produced. The crack sizes are shown in Table N1.

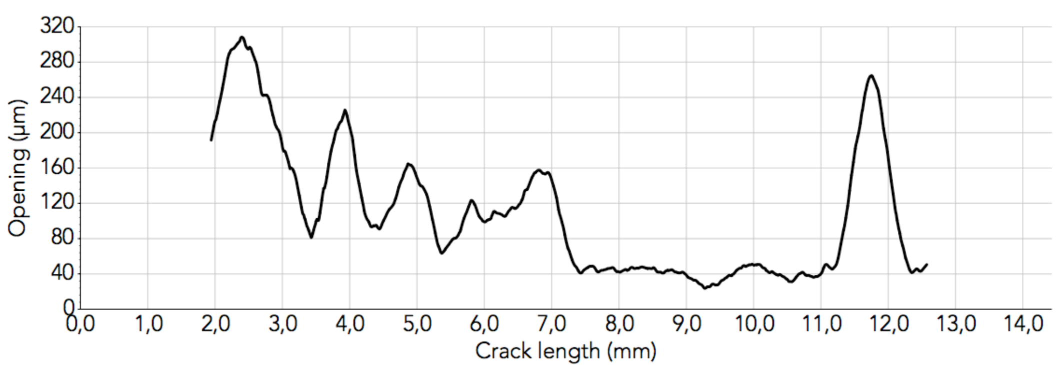


Figure 6. Example surface opening profile from a produced crack.

Table1. Manufactured crack dimensions.

Trueflaw flaw ID	Size (l x a)
229BBB1385	32.7 x 5.3
142BBB1346	24 x 4.3
c089BBB1299	12.0 x 1.7
143BBB1374	5.2 x 0.9
213BBB1375	3.8 x 0.9

3 SURFACE DEFECT DETECTION BY ULTRASONIC TECHNIQUES

Several methods were used to study surface defect detection and sizing. Some of the methods were applied manually and some using mechanized inspection. Surface wave technique (90°, two probes in similar configuration like in TOFD-method) was not used because the surface condition was not sufficient good and there were several secondary cracks near the actual crack as mentioned already in crack manufacturing part. The applied methods are named in Table 2. More advanced methods like SAFT /4/ or sampling phased array /5/ are also usable for surface breaking defect detection but those methods have not yet applied.

Table 2. The applied ultrasonic inspection methods to detection of surface breaking defects

Manual detection and sizng			
Technique	Detection	Depth Sizing	Length Sizing
T55 (conposite)	X	X	not applied
TRL-70 - 2 MHz	X	X	not applied
WSY-70 - 2MHz	X	-	not applied
PA (angular scanning	X	X	not applied
Mechanized detection and sizng			
Technique	Detection	Depth Sizing	Length Sizing
T55 (conposite)	X	X	x
TRL-70 - 2 MHz	X	X	x
WSY-70-2 MHz	X	-	x
PA (angular scanning	X	X	x
TOFD	X	X	x
Material property probe	x	-	x

3.1 Angle probe detection

Angle probe measurements can be done typically with single element or dual element probe. In this case the applied single element probe was shear wave probe having 55° angle of incidence. In order to evaluate the depth of a crack the tip diffraction can be used. In the crack three different areas can be distinguished /6/:

- Corner, which corresponds to CMOD (crack mouth opening displacement)
- Crack face, which corresponds to fracture surface of the crack
- Crack tip, which corresponds to effective area of crack tip opening (plastic zone), CTOD (crack tip opening displacement) and variable loading conditions

All these areas have own impact to the ultrasonic response. The size of the crack tip area is actually dependent on the load at the crack tip. Under tensile load the area can be estimated to be 3-4 x crack tip opening width (plastic zone) where crack tip affects. The possible echoes from crack face have to be taken in consideration also in evaluation of surface breaking defect, Figure 7. Crack tip diffraction techniques has been described in /7/

The depth sizing is very simple applying the formula 1

$$d = c\Delta t \cos(\alpha) \tag{1}$$

where d is the depth of a crack, c is the sound velocity of the inspected material, Δt is time of flight to crack tip and α is the angle of incidence.

The shear wave angle probe is usable there where grain size is small enough, but for instance in austenite materials shear wave probe can be applied successfully using short pulses either with high damped probes or as in our case composite probes. In case of cast iron there can be also echoes from voids and porosities originating from casting near crack tip which can cause errors in sizing. TRL-probe applies longitudinal wave which is less sensitive to larger grains in general, but in fact the wavelength vs. grain size is the actual parameter. In TRL probe near area of the signal has low noise level which is good for detection of surface defects. This is one of the main reasons for the use of TR-type of probes for surface defect detection. The TRL probe is especially good for detection of crack tip signals, which is well known in austenitic inspections. In these measurements the crack tip signals were applied for sizing. The calibration of TRL probe is more complicated compared to single element angle probe. Using TRL probe the angle of incidence varies a little in different depths. This can have an affect the sizing results. The angle variation can be gained in calibration using holes of varying depths. In this study the angle variation was not measured.

3.2 TOFD

Measuring the amplitude of the reflected signal can be an unreliable method of sizing defects because the amplitude strongly depends on the orientation of the crack. Instead of amplitude, TOFD (Time Of Flight Diffraction) uses the time of flight of an ultrasonic pulse to determine the position of a reflector/8/. In a TOFD system, a pair of probes is turned against each other. One of the probes transmits an ultrasonic pulse that is received by the other probe. In undamaged material, the signals picked up by the receiver probe are from two waves: first one that travels along. TOFD technique is well explained in /9/.

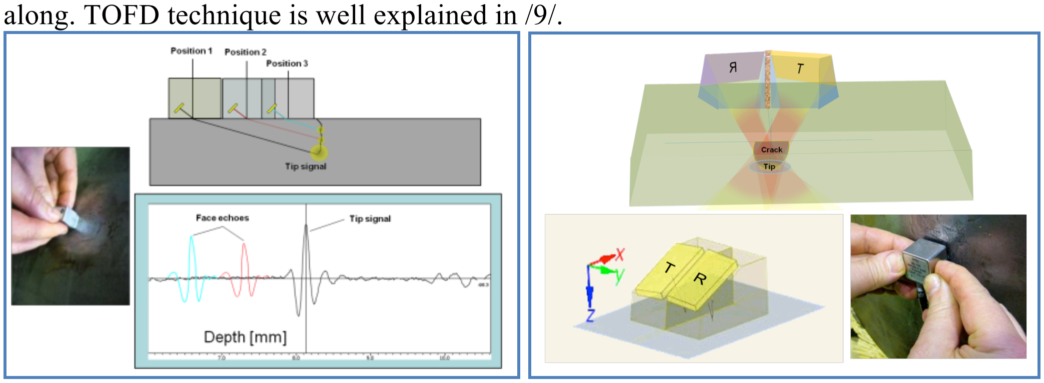


Figure 7. Sizing applying angle probe: Shear wave probe T55°- 4MHz (single element probe, left) and longitudinal wave probe TRL70-2MHz (dual element probe, right)

the surface and the other one that reflects from the back wall. When a crack is present, there is a diffraction of the ultrasonic wave from the tip(s) of the crack. Using the measured time of flight of the pulse, the depth of a crack tip can be calculated by simple trigonometry. TOFD technique uses normally longitudinal waves for detection and sizing. The main principle is to use crack tip signals in order to receive the dimensions of the crack. The depth of surface breaking crack can be estimated according to following way /10/:

$$d = 0.5\sqrt{(c\Delta t)^2 + 4c\Delta t S} \qquad (2)$$

Where d is the depth of a surface breaking crack, c is the sound velocity of the longitudinal wave in the inspected material, Δt is time difference between from lateral wave time of flight to crack tip, 2S is the separation between probes, which is in these measurements 16 mm. The calibration curve shows a good sizing capability for TOFD technique, as shown on the right in Figure 8.

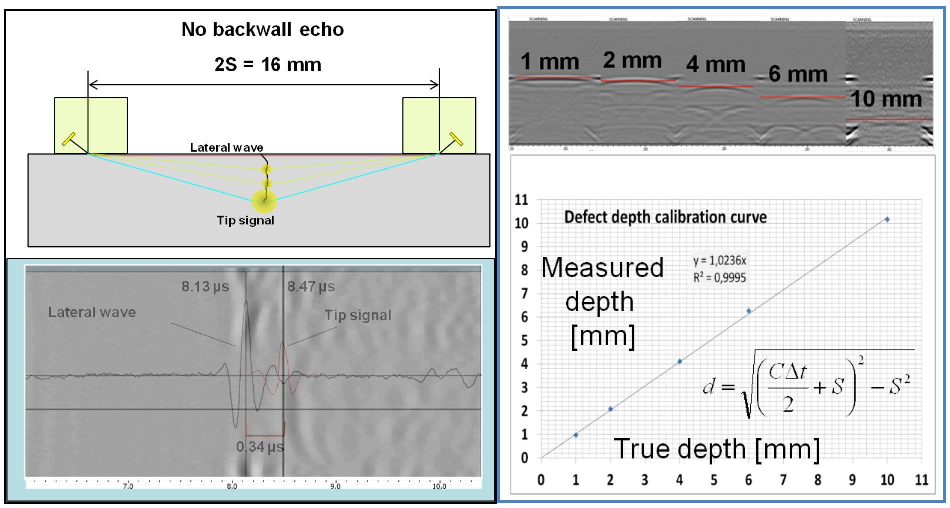


Figure 8. The measurement setup for surface breaking crack applying TOFD technique (left), calibration for measurement using notches having varying depths (1, 2, 4, 6, 10 mm) and corresponding calibration curve (right).

3.3 Phased array technique

Phased array probes consist of an array of elements. Driving electrically these elements sound field is produced into the material. Some of phased array parameter measurements is described in /11/. The principle is well known but the industrialized phased array systems came into use at the beginning of 2000. These systems were able to do manual or mechanized inspection. The best performance of the phased array system can be achieved by the angular scanning often called also sector scanning for sizing. There are several ways to use sectorial scanning. In this we are concentrated to sectorial scanning and the defects are on the same side as the probe. This makes the detection of the small surface defects more difficult, because the angle of incidence must be large. And the elements have a certain aperture, which affects the angular sensitivity of the probe in the larger angle range. This is depending mainly on the size of the single element in the active part of the phased array. The crack tip detection is clearly enhanced by focusing the ultrasound near the tip /12/.

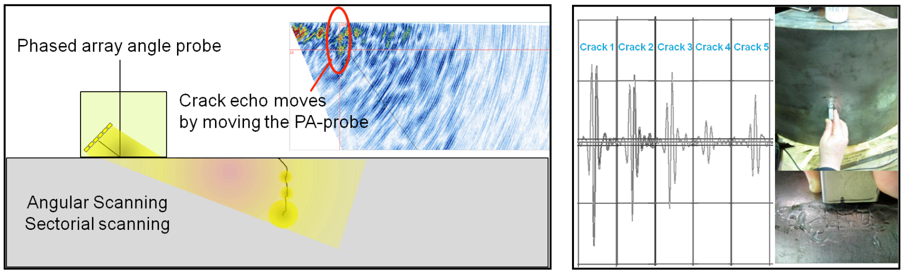


Figure 9. Phased array probe measurement of the cracks (on the left) and calibration results from the Creeping wave probe reflections from cracks of varying sizes.

3.4 Creeping wave probe

Creeping waves has been studied in many applications for crack detection successfully. The use is mostly applied to secondary creeping, which means crack detection in the opposite side as the probe is. In this studied case the cracks are in the same side as the probe and so called primary creeping are used for the detection of surface breaking cracks. The creeping wave probe is not applicable for sizing. The primary creeping can be calibrated using notches of varying depths. There are critical discussions of the existence of creeping waves (Blashan & Ginzel,2004). In spite of these wave type differences the method is usable for crack detection. In this study the term of creeping wave is used. The creeping wave probe can be calibrated either on shear wave or longitudinal wave velocity. In the measurement longitudinal wave calibration was applied. The primary creeping wave detectability of the manufactured 5 cracks was demonstrated manually as shown in Figure 9. All manufactured 5 cracks were clearly detectable as a minimum S/N 17 dB. The detection of creeping wave probe is not affected even if the crack is not oriented perpendicular to the sound beam of the probe. This is a good property as well as the high detectability of small cracks (depth of the crack is small). The characteristics of the creeping wave probe is discussed more detailed in Erhard study /13/

3.5 Material property probe

Surface (Rayleigh-waves) and leaky-Rayleigh waves are widely used in acoustic microscopy to characterize different materials and thin surface films and coatings. Much less is reported about the application of the same wave types in the low-frequency range. However, the same theoretical background and principles on which the high-frequency acoustic lenses are based can be utilized in low-frequency immersion and contact transducers. The low-frequency (2-15 MHz) transducers technique used for creating Rayleigh and leaky-Rayleigh-waves on the surface of a material can be applied for surface defect detection. The information received from material properties are measured with a special ultrasonic probe optimized for surface measurement and with a 0° longitudinal wave probe. The technique is based on combination of three factors: using back scattered ultrasonic signals and induced leaky Rayleigh wave information (1), and simple statistical data analysis (2) in combination with optimized ultrasonic transducer (3). The back scattered ultrasonic signal is a measure of the amount of geometrical reflectors such as micro-pores, inclusions, precipitations, segregations, micro-cracks and cracks as well as of back-scattering from phase boundaries during fatigue damaging and increase of degradation inside the material /14/. The leaky Rayleigh wave component is sensitive to surface properties as known from normal Rayleigh wave probes. Especially cracks cause strong effect on the leaky Rayleigh wave. If the crack is deep it cancels the leaky Rayleigh wave signal totally.

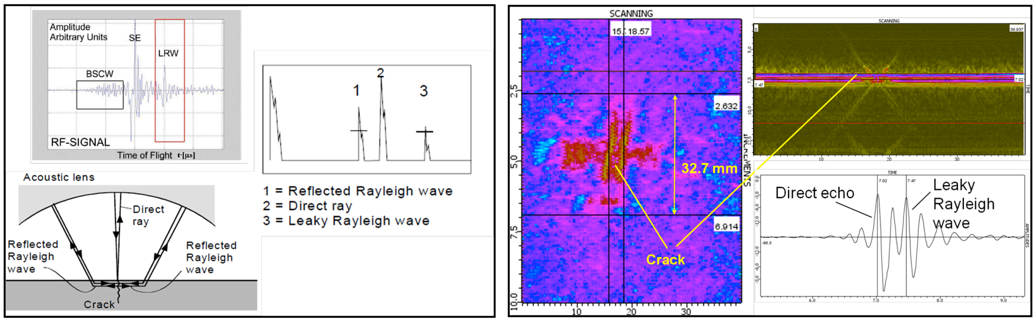
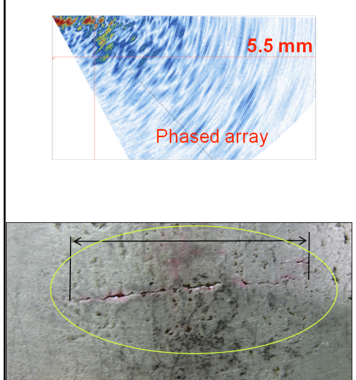


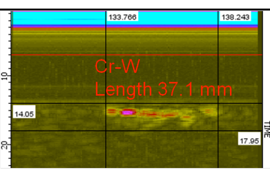
Figure 10. The principle of material property probe (left) and images (C-, B- and A-scans) from a crack measurement (right).

4 MEASUREMENTS

Both mechanized and manual inspections were carried out applying real size mock up, which was cut from actual nodular cast iron insert component. To this mock up were manufactured artificial cracks as described earlier. All the inspection methods were applied to these cracks. The main emphasis was the detection and sizing of the cracks. The results will be discussed crack wise.

The cracks were quite tight according to the crack manufacturer and this was also seen in the measurements. Other factor was the surface roughness which is clearly affecting the detection and sizing capability. The specified roughness Ra was 12.3 µm, which is clearly too rough for the ultrasonic measurements.





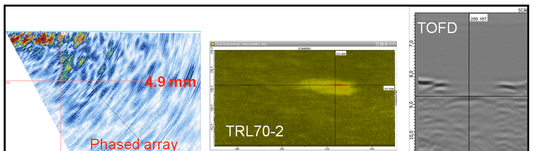
Crack 1	Length [mm]	Depth [mm]
TF	32.7	5.3
TOFD	18.7 (33.2)	6.1
PA-AS	-	5.5
T55	-	5.4 – 5.9
TRL70-2	10	6.0
Cr-W	37.1	-
MPP	33.0	-

Figure 11. The results from the ultrasonic sizing measurements applied to the crack 1

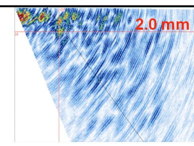
Crack 1 was according to manufacturing data (33 mm in length x 5.3 mm in depth) the deepest crack and similar results were estimated using applied ultrasonic methods. The crack size in depth and length is deeper than allowable defect size. The detectability was clear using all methods. The depth sizing gave a little deeper depth (5.4 - 6.1 mm) than the manufacturing data assumed, Figure 11. The difference was less than 1 mm. The length sizing gave 33 mm using TOFD and Material property probes, which was same as surface size estimated by the manufacturer. Creeping wave probe gave longer length (37 mm) and TRL probe gave clearly shorter length (10 mm) than the actual length of the crack.

Crack 2 was according to manufacturing data (24 mm in length x 4.3 mm in depth) the second deepest crack and similar results were estimated using applied ultrasonic methods. The crack size in depth and length is similar to allowable defect size. The detectability was clear using all methods. The depth sizing gave a little deeper depth (4.5 - 5.1 mm) than the manufacturing data assumed, Figure 12. The difference was less than 1 mm. The length sizing gave 23-24 mm using TOFD and Material property probes, which was same as surface size estimated by the manufacturer. Creeping wave probe gave only little bit shorter length (19.9 mm) and TRL probe gave clearly shorter length (11.6 mm) than the actual length of the crack, Figure 12 (left).

Crack 3 was according to manufacturing data (12 mm in length x 1.7 mm in depth) middle deep crack and similar results were estimated using applied ultrasonic methods. The crack size in depth and length is clearly smaller than allowable defect size. The detectability was clear using all methods. The depth sizing gave a little deeper depth (1.5 - 2.0 mm) than the manufacturing data assumed, Figure 12. The difference was less than 1 mm. The depth sizing was clearly more difficult compared to crack 1 and crack 2. The length sizing gave 11.0 mm using creeping wave probe and 10.4 mm material property probes, when the actual length was 12.0 mm estimated by the manufacturer. TOFD probe gave shorter length (6.0 mm) than the actual length of the crack and using TRL probe the length sizing was not successful, Figure 12 (right).



Crack 1	Length [mm]	Depth [mm]
TF	24.0	4.3
TOFD	15.4 (23.3)	5.1
PA-AS	19.9	4.9/5.3
T55	-	4.7
TRL70-2	11.6	4.5
Cr-W	19.9	-
MPP	23.6	-

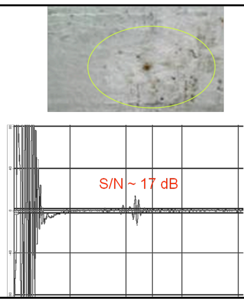


Crack 1	Length [mm]	Depth [mm]
TF	12.0	1.7
TOFD	6	1.9*
PA-AS	-	2.0
T55	-	-
TRL70-2	-	1.5 - 1.7
Cr-W	11.0	-
MPP	10.4	-

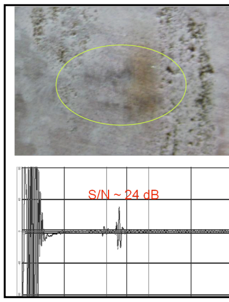
Figure 12. The results from the ultrasonic sizing measurements applied to crack 2(left) and crack 3(right).

Crack 4 was according to manufacturing data (5.2 mm in length x 0.9 mm in depth) small crack and detectability was clearly difficult. The crack size in depth was less than 1 mm, which is clearly less than allowable depth (4.5 mm) and in length in the range of sound field size (6 dB). The crack was not detectable in the data of mechanized measurements except in the data of the material property probe. Detection was not so clear also using the material property probe, but the length sizing could be done giving length 5.4 mm. The depth sizing was not successful, Figure 13 (right). Using manual inspection of creeping wave probe the crack could be detected clearly with S/N 17 dB.

Crack 5 was according to manufacturing data (3.8 mm in length x 0.9 mm in depth) smallest crack and detectability was clearly difficult. The crack size in depth was less than 1 mm, which is clearly less than allowable depth (4.5 mm) and in length in the range of sound field size (6 dB). The crack was not detectable in the data of mechanized measurements except in the data of the material property probe. Detection was not so clear also using the material property probe, but the length sizing could be done giving length 3.5 mm. The depth sizing was not successful, Figure 13 (left). Using manual inspection of creeping wave probe the crack could be detected clearly with S/N 24 dB.



Crack 1	Length [mm]	Depth [mm]
TF	5.2	0.9
TOFD	-	-
PA-AS	-	-
T55	-	-
TRL70-2	-	
Cr-W	Manually	-
MPP	5.4	-



Crack 1	Length [mm]	Depth [mm]
TF	3.8	0.9
TOFD	-	-
PA-AS	-	-
T55	-	-
TRL70-2	-	-
Cr-W	Manually	-
MPP	3.5	-

Figure 13. *The results from the ultrasonic sizing measurements applied to crack 4 (left) and crack 5 (right).*

5 SUMMARY AND CONCLUSIONS

The nuclear fuel disposal canister contains nodular cast iron insert. the insert is the load bearing component is the structure. One loading possibility is rock shear case, which according present fracture mechanics computations has given allowable defect size in circumference direction 27 mm in length x 4.5 mm in depth. In this study several ultrasonic measurement techniques has been applied to detect and size artificial cracks on the surface of real size mock up.

These cracks are very tight and thus more difficult for ultrasonic testing. In the mock up the surface roughness according to manufacturing specification was 12.3 µm, which is clearly too rough for the ultrasonic measurements. This is already noticed and the manufacturing specification has been changed to have smaller surface roughness.

The detectability was sufficient to detect not allowable and allowable surface breaking crack size. Even clearly smaller crack than allowable (12 mm in lenght and 1.7 mm in depth) was clearly detected. Only the smallest cracks could not be found clearly. The surface roughness and tightness had of course affect on the detectability of those small cracks.

The sizing of the cracks could be applied using several methods. The simplest methods for depth sizing were clearly TOFD and PA applying angular scanning. The best method to size the crack lenght was the use of the material property probe. The TOFD technique was also applicable for lenght sizing even though the smallest defect were not successfully sized.

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