

# **ADVANCES IN PRODUCTION OF REALISTIC CRACKS TO NDT DEVELOPMENT AND QUALIFICATION PURPOSES OF STEAM GENERATOR TUBES**

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## **Abstract**

Realistic defects are needed for steam generator tube inspections when developing new NDT methods or assessing the performance and reliability of methods and procedures used. Furthermore, realistic defects give the most reliable results in assessing service-related reliability of steam generator tubes by, for example, burst or leak tests. It is crucial to have representative defects as the defect characteristics has marked effect on the results both in NDE, burst and leak tests. Representativeness should be to the actual service-induced defects, and the evaluation should be based on the essential defect characteristics.

In this paper realworld application cases are presented about crack production to steam generator tubes. Crack production technique used is based on controlled thermal fatigue process creating natural cracks. Such cracks have been produced in Alloy 690 and austenitic stainless steel steam generator tubes. These cracks have been used, for example, for advanced NDT qualification purposes of a new build nuclear power plant.

Paper presents results of the destructive tests performed after validation tests of the crack manufacturing in the Alloy 690 and austenitic stainless steel. These results are shown for both of the materials with measured essential crack characteristics.

In addition to metallographic analysis, the paper presents the results of performed NDT inspections for the Alloy 690. Results have been obtained with an advanced inspection technique developed and used for today's inspections of steam generator tubes in nuclear power plants.

## **1. Introduction**

Nuclear power plant steam generator tubes have been found susceptible to cracking in various conditions. These tubes are an integral part of the reactor coolant pressure boundary. The steam generator tubes are also relied upon to isolate the radioactive fission products in the primary coolant from the secondary system. Primary coolant can leak through cracks to secondary coolant and ultimately, severe cracking can lead to tube rupture. On some reactor types, this can lead to release of radioactivity to the environment outside the reactor containment through the pressure relief valves in the secondary system [1]. Consequently, cracking in steam generator tubes is of significant concern and can lead to leaks and ultimately compromise the safe operation of the plant. [1,2].

The mitigation of steam generator degradation can be classified to three stages. Firstly, effective in-service inspection is used to detect cracking. When cracking is detected, the tube in question can be plugged to prevent further damage. The detection and characterization of steam generator damage, however, remains challenging and better methods are continuously developed to improve inspection (e.g., [3]). Secondly, if a through wall crack is present, the leak rate expected from such a crack must be known in order to assess the safety-significance of possible leaks (see, e.g. [4]). Finally, the limits of structural integrity of a cracked tube must be known in order to properly set inspection goals and risk estimates (see, e.g., [5]). To this end, the cracked tubes are often modelled and experimental rupture-tests performed ([6]) to confirm the expected behaviour.

In summary, the expected behaviour of degraded (i.e. cracked) tubes must be estimated and investigated. That is, for all the mitigation efforts mentioned above, it is necessary to understand and estimate the behaviour of cracked steam generator tubes in service conditions. Experimental studies are necessary to validate the mitigation techniques used. For such experimental studies, e.g., to improve, and qualify NDE methods, samples with cracks representative of the expected service-induced cracking are needed. However, manufacturing of such cracked samples has been a major challenge. In order to get representative experimental evidence, essential crack characteristics must be well represented in the test samples; e.g. crack opening and tortuosity, crack surface roughness and crack tip radius for NDE and leak studies and crack tip stress intensity for integrity assessment. In practice, this necessitates the use of test specimens with controlled natural cracks.

This paper describes a new technology to produce cracked test samples that can be used to gain information on the behaviour of cracked steam generator tubing. So far, the technology has been used mainly for NDE training and qualification. This paper presents some early application cases of the production technology for steam generator tube use.

## **2. Trueflaw Technology**

Trueflaw produces defects using controlled natural thermal fatigue damage process. The defects are grown in much the same way as could occur during service conditions. However, the growth is accelerated to make production times practical and controlled to enable predetermined flaw

parameters. Flaw production is done in-situ to ready-made sample. Cyclic thermal fatigue loading is induced locally by alternating heating and water spray cooling, as described by Kemppainen [7]. Loading is based on pure thermal loading and there is no welding, machining, or mechanical treatment applied. No artificial initiators of any kind are used and the material microstructure is not disturbed in the process. More detailed information on the properties and use of produced cracks has been presented earlier [8-11].

## **2.1 Characteristics of the growth procedure**

Manufacturing of real cracks has traditionally been restricted to simple component shapes and small components. Providing the stress for crack growth mechanically becomes impractical when the sample geometry becomes more complicated. Also, accurate control of induced stress in complex shapes during crack growth is very difficult and it is not possible to limit the stress only to desired areas where defects are needed. In contrast, thermal loading can be applied to local areas in complicate sample geometries. Since only a limited area is stressed at any given time, the needed equipment is relatively light. Furthermore, the ability to locate and control the stressed area enables accurate control over crack growth location and crack parameters.

## **2.2 Confirming essential flaw parameters without supplementary NDE inspections**

Often, the dimensions and other characteristics of the cracks must be known. Some of the parameters, like surface length, can be readily measured. However, for many important defect parameters, depth in particular, this is not possible from the final sample. In Trueflaw technology, these parameters are known by destructive validation. When there is no experience on the specified crack, the intended crack is first produced to a representative validation sample. This sample needs to have similar material and similar local geometry, but can be simplified and smaller compared to the actual test sample. This validation crack is destructively examined to reveal the true crack depth and other specified parameters (e.g, crack opening, surface roughness etc.). Then, using the same procedure, a similar crack can be produced to any number of actual test samples repeatably.

The Trueflaw technology has been available on the market since 2001. During that time, the technology has been developed immensely. It has been applied to numerous different materials and component geometries. It has been used to solve various problems requiring information about response of cracked components in nuclear and conventional energy production, as well as in aerospace and railroad industries. It has been tried and tested. Most of the applications to date have been on inspection training and qualification samples. There has also been several application cases for using such cracks in developing existing and new NDE techniques (see, e.g., [11]).

## **3. Application Cases**

Most of the application cases for Trueflaw cracks to date have been related to inspection training and qualification samples. The use of the technology for steam generator tube cracking is still quite uncommon. Below, two example cases are presented, which show some of the potential

uses of this technology to steam generator tubes. The first case details inspection qualification on steam generator tubes manufactured from Inconel 690. The second case shows crack production validation for a more traditional stainless steel tube material.

### 3.1 Crack production in Inconel 690 steam generator tubes

Inconel 690 steam generator tubes are used in the modern EPR reactor type that is currently under construction in Olkiluoto (later "OL3"), Finland. This material has been selected due to its high resistance to stress corrosion cracking that has caused problems in older reactor types (made from stainless steel or Inconel 600). According to Finnish regulations, all in-service inspections to be performed to the new power plant must be qualified. In qualification, the performance of the inspection technique to be applied is shown on realistic defects. Hence, also the SG-tubes were qualified according to Finnish regulations.

The qualification done for OL-3 was the first to be completed on Inconel 690 tubes with real cracks. Consequently, no cracked specimens were available nor had such specimens ever had been manufactured. Areva NP approached Trueflow to manufacture the cracked samples. Figure 1. shows drawing of the tube sample used in qualification.

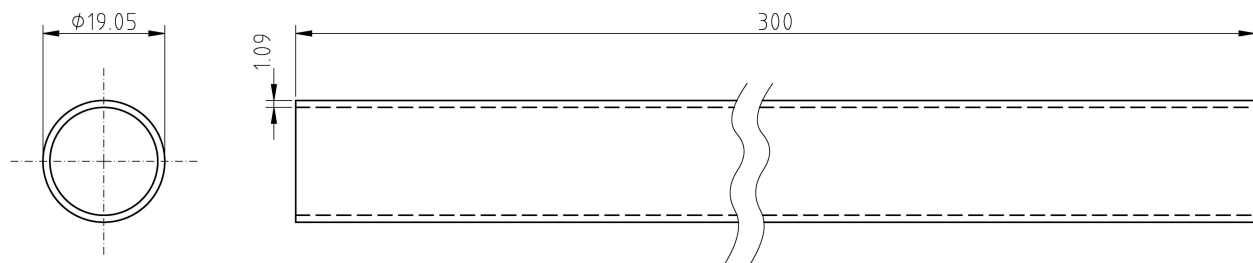


Figure 1 Tube sample drawing. The material is Inconel 690.

#### 3.1.1 Development and validation of crack production to Inconel 690 steam generator tubes

Crack production to Inconel 690 steam generator tubes posed several challenges. Firstly, due to the thin wall section and correspondingly small crack depth targets, the tolerances for crack production were set very tight.

Hence, the first target was to obtain successful small crack initiation to this new material with the thin wall section. After several trials, successful circumferential cracking was obtained (Figure 2). However, rather unexpected difficulties were met when developing technique for axial cracking. As it turned out, the material was highly anisotropic with respect to cracking. Presumably this is caused by the microstructural texture resulting from tube manufacturing. It was noticed, that the samples strongly preferred circumferential cracking over axial cracking. Consequently, no axial cracking could be produced without accompanying circumferential cracking.





Trueflaw

218AHB594

1 mm

Figure 2 Small crack initiation in Alloy 690 steam generator tube; a dye penetrant indication.

The specified cracking included long and shallow cracks, i.e. the cracking extended up to several millimeters around the circumference but only a fraction of a millimeter in depth direction. Consequently, the production was met with a problem of through wall cracking. That is, successful crack initiation was obtained, but as soon as the surface length of the crack was extended, cracks rapidly grew through-wall. To overcome this problem, it was decided to produce the desired dimensions with non-contiguous cracking. Figure 3 shows such a non-contiguous crack pattern produced.



Trueflaw

311AHB665

1 mm

Figure 3 Circumferential cracking in steam generator tube samples.

The validation samples were then sent to Intercontrol for inspection (see paragraph 3.1.2). The purpose of these inspections was to confirm that the produced samples are suitable for the intended use and to give the inspectors early experience on the cracked samples. Finally, the

validation samples were destructively examined by Trueflaw in order to confirm the depth of the cracks. Figure 4. shows an image of destructive examination of a validation sample.

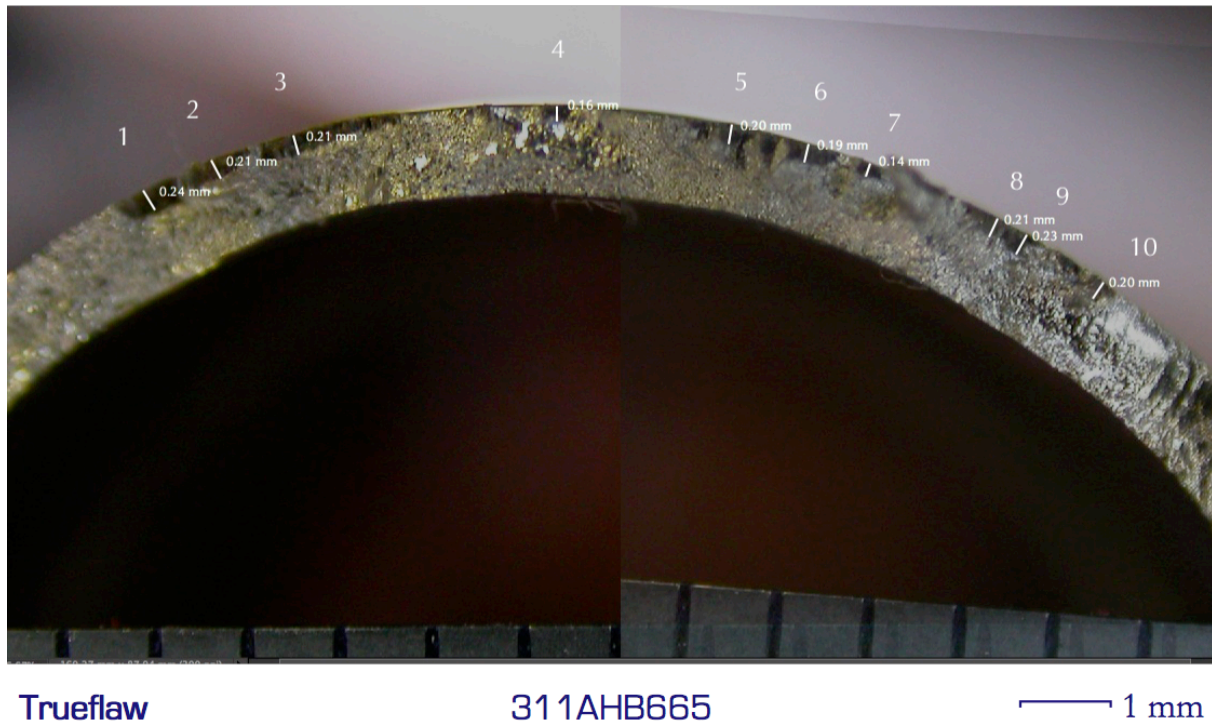


Figure 4 Destructive examination of produced validation cracks in the SG tube sample.

### 3.1.2 Inspection results

Three samples were inspected with eddy current inspection by Intercontrole. The samples are detailed in Table 1. Inspection was carried out with two different probes: bobbin probe and rotating probe (Figure 5).

Table 1 Samples in eddy current inspection. All cracks were circumferential. The depth values for samples 1 and 2 are measured from destructive examination of sample 1. Other values are directly measured on the sample.

#	Cracks	Note
1	OD crack, 20% depth, 100° angular extension	destructively examined
2	OD crack, 20% depth, 140° angular extension	
3	through-wall crack, 48° angular extension	

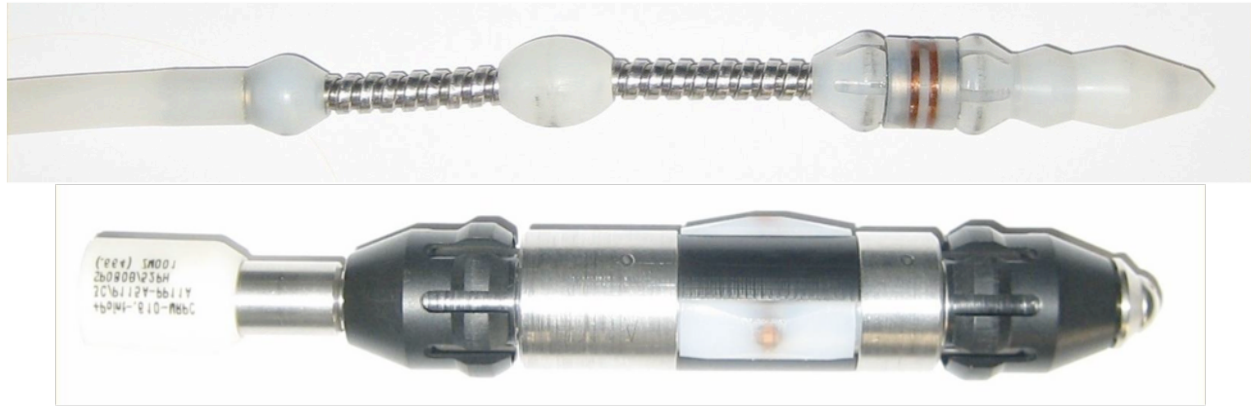


Figure 5 The probes used in the inspection were ET Bobbin probe, Zetec 610UL (upper image) and ET rotating probe, Zetec 3 coil 610PP with 1 +point coil PP11A, 1 pancake coil 115MR Ø 3 mm (medium range) and 1 pancake coil 080 HF Ø 2 mm (High frequency) (lower image).

The EC response of cracks in each sample with two different probes can be seen in Figures 6-14. Three different pictures are shown for each sample: first the result of bobbin probe then results of rotating probe signals and finally topographic picture of the rotating probe response. The crack signal is marked to each image. The ET bobbin probe clearly detects single indication for all the inspected samples. For samples 1 and 2 the indication is correctly interpreted as OD defect and for sample 3 the indication is correctly interpreted as through-wall defect.

The results for the rotating probe are summarized in Table 2. The sizing results from the rotating probe agree very well with the true crack sizes. For the sample 1, where direct destructive results are available, the depth sizing is within 5%-units of the true depth, which corresponds to about 0.05 mm. For the sample 2, which was produced similarly to sample 1, the inspection results are within expected crack depth variance  $\pm 0.3$  mm. Furthermore, the EC inspection indicated that the thermal loading had caused slight local denting of the tube. However, this did not disturb the inspection.

Table 2 Results for the rotating probe inspection.

Sample	Amplitude (V)	Phase (OD plane, °)	Depth (%)	Angular extension (°)
1	0,17	87	15	115
2	0,26	79	45	140
3	19,07	35	100	140



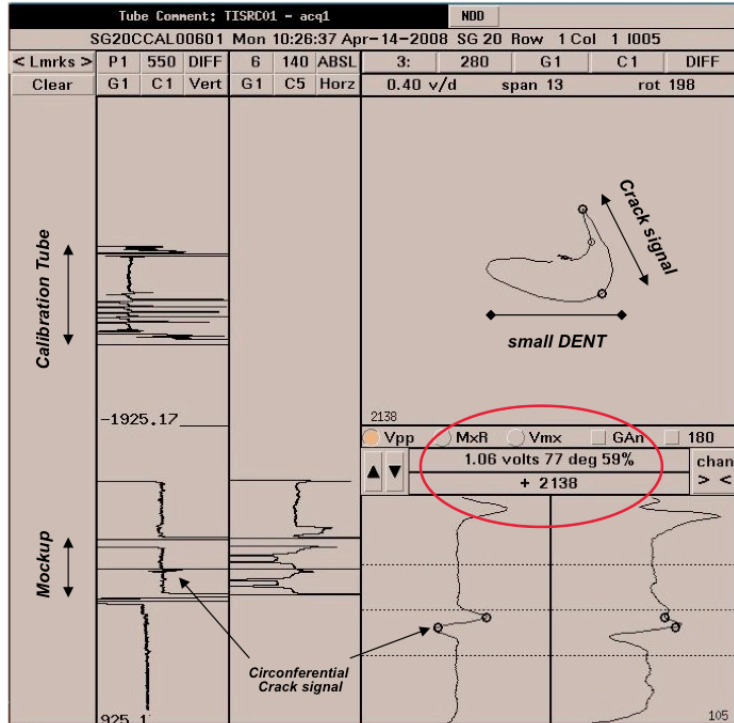


Figure 6 ET probe results for sample 1 for the bobbin probe.

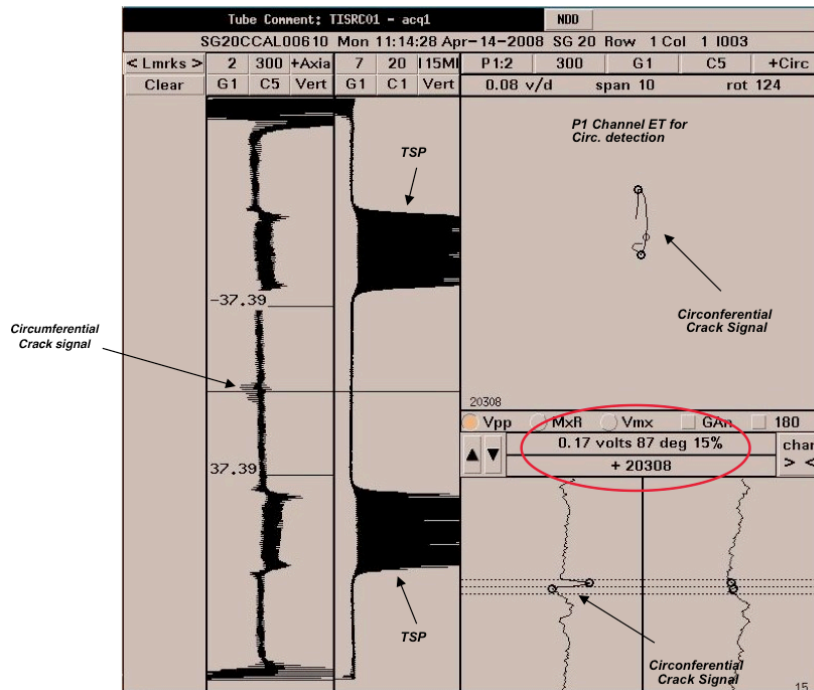
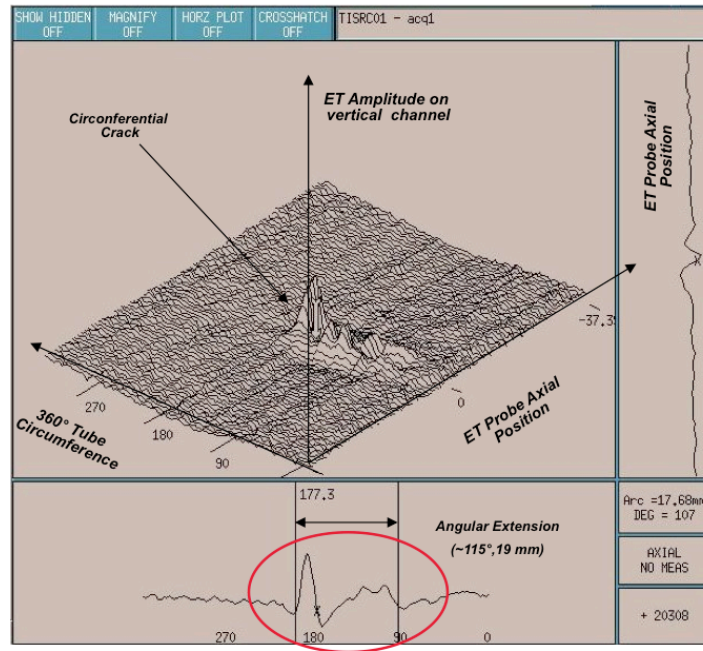


Figure 7 ET probe results for sample 1 for the rotating probe.



360° Tube Circumference  
Figure 8 ET probe results for sample 1 for the rotating probe.

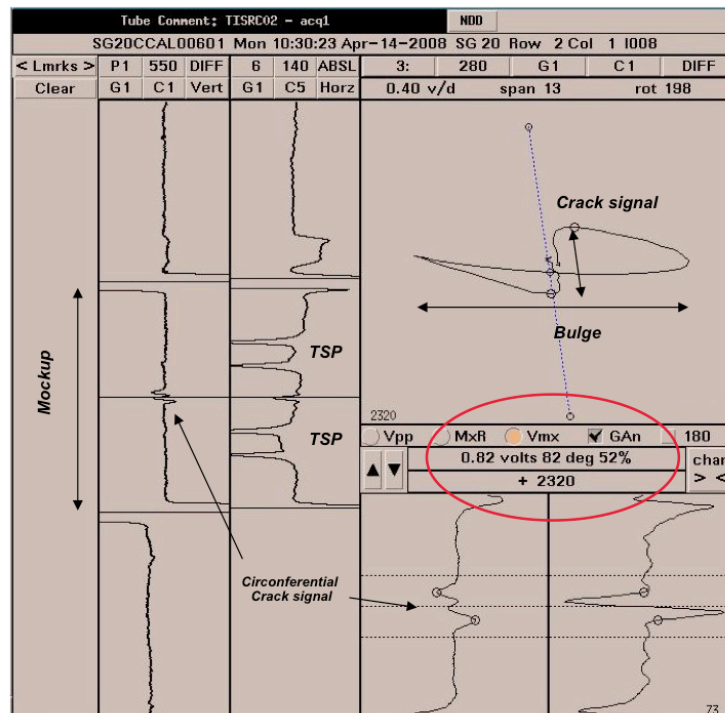


Figure 9 ET probe results for sample 2 for the bobbin probe.

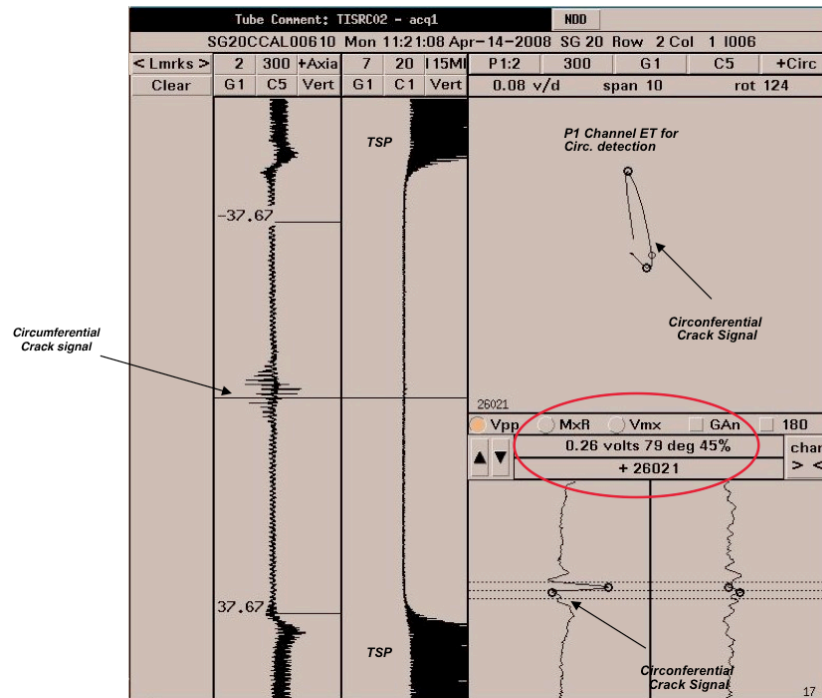


Figure 10 ET probe results for sample 2 for the rotating probe.

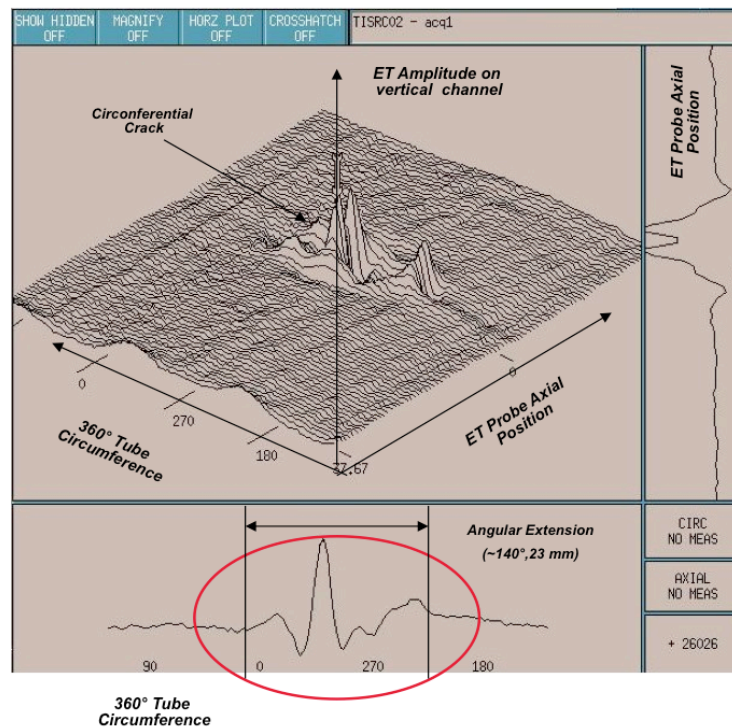


Figure 11 ET probe results for sample 2 for the rotating probe.

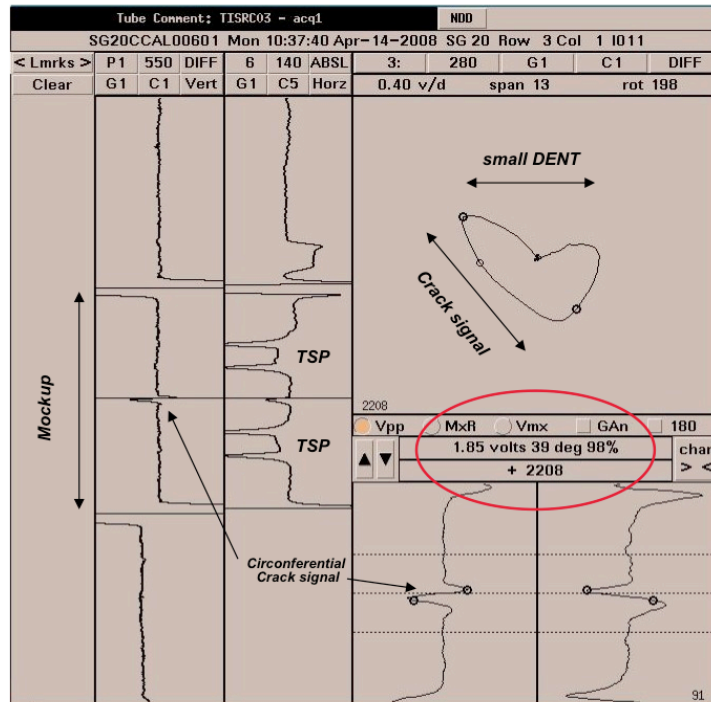


Figure 12 ET probe results for sample 3 for the bobbin probe.

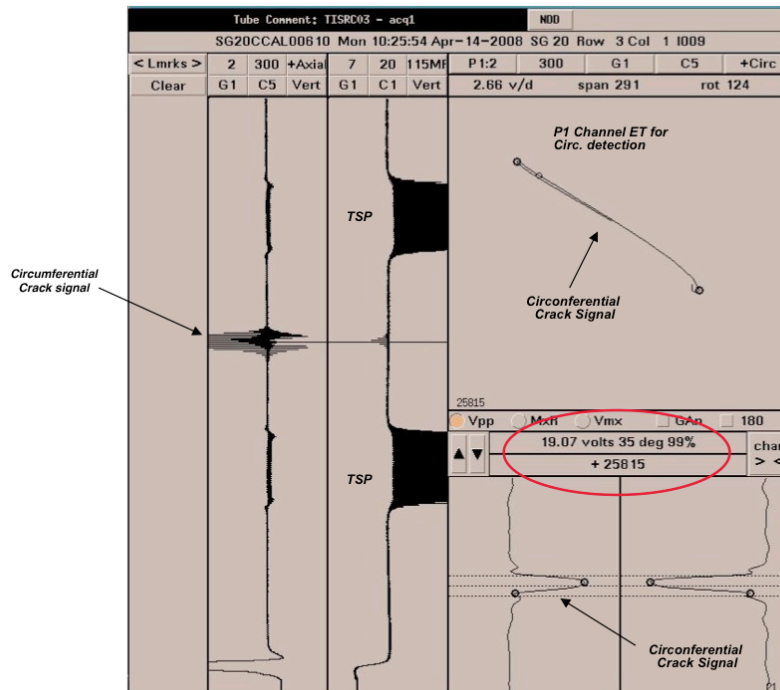


Figure 13 ET probe results for sample 3 for the rotating probe.

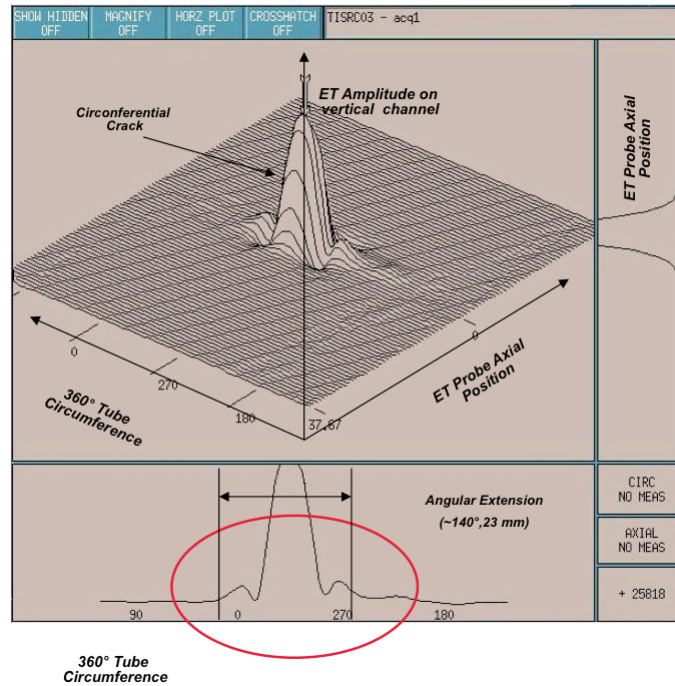


Figure 14 ET probe results for sample 3 for the rotating probe.

### 3.1.3 Conclusions

Cracks were successfully produced to Inconel 690 samples in circumferential direction. Samples strongly preferred circumferential crack growth over axial crack growth. The cracked samples showed that the specified crack sizes can be reliably detected and characterized with the used probe design, even with the complex non-contiguous cracking morphology. The inspection method was successfully qualified for OL3.

## 3.2 Crack production in stainless steel steam generator tubes

The Research Institute of Nuclear Power Operation (RINPO), China, approached Trueflow in late 2008 for possibility to produce cracked steam generator tube samples to be used for burst tests to qualify the extreme load of defective tube. The tube in question is austenitic stainless steel tube, typical for WWER reactors. It was decided to do production trials to investigate the possibility and suitability of Trueflow cracks in this case. For this use RINPO send Trueflow sample tube to be used in the production trials. The interesting crack type was axial cracking.

### 3.2.1 Production trials

Trueflow completed altogether nine production tests for this tube. With these tests, it was shown that axial cracking can be repeatably initiated to austenitic stainless steel tubes and size controlled to produce axial cracks with known size. During the limited testing, however, the method was not conclusively validated. The follow-up for this work is currently considered. Typical initiation images are shown in Figure 15. Produced cracks are very tight and thus PT image show very poor contrast. Corresponding images from destructive examination are shown



in Figure 16. It can be seen, that the crack is continuous and follows the long-but-shallow aspect ratio specified for these cracks.

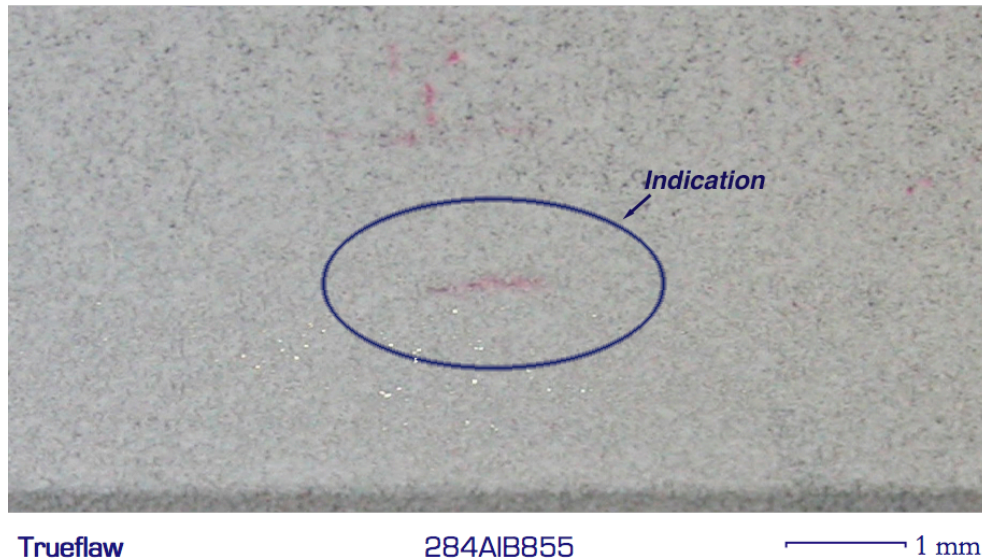


Figure 15 Typical initiation images for axial cracks in austenitic stainless steel steam generator tubes.

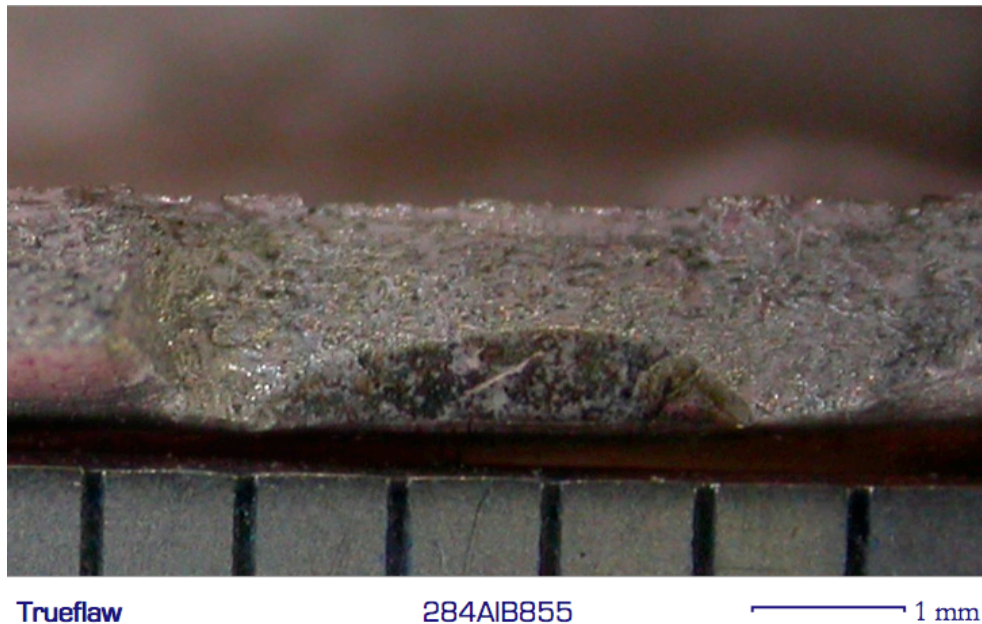


Figure 16 Destructive examination results for axial cracks in austenitic stainless steel steam generator tubes.

### 3.2.2 Conclusions

Cracks were successfully produced to stainless steel tube samples in both axial and circumferential directions. It was shown that Trueflaw technology is well applicable to the intended use.

#### 4. Conclusions

Cracked steam generator tube samples can be used in various applications where the real response of cracked tubes needs to be known. These include NDE qualification, validation of safety calculations in burst tests and leak rate tests. The use of cracked sample is still quite uncommon. However, the technology for the more widespread use of cracked samples is now available and some successful early experience has already been obtained.

#### 5. Acknowledgements

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