STATE AND PERSPECTIVES OF MEASURING AUTOMATED ULTRASONIC INSPECTION OF NUCLEAR REACTOR EQUIPMENT

Vladimir G. Badalyan, Pavel F. Samarin
SPC "ECHO+", Moscow, Russian Federation

Introduction

Using modern technical achievements of non-destructive testing is the major requirement for providing safety work of nuclear power plants (NPP), in particular, automated ultrasonic testing (AUT) with the coherent data processing, widely applied in scientific production center (SPC) «ECHO+». Using the inspection data coherent processing allows to determine flaws geometry with high exactness, sizing inaccuracy is about ~ λ (ultrasonic wave length). Information about revealed flaws geometry, their position in an object is necessary to carry out the object strength analysis and making decision about its exploitation terms. In methodologies developed in SPC «ECHO+» the AUT procedure of responsible pipelines welded joints on operating NPP with reactor facilities RBMK, VVER-440 and VVER-1000 is described. Inspected welded joints are characterized by the large dimension types variety, using materials, constructions and work conditions. All these features are taken into account in AUT technology of the developed methodologies.

In this article the examples of the developed methodologies for AUT welded joints on the NPP are examined, features of their tests and attestation are described. And also typical flaws acoustic images, comparison results with destructive inspection information are given.

Inspection procedures using AUGUR 5.2 systems

NPP safety is provided by the inspection of reactor facility primary coolant circuit metal condition. Therefore, most of AUT methodologies developed in SPC «ECHO+» are related with inspection technology of reactor facility primary coolant circuit welded joints.

Since 2004 year in the SPC «ECHO+» AUT methodologies using new generation Augur 5.2 systems have been developed for NPP pipelines welded joints inspection. Construction principles and architecture of the AUGUR 5.2 series systems are considered in detail in the article [2], its hardware facilities are represented by wide system application possibilities at the inspection of various welded joints. Ultrasonic testing results in the AUGUR series systems are represented as the images of B-, C- , and D- type, it provides additional possibilities for received data analysis and assessment. AUGUR 5.2 system software enables to systematize measured and processed data in an objects welded joints general database. The database allows effectively look after the flaws size changes and quickly find information by (about) numerous AUT parameters.

A number of measuring AUT methodologies, which applies while welded joints inspection in the NPP with reactor RBMK, VVER-1000 and with VVER-440, was developed in the SPC «ECHO+». In the Table 1 main NPP object characteristics which inspected in the measuring mode using the AUGUR series systems are shown.

Table 1. Inspected NPP objects using AUT

NPP reactor facility type	AUT object	Thickness, mm	Diameters, mm	Welded joints material
RBMK, VVER-440, VVER-1000	Girth pipelines welded joints Du200, Du300	11 ÷ 25	219 ÷ 325	Austenite
RBMK	Girth and longitudinal pipelines welded joints Du800	24 ÷ 50	800 ÷ 870	Perlite with welding
VVER -440, VVER -1000	Girth pipelines welded joints Du400, Du500 and Du1100	40 ÷ 85	400 ÷ 1140	Composite
VVER -1000	Girth pipelines welded joints Du1200	70 ÷ 80	1340 ÷ 1370	Perlite
VVER -440	Girth and longitudinal pipelines welded joints Du500	35 ÷ 240	540 ÷ 750	Austenite

Testing procedures using AUGUR 5.2 system consists of two successive modes:

- «searching AUT» – is executed for the quick inadmissible flaws revelation according to a amplitude attribute with determination of equivalent reflectors areas and convectional reflectors lengths;
- «measuring AUT» – is intended for the detailed measurement of the ultrasonic field scattered by reflectors and then for the real reflectors geometry determination.

Welded joint quality assessment by searching AUT results is defined by the sorting parameters in the proper inspection methodology.

Parameters of revealed flaws, that requiring fixings are specified at measuring AUT. For this purpose, the measuring inspection mode is used in the areas of flaws revealing with more detailed scan-out. Application of coherent data processing determines geometrical sizes of these flaws.

Exploitation experience noticed that for some objects the measuring AUT is only rational.

Application methodology features, its typical A-scans and flaws acoustic images are exampled of two developed methodologies:

- AUT of perlite welded joints Du1200 steam generators with VVER-1000 [3];
- AUT of composite welded joints Du1100 steam generators with VVER -440 [4].

AUT of perlite welded joint Du1200

Welded joint Du1200 is one of the responsible welded joints in the NPP with VVER-1000 equipment. This welded joint is a difficult junction because it is possible in its internal cavity the formation of flaws in the process of exploitation. Primary inspection purpose is revealing the most critical two-dimensional flaws and their size.

Welded joints Du1200 methodology [3] provides revealing and localization of technological and operational flaws, which equivalent squares are equal or exceed 3,5 mm^2. Equivalent square of inadmissible flaws according to methodology is equal or exceeding 7 mm^2. Methodology also provides revealing of different orientation cracks – longitudinal, transversal and diagonal (under the corner of 45° to the welded joints axis) and about it – length 10 mm and more and high (depth) 2 mm and more and their sizing.

Welded joints Du1200 №111 inspected by piezoelectric transducers in which both shear waves and longitudinal waves with beam angle 0°, 40°, 50° and 55° with operating frequency 2.5 MHz were used. Piezoelectric transducers features are the quite wide operating frequency band and rather wide directivity diagram. The requirements balance of high sensitivity with wide frequency band and necessary configuration of the receiver-transmitter acoustic field is followed.

On a fig. 1 is represented the welded joint junction of collector welding with the steam generators nozzles Du1200 and the acoustic technique with the use of piezoelectric transducers. The weld region is marked by a grey color.

Typical for the inspected object flaws forms because of intensive metal corrosion at the irregular tense state during exploitation [5]. Metallographic and fractography researches of defective welds Du1200 are showed that the basic mechanism in forming critical defects was cracks formation in fillet area. They are rose in the pipeline inner surface from welded joint root and fillet and developed toward to the weld outside surface. For flaws detection, type determination, sizing and risk level estimation two modes are used in AUT – searching and measuring.

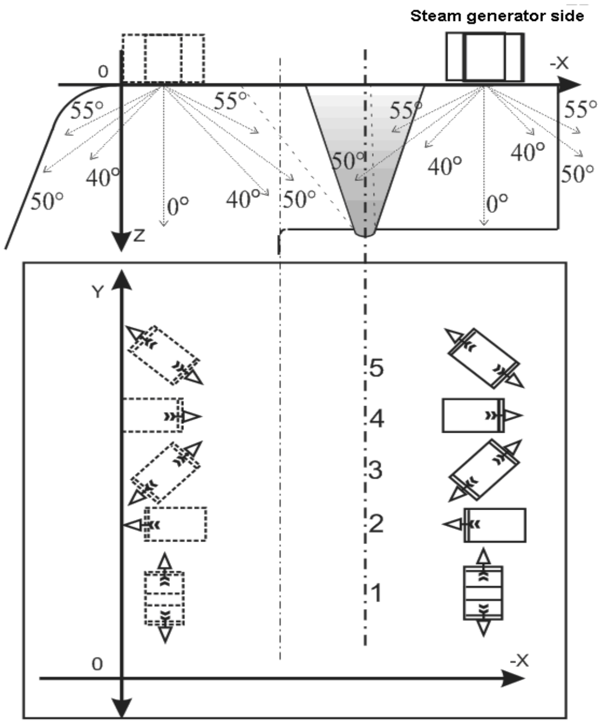


Fig. 1. Technique for welded joints Du1200 and transducers location during scanning.

Because of different tasks, these inspection modes are used other techniques with piezoelectric single crystal probe with different waves types (see Table 2).

Table 2. Piezoelectric transducers using in AUT

№ on fig. 1; Transducer type	Beam angle, wave type*	Orientation for axis weld, degree	Inspection mode	Identifiable flaws orientation
1; L2S2.5H0T50	50°, S	180	Searching, measuring	Transversal to welded joint axis, location in welded joint thickness
	0°, L	-		
	50°, S	0		
2, 4; 2S2.5H40T55	40°, S	+90	Searching, measuring	Longitudinal to welded joint axis
	55°, S	-90		
3, 5; 2S2.5H50	50°, S	+45	Searching	Diagonal to welded joint axis
	50°, S	-45		

*) L – Longitudinal waves; S – shear waves.

Welded joint quality estimates on searching AUT results according to acceptance level of sensitivity and reporting level of sensitivity flaws detection (equivalent squares).

Revealed flaws area is inspected in the measuring mode; field scattered by flaws is measured more detailed to answer coherent data processing [1]. Transducers move along a coherent axis with a step 0,3 mm on an aperture ~100 mm at the measuring mode.

Data received at measuring form acoustic coherent images using holographic processing algorithms. Each such image is three-dimensional with high resolution in plane axis Z (coherent axis).

Mock-up with incipient and developing flaws models for AUT methodology inspection and tests was made. Mock-up (fig .2) is a part of the real welded joint of heat-carrying collector junction welding with the nozzle Du1200 of steam generator. There were 24 artificial and 4 technological flaws in the mock-up – cracks in a fillet. Welded joint mock-up thickness is 72,5 mm. Flaws location and geometry is shown in Table 3 [6].

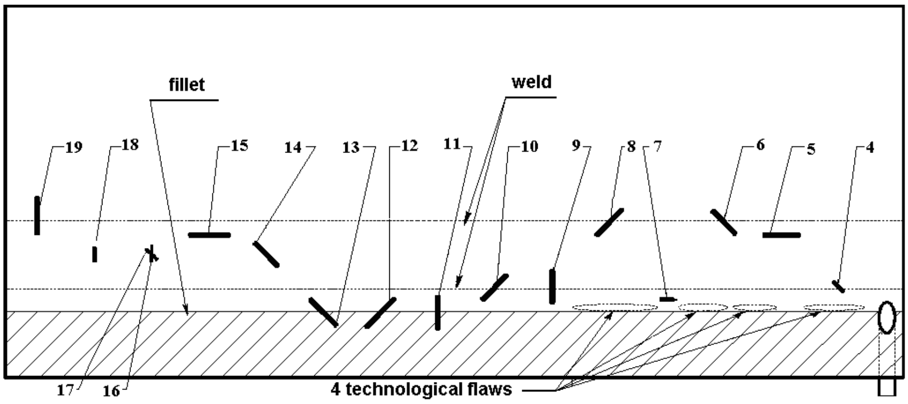


Fig. 2. Flaws location in the Du1200 mock-up, inner face.

Table 3. Flaw sizing in the Du1200 mock-up.

Flaw number	Real sizes		Sizes measured by Augur system		Sizing inaccuracy (rounding to 0,5 mm)	
	Length, mm	Heigth, mm	Length, mm	Heigth, mm	Length, mm	Heigth, mm
ARTIFICAL FLAWS						
1	50	2,0	50	2	0	0
2	50	2,1	50	2	0	0
3	51,9	2,0	50	2	-2	0
4	10,2	0,8	-	-	-	-
5	25,9	3,9	32	5	+6	+1
6	24,2	3,0	22	3	-2	0
7	10,1	0,8	10	1	0	0
8	26,5	3,8	20	3	-6	-1
9	22,8	3,0	30	3	+7	0
10	27,2	4,2	22	3	-5	-1
11	29,2	3,2	20	4	-9	+1
12	33,8	4,8	22	3	-12	-2
13	33,7	3,3	36	3	+2	-0,5
14	23,8	2,9	20	2	-4	-1
15	29,0	4,9	40	6	+11	+1
16	9,4	0,60	18	1	+8,5	+0,5
17	9,5	0,60	16	1	+6,5	+0,5
18	9,1	0,7	15	1	+6	+0,5
19	28,1	4,20	25	2	-3	-2
20	35,9	2,1	40	2	+4	0
21	51,5	2,0	58	2	+6,5	0
NATURAL FLAWS						
Corrosion pits 1*	-	-	25	1	-	-
Corrosion pits 2*	-	-	15	1	-	-
Corrosion pits 3*	-	-	30	1	-	-
Crack	-	~ 4**	35	5		+1
Lack of fusion	70	-	80	1	+10	-

The results are shown received in mock-up by the AUGUR system of flaws sizing. Inaccuracy of flaws parameters measurement was: height ±1,5 mm, length ±7 mm (in a 95% confidence interval).

Welded joints Du1200 AUT methodology [3] was ratified in 2006, and welded joints in all blocks VVER-1000 in Russian Federation are inspected yearly by using it.

Real welded joint AUT data are shown on a fig. 3. A-scans amplitude is between recording and acceptable levels. Flaws presence in the structural reflector area (fillet) is possible according to A-scans information, however it is impossible to define their location and height. There are no reflectors in this area according images information after the coherent data processing (fig. 3. on the right), however there are few lacks of fusion in the welded joints edge. These reflectors height didn't exceed 2 mm, all revealed flaws are not critical.

Real welded joint AUT results are shown on a fig. 4. The defects are rose in the fillet and further increasing to the weld.

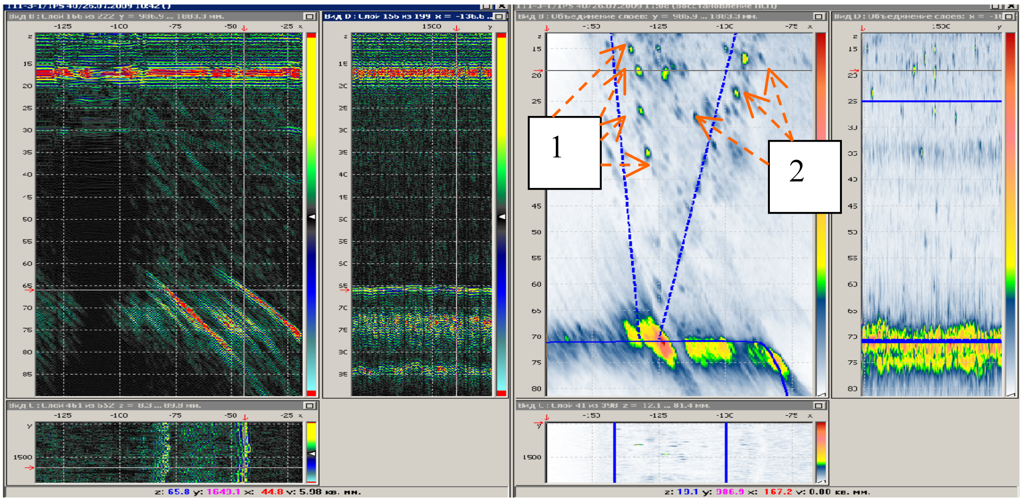


Fig. 3. Projection views B-, C- and D-type A-scans measuring AUT mode and reconstructed images. Welded joint scheme is shown by dark blue lines. Flaws located in the welded joint edge are marked by the numbers 1 and 2.

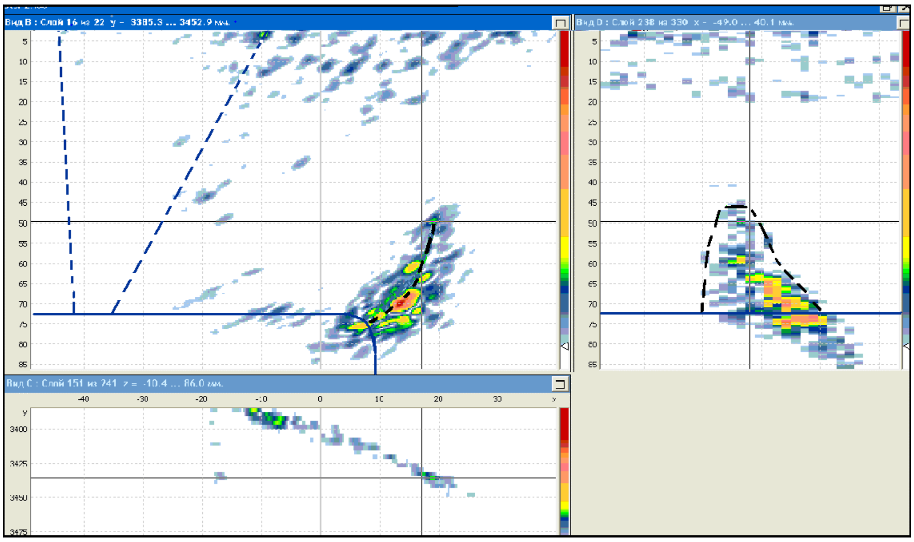


Fig. 4. Reconstruction images of projection views B-, C- and D-type AUT. Welded joint scheme is shown by dark blue lines. Crack is marked by the black dotted line.

AUT of composite welded joint Du1100

Composite welded joint Du1100 methodology is used in welded joint of adapter ring and nozzle of Du1100 steam generator with VVER-440 operating AUT [4].

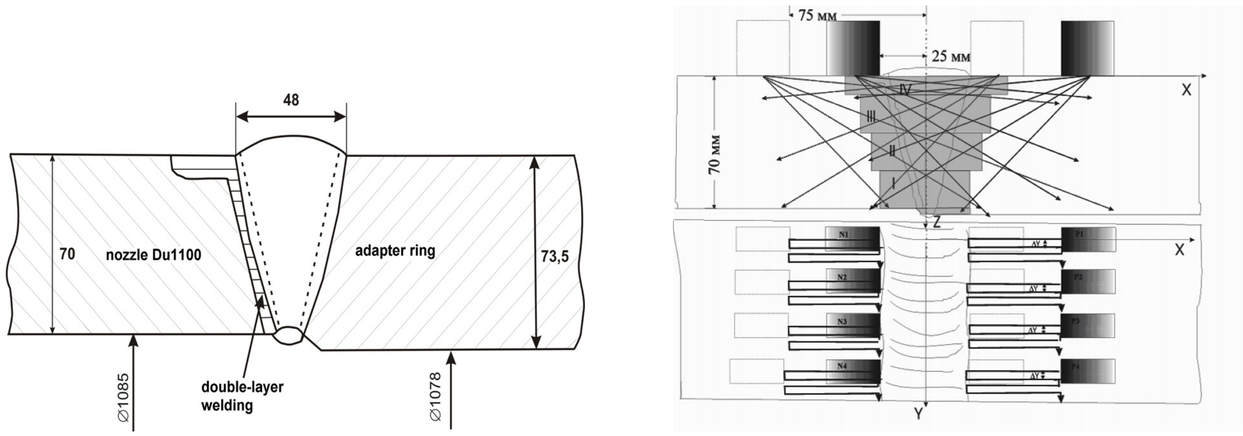
Welded joint specifications:

- material of steam generator nozzle Du1100 is perlite steel 22K;

- material of adapter ring is austenite of 8X18H10T;
- weld material is austenite ЭА400/10Y;
- material of double-layer welding is austenite ЭА395/9 and ЭА400/10Y.

AUT according to this methodology leads is performed only in the measuring mode. Program can calculate equivalent reflection power from echo signals in the Analysis module that allows to sort revealed flaws. The welded joint flaws with equivalent square more than 30 mm^2 and with a conditional length more than 50 mm are inadmissible.

For the Du1100 welded joint inspection (see fig.5) are used shear and longitudinal wave single-mode wideband transducers with central frequency 1,8 MHz and with beam angle 45°, 55°, 75°, and also head wave transducers, which inspected accordingly: I, II, III, IV regions of the weld.



a) b)

Fig. 5. Welded joint configuration (a) and Du1100 welded joint techniques (b).

For the methodology testing the mock-up of the composite Du500 welded joint №10 was used, its material is similar to the Du1100 welded joint by acoustic properties and thicknesses [7]. Welded joint №10 mock-up corresponded the sector of the full-scale composite nozzle welded joint Du500 of reactor VVER 440 vessel with a conical austenite socket. The models of the longitudinal flaws as ellipses and semi ellipses in the welded joint metal were in the mock up.

Real geometrical sizes and all flaws positions were estimated by the images information in the AUT measuring mode. On a fig. 6 the flaws № 3 and 4 images are resulted. Flaw sizing is resulted (shown) in a table 4.

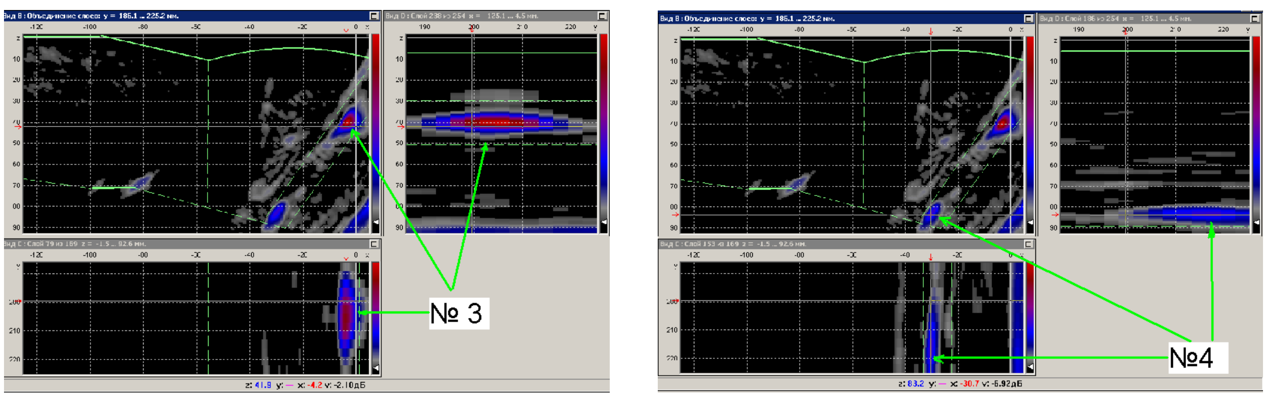


Fig. 6. Flaws №3 (on the left) and №4 (on the right) images after A-scans processing. Data acquired in the AUT welded joint №10 mock-up in the measuring mode.

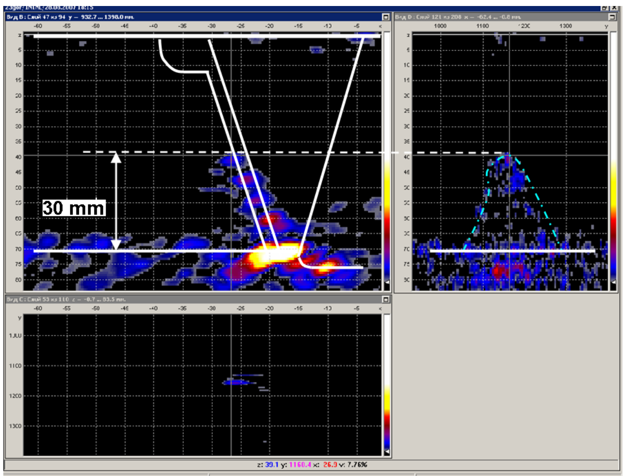
There are mainly two flaws groups in the real Du1100 welded joints. First type flaws are located in the root of the weld, other in the austenite weld line. Flaws located in the weld root are the most dangerous; the second group is not dangerous. The defects in the mock-up are located in pairs in the welded joint head and bottom.

It is impossible to reveal reflectors, its geometry and belonging to the first or second group in the manual UI (bad resolving power). Therefore manual UT leads to the false revealing of these welded joints or to underestimation of dangerous flaws.

Table 4. Flaws sizing in the welded joint №10 mock-up.

Flaw number	Passport flaws sizes (ellipse: major axis × minor axis, semi ellipse: major axis × minor axis)	Maximal coordinate of overhead flaw edge, mm	Maximal coordinate of overhead flaw edge according AUT data	Maximal coordinate inaccuracy, mm
1	Ellips 6 x 3,2	23	24	-1
2	Semi ellips 6 x 3,2	65	64	1
3	Ellips 10 x 5,1	23	20	3
4	Semi ellips 10 x 5,1	65	64	1
5	Ellips 8 x 4,8	23	18	5
6	Semi ellips 6 x 3,2	65	60	5
7	Ellips 8 x 4,8	23	20	3
8	Semi ellips 6 x 3,2	65	64	1
9	Ellips 6 x 3,2	23	18	5
10	Semi ellips 6 x 3,2	65	60	5
11	Ellips 10 x 5,1	23	25	-2
12	Semi ellips 8 x 3,6	65	61	4

Revealed flaw (longitudinal crack in the welded joint) is shown on a fig. 7 (a) – welded joint Du1100 A-scans and images on a fig. 7 (b). Continuous white lines show the weld line, green dotted lines mark a flaw.



a) b)

Fig. 7: a – echo-signals received during AUT Du1100 in flaw area;
b – coherent image of high planar flaw**.**

Welded joint was inspected from the austenitic material side. The revealed flaw was disposed between the perlite nozzle and two-layer austenitic welding, that was confirmed by metallographic researches. Comparisons between AUT measuring mode results from the austenite socket side with metallographic researches information of these welds were allowed to define that crack height determination inaccuracy did not exceed 6 mm (in 95% of confidence interval). The inaccuracy value exceeds the ultrasonic wavelength value ($\lambda \approx 3$ mm) because of ultrasound propagation in the austenite welded joints features.

Discussion

Measuring inspection mode using on NPP has a large prospect, because it promotes inspected objects safety and operating reliability because of the NDT results effective use in strength estimations for objects reliability and its service life. The most effective flaw detectors for measuring inspection realization are UI flaw detectors with the coherent data processing, such as flaw detectors with phased array (PA) and detectors used synthesized aperture technology (SAFT, FT-SAFT, C-SAFT), for example, AUGUR series flaw detectors. Flaws sizing accuracy depends on the scanning zone, coherent data processing depends from inspected volume parameters. So inspected volume is very important in choosing detectors for the concrete objects inspection. Particularly, objects with flaws locating in phased array near-field region should be inspected by flaw detectors with phased arrays. For example, in 2009 AUT pipelines welded joints Du300 methodology using phased arrays was enforced [8]. For the large thickness objects inspection, for example, welded joint of adapter ring and steam generator nozzle Du1100 with VVER-440 the possible flaws localization is far from ultrasonic signals reception. So the devices with synthesized aperture technology and coherent data processing based on the SAFT, FT-SAFT and other algorithms are used.

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