Testing of VVER reactor pressure vessels by TOFD method

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Introduction

The remote automated testing of VVER vessels is performed by ŠKODA JS since 1981. From that time to January 2002, six pre-service and forty one in-service inspections of VVER vessels from inner surface were done, as well as six pre-service and twenty one in-service inspections from the outer surface. All these inspections were performed by ultrasonic pulse echo method, combined from 1996 with eddy current testing. All that time we were aware of weak points of such testing, most important of which is the impossibility to measure accurately the real dimensions of discontinuities found in the tested material.
New ultrasonic testing methods capable to obtain the real dimensions of flaws emerged in last decades of twentieth century. One of them is the Time of flight diffraction method (TOFD).

TOFD Method

This ultrasonic testing method is based on diffraction of ultrasonic waves on tips of discontinuities, not on the geometrical reflection on the interface of discontinuities. Those waves are much more weaker than reflected waves, which are used by pulse echo method, therefore a pre-amplifier must be used for the testing.
Two high damped broadband longitudinal wave probes working in pitch-catch mode are used for TOFD testing. Probes are fixed to wedges, which in steel produce the angles 45°, 60° or 70°. Longitudinal waves are used preferably for TOFD testing, as their velocity in steel is almost twice the velocity of shear waves and so the longitudinal waves are received well ahead of other waves and all signals used for TOFD data evaluation can be easily identified.
The signals diffracted on the lower and upper edge of the flaw have the maximal amplitude for the angle of incidence about 65° and this amplitude changes less than 6 dB in the range of angles from 38° to 80°.
The signals of TOFD probes are digitised, stored and processed by personal computer and resulting B-scan is presented on computer screen. The real dimensions and orientation of discontinuities are therefore clearly presented by TOFD data. The sizing is based on accurate measurement of time, not on the signal amplitude
One of advantages of TOFD method is the good detection of planar flaws perpendicular to the surface, including the flaws located in the middle of wall thickness, which are not easily detected by pulse echo single probe technique.
Another advantage of TOFD is the fact that real dimensions of flaws are evaluated from TOFD signals, not equivalent dimensions resulting from pulse echo data evaluation. The accuracy of sizing depends on the frequency of used TOFD probes – a higher frequency gives higher accuracy.
The theoretical accuracy of through wall extent of planar flaws sizing is $h = h^* \pm \lambda / 10$, practically achievable accuracy is $h = h^* \pm \lambda / 2$,
where h is the flaw through wall extent sized by TOFD
h^* is the real flaw through wall extent
λ is wavelength of the ultrasonic wave [mm]

Laboratory tests

A series of laboratory tests were performed by ŠKODA JS to test the suitability of TOFD method for VVER reactor parts testing. First tests done on test pieces made from VVER 440 base metal with EDM notches confirmed the ability of TOFD method to detect planar flaws perpendicular to the surface and the accuracy of flaw through wall extent sizing by TOFD.
The most important experiments were made on clad samples with artificially introduced cracks. The samples were made from VVER 440 material, their thickness was 70 mm. Cracks of two different shapes – semi elliptical and constant depth cracks were made by cyclic load in the samples and the cracks were welded over by austenitic cladding corresponding to the cladding used on VVER 440 reactor vessels. The through wall extent of cracks was measured by TOFD method from the clad and unclad side of the sample using 5 MHz, 6 mm TOFD probes in 60º wedges. All samples were later analysed destructively in the Nuclear research institute (NRI) Řež and real crack heights were measured. The results obtained by TOFD and real crack heights are presented in Table 1.
The difference between the real crack height and the height measured by TOFD was from –1.5 to +0.9 mm.

Sample No.	Sample ID	Clading thickness t_{NS} [mm]	Crack through wall extent measured by TOFD		Real crack through wall extent (NRI Řež) h_S [mm]
			testing from clad side h_1 [mm]	tested from unclad side (base metal) h_2 [mm]	
1	**PHA V202**	**9,0**	**16,8**	**17,4**	**18,3**
2	**PHA V104**	**8,8**	**17,6**	**19,1**	**18,3**
3	**PHB V202**	**8,7**	**8,7**	**10,2**	**9,9**
4	**PHB V104**	**8,7**	**14,2**	**15,5**	**15,2**
5	**PH1C V102**	**7,9**	**13,7**	**14,5**	**14,9**
6	**PH1C V104**	**8,7**	**20,6**	**21,0**	**20,3**
7	**PH3D V102**	**7,2**	**15,0**	**16,9**	**16,0**

Table 1 Results of crack sizing by TOFD

Qualification

The Czech Atomic law demands the qualification of systems and methods used for the in-service inspections of nuclear reactors. The qualification is done in accordance with ENIQ methodology and consists of preparation of the Technical Justification and practical tests made under the surveillance of Qualification Body.
ŠKODA JS intends to qualify systems and methods used for the automated ultrasonic testing of VVER 440 and VVER 1000 reactor components. The qualification of ultrasonic testing of VVER 440 vessel circumferential welds with nominal thickness 140 mm was finished in May 2002, the qualification of ultrasonic testing of VVER 440 nozzle dissimilar weld and nozzle inner radius shall be finished before the end of 2002.
The optimisation of inspection procedures and practical tests of procedures and devices used for the ultrasonic testing of VVER 440 vessel circumferential welds were performed on the qualification sample KB 140. The sample (Fig. 1.), simulating the VVER 440 vessel circumferential weld, is made from the VVER 440 base metal 15Ch2MFA. The weld and

cladding were manufactured according to the procedures used for the production of VVER 440 reactor pressure vessels.

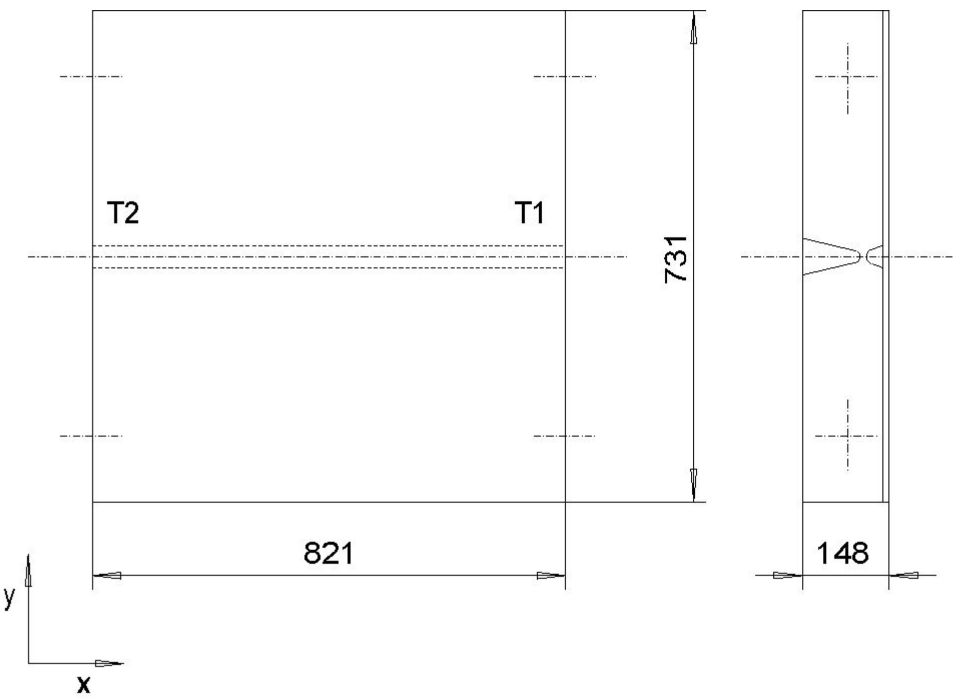

Fig. 1. Qualification sample KB 140

The sample contains 23 artificial flaws of two types - PISC Type A artificial flaws simulating cracks and EDM notches simulating lack of fusion- overview of flaws is in Table 2.
Before the qualification started, qualification goals were given, most important of them were:

- all artificial flaws in the qualification sample with through wall extent over 6.5 mm must be detected
- 80% of artificial flaws in the qualification sample with through wall extent from 3 mm to 6.5 mm must be detected
- position of flaws in circumferential direction must be measured with accuracy ±20 mm
- flaw height must be measured with accuracy ±5 mm
- flaw length must be measured with accuracy ±10 mm

The tests on the qualification sample revealed that all artificial flaws, except flaw R2, which was not expected to be detected due to the orientation, were detected by TOFD method and that planar discontinuities perpendicular to the sample surface located in weld root area are detected reliably by TOFD method from both surfaces of the vessel. The results of root area testing by TOFD method from outer surface are on Fig.2. Those flaws were either not detected or detected with amplitude below recording level by pulse echo method and probes used routinely for the in-service inspections.
Also the flaws simulating under cladding cracks were detected by TOFD from both surfaces, but only one flaw edge is detected clearly, the second one is hidden in the signal from cladding interface. That can be seen on Fig. 3. When the through wall extent of these artificial flaws was measured, the cladding interface was taken as one flaw edge. These flaws are

detected reliably by pulse echo method only from the inner surface by 70º TRL probes, but their through wall extent cannot be sized accurately by pulse echo method.
The optimal frequency, crystal size and probe distance were found experimentally for testing of the root area and the cladding interface. The through wall extent of the artificial flaws was measured by TOFD from both surfaces after the optimisation. The results for flaws simulating under cladding cracks and flaws in the root area are in Table 3.

Legend to Table 2	
Flaw	Identification number of the artificial flaw.
Orient	Orientation of the artificial flaw (the flaw is parallel to the indicated axis).
Type	Type of artificial flaw (A - „PISC type A“, II - rectangular notch of constant width).
x , y	Co-ordinates of the flaw geometrical centre.
d	Distance of the flaw upper tip from the sample inner surface.
h	Through wall extent of the artificial flaw.
l	Length of the artificial flaw

Flaw	Orient.	Type	X	Y	d	h	l
I1	Y	A	220	264	12	6	23
I2	Y	A	220	-268	12	10	32
I3	Y	A	620	-273	12	15	43
I4	Y	A	620	267	12	10	33
I5	Y	A	420	264	12	8	28
I6	Y	A	420	-268	12	12	38
I7	Y	A	320	-268	12	3	20
I8	Y	A	520	-268	12	4	21
F1	X	A	226	0	12	18	51
F2	X	A	107	0	12	5	22
F3	X	A	417	0	12	8	26
H1	X	II	489	0	58	6	15
H2	X	II	759	0	52	11	30
H3	X	II	157	0	51	13	30
G1	Y	II	357	0	34	6	16
G2	Y	II	631	0	34	9	16
G3	Y	II	547	0	34	11	16
L1	X	II	160	-31	134	7	15
L2	X	II	287	-31	131	10	24
L3	X	II	687	31	127	12	30
L4	X	A	563	-31	138	10	30
R1	Y	A	220	264	143	5	19
R2	45°	A	225	-258	143	5	19

Table 2. Overview of artificial flaws in KB 140

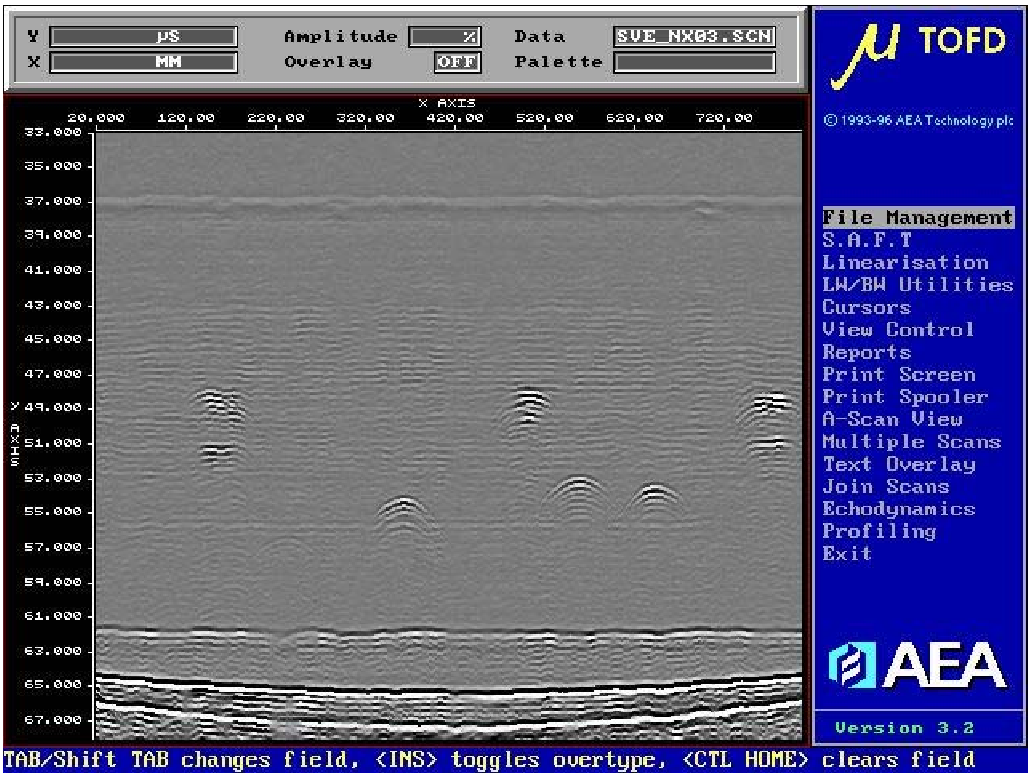

Fig.2. Artificial flaws in root area of KB 140 detected by TOFD from outer surface

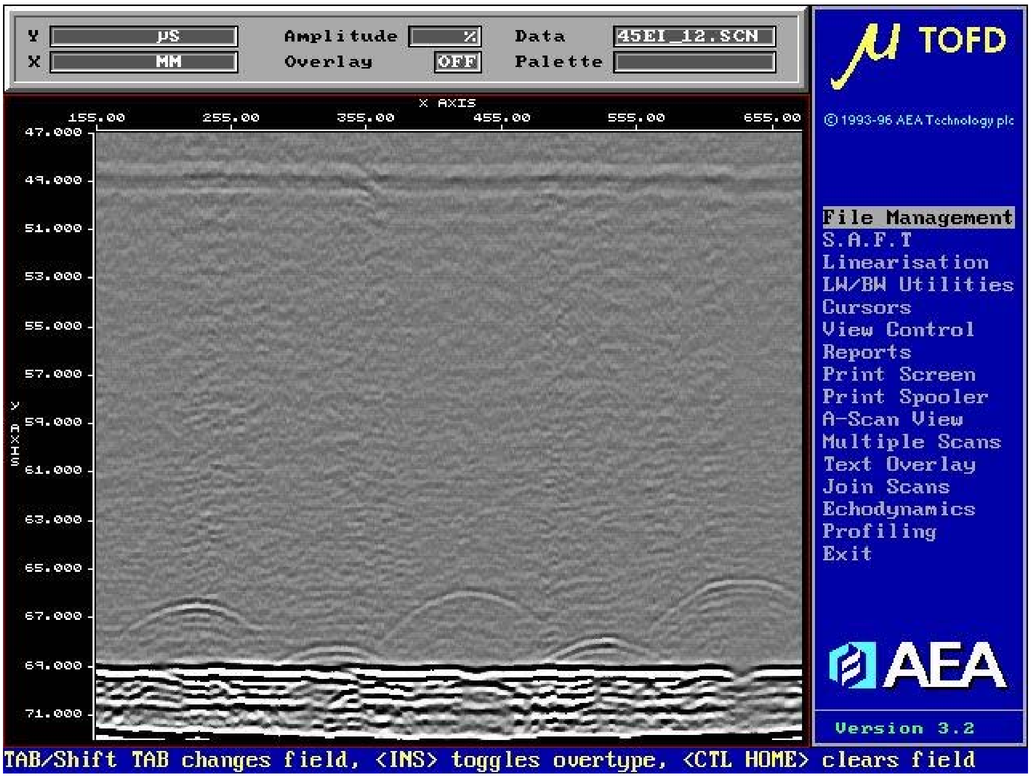

Fig.3. Artificial flaws simulating under cladding cracks in KB 140 detected by TOFD from outer surface

Legend to Table 3		
Flaw		Identification number of the artificial flaw.
h	[mm]	Real through wall extent (TWE) of the artificial flaw
h TOFD	[mm]	TWE of the artificial flaw measured by TOFD
Δh	[mm]	Difference between TWE measured by TOFD and real TWE

Flaw	**h**	**From inner surface**		**From outer surface**	
		h TOFD	**Δh**	**h TOFD**	**Δh**
I1	6	8	2	6	0
I2	10	11	1	11	1
I3	15	16	1	15	0
I4	10	11	1	11	1
I5	8	10	2	9	1
I6	12	14	2	13	1
I7	3	5	2	4	1
I8	4	5	1	5	1
H1	6	6	0	7	1
H2	11	11	0	12	1
H3	13	11	-2	13	0
G1	6	4	-2	5	-1
G2	9	8	-1	7	-2
G3	11	9	-2	10	-1

Table 3. Results of through wall extent sizing by TOFD after optimisation

The qualification goals of VVER 440 vessel circumferential weld testing were achieved when TOFD method was added to the standard pulse echo testing. The demanded accuracy of through wall extent sizing was achieved only by TOFD method. Without TOFD, the artificial flaws in root area of KB 140 were not detected reliably.
Following important facts result from the qualification of methods and systems used by ŠKODA JS for VVER 440 circumferential weld testing:

- The planar flaws perpendicular to the surface located in the weld root area are detected reliably by TOFD from both surfaces.
- The under cladding cracks are detected reliably by TOFD from both surfaces.
- The through wall extent of flaws can be sized accurately by TOFD method.

Field usage of TOFD

Based on good results of laboratory test, the TOFD method was used on Czech and Slovak VVER reactors for sizing of the trough wall extent of flaws found during the in-service

inspections. Under cladding cracks were sized by TOFD from the outer surface and a flaw of volumetric character was sized from the inner surface.
As a result of methods and systems qualification, TOFD method will be used routinely by ŠKODA JS from this year for sizing of flaws exceeding the acceptance criteria and also for detection of flaws in the root area.

Conclusions

The laboratory experiments on samples with artificial flaws and samples with artificially prepared cracks confirmed the high accuracy of flaw through wall extent sizing by TOFD. This accuracy was confirmed by qualification of methods and systems used by ŠKODA JS for the in-service inspections of VVER 440 vessel circumferential weld. The qualification also confirmed the ability of TOFD to detect reliably flaws, which can are not reliably detected by standard pulse echo testing.
Based on the result of experiments and qualification, the TOFD method shall be used routinely by ŠKODA JS for the inspection of vessel circumferential welds root area and for sizing of flaws exceeding the acceptance level.