Safe Product Design -The Role of the NDE Reliability Analysis

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Abstract
When pushed to the limits of their detection capability, NDE systems do not produce consistent hit/miss indications. Their capability of detecting small defects is therefore expressed in terms of POD. An adequate NDE system is required to ensure the structural integrity. In conventional signal response analysis, the POD is expressed as a function of the defect size, and its adequacy for the inspection task is tested against the maximum allowable defect size which will not undermine the structural integrity. Analyses of modern structures show that other parameters, beside the defect size, can both significantly influence the POD and determine the severity of the defect for the structure. Within the multi-parameter reliability analysis, the POD is expressed as a function of those influencing parameters. When determining the adequacy of the NDE system, the capability of detecting a defect has to be expressed and tested against the critical value of exactly that parameter that determines defects severity for the structure. Failing to do so can lead to a rejection of the healthy, or acceptance of the bad part. The principle is demonstrated on the example of the Transmit-Receive Longitudinal (TRL) ultrasonic inspection of the iron cast component for semi-elliptical surface defects.

Keywords: reliability, probability of detection (POD), multi-parameter, ultrasonics, transmit receive longitudinal (TRL)

1. Introduction

There is a constant strive to produce engineering structures which perform a specified function with ever higher degree of reliability and safety. This is accomplished through good design, manufacturing, test and operational practices. During operational life, structures need to withstand loads imposed on them. These loads can be mechanical (static, dynamic), environmental (temperature, humidity) or chemical. They are the reason for structural degradation and resulting damage. The damage may be generated at microscopic level and may gradually progress until it becomes observable and eventually critical. The combination of fatigue loading and fracture mechanics allowed the new principle of damage tolerant design to be established. This principle, as opposed to safe life design, allows damages such as cracks to be present in a structure as long as the overall integrity of the structure is not compromised. This is achieved by either monitoring slow crack growth through well-defined inspection intervals or building in load redundancy [1].

One way in which a structure may fail is mechanical failure. This occurs when the structure, or part of it, loses its mechanical integrity to such an extent that it ceases to perform as designed. The mechanical integrity required to function as designed is called the structural integrity. There are many ways in which components can fail mechanically.

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They may be overloaded, wear out, be exposed to a corrosive environment outside of that for which they were designed. They may also be badly designed, or manufactured, or be operated in an abusive way. However, one of the most frequent causes of failure is the presence of crack-like defects [2].

The real tensile strength of hard brittle materials is significantly lower than their theoretically predicted strength, by considering the effect of small cracks and/or other crack-like defects. Cracks introduce high stress concentrations near their tips in an elastic brittle material and, therefore, the tensile strength of material is exceeded earlier than when the stress is uniformly distributed in the material. Although any single failure event may seem to be relatively inconsequential in isolation, it can be the forerunner of a chain of events (cascading failure), which result in truly catastrophic consequences [2]. A catastrophic failure is an event that results in loss of life or serious person injury, drastic change to environment or significant physical damage or destruction.

Non-destructive evaluation (NDE) plays a significant role in minimizing the possibilities of failure. Evaluating the test object without changing or altering it in any way, the quality or integrity of a structure aimed to be determined. NDE cannot however guarantee that the failure will not occur. Bad design or improper application may be a cause of the failure even if the NDE was properly applied. To detect a defect, an adequate inspection system has to be available. The smaller the defect that can be detected with the NDE system, the lighter and thinner the structure can be [3].

When NDE systems are driven to their extremes of finding small flaws, not all flaws of the same size will be detected. Repeated inspections of the same flaw will not produce consistent detection indications. The capability of finding flaws is therefore expressed in terms of reliability. The POD analysis is considered to be a standard method for quantifying NDE system performance [4].

2. Methods and Materials

2.1 Project background -safe disposal of nuclear waste

Nuclear industry, including nuclear waste disposal, is a field in which overseeing a critical defect can lead to catastrophic consequences. It is a technical consensus of most waste management specialists that geological disposal, using a system of engineered and natural barriers, is the preferred means of disposal for high level and long lived radioactive wastes [5]. The concept of the deep geological disposal developed in Sweden is named KBS-3. The safety is guaranteed by the multiple technical and natural barriers [6]. The most important technical barrier is a canister in which the radioactive waste will be encapsulated, shown in Figure 1.

The inner part of the canister is made of a cast iron and its role is to withstand mechanical loads imposed on the canister in the repository. The shell of the canister, made of copper, has a function to isolate the radioactive material from the environment. The lid and the bottom are welded to the tube once the spent nuclear fuel has been put inside the canister. To make sure that the canisters will fulfil the function of safe long-term storage, all canister parts and the sealing weld will be inspected for defects with NDE systems, before the canister is put into the final repository. The reliability study, as a part of the repository assessment, needs to evaluate the NDE methods used for the inspection of the canisters.

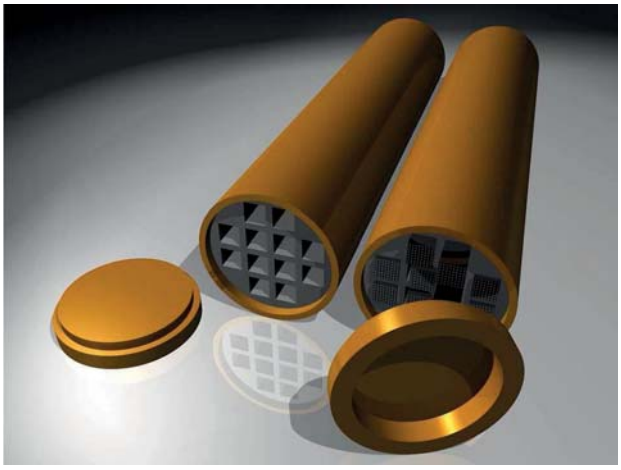
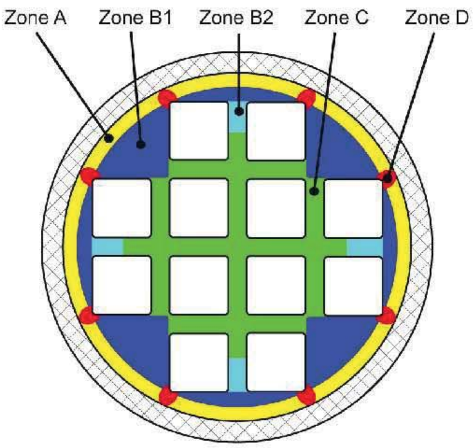


Figure 1. Canisters for a long-term storage of nuclear waste

2.2 Damage Tolerance Analysis

Using the damage tolerance analysis, the influence of different types of postulated defects under different types of loading in the repository on the structural integrity of the canister was calculated [7]. To simplify the connection between the results of the analyses and the non-destructive testing results, the insert was divided into zones, as shown in Figure 2 (a). This means that also the location of the defect within the canister determines its influence on the structural integrity. As the most dangerous defect in the shear loading case, the surface semi-elliptical defect (notch), shown in Figure 2 (b), was identified. Acceptable sizes of those defects are shown in Table 1.



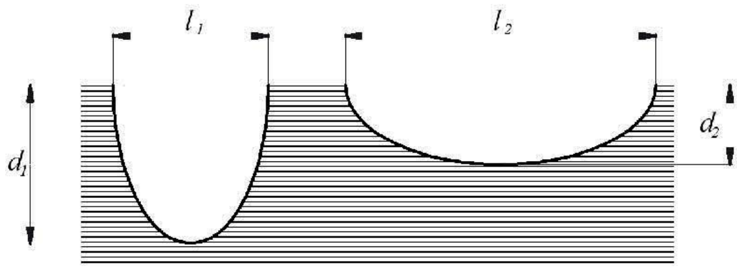


Figure 2. Cross section of the iron cast insert, divided in zones to facilitate easier NDE and damage tolerance analysis (a) and surface, semi-circular crack-like defects (b)

Table 1. Acceptable sizes for postulated semi-elliptical surface crack-like defects

Density of bentonite [kg/m^3]	Acceptable depth *d* [mm]	Acceptable length *l* [mm]	Area ($A = 1/4\ \pi\ d\ l$) [mm^2]
2050	4.5	27	95
2000	8.7	52.2	357
1950	>10	>60	>471
Exemplary notch (42% of the length and depth of the most critical defect):			
n/a	1.89	11.34	16.8

2.3 Transmit Receive Longitudinal (TRL) Ultrasonic Inspection of the Cast Iron Insert

The insert of the canister is manufactured from a nodular cast iron. The performance of the ultrasonic inspection of cast iron is degraded because of the coarse grain structure, which leads to attenuation losses and scattering noise. Conventional UT techniques are less applicable for these materials because of the commonly very low signal-to-noise ratio (SNR) achieved. To overcome these difficulties, low frequency TRL ultrasonic probes are suggested for inspection to reduce backscattered noise and therefore enhance the SNR, especially in close to surface regions [8]. The TRL transducer is used for ultrasonic inspection of the close to surface zone of the insert. The inspection spans over the whole length of the insert and includes the depth down to 40 mm. The aim of the inspection is to detect volumetric and crack-like defects within the inspection range. The inspection is performed with four 2MHz TRL transducers with a 70º angle of incidence and 90º separation.

2.4 Reliability Analysis

The reliability analysis was performed both with the conventional signal response and with the multi-parameter method. For the analysis, 20 electric discharge machined (EDM) notches with depths in range from 1 to 5 mm and lengths in range from 1 to 30 mm were manufactured in the test specimen.

The conventional signal response analysis assumes linear dependence of the recorded signal amplitude and the size (area) of the notch in logarithmic scale [9]. Measured response signals values were plotted against the notch area. Setting the decision threshold to 3 SNR, the POD as a function of the notch area was calculated.

The multi-parameter analysis assumes linearity between the measured response signal and the theoretically predicted signal [10]. The predicted signal is calculated as a function of the parameters that influence the response signal. In the case of the TRL inspection of the semi-elliptical notch, the POD was calculated as a function of the notch length and depth.

3. Results

3.1 Conventional Signal Response Reliability Analysis

The POD curve with lower 95% confidence band calculated with a conventional signal response analysis is shown in Figure 3. The curve is plotted as a function of the notch area. The notch that will be detected with 90% probability with 95% confidence – the a90/95 point – is calculated to have the area of 15.9 mm2.

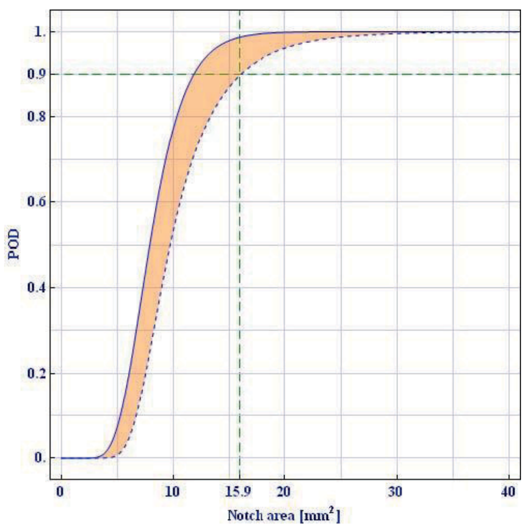


Figure 3. POD curve with lower 95% confidence band as a function of the notch area with indicated a90/95 point

3.2 Multi-parameter Reliability Analysis

The multi-parameter reliability analysis, performed using notch depth and length as parameters, resulted in the POD surface shown in Figure 4. The POD is plotted against the notch depth and notch length. This kind of representation is only suitable to get a general impression of the POD behaviour. To read out the values, more convenient diagrams, shown in Figure 5, are created. These diagrams show only the lower 95% confidence bands. The POD curves are omitted for clarity. In the diagram in Figure 5 (a), the lower 95% confidence bands are plotted as a function of notch depth, calculated for three different notch lengths. In the diagram Figure 5 (b), the lower 95% confidence bands are plotted as a function of notch length, calculated for three different notch depths.

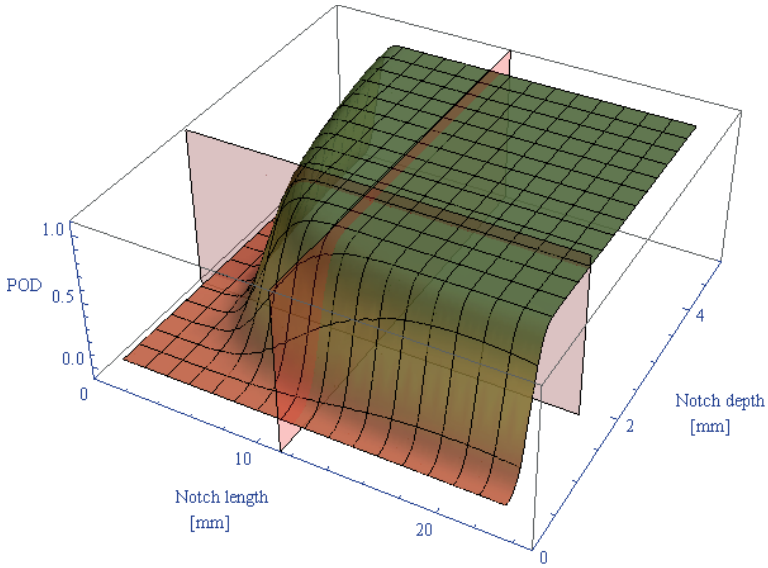


Figure 4. POD surface as a function of the length and depth of the notch with indicated length and depth of the exemplary notch

3.3 Comparison of the Conventional and Multi-parameter Analysis

To make a direct comparison between the two methods, the POD is calculated with multi-parameter analysis as a function of the notch size. Figure 6 shows the lower 95% confidence bands calculated for different notch depths (dashed lines) and the lower 95% confidence band calculated with a conventional signal response analysis (solid line).

4. Discussion

If we assume, as commonly used in the damage tolerant design, the a90/95 point as a measure of the minimum size of the defect which would still be reliably detected by the inspection system (15.9 mm2 from the diagram in Figure 3), and compare it with the maximum allowable defect size (in the worst case scenario regarding the density of the bentonite 95 mm2 from Table 1) we can see that the maximum allowable defect size is almost 6 times larger than the size of the one which would still reliably be detected. It can be concluded that the system is adequate for the inspection task.

The same conclusion comes from the multi-parameter analysis. From the Table 1, in the worst case scenario regarding the density of bentonite maximum allowable defect depth is 4.5 mm and the maximum allowable length is 27 mm.

This is much larger than the minimum reliably detected notch, both in terms of notch length and depth (Figure 4). It can be concluded that the inspection system is capable of detecting all defects sizes which would be a reason for the part rejection i.e. the inspection system is adequate for the inspection task. However it is evident that the POD grows with respect to depth and length asymmetrically.

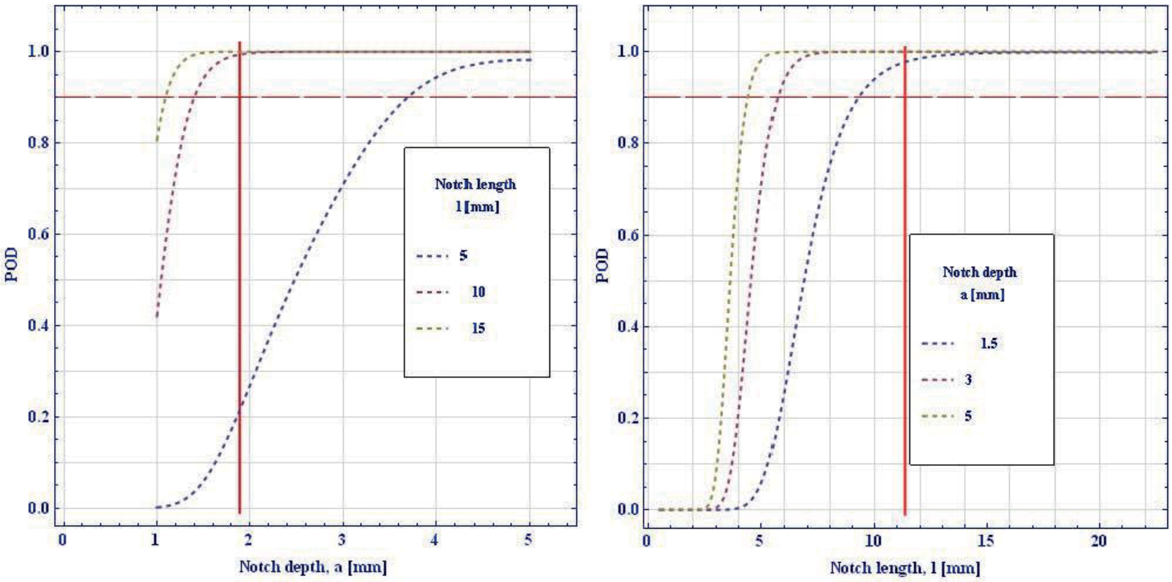


Figure 5. Lower 95% confidence bands as a function of the notch depth (a) and length (b). The 1.89 mm depth and 11.34 mm length of the exemplary notch is indicated with a red vertical line

To illustrate the importance and an advantage of the multi-parameter reliability analysis over the conventional one, the case with much smaller exemplary notch which has only 42% of the length and depth (which is 17.7% of the area of the notch) of the worst case scenario notch from Table 1 will be investigated. Assuming that this is the maximum allowable notch size, it will be compared with the a90/95 of the inspection system. In Figure 4, the length and the depth of the exemplary notch are drawn in the POD diagram as planes intersecting the POD curve. As it is assumed that these are the values of maximum allowable notch size, the inspection system needs to reliably detect all defects which are larger than this one (the upper right quadrant in the diagram). Much easier to read are the cross-sections of this surface shown in Figure 5. The red vertical line in both diagrams represents dimensions (depth and length respectively) of the exemplary notch. It can be seen from the diagram in Figure 5 (a) that the inspection system would be adequate for the exemplary notch, if it would have depth of 10 or 15 mm (the intersection of the lower 95% confidence band and 90% probability is smaller than the exemplary notch depth), but not if the notch is 5 mm long (the a90/95 is larger than the depth of the exemplary notch). It can be confusing that the POD is increasing with smaller depths. This will be explained little later. From the diagram in Figure 5 (b) it can be seen that the inspection system is adequate for notches of all three plotted depths.

To make a direct comparison with the conventional signal response analysis, the diagram in Figure 6 should be analysed. The red vertical line is once again the area of the exemplary notch. The intersection of the green solid line from the conventional analysis and 90% probability is smaller than the maximum allowable defect size. Therefore, the conventional analysis would declare the NDE system as adequate for the inspection task.

However, from the multi-parameter analysis there are curves available for notches with different depths. Again, somewhat confusingly, the POD of the notch drops with the increase of the notch depth.

This can be explained if we look at the area of the exemplary notch. The lower 95% confidence band of the exemplary notch that is 3 mm deep is almost 100%. The notch with the same area but deeper, with 5 mm depth, has the lower 95% confidence band at the level of about 86%. To have the same area, this notch needs to be longer. So both notches have the same area, but different aspect ratio. We can see that not only the area but also the orientation (or aspect ratio) of the notch influences the POD. This is illustrated also in Figure 2 (b). Two notches, having the same area but different orientation, have different POD.

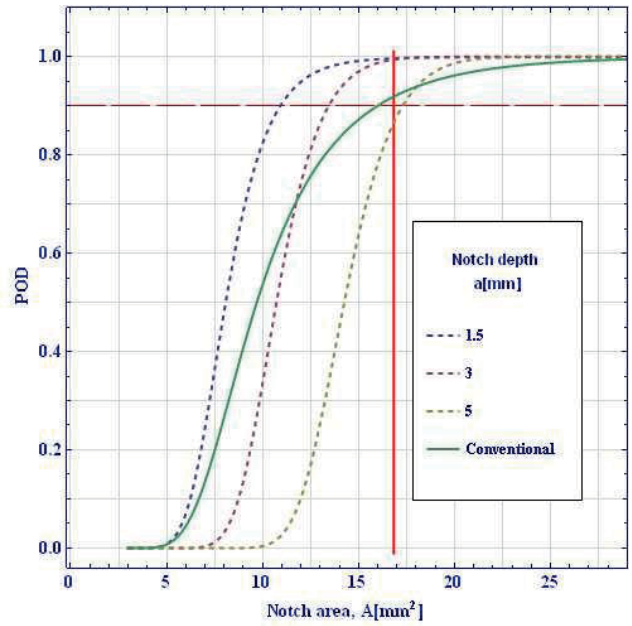


Figure 6. Comparison of the lower 95% confidence bands expressed as a function of the notch area calculated with the conventional signal response analysis (solid curve) and with multi-parameter reliability analysis (dashed curves). The red vertical line marks the exemplary defect with the area of 16.8 mm2

5. Conclusions

In a constant pursuit of creating safer and more reliable products, NDE plays an important role in all stages of operational life. To be able to detect defects which might be present in a structure, an adequate NDE system is needed. When applied to their limits, the NDE systems will not produce consistent indications. The capability of detecting defects is therefore described as the reliability of NDE, whereas the POD curves are considered as a standard way of quantifying the NDE system's capability of detecting defects. The reliability analysis is specifically performed in fields, where missing a defect can lead to catastrophic consequences.

The adequacy of the NDE system was traditionally judged by comparing the minimum defect size as reliably detected (such as a90/95 point) with a maximum allowable defect size. However, new challenges posed by new materials and geometries of the parts need to be inspected and new, advanced inspection systems, change this simple criterion. Neither the POD of the defect is determined by the defect size only, nor is the severity of the defect for the structure determined only by the defect size.

It can be seen from the fracture mechanics analysis of the iron cast insert for nuclear waste containers that the maximum allowable defect length is larger than the maximum allowable defect depth i.e. the canister is more sensitive on the defects that extend in the depth. The TRL inspection system also demonstrated different detection probabilities, depending on the defect orientation. Defects that are deeper will have smaller POD than the shallower defects, having the same size (area).

The multi-parameter reliability analysis gives an opportunity to express the POD of the defect as function of different influencing parameters and compare it to exactly those parameters, which define the severity of the defect for the structure. Only in this way, an acceptance of a bad part or rejection of a healthy one can be avoided.

References

1. *C Boller and F-K Chang and Y Fujino, 'Encyclopedia of Structural Health Monitoring'', John Wiley and Sons, 2009.*
2. *I Milne and R O Ritchie and B Karihaloo, 'Comprehensive Structural Integrity: Fracture of Materials from Nano to Macro ', Elsevier Science Ltd, 2003.*
3. *C Hellier, 'Handbook of Nondestructive Evaluation', McGraw-Hill, 2003.*
4. *W D Rummel, 'Probability of Detection As a Quantitative Measure of Nondestructive Testing End-To-End Process Capabilities', Materials Evaluation, 1998.*
5. *IAEA, 'Scientific and Technical Basis for Geological Disposal of Radioactive Wastes', International Atomic Energy Agency, 2003.*
6. *SKBF/KBS, 'Final Storage of Spent Nuclear Fuel – KBS-3', SKBF/KBS, 1983*
7. *SKB, 'Design, production and initial state of the canister', SKB, 2010*
8. *M Delaide and G Maes and D Verspeelt, 'Design and Application of Low-Frequency Twin Side-by-Side Phased Array Transducers for Improved UT Capability on Cast Stainless Steel Components', Procedeeings of the 2nd International Conference on NDE in Relation to Structural Integrity for Nuclear and Pressurized Components, New Orleans, 2000.*
9. *A P Berens, 'NDE Reliability Data Analysis', ASM International, 1989*
10. *M Pavlovic and K Takahashi and C Mueller, 'Influence of Multiple Parameters on the Probability of Detection of the Flaw', Preprint submitted to NDT and E International, 2011*