FEASIBILITY STUDY OF USING EFLAWS ON QUALIFICATION OF NUCLEAR SPENT FUEL DISPOSAL CANISTER INSPECTION

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ABSTRACT

The Swedish KBS-3 design for the disposal of spent fuel is based on the encapsulation of the fuel in canisters that consist of cast iron inserts and an outer 5-cm-thick shell of copper. To verify that the copper canisters fulfil the requirements, an extensive program for quality control is under development. In this program, the use of non-destructive testing (NDT) is vital, and it is therefore very important to develop reliable NDT methods, demonstrate their capability and, finally, qualify the NDT procedures.

The qualification of NDT procedures traditionally requires representative mock-ups with a significant number of representative flaws. For the copper canister weld inspections, the expected flaw types and their NDT responses are well characterized due to extensive research [1]. However, there are limited possibilities for the artificial manufacturing of representative flaws with pre-defined sizes. In addition, the data collection is highly automated and reliable, and the main focus for qualification is thus in the data analysis.

In present report, the use of the eFlaw technology has been developed and evaluated for the purpose of qualifying the weld inspection. The eFlaw technology allows extracting flaw signals from the existing NDT data files and introducing them back into the data files in different locations. Thus, the existing NDT data files can be used to produce a high number of "flawed" data files for training and qualification purposes. The copper canister inspection is fully automated and thus well suited for the method. The previously available technology has been developed further to be applicable to the copper canister inspection. In particular, the ability to use a single dataset containing flawed and unflawed regions for the flaw extraction has been developed and evaluated.

With eFlaw, a limited number of collected data files can be used to produce a virtually unlimited number of blind data files for training and qualification purposes. With good access to variable training data, the data evaluators can improve their skills, become more confident and perform better. For qualification, each candidate can receive an individual blind data file, thereby improving the confidence level of the personnel qualification and, thus, its reliability. Furthermore, the time-consuming collection of ultrasonic data for each data set is avoided.

INTRODUCTION

SKB is developing nondestructive testing (NDT) methods for inspecting copper canisters that are for the final disposal of spent nuclear fuel [1]. The methods and procedures will be qualified according to the Swedish requirements, which follow the guidelines published by the European Network for Inspection and Qualification (ENIQ). At the same time, the inspection requirements and conditions for the canisters are markedly different from typical nuclear inspections previously qualified in Sweden. Thus, it is expected that the qualification will need to be adapted significantly to suit the needs of this particular inspection.

The ENIQ publishes a methodology document and set of recommended practices for conducting inspection qualification [2]. These form a flexible set of guidelines and are explicitly meant to be adapted for varying legal, regulatory and technical requirements.

In the ENIQ methodology, the qualification consists, in simple terms, of

- input information, which details the inspection target,
- technical justification, which justifies the applicability of the chosen inspection technology,
- open trials, which show the capability of the system on representative, known mock-ups, and finally,
- blind trials, which show the capability of the inspection personnel on representative mock-ups containing defects unknown to the inspector.

Both the open and blind trials traditionally require representative mock-ups. The manufacture of these representative mock-ups containing flaws is challenging. Often, the availability of representative mock-ups with a sufficient number of defects is one of the key challenges in qualification. This is one of the key reasons for having the technical justification in such an important role in the ENIQ methodology. In addition to the qualification mock-ups, the inspectors will need additional samples for training and method development.

The challenge in providing representative mock-ups is common for all qualifications. For the canister inspection, there are additional challenges due to the rather unique materials and flaw types that are not well represented in traditional artificial flaw manufacturing methods. Furthermore, the canister inspection requires a highly specialized and fixed setup that will collect the inspection data. These requirements place some limitations on the way in which data collection can be done during the qualification exercise.

Ideally, the qualification mock-ups should contain a sufficient number of various flaws to give a reliable (in statistical terms) picture of the capabilities of the inspection. Because the reliability requirements of the inspections are high, it follows that the number of flaws needed to provide statistical assurance of meeting the reliability is also high. For example, the ASTM-E2862 standard for probability of detection analysis [3] requires 60 flaws to define the 90% POD flaw size with 95% confidence. The mock-ups should also provide a sufficient number of defect-free areas to provide ample opportunity for detecting excessive false-call rates. Sufficient mock-ups should be available for training, open trials and blind trials. For the blind trials, there is also the risk of inspectors "learning the mock-ups"; thus, additional mock-ups are needed to provide sufficient variation in qualification trials and avoid developing dependence between supposedly independent qualification trials. These factors compound and cause the number of required mock-ups and flaws to become unmanageable for the traditional approach.

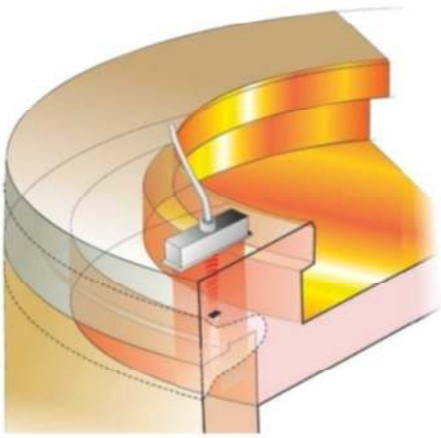
Modern automated inspections, such as the highly specialized system applied in canister inspection, provide new opportunities to work around these traditional limitations. With automated inspection, the data gathering and analysis are separated into distinct steps. This separation allows new possibilities for training and qualification. Because the analysis now operates, essentially, on pre-recorded data, the need for different physical training samples and training data sets is also separated. The data gathering can be developed and qualified on physical samples, and the more demanding data analysis can be completed on a separate data set. The needs for these two steps are quite different. For data gathering, a representative sample is needed, but the problematic need for a high number of representative flaws primarily concerns data analysis. Consequently, being able to modify the gathered data sets to include non-existing virtual flaws offers several significant advantages: the number of physical test blocks and flaws can be reduced, the number of flaws in the data can be increased to give statistically significant results and the number of different data sets available can be increased such that every trainee or qualification candidate receives a fresh data set.

This is the central idea of the eFlaw technology developed by Trueflaw [4]: a pure flaw signal is extracted from flawed data set and then re-introduced into various locations in the data set to provide a virtually unlimited number of different data files for training and qualification purposes.

In this feasibility study, the previously developed eFlaw technology was further adapted for the SKB canister weld inspection case, and the resulting data files were evaluated for applicability for the intended training and qualification purposes. Previously, the flaw extraction had been done with two separate data files that were acquired before and after the flaw production. This process was not possible in this case because the flaws of interest are manufacturing flaws inadvertently created during the welding trials and cannot be manufactured artificially for a ready-made mock-up. Thus, the technology was developed to extract the flaw signal by comparing two different areas in the data file (flawed and unflawed). In addition, one of the challenges for such technology is the obscurity of the data file formats produced by the used ultrasonic inspection equipment. Consequently, significant adaptation was also necessary to facilitate use of this technology with the file formats presently applied by SKB.

MATERIALS AND METHODS

The preliminary ultrasonic inspection of the canister weld is performed using a linear array from the top of the copper lid, as shown in figure 1.



Probe parameter	Value
Centre frequency	3.5 MHz
Number of elements	128
Pitch between elements	1.0 mm
Passive aperture size	16 mm

Figure 1. Ultrasonic inspection setup of the canister weld. [1]

The phased array ultrasonic data files consist of a number of individual ultrasonic channels that apply electronic scanning using different inspection angles and focus depths according to table 1.

Table 1. Ultrasonic inspection setup of the canister weld.

Channel	Region	Angle	Depth range	Aperture (elements)	Focus depth
+20° root	Root	20°	40-65 mm	50	60 mm
+12° root	Root	12°	40-75 mm	50	60 mm
0° root	Root	0°	51-76 mm	50	60 mm
-12° root	Root	-12°	50-80 mm	40	67 mm
-20° root	Root	-20°	55-75 mm	28	67 mm
+35° shallow	Upper part excl. root	35°	30-63 mm	42	47 mm
+35° deep	Lower part excl. root	35°	57-88 mm	55	75 mm
+25° shallow	Upper part excl. root	25°	30-62 mm	39	45 mm
+25° deep	Lower part excl. root	25°	57-88 mm	50	75 mm
0° shallow	Entire weld excluding surface	0°	30-90 mm	32	60 mm

SKB provided the data file from weld "FSW105" for this study. In the file, one root indication is clearly seen at the inspection channel "-20° root" at the circumferential position of 15°.The circumferential section 240°-300° is free of indications. Thus, the data in the "-20° root" ultrasonic channel at the circumferential position of 12°-18° were designated as the defect data, and the circumferential position 240°-300° were designated as the non-defect data volume to be used as the reference for the flaw signal extraction.

The target UT data (corresponding with channel "-20° root") were extracted from the .uvdata file format. The data were then processed to extract the pure flaw signal, as described below. Then, the extracted flaw signal was re-introduced to the original data in different locations to produce a modified UT data set. Finally, the modified UT data were written back to the original .uvdata file to produce a modified .uvdata suitable for use in training or for evaluation purposes. Each of these steps is described in more detail below.

Available UT channels

Each channel contains an array of A-scans (i.e. recorded UT amplitudes as function of time). The corresponding data for each channel were extracted, and a C-plot was generated from the data (i.e. projection of the data in parallel to the scanning surface). These are shown in figure 2. The horizontal axis shows the circumferential scans around the canister weld from 0 ... 360°, and the Y-axis shows the radial direction. Each pixel represents a maximum value of the A-scan in the relevant position. The raw data is stored in 16 bit values (i.e., possible values range from 0 to 65536). However, true measured values use only a fraction of the possible range, and the colors are thus scaled to range from 0 to 6% of the possible range (roughly equal to 24 dB "software gain").

The analysis was completed on the UT data corresponding to the "-20° root" channel in the .uvdata file provided. The data consisted of 1834 circumferential positions (0.2°/step, approximately 360°), with 25 a-scans per position and 150 data points per a-scan. Each data point is a 16-bit unsigned integer value. An overview of the target data is shown in figure 2. The designated flaw region and the unflawed region are shown in more detail in figures 3 and 4, respectively.

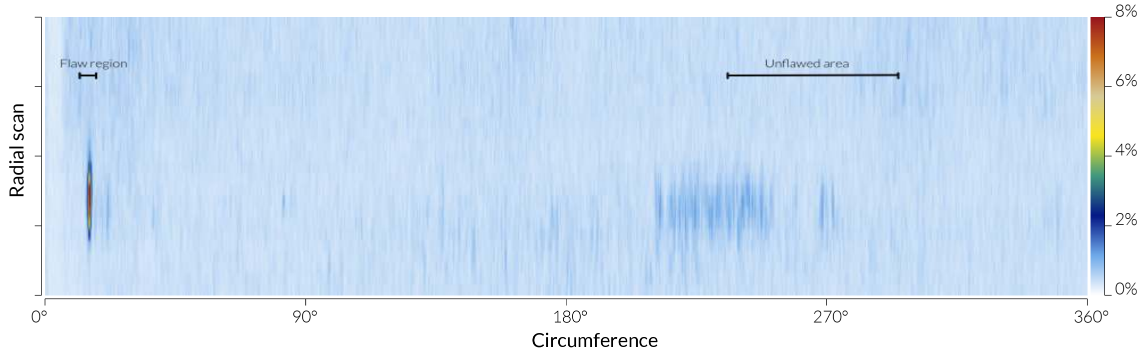


Figure 2. C-plot from the target ultrasonic channel "-20° root"

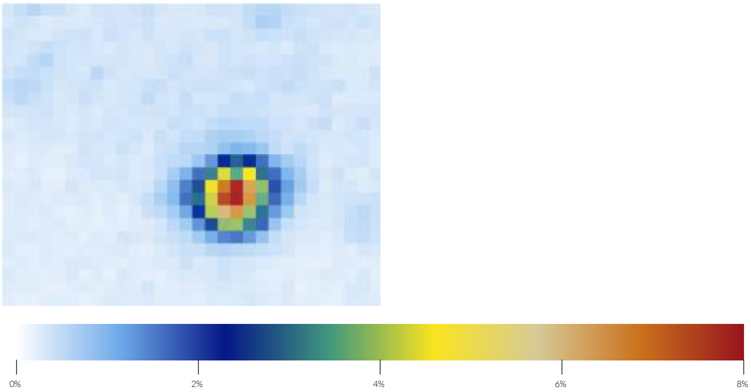


Figure 3. Detailed view of the designated flawed region (12° – 18°, scanlines 60-90)

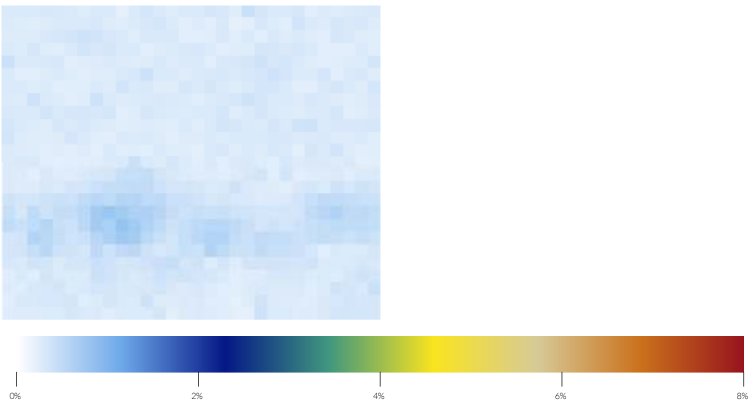


Figure 4. Detailed view of the designated unflawed region (250° – 256°, scanlines 1250-1310)

Flaw signal extraction

To extract the flaw signal, the difference between the flawed region and the corresponding unflawed region was taken data point by data point. Due to the variation in the noise, some of these differences were negative. Consequently, the difference signals were stored as signed values.

Due to the difference in the noise level between the designated flawed region and the unflawed region, the extracted signal could not be used directly. When this was tried, a noticeable difference in the noise level of the modified data was observed. This difference gives away the flaw location and thus interferes with the use of the data file for the intended purpose. To alleviate this problem, a histogram filter was applied to the extracted flaw signal, thereby reducing the noise level but leaving the flaw signal intact. The filter is depicted in figure 5. The threshold was adjusted until no adverse effect was noticed to 10%. By using this filter, the difference in the noise level was removed, and good data files were obtained. Filtering the extracted signal potentially disturbs the flaw signal and may affect data analysis. Thus, a filter with minimal impact on the signal was sought and the threshold value set on trial-and-error basis to avoid disturbing the signal. Some sizing techniques (most notably the various dB-drop techniques) may be sensitive to filtering.

To re-introduce the flaw signal to another location in the data file, a process roughly inverse to the extraction was applied. That is, the extracted flaw signal was summed, data point by data point, to the chosen location.

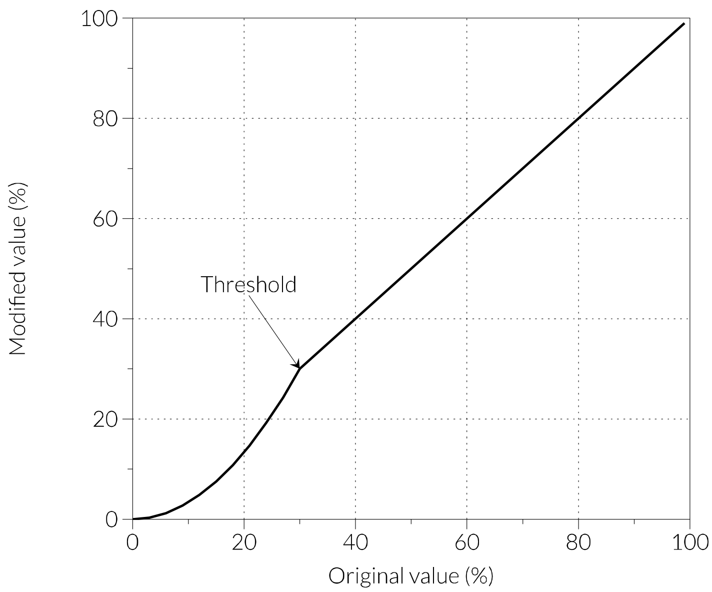


Figure 5. Histogram filter applied to the flaw data to remove noise effects on re-introduction of the flaw signal. A threshold value is determined as a percentage of the maximum peak value present in the data. Values above this value are not modified. Values below this value are multiplied by linearly decreasing factor resulting in a histogram filter as shown. (Negative values are similarly adjusted.) Threshold is set high for illustration, true threshold was adjusted to data.

RESULTS

With the tool set developed as described above, three modified data files were generated for detailed evaluation of the data. Figure 6 show C-scans from three generated data files. The images show that the flaw can be re-introduced to designated locations, and no noise difference or other artefacts are observable. To further investigate possible artifacts introduced by the data modification, the UT data were analyzed at the a-scan level. Figure 7 shows a-scans from the original flaw, the original signal at the re-introduction location and finally, the modified a-scan with the flaw introduced. The images indicate that the a-scans do not show any noticeable artifacts resulting from the modification process.

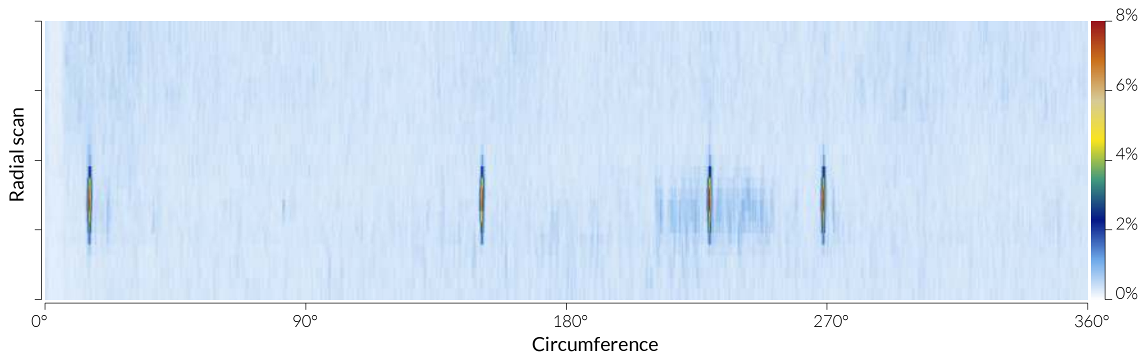


Figure 6. C-scan from modified data file showing the original flaw and the three times re-introduced flaw at locations 150°, 230° and 270°.

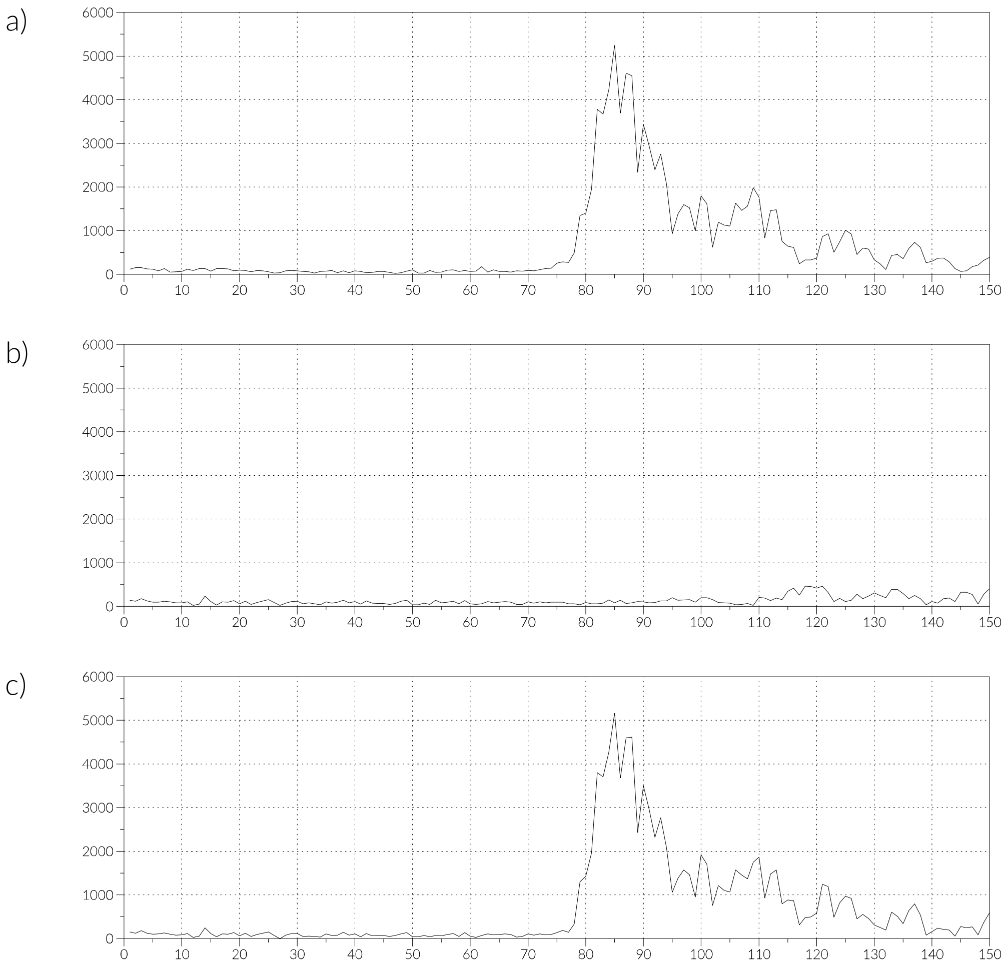
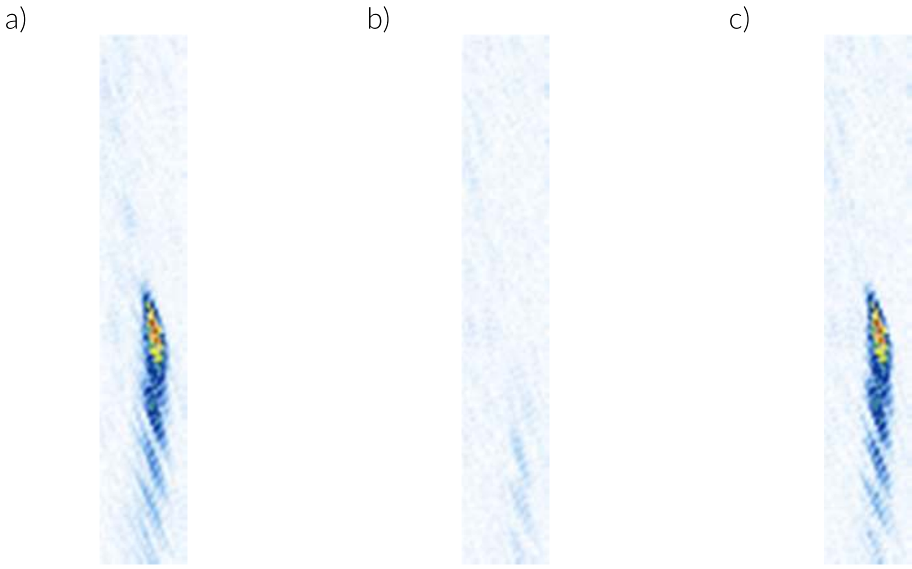


Figure 7. A scan from the: a) original flaw location, b) re-introduction location before modification, and c) after modification.

Finally, the flaw location was compared at the sector level to ensure that the modification did not induce any cutoff in the flaw signal or other similar artifacts. Figure 8 shows the comparison for a single sectorial position. The figure shows that there is no cutoff or other visible artefacts.



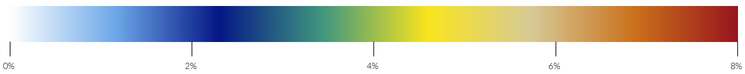


Figure 8. Sector (B) scan from the original flaw location (a), re-introduction location before modification (b) and after modification (c).

DISCUSSION

The flaw signal was extracted from the designated location and applied to different locations to form modified data files with additional flaws. The resulting data files were carefully evaluated for any possible artefacts caused by the modification operation. The flaw signal integrated well with the existing signal, and no artefacts were noted. Consequently, the data file modification was successful in all accounts.

The current analysis was limited to a single .uvdata file and a single flaw signal. Thus, it is appropriate to discuss the extensibility of these results to wider applications with different data files and flaw signals.

The current process of flaw extraction, which uses a flawed region and an unflawed reference region, worked quite well for the present data file and flaw signal. However, due to the different noise level between the locations, some additional filtering was necessary to remove the effects of this noise difference from the extracted flaw signal. The flaw in question has a very good signal-to-noise ratio, and the filtering could thus easily be done without affecting the flaw signal. However, if the signal-to-noise ratio were very small, it would become increasingly difficult to differentiate between the flaw signal and the noise signal. Thus, setting the filtering parameters may need manual adjusting when the process is applied to flaws with a very different signal-to-noise ratio. In addition, for flaws with a very low signal-to-noise region, the reference region must be chosen to have a very similar noise level, and/or more sophisticated filtering may be necessary for good results. This is the price for extracting the flaw signal from a single file (and not files acquired before and after flaw production).

In summary, the feasibility study developed and documented here indicates that the eFlaw technology is well suited for training and inspection of the SKB canister. The chosen reference defect could be extracted successfully and re-introduced to different locations. The method is expected to be widely applicable to different data files, channels and flaws with sufficient signal-to-noise ratio.

CONCLUSIONS

The following conclusions can be drawn from this feasibility study:

- a flaw signal could be extracted successfully from the flawed and unflawed areas;
- the extracted flaw signal could be re-introduced without introducing visible artefacts to the data;
- the data file thus generated is applicable for training and qualification purposes; and
- the developed capability is expected to be widely applicable to different data files, channels and flaws.

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