Steam Generator Tubing Inspection

Human Factor Estimation for ET Results Reliability of SG Tubes of NPPs with VVER

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1. INTRODUCTION. ET RELIABILITY

Steam generator (SG) tube integrity is of great importance for safe and reliable nuclear power plant (NPP) operation. The application of eddy current testing (ET) to evaluate SG tube integrity is recognized worldwide and has been used over several decades. However, at times, ET results are considered questionable.

A decision to leave a defective SG tube in operation is made based on the ET results acquired. The reliability of ET can be expressed by the following equation [1, 2, 3]:

$$R = f(IC) - g(AP) - h(HF),$$

where R - total reliability of the ET system; $f(IC)$ - intrinsic capability of the system driven by physical laws and technical potential, generally considered as an ideal upper bound; $g(AP)$ - the effect of an application parameter, such as ET system-specified parameters and conditions of ET performance; and $h(HF)$ - the effect of human factors. In many cases, the human factor parameter $h(HF)$ cannot be separated from $g(AP)$ because $h(HF)$ is included as a part of the effect of the application parameter.

This paper describes several available methodologies for obtaining numerical values with which to directly estimate the effect of human factors on ET reliability. We investigated the possibility of applying available approaches for estimating the human factor effect by applying two methodologies [4, 5] to the issue of ET reliability.

2. HUMAN RELIABILITY ANALYSIS TASK DEFINITION

To estimate the effect of the human factor in ET reliability, we applied the Human Reliability Analysis (HRA) methodology.The aim of HRA is the quantification of human error probability. The methodology usually is used to evaluate human reliability of NPP operations personnel. Typically, HRA is incorporated into the PRA model. The main requirement for an HRA assessment is that results be documented sufficiently well according to all assumptions defined to enable their replicability in subsequent assessments.

Human Reliability Analysis (or Human Factor Analysis) is the characterization of relationships between personnel (in our case, technical personnel performing ET of SG heat exchanger tubes during an NPP outage) and reactor unit systems and analysis of effects on system reliability resulting from such interaction.

Personnel actions include any activity, such as direct performance of operations, decision making, or mental activity, performed individually or collectively by NPP personnel, that affect NPP operational status (for example, equipment stage, systems configuration). The result of personnel action performance can be either success or failure (personnel error). And personnel error is a basic event that introduces mistakes during the performance of needed action—mistakes that lead to failure of safety functions, systems, or equipment.

In addition, the HRA methodology has general assumptions and limitations [6]. Those specific to NDT include the following:

1. Only personnel errors that occurred during performance of definite tasks by personnel are considered.
2. It is assumed that NDE personnel are acting in the best interests of the NPP.
3. The NPP unit is shut down for maintenance. Operator stress level is normal.
4. Tasks are performed by competent, qualified NPP personnel with at least 6 months' experience in their respective positions.

In our research, the subjects were maintenance personnel, specifically those personnel performing ET of SG heat exchanger tubes. According to [4, 5], errors stemming from manual actions rather than from the decision-making process are more typical for this type of staff.

3. DESCRIPTION OF METHOD

Conducting an HRA includes performance of several tasks. In accordance with [7] and taking into account our area of research, these tasks contain the following items [8] (see Fig. 1):

1. Familiarization with NPP and data acquisition and identification of personnel actions;
2. Selection of more important (essential) events, errors, actions;
3. Performance of detailed analysis after selection of actions for this detailed analysis. At this step, the action (event) is defined in more detail; methodology for quantity assessment is selected; quantity analysis (i.e., data acquisition for quantity assessment) is conducted;
4. Quantification of analysis (calculation of errors probability);
5. Documentation.

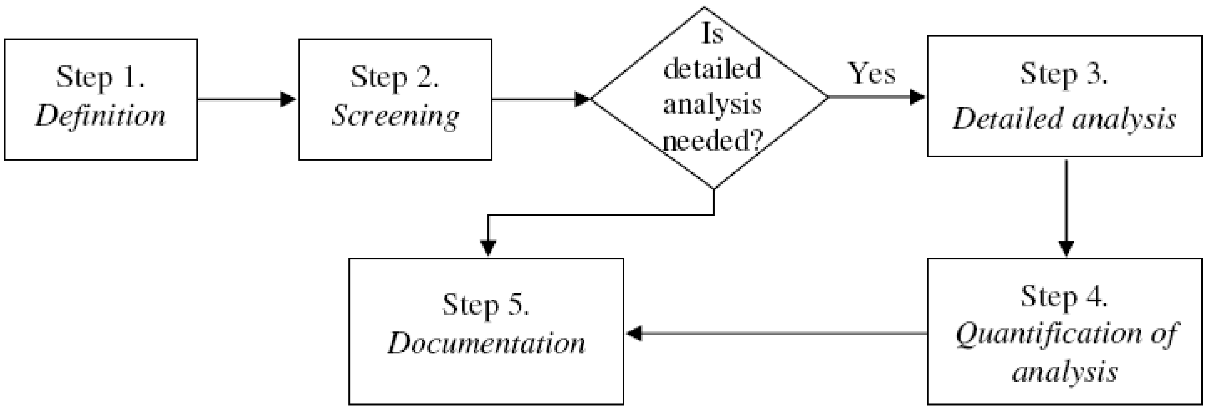

Figure 1 - Systematic analysis of human error applied to ET of steam generator heat exchanger tube performance

4. METHOD APPLICATION

After familiarization with actions performed by NDE operators during eddy-current inspection of SG heat exchanger tubes, a list of actions conducted was developed. Actions performed by staff but without ET system effect were selected. At the next step, the most important and essential events, errors, and actions were screened. All actions were found to need more detailed analysis. To perform quantitative estimation, the methodology for quantification was selected.

Currently, no models of personnel behavior can describe human behavior in detail and consistently, nor can they present a precise definition of reliability parameters. Therefore, methods of HRA quantification take into account a limited number of aspects of personnel behavior, and it is assumed that these aspects have the most important impact on human reliability.

In our work, we selected two methodologies for HRA quantification:

1. ASEP [5];
2. Decision Tree Approach [9].

Of the two methodologies, ASEP—*Accident Sequence Evaluation Program Human Reliability Analysis Procedure*—is more conservative. It is less time-consuming and has a procedure for screening. This screening procedure permits more attention to be focused on detailed analysis of the most important human errors.

The Decision Tree Approach is a more detailed methodology that uses data specified for our concrete case based on expert judgments.

4.1 ASEP Methodology

Taking into account that basic human error probability (HEP) consists of errors of omission and errors of commission [5], it is assigned a total basic HEP for each critical action:

$$\sum HEP = \sum HEP_{omis} + \sum HEP_{com} .$$

Based on [5], we assumed that a basic HEP for each error of omission is equal to 0,02 and a basic HEP for each error of commission is equal to 0,01. Therefore, for each critical action, the full basic HEP is equal to 0,03. This value is conservative, and suggests that NDT staff at an NPP must not be very well qualified if the basic HEPs were to be increased. It is assumed to apply error of omission and error of commission as the same value with HEP = 0,03. According to ASEP methodology, the final value of HEP must be derived by multiplying the basic HEP on recovery factors.

Four critical actions are performed by NDE operator-analysts who interpret ET results. In our study, two optimum conditions can be applied, according to the procedure for performing ET of steam generator heat exchanger tubes at NPPs of Ukraine. These conditions and their associated recovery factors are as follows:

- direct performance of ET by a second person to check correctness of ET analysis performed by the first operator. The HEP for this recovery factor is equal to 0,1.
- performance of inspection of another physical nature after ET completion. The HEP for this recovery factor is equal to 0,01.

These two recovery factors reduce the HEP for the activity. Finally, quantitative assessment of human reliability analysis has the following form:

$$\sum HEP_{analytic} = 0{,}03 \cdot 4 \cdot 0{,}1 \cdot 0{,}01 = 0{,}00012 .$$

So, the most conservative assessment of HEP for ET results interpretation is $12 \text{ x } 10^{-5}$.

Because ET of SG heat exchanging tubes is performed by two types of staff (ET data acquisition and ET results interpretation), we also apply the ASEP methodology to operators who performed ET data acquisition. There are four critical actions performed by these NDE operators as well. In addition, a recovery factor that involves performance testing of ET data acquisition (HEP = 0,01) can be applied. Finally, the HEP for staff performing ET data acquisition is the following:

$$\sum HEP_{data\_acq} = 0{,}03 \cdot 4 \cdot 0{,}01 = 0{,}0012 .$$

And the total HEP of personnel performing SG heat exchanger tubes ET is equal:

$$HEP_{ET} = 0{,}00012 + 0{,}0012 = 0{,}00132 .$$

4.2 Decision Tree Approach

The decision tree approach to human error analysis requires performing an investigation dealing with all factors (such as time limitations, stress level, knowledge level, experience) that affect operator actions. The graphical form of these factors (as a “tree”) is constructed, and such representation enables the making of justified conclusions corresponding to the most risk significant factors, and, at the end, human error reliability will be quantified (“decision” will be achieved).

The main components of the decision tree are

1. headings or performance shaping factors arranged in order of decreasing significance;
2. logical structure that consists of many branches corresponding to possible values of performance shaping factors;
3. probabilities that correspond to end states.

The basic task one must apply when using the decision tree approach include 1) identification of performance shaping factors (headings) and their order of location in the decision tree; 2) identification of possible values of performance shaping factors (branches of decision tree), i.e., logical structure; and 3) identification of probabilities that correspond to decision tree end states.

Experienced NPP expert operators were used when completing the tasks listed above. First, an ET expert was interviewed and a full list of performance shaping factors (PSFs) was prepared as a result of this interview. This list consists of 14 factors for operators-analysts and 9 factors for operators who perform an acquisition of ET data. Based on results of this interview, two different questionnaires for two types of ET personnel, namely, ET data acquisition and ET results analysis, were prepared. These questionnaires include all PSFs.

At the second step, a preliminary decision tree was developed based on expert judgment of this experienced operator. A logical structure with two to three branches for each PSF with specified qualitative assessments of each branch was developed as well. It was decided to develop a decreasing decision tree.

The next step involved conducting a personal interview according to questionnaires with each participant of these two groups. We asked operators to define the order of risk-significance for these PSFs in a decreasing direction. It was assigned that worst qualitative assessment of each PSF is 1, and operators were asked to define a quantitative value of best qualitative assessment for each PSF that must be less than 1 (but more than 0). A middle value of PSF (if any), was assigned as the average value between best and worst values. Interviews were conducted with eight operators-analysts and nine operators who acquire ET data.

Next was development of the final decision tree. First, all decision tree headings (PSFs) were classified according to judgments of experts. Two different decision trees for operators-analysts and one decision tree for operators that acquire ET data were developed.

In the first case for operators-analysts, the order of PSFs defined by one main expert was accepted as the order of headings in the decision tree. At the next stage, the last four factors from this arranged list were delayed so they have very small significant effect on operator actions. Based on that, quantitative assessments for each branch for each PSF of the decision tree were calculated as the average between corresponding values for the entire group except for the values of the main expert. In this way, values for the intermediate decision tree were established. Then final probabilities for each branch of PSFs were quantified as averages corresponding to the values assigned by main experts and values from the intermediate decision tree.

In the second case for operators-analysts, three of the best-experienced experts were selected from the group of operators questionnaires. In this case, the specific order of decision tree headings was defined as the average between orders specified by main experts selected. As in the previous case, last 4 factors so they have very small significant and effect on operator actions were delayed. Quantifications of probabilities for each branch of PSFs were calculated as an average between corresponding average values of main experts and average values of remained group of experts.

For the operators who acquire the ET data, the order of decision tree headings was determined as the average of PSF orders of the entire group. PSF probabilities were calculated also as average values of the entire group of experts.

An anchor probability value was selected as 0,03—a conservative value accepted by all experts of human analysis.

As a result, we developed three decision trees with many branches. Due to the large sizes of decision trees developed, we present just a fragment of the decision tree developed according to our first approach (indicated above) as Figure 2.

In our case, a simplified model was developed for a decision tree in which all PSFs were assigned as factors with equivalent weight. For more in-depth analysis of human factor, usually it is specified weight coefficients for each heading according to expert judgments.

Operator action	1. Operator knowledge level	2. Operator expirience	3. Training performance	4. Operator physical state (fatigue)	5. Signal amplitude from uncer-tainty	6. Sygnal / noise ratio	7. Detected indication type determination	8. Dependence of uncertainty location at tube	9. Operator intuition	10. Consultation (relationship) with other personnel (experts) of NPP	HEP

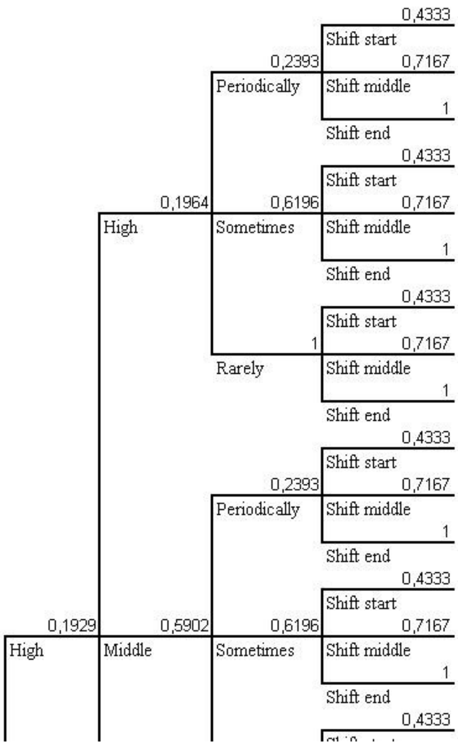

Figure 2 - Fragment of decision tree for calculation of operator-analyst HEP (decision tree was developed based on one main expert judgment)

In the final stage of using the decision tree methodology, final tables were prepared to calculate human error reliability, taking into account all risk-essential factors. These tables are presented as Tables 1, 2, and 3. The HEP is calculated as a multiplication of anchor probability value and quantitative assessments of each PSF. For example, five different possibilities for calculating the probabilities of five different operators for each case have been considered.

In a case of more in-depth analysis of human factor, each value also is multiplied by the weight coefficients specified.

Taking into account that the human factor of ET consists of human factor of personnel acquiring ET data and human factor of personnel interpreting ET results, the resulting HEP will be the following:

$$HEP_{ET} = HEP_{acq\_data} + HEP_{analyz}\,.$$

5. CONCLUSIONS

In this paper, we examined the application of HEP to ET for steam generator tubes, to quantify the human factor and to assess its effect on NDT results reliability.

This work resulted in two different assessments of HEP. In the case of ASEP, a conservative estimate was obtained. This methodology does not take into account specific details of ET performance.

Table 1 - Resulting table of decision tree for calculation of operator-analyst HEP (decision tree was developed based on one main expert judgment)

Operator-analytic actions	Code	1. Operator knowledge level	2. Operator experience	3. Training performance	4. Operator physical state (fatigue)	5. Signal amplitude from uncertainty	6. Signal/noise ratio	7. Detected indication type determination	8. Dependence of uncertainty location at tube	9. Operator intuition	10. Consultation (relationship) with other personnel (experts) of NPP	HEP
Error of operator No. 1 action	HFE_1 AN1	0,1929	0,1964	0,2393	1	0,625	0,6464	0,1971	0,2214	0,1836	1	8,8035E-07
Error of operator No. 2 action	HFE_1 AN2	0,5964	1	0,6196	0,4333	0,25	0,2929	0,5986	1	0,1836	0,2007	7,7585E-06
Error of operator No. 3 action	HFE_1 AN3	0,1929	0,1964	0,2393	0,7167	0,625	0,6464	0,1971	0,2214	0,5918	0,6004	1,2211E-06
Error of operator No. 4 action	HFE_1 AN4	0,1929	0,5902	1	0,4333	0,25	0,6464	1	0,6107	1	0,2007	2,9313E-05
Error of operator No. 5 action	HFE_1 AN5	0,5964	0,5902	0,6196	0,7167	0,625	1	0,5986	0,6107	0,1836	0,2007	3,9479E-05

Table 2 - Resulting table of decision tree for calculation of operator-analyst HEP (decision tree was developed based on three main experts' judgment)

Operator-analytic actions	Code	1. Operator physical state (fatigue)	2. Signal amplitude from uncertainty	3. Operator experience	4. Signal/noise ratio	5. Operator knowledge level	6. Time limitation	7. Training performance	8. Detected indication type determination	9. Dependence of uncertainty location at tube	10. Operator intuition	HEP
Error of operator No. 1 action	HFE_3 AN1	0,364583	0,6583	0,2617	0,33	0,2533	0,2983	0,2927	0,6267	0,35	0,265	7,9936E-07
Error of operator No. 2 action	HFE_3 AN2	0,6822916	0,3167	0,2617	0,665	0,6267	0,2983	0,6458	0,2533	0,35	0,6325	7,6373E-06
Error of operator No. 3 action	HFE_3 AN3	1	1	0,6308	0,33	0,2533	0,6492	1	0,6267	0,675	0,265	0,00011512
Error of operator No. 4 action	HFE_3 AN4	0,364583	0,6583	0,6308	1	0,6267	0,6492	0,2927	1	0,35	0,6325	0,00011974
Error of operator No. 5 action	HFE_3 AN5	0,364583	0,3167	1	0,665	0,2533	0,2983	0,2927	0,2533	0,675	1	8,7104E-06

In the case of the decision tree, we obtained essentially smaller values. This approach takes into account not only features and factors of the ET method but the ET system as well (according to definition that ET system includes equipment and personnel performing inspection with this equipment). With the application of decision trees developed, it is possible to calculate HEP for each operator based on his personal possibilities.

After analysis of HEP values, we may propose to select as a basic HEP for ASEP and anchor probability value for decision tree higher than 0,03. Reason for this suggestion: it is assumed to use 0,03 as basic HEP and anchor probability value for HRA of NPP operations personnel, but maintenance staff is subject of our research. Based on that, a new approach to derive basic HEP for ASEP and anchor probability value should be considered.

Table 3 - Resulting table of decision tree for calculation of HEP of operators who acquire ET data

Actions of operator that acquire ET data	Code	1. Operator knowledge level	2. Operator experience	3. Operator physical state (fatigue)	4. Training performance	5. Quality of equipment preparedness for data collection	6. Time limitation	7. ET probe quality	8. Quality of tube coordinates establishment at push-puller	9. Complexity of "decision making for tube ET results quality	HEP
Error of operator No. 1 action	HFE_DATA _ACQ1	0,5722	0,4422	0,5372	0,6222	0,4	0,3556	0,4688	0,4389	0,1956	1,45244E-05
Error of operator No. 2 action	HFE_DATA _ACQ2	0,4326	0,4422	0,2875	0,8056	0,7	0,3556	0,7343	0,6611	0,5978	9,60152E-05
Error of operator No. 3 action	HFE_DATA _ACQ3	0,5722	0,4422	0,2875	0,6222	0,4	0,6528	0,4688	0,4389	0,1956	1,42698E-05
Error of operator No. 4 action	HFE_DATA _ACQ4	0,4326	0,4422	0,5372	0,6222	0,7	0,3556	0,7343	0,6611	1	0,000231789
Error of operator No. 5 action	HFE_DATA _ACQ5	1	0,7211	1	1	0,7	0,3556	0,4688	0,4389	0,5978	0,000662347

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7. REFERENCES

1) Taylor T. and Doctor S., "What is NDE Reliability Anyway? A Proposed Definition and Review of Workshop Relationship", Second American-European Workshop on NDE Reliability, Boulder, CO, USA, 1999.
2) Muller C., Ewert U., Scharmach M., Volker J., Schaefer L. and Wilrich P.-T. "Concepts in Reliability Measurements", 3rd European-American Workshop on Reliability of NDE and Demining, Berlin, 2002.
3) Stephens H. "Long Term Experience With Evaluation and Improvement of the Human factor in NDE Reliability", 3rd European-American Workshop on Reliability of NDE and Demining, Berlin, 2002.
4) A.D. Swain and H.E. Guttmann, Handbook of Human Reliability Analysis with Emphasis on Nuclear Power Plant Application, Final Report", NUREG/CR-1278, 1983.
5) Swain A.D., Accident Sequence Evaluation Program Human Reliability Analysis Procedure, NUREG/CR-4772, 1987.
6) PRA Procedures Guide: A Guide to the Performance of Probabilistic Risk Assessments for Nuclear Power Plants, NUREG/CR-2300, 1983.
7) Rovno NPP. Unit 4. Final Safety Analysis Report. Project Guideline. Human Reliability Analysis. 43-923.203.006.MD.13, 2004.
8) IAEA. Gruppa po rassmotreniyu voprosov expluatazionnoy bezopastosti OSART, Vienna, 1995. (in Russian)
9) Hall R.E., Fragola J. and Wreathall J, Post Event Human Decision Errors: Operator Action Tree/ Time Reliability Correlations, NUREG/CR-3010, 1982.