Increasing Results Reliability for SG Tubes of NPPs with VVER based on Experimental Assessment of Human Factor

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1. INTRODUCTION

Problem of nuclear power plant (NPP) safe operation and risks reducing for nuclear power plants is one of the most actual ones. Taking into account the fact that NPP unit lifetimes are being extended beyond their design period, this problem becomes more and more important.

One of the main and critical subsystems for NPP safe operation is steam generator (SG) consisting of (except other systems) about 11 thousands heat exchanging tubes, being the only boundary between primary and second circuits. During operation time the SG heat exchanging tubes are being affected with several degradation processes and mechanisms. This affects tubes integrity, NPP safety and economical effectiveness.

Eddy current testing (ET) is the most effective, reliable and safe for personnel method of nondestructive testing (NDT). ET has the following advantages in comparison with other NDT methods that are also used at NPPs for detection of surface and subsurface flaws – visual, penetration and magnetic power: higher sensitivity in comparison with other surface methods; remotability and speed of ET performance that allow to reduce doses for personnel, performing NDT; and also possibility to detect not only surface flaws but also volume ones. Therefore ET is the most acceptable NDE method for SG tubing examination and ET results reliability enhancement is one of the most important problems.

2. ET RELIABILITY PROBLEM DEFINITION

Application of generally accepted formula [1-3] of NDE system full reliability for case of ET performance was performed. It has the following form:

$$R = f(IC) - g(AP) - h(HF) \tag{1}$$

where R – Reliability of an NDE system for ET performance;

f(*IC*) Intrinsic Capability of the system generally considered as an upper bound. In our case this factor includes the following: SG heat exchanging tubes with ideal surface; ideal ET probes; ET system with ideal sensitivity etc;

g(*AP*) effect of Application Parameters, such as access restrictions and surface state; generally reducing the capability of an NDE system. In our case there are access, humidity, quality of internal surface of heat exchanging tubes processing, sensitivity of ET probes and ET system at all etc.;

h(*HF*) effect of Human Factor, generally reducing the capability or effectiveness; therefore this is quality and reliability of ET results data processing by operators.

One of the factors that affect ET results reliability is human factor (HF) effect. In this paper HF parameter is a subject for estimation based on experimental investigations.

Estimation of human factor effect in ET can be presented as an estimation of correctness of two actions performance: defect detection and defect parameters estimation. Therefore, situation when heat exchanging tubes, which may be left in operation for additional time, will be plugged, may happen. Taking into account limited quantity of heat exchanging tubes that can be plugged at one SG, the plugging due to lack of reliable information about SG tubes leads to premature replacement of SG and, therefore, to essential financial losses. In other hand, NPP unit extra-planned shutdown due to coolant leakage from primary circuit to secondary one through leaky heat exchanging tubes is possible too.

Based on that it is proposed to estimate *h*(*HF*) as precision assessment of ET indication parameters as well as reliability of detection of defects according to ET results.

The task of this article is to determine range of *h*(*HF*) variation for different operators. Also, it is discussed *h*(*HF*) variation in dependence on conditions of ET performance, namely, real conditions of ET performance and modeling of ET results.

3. EXPERIMENT No.1 DESCRIPTION

To evaluate human factor caused by operator, practical experiment indicated below was performed. Set of SG heat exchanging tubes fragments was tested by ET method with using of two different ET systems, namely: 1) ET probe No.1 and ET device No.1 and 2) ET probe No.2 and ET device No.2. Both ET systems include similar ET device of the same manufacturer and similar ET probes with the same design of the same manufacturer. Then the same set of files with ET results was provided to 3 NDE operators asked to do interpretation of data acquired. The same ET software was used for ET results analysis performance. Tube fragments for this testing were available from NPP.

Based on results of ET performance several fragments of SG heat exchanging tubes with defects were selected and pulled out. Few fragments were used for metallography study (Fig. 1). 17 fragments that were not received for metallography study have been taken for performance of experiment No. 1 indicated above.

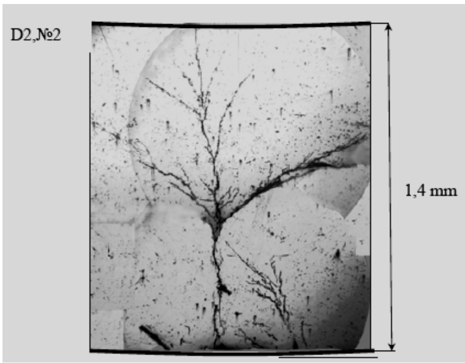

Fig. 1 - Results of metallography study. Defect depth: 100%. Extension: 7 mm

ET results interpretation was performed at 3 frequencies: F2 – main frequency, F1 – high frequency (F1 is approximately 2 times higher than F2) and F3 – low frequency (F3 is half as F2).

Also 2 systems to estimate effect of capability of NDE system have been used.

4. RESULTS OF EXPERIMENT No. 1

4.1 Estimation of human effect on experiment No. 1 results

To estimate precision of ET indication parameters, statistical analysis of ET results interpreted by three operators for two ET systems was applied. During ET results interpretation each operator defines indication location, ET amplitude, phase and depth of defect. These four parameters were subject for analysis and are presented in Table 1below as mean-square deviations for parameters indicated above.

Also to analyze parameters indicated, correlation coefficients of parameters for different operators for both ET systems were calculated according to the following formulae:

$$r = \frac{n\sum M_i T_i - \left(\sum M_i\right)\bullet\left(\sum T_i\right)}{\sqrt{\left[n\sum M_i^2 - \left(\sum M_i\right)^2\right]\bullet\left[n\sum T_i^2 - \left(\sum T_i\right)^2\right]}}, \quad (2)$$

where M_i, T_i – two sampling with values of parameters defined by two different operators according to interpretation of ET results obtained by one ET system; n – number of values in sampling.

This formula was applied for calculation of correlation coefficients of indications location (Table 2), average values of defect depth for main frequency F2 and other two frequencies (Table 3) and defect depth estimated by different operators at main frequency F2 (Table 4) for both ET systems. All data sets are rather in a very well correlation.

Table 1 - Mean-square deviations of indication location, ET amplitude, phase and defect depth estimated for each indication calculated for three frequencies and for both ET systems

Range of mean-square deviations of	ET system	Frequency F1	Frequency F2	Frequency F3
indication location, %	ET system No. 1	[0; 10,8]		
	ET system No. 2	[0; 10,8]		
ET amplitude, %	ET system No. 1	[1,35; 11,1]	[0,6; 5,2]	[0; 12,4]
	ET system No. 2	[1,35; 17,4]	[0; 7,7]	[2,08; 9,8]
ET phase	ET system No. 1	[0,7; 19,4]	[0; 4,8]	[0; 8,6]
	ET system No. 2	[0; 14,9]	[0; 3,9]	[0; 18,4]
defect depth estimated according to ET results	ET system No. 1	[0,7; 3,7]	[0; 13,3]	[0; 13,3]
	ET system No. 2	[0; 22,2]	[0; 8,6]	[0; 39,8]

Table 2 - Correlation coefficients of indications location for different operators

	ET system No. 1	ET system No. 2
Correlation coefficients, operators No. 1 and No. 2	0,9	0,9
Correlation coefficients, operators No. 1 and No. 3	0,7	0,9
Correlation coefficients, operators No. 2 and No. 3	0,9	0,8

Table 3 - Correlation coefficients of average values of defect depth estimated according to ET results for main frequency F2 and other four frequencies for both ET systems

	ET system No. 1	ET system No. 2
Correlation coefficients, frequencies F2 and F1	0,7	0,8
Correlation coefficients, frequencies F2 and F3	0,8	0,9

Table 4 - Correlation coefficients of defect depth estimated according to ET results at main frequency F2 for different operators

	ET system No. 1	ET system No. 2
Correlation coefficients, operators No. 1 and No. 2	0,99	0,99
Correlation coefficients, operators No. 1 and No. 3	0,99	0,99
Correlation coefficients, operators No. 2 and No. 3	0,99	0,996

To estimate correctness of second action performed by ET operator, namely defects detection, probability of detection for all three operators was calculated based on total number of defects detected by all three operators under the ideology of plugging from [4]. Results of these calculations for each ET system are presented in Tables 5 and 6.

Table 5 - Probability of detection for all three operators based on total number of defects detected by all three operators in different zones of plugging criterion. ET system No. 1

Operators, which data is compared	Probability of detection	Probability of detection in zone of mandatory plugging	Probability of detection in zone of necessary additional analysis	Probability of detection in “safe zone”
Operators No. 1	0,9	0,8	0,8	1
Operators No. 2	0,8	0,7	0,8	1
Operators No. 3	0,9	0,9	1	0,5

Table 6 - Probability of detection for all three operators based on total number of defects detected by all three operators in dependence on zone of defect location. ET system No. 2

Operators, which data is compared	Probability of detection	Probability of detection in zone of mandatory plugging	Probability of detection in zone of necessary additional analysis	Probability of detection in “safe zone”
Operators No. 1	0,9	0,8	0,9	1
Operators No. 2	0,9	0,8	0,9	1
Operators No. 3	0,9	1	0,9	1

The following conclusions can be made based on experiment No. 1 performed:

1) results precision of parameters measurements, namely ET amplitude, phase and defect depth estimated, for different operators are in range (10 ÷ 15)%;
2) values of indication locations and defect depths estimated by different operators at main frequency F2 correspond quite well;

First two items indicate that all operators perform procedure of ET results parameters estimation well enough, uniform and at this stage of ET performance the effect of human factor is not essential;

3) probability of detection for all three operators based on total number of defect detected by all operators is equal 1 only for defects located in “safe zone”. In other zones of plugging criteria this value varies 0,7 ÷ 0,9;
4) to verify results measured and analysis performed it will be better to have results of metallography study for tube fragments researched. And in future it is planned to perform such study for some fragments.

4.2 Estimation of NDE system capability effect

Analyzing data of ET results interpretation, an attempt to estimate effect of NDE system capability was performed. With this aim a calculation of correlation coefficients according to (2) for defects location, ET amplitude and phase and defects depth estimated according to ET results of each operator between two different ET systems were performed. Results are presented in Table 7 below.

Table 7 - Correlation coefficients of defects location, ET amplitude and phase and defect depth estimated according to ET results for each from three operators between two ET systems

	Correlation coefficient of defects location	Correlation coefficient of ET amplitude	Correlation coefficient of ET phase	Correlation coefficient of defect depth estimated
Operator No.1	0,95	0,99	0,99	0,8
Operator No.2	0,999	0,7	0,96	0,8
Operator No.3	0,9	0,99	0,99	0,8

All data sets are in good correlation, so both systems can provide good repeatability of ET results.

At the next step, to estimate of ET system effect on definition of ET signal parameters, mean-square deviations of defects location, ET amplitude and phase and defect depth at frequency F2 between two different ET systems have been calculated for each separate operator as well. Results are presented in Table 8.

Table 8 - Range of mean-square deviations (%) of defects location, ET amplitude and phase and defect depth between two ET systems for each operator. Frequency F2

	Range of mean-square deviations of defects location, %	Range of mean-square deviations of ET amplitude, %	Range of mean-square deviations of ET phase, %	Range of mean-square deviations of defect depth evaluated, %
Operator No.1	[0; 3]	[1,7, 19,1]	[0; 30,1]	[0, 32,4]
Operator No.2	[0; 4]	[1,7; 21,1]	[1,3, 30,1]	[0,9; 42,6]
Operator No.3	[0; 5,2]	[1,26; 26,4]	[0; 22,9]	[0,8; 31,8]

Due to the considerable variation of mean-square deviations of ET indication parameters, an additional research of ET data interpretation was performed. It was found out that a calibrated of analog devices of both ET systems was performed in a different way. As a result, performance of estimation of ET system effect is impossible in this case.

To estimate this value it is proposed to perform in future a research, under which a fragment of SG tubes should be ET inspected at least five times with each ET system, all ET results acquired should be interpreted by each ET operator and presented for further statistical analysis.

5. EXPERIMENT No.2 DESCRIPTION

In addition, the same group of analysts received set of files with signals acquired during ET of SG tube. These files have been prepared specially for this research in the following way.

Real digital data acquired from defect imitators from ASME calibration block were inserted (implanted) in files with real ET results of SG heat exchanging tubes with own software developed. Here superposition of signal part from real ET results with signal from calibration block was performed. Signals from defects were scaled according to amplitude during implantation. Such "defects" were implanted in different parts of real SG tube signals. As a result, 10 files with 19 implanted defects and 2 defects existing in these files initially were created. Total, there were 10 files with 21 defects proposed for interpretation to the same 3 operators that took participation in first experiment.

In contrast to experiment No. 1, files presented ET results of SG heat exchanging tubes with full length were provided to ET operators for interpretation (in first experiment ET results of SG tube fragments were provided). In addition, there were created conditions that may rarely appear in real ET raw data. Results of interpretation were analyzed with F2 frequency.

6. RESULTS OF EXPERIMENT No. 2

6.1 Estimation of ET indication parameters

Similar to experiment No. 1, to estimate correctness of ET indication parameters definition, statistical analysis of ET results interpretation was performed. Variation ranges of mean-square deviations of locations, ET amplitude and phase and defect depth for each indication defined by different operators were calculated (Table 9).

Table 9 - Range of mean-square deviations of indications parameters for different operators

Range of mean-square deviations, %	for indications location	for ET amplitude	for ET phase	for defect depth estimated
	[0; 5,1]	[0; 7,9]	[0; 2,5]	[0; 6,2]

Also correlation coefficients of indications location, ET amplitude, phase and defect depth estimated for different operators were found according to (2). Results of these calculations are presented in Table 10.

Table 10 - Correlation coefficients of indications parameters for different operators

Operators, which data is compared	Correlation coefficients of			
	indications location	ET amplitude	ET phase	defect depth estimated
Operators No. 1 and No. 2	1	0,998	0,9998	1
Operators No. 1 and No. 3	1	1	1	1
Operators No. 2 and No. 3	1	0,998	0,998	0,998

Result of this investigation: data with parameters of indications do correlate very well and all parameters of ET indications are estimated by all three operators identically.

6.2 Comparison of ET results parameters with real parameters of defects implanted

Since real parameters of defect implanted are known for us, comparison of parameters determination by each operator and real parameters was performed. This analysis could be useful to estimate precision of parameters estimation and, as a result, effect of human factor.

Comparison of calculated average means of ET amplitude, phase and defect depth estimated with real values of these parameters of defects implanted was performed and ranges of mean-square deviations of these parameters are presented in Table 11.

Table 11 - Range of mean-square deviations of indications parameters for different operators

Range of mean-square deviations, %	for ET amplitude	for ET phase	for defect depth estimated
	[0; 14,1]	[0; 3]	[0; 4,7]

Correlation coefficients of ET amplitude, phase and defect depth estimated by each operator and real parameters data were found according to (2) as good enough. Results of these calculations are presented in Table 12 below.

Table 12 - Correlation coefficients of ET amplitude and phase and defect depth estimated according to ET results by each operator and real parameter values

	Correlation coefficient of ET amplitude	Correlation coefficient of ET phase	Correlation coefficient of defect depth estimated
Operator No.1 and real parameters	0,99	0,998	0,998
Operator No.2 and real parameters	0,99	0,997	0,997
Operator No.3 and real parameters	0,99	0,997	0,997

After this investigation performed a conclusion can be made that defect parameters estimated by all three operators correlate with real parameters of defects quite well and deviations of parameters estimated by operators from real defect parameters are small. So, estimation of parameters of defects detected is performed good enough, and effect of human factor is not so high at this stage of ET data analysis.

6.3 Probability of detection

To estimate human factor effect on reliability of defects detection, a probability of detection was calculated also. Taking into account that total number of defects in files available is known, probability of detection for operators in total and for each operator separately was calculated and results are presented in Table 13.

Table 13 - Probability of detection of defects for each operator and in total

Operators, which data is compared	Probability of detection
Operators No. 1	0,8
Operators No. 2	0,8
Operators No. 3	0,9
Total	0,8

Also defect distribution in different zones indicated in plugging criteria [4] was built graphically according to defect parameters (depth estimated according to ET results and amplitude) (see Figure 2). Probability of detection of defects was calculated too for each operator for these zones. Results are presented in Table 14.

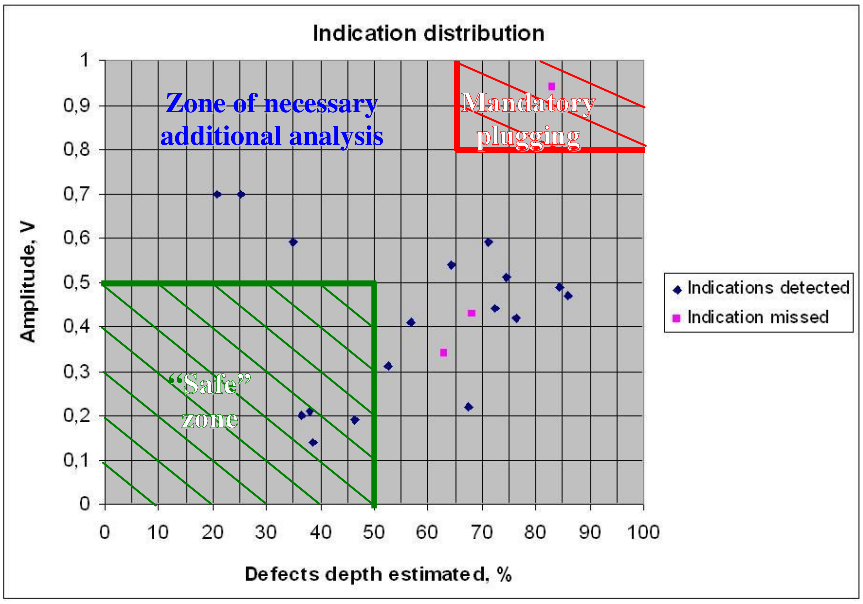

Figure 2 - Distribution of defects in different zones indicated in plugging criteria according to defect parameters (depth estimated according to ET results and amplitude)

Table 14 - Probability of detection of defects for each operator and in total for zones of plugging criteria

Operators, which data is compared	Probability of detection in zone of necessary additional analysis	Probability of detection in "safe zone"
Operators No. 1	0,8	1
Operators No. 2	0,8	0,7
Operators No. 3	0,9	1
Total	0,9	1

As a result of experiment No. 2 performance, the following conclusions are made:

1) 10 files with ET results for SG heat exchanging tubes with full length were modeled. In addition, conditions that can appear in real ET results rarely were created. For example, defect located in SG tube in area of collector was implanted, and operators missed it;
2) determination of defects parameters is performed well, and effect of human factor is not so high at this stage of ET data analysis;
3) detection of defects is not good enough, in general;
4) probability of defects detection in "safe" zone may be considered as a good and one can say with high probability, that whole SG tube will not be plugged;
5) due to low statistics in the zone of mandatory plugging, a correct conclusion can not be made;
6) operators missed indications in the necessary additional defect analysis zone.

So, effect of human factor at the stage of indications detection is high enough.

7. ESTIMATION OF EXPERIMENTS RESULTS. ASSESSMENT OF HUMAN FACTOR EFFECT AT ET RELIABILITY

To estimate human factor effect on parameters definition, results of investigations performed in both experiments were compared and Table 15 presents ranges of mean-square deviations of ET amplitude and defect depth (in %) for all operators and all indications. Ranges for mean-square deviations are similar.

Therefore, parameters of ET results were estimated with similar precision, and effect of human factor on parameter estimation is not essential.

Table 15 - Comparison of mean-square deviations of parameters estimation performed by all operators in two experiments

	Range of mean-square deviations of ET amplitude, %	Range of mean-square deviations of defect depth evaluated, %
Experiment No. 1, ET system No.1	[0,6; 5,2]	[0; 13,3]
Experiment No. 1, ET system No.2	[0; 7,7]	[0; 8,6]
Experiment No. 2	[0; 7,9]	[0; 6,2]

To estimate human factor effect on defects detection, comparison of probabilities of detection calculated for each operator in two experiments was performed according to Tables 5, 6, 13 and 14. And a result of comparison is the conclusion that probability of detection calculated for both experiment is not high enough.

Therefore, taking into account limited scope of statistical data, conclusion can be made that a probability of detection (PoD) has the most essential contribution for human factor estimation. And it can be proposed to estimate a human factor in a following way:

$$h(HF) = 1 - \text{PoD}.$$

8. CONCLUSIONS

In this paper we tried to perform an estimation of human factor effect with experimental approach. The conclusions of this investigation are as follows:

1) correlation coefficients of defect depths estimated for different operators at main frequency F2 correspond quite well;
2) ET indication parameters estimated by all three operators are similar;
3) all operators perform procedure of ET parameters estimation in the similar way;
4) effect of human factor is not essential for ET indication parameters estimation;
5) probability of detection calculated in both experiment is not good enough;
6) to verify results measured and analysis performed in first experiment it would be better to rely upon the results of metallography study for tube fragments available. In a future it is planned to perform such study for some tube fragments;
7) results of two experiments for human factor estimation are similar. Therefore, approach of implantation of additional indications by modeling in real files with ET results can be applied for estimation of human factor effect;
8) based on limited scope of statistical data, it can be proposed to estimate a human factor as $h(HF) = 1 - \text{PoD}$.

9. REFERENCES

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