Transactions of the 17th International Conference on *Paper # O01-2*
*Structural Mechanics in Reactor Technology (*SMiRT 17)
Prague, Czech Republic, August 17 –22, 2003

Qualification of UT Methods and Systems Used for In-service Inspections of VVER 440 Vessels

Zdeněk Skála, Jan Vít,
ŠKODA JS a.s., Plzeň, Czech Republic

ABSTRACT

ŠKODA JS has been performing automated in-service inspections VVER reactor pressure vessels for more than twenty years. All of these inspections were performed by ultrasonic pulse echo method, combined from 1996 with eddy current testing. The Time of flight diffraction method (TOFD) is one of modern methods of ultrasonic testing. The accuracy of sizing the through wall extent of a flaw by TOFD is much more better than the accuracy achievable by the pulse echo method. A series of laboratory tests were performed by ŠKODA JS and confirmed the suitability of TOFD method for VVER reactor parts testing. 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 from the inner as well as from the outer surface. The accuracy of the flaw through wall extent sizing by TOFD was confirmed by the qualification of methods and systems used for the testing of VVER 440 vessel circumferential weld and so 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.

KEY WORDS: automated testing, ultrasonic testing, VVER, ENIQ, qualification, TOFD, detection, sizing, accuracy, in-service, inspection, manipulator, method, pulse-echo

INTRODUCTION

The remote automated testing of VVER vessels is performed by ŠKODA JS since 1982 [1]. From that time to January 2003, six pre-service and forty two in-service inspections of VVER vessels from inner surface were done, as well as six pre-service and twenty three in-service inspections from the outer surface. Inspections from inner surface were performed by Reactortest TRC system from 1982 until 1992 and have been performed by SKIN system since 1992. Inspections from outer surface have been performed by USK-213, upgraded in 1996 on NPP Dukovany and in 1999 on NPP Mochovce. 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 pulse echo testing, most important of which is the impossibility to measure accurately the real dimensions of flaws 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 [2, 3, 4] is based on diffraction of ultrasonic waves on tips of flaws, not on the geometrical reflection on their interface. Those waves are much more weaker than reflected waves, which are used by pulse echo method, therefore a pre-amplifier must be used usually 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 an angled ultrasonic beam. Angles 45°, 60° or 70° are most common, but also other angles can be used for the testing. 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 flaws 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 planar flaw through wall extent sizing can be done with accuracy:

$$h_m = h \pm \lambda / 2 \quad (1)$$

where h_m 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

Preliminary testing of TOFD method on a test sample made from VVER 440 base metal, 150 mm thick, was done in AEA Technology by ŠKODA technicians. EDM notches 5 to 15 mm deep were prepared on the inner and outer surface and also in a depth corresponding to the weld root area. TOFD method was applied from both surfaces. This testing proved that this method can be successfully used on VVER 440 reactors and necessary hardware and software was purchased by ŠKODA JS.

A series of laboratory tests in ŠKODA JS premises followed to test the suitability of TOFD method for VVER reactor parts testing more thoroughly. The tests done on full thickness 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 located in any depth and the accuracy of flaw through wall extent sizing by TOFD.

The most valuable 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 height measured by TOFD and the real crack height was from –1.5 to +0.9 mm.

Table 1 Results of crack sizing by TOFD

Sample No.	Crack through wall extent measured by TOFD		Real crack through wall extent	Difference h1- hs	Difference h2 - hs
	from clad side h1 [mm]	from unclad side h2 [mm]	hs [mm]	Δh_1 [mm]	Δh_2 [mm]
1	16,8	17,4	18,3	-1,50	-0,90
2	17,6	19,1	18,3	-0,70	0,80
3	8,7	10,2	9,9	-1,20	0,30
4	14,2	15,5	15,2	-1,00	0,30
5	13,7	14,5	14,9	-1,20	-0,40
6	20,6	21,0	20,3	0,30	0,70
7	15,0	16,9	16,0	-1,00	0,90

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 and IAEA methodology and consists of several steps. The Qualification Body defines qualification goals as a first step of the process. Inspection procedures for testing methods are optimised by repeated experiments on qualification samples and the results of optimisation are included in the Technical Justification document, which contains all information on tested part, inspection system and inspection procedures, confirming that qualification goals shall be achieved. The Qualification Body makes a review and assessment of the inspection procedures and the Technical Justification before practical tests are organised. Practical tests under the surveillance of the Qualification Body performed by the optimised inspection procedures are the last step of the process.

ŠKODA JS started the qualification of systems and methods used for the automated ultrasonic testing of VVER 440 and VVER 1000 reactor components. The qualification of procedures and equipment used for the UT of VVER 440 vessel circumferential welds with nominal thickness of 140 mm was successfully finished by practical tests on qualification sample in May 2002.

Other qualifications are in progress now - the qualification of ultrasonic testing of VVER 440 nozzle dissimilar weld and nozzle inner radius, the qualification of ultrasonic testing of VVER 1000 nozzle homogeneous weld and the qualification of ultrasonic testing of VVER 1000 vessel circumferential welds.

The pulse echo method has been used since the beginning of in-service inspections in ŠKODA JS. We have gathered a lot of experience with automated testing using pulse echo method and we know the drawbacks of this method caused by the fact that the interpretation of results is based on the amplitude of received signal.

The laboratory tests of TOFD method confirmed the ability of this method to detect flaws perpendicular to the tested surface located in the weld root area or any other depth of tested material, and to measure the trough wall extent of all detected flaws with better accuracy than the standard pulse echo method.

Based on this experience, we have decided to combine standard pulse echo testing with TOFD method to achieve higher accuracy of flaw sizing and to detect reliably flaws not detectable by single probe pulse echo testing. The standard pulse echo method shall be used for the detection of flaws and assessment of their length while TOFD method shall be used for the sizing of the through wall extent of flaws found by standard pulse echo method and also for detection of flaws perpendicular to the tested surface located in the weld root area.

The combination of both methods applied from both surfaces of the reactor pressure vessel shall be qualified for VVER 440 and VVER 1000 reactor vessel ultrasonic testing. Inspection procedures for both testing methods had to be optimised to achieve the goals of qualification.

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. Results of this qualification are presented in following paragraphs.

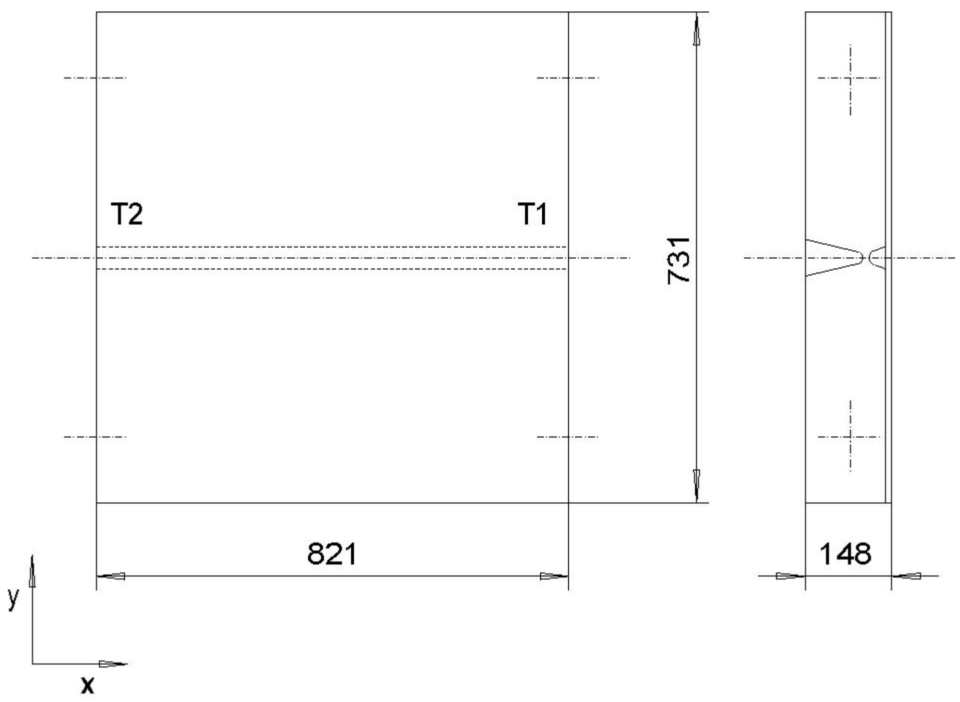

Fig. 1. Qualification sample KB 140

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 in accordance with the procedures used for the production of VVER 440 reactor pressure vessels.

The sample contains 23 artificial flaws of two types - PISC Type A artificial flaws simulating cracks and EDM notches simulating lack of fusion. An overview of artificial flaws manufactured in KB 140 qualification sample is in Table 2.

Before the qualification started, qualification goals were given, most important of them were:

- all of the 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
- flaw ligament must be measured with accuracy ±4 mm

Table 2. Overview of artificial flaws in KB 140

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

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

Detection

The tests on the qualification sample KB 140 revealed, that all artificial flaws detected by pulse echo method were detected by TOFD. Moreover, planar flaws perpendicular to the sample surface located in weld root area were detected reliably by TOFD method from both surfaces of the sample. Flaws in this area 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 was detected clearly, the second one was hidden in the signal from the cladding interface. These flaws are detected reliably by pulse echo method only from the inner surface by 70º TRL probes.

The comparison of pulse echo and TOFD methods ability to detect flaws in KB 140 qualification sample is presented in Table 3.

TOFD probes with crystal diameter 12 mm were used for the testing; frequency 5 MHz and angle 60º were used from the inner surface, frequency 2.5 MHz and angle 45º from the outer surface as a result of TOFD testing optimisation.

Table 3. Detectability of flaws in KB 140 by standard pulse echo and TOFD

Flaw	**Detected from inner surface**		**Detected from outer surface**	
	by pulse echo	**by TOFD**	**by pulse echo**	**by TOFD**
I1	Yes	Yes	Yes	Yes
I2	Yes	Yes	Yes	Yes
I3	Yes	Yes	Yes	Yes
I4	Yes	Yes	No	Yes
I5	Yes	Yes	Yes	Yes
I6	Yes	Yes	Yes	Yes
I7	Yes	Yes	Yes	Yes
I8	Yes	Yes	Yes	Yes
F1	Yes	Yes	Yes	Yes
F2	Yes	Yes	Yes	Yes
F3	Yes	Yes	Yes	Yes
H1	Yes	Yes	No	Yes
H2	Yes	Yes	No	Yes
H3	Yes	Yes	No	Yes
G1	No	Yes	No	Yes
G2	No	Yes	No	Yes
G3	No	Yes	No	Yes
L1	Yes	Yes	No	Yes
L2	Yes	Yes	No	Yes
L3	Yes	Yes	No	Yes
L4	Yes	Yes	No	Yes
R1	Yes	NA	No	Yes
R2	No	NA	No	No

Note: NA means that the method was not applied to detect the artificial flaw

Table 4. Results of through wall extent sizing by TOFD

Flaw	Real through wall extent (TWE)	TWE measured by TOFD from inner surface	Difference	TWE measured by TOFD from outer surface	Difference
	h	$\mathbf{h_{Ti}}$	$\mathbf{h_{Ti} - h}$	$\mathbf{h_{To}}$	$\mathbf{h_{To} - h}$
	[mm]	[mm]	[mm]	[mm]	[mm]
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
F1	18	21	3	19	1
F2	5	6	1	6	1
F3	8	11	3	8	0
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
L1	8	8	0	13	5
L2	11	9	-2	7	-4
L3	14	19	5	10	-4
L4	10	12	2	10	0
R1	5	NA	NA	4	-1

Note: NA means that the method was not applied to detect the artificial flaw

Sizing

Four parameters of flaws in qualification sample were evaluated and compared with real values – the position, the length, the through wall extent and the ligament. The practical tests confirmed that the position of flaw was evaluated with demanded accuracy either from pulse echo data or TOFD data, when qualified inspection procedures were followed.

Tests on qualification sample proved, that the flaw real length can be estimated from pulse echo data with demanded accuracy, if the flaw is detected by this method and data evaluated by qualified evaluation procedure. It is possible to evaluate this value from TOFD data, but the evaluation is more complicated and is not more accurate, so this possibility was not used in the qualification process.

The optimisation experiments made on KB 140 before the practical qualification tests showed that the through wall extent of some of the flaws cannot be evaluated with demanded accuracy from the pulse echo data. This parameter of the artificial flaws was therefore evaluated from TOFD data obtained from both surfaces of the qualification sample. When the through wall extent of the artificial flaws representing under cladding cracks was measured by TOFD, the cladding interface was taken as one flaw edge, as the signal of one flaw tip was covered by the signal from cladding interface. The evaluation of through wall extent of artificial flaws in KB 140 by TOFD is in Table 4.

The ligament was also evaluated from TOFD data with the accuracy equivalent to the accuracy of through wall extent evaluation.

Qualification Results

The qualification goals of VVER 440 vessel circumferential weld testing were achieved when TOFD method was added to the standard pulse echo testing. While the position and length of artificial flaws were evaluated with demanded accuracy from pulse echo data, the demanded accuracy of through wall extent sizing was achieved only by TOFD method. Only this method also detected reliably the artificial flaws in root area of KB 140.

Following important facts on application of pulse echo and TOFD methods 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, pulse echo method does not detect these flaws reliably.
- The under cladding cracks are detected reliably by TOFD from both surfaces, pulse echo detects them reliably only from inner surface.
- The position and length of flaw can be evaluated from pulse echo data with accuracy given in qualification goals, if the flaw is detected by this method.
- The through wall extent of all flaws can be sized by TOFD method with the accuracy given in qualification goals, this accuracy cannot be achieved by pulse echo method.
- The ligament is evaluated by TOFD method with the accuracy given in qualification goals, this accuracy cannot be achieved by pulse echo method.

IMPACT OF QUALIFICATION

Based on good results of laboratory test, the TOFD method has been 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, which had been found from the inner surface, were sized by TOFD from the outer surface and flaws in circumferential welds were sized from the both surfaces. Example of one real under cladding crack sized by TOFD from the outer surface of the reactor pressure vessel is on Fig. 2.

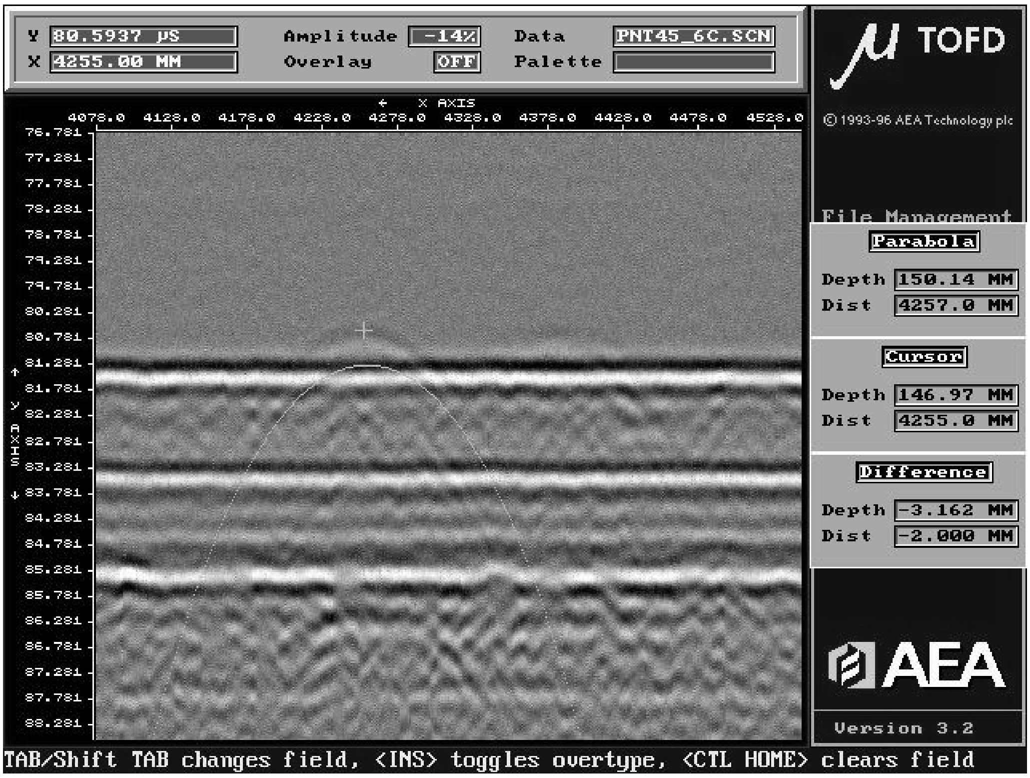

Fig. 2 Sizing of a real under cladding crack by TOFD from the outer surface

As a result of methods and systems qualification, TOFD method, applied from both surfaces of VVER reactor vessel, is used routinely by ŠKODA JS since 2002 for the sizing of flaws exceeding the acceptance criteria and also for the detection of flaws in the weld root area.

CONCLUSIONS

ŠKODA JS has a long time experience with automated testing of VVER reactor pressure vessels performed from both surfaces. The main method used for the testing has been the ultrasonic pulse echo method. The TOFD method was adopted by ŠKODA JS to eliminate the drawbacks of pulse echo testing. The laboratory experiments performed by ŠKODA JS on samples with artificial flaws and samples with artificially prepared cracks confirmed the high accuracy of flaw through wall extent sizing and ligament evaluation by TOFD.

Systems and methods used for the in-service inspections of nuclear reactor components must be qualified in accordance with ENIQ methodology in Czech republic. ŠKODA JS started the qualification of systems and methods used for the ultrasonic testing of reactor pressure vessel. Ultrasonic testing comprising pulse echo and TOFD methods applied from both surfaces of reactor vessel are qualified by ŠKODA JS. The qualification confirmed qualification goals were achieved by this combination of ultrasonic testing methods.

Based on the results of experiments and qualification, the TOFD method is used routinely together with pulse echo by ŠKODA JS for the ultrasonic testing of VVER vessel circumferential welds.

REFERENCES

1. Skála, Z., Přepechal, J., Sladký, J. and Vít, J., "Remote and Automated NDE in ŠKODA JS", *Proc. Of the First International Conference on NDE in Relation to Structural Integrity for Nuclear and Pressurised Components,* Amsterdam, EUR 18674 EN, 1999, pp. 364 - 373

2. Temple, J.A.G., "Time-of-flight inspection: theory*", Nuclear Energy*, 1983, 22, No. 5, Oct. pp. 335-348

3. Betti, T. et al, "TOFD – the emerging ultrasonic computerized technique, for heavy wall Pressure Vessel welds examination", *NDT.net*, September 1999, Vol.4 No. 9

4. Mondal, S. and Sattar, T., "An overview TOFD method and its Mathematical Model", *NDT.net*, April 2000, Vol. 5 No. 04