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Safety investigation of team performance in accidents

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Abstract

The paper presents the capacities of the performance evaluation of teamwork (PET) method. Its practicability and efficiency are illustrated by retrospective human reliability analyse of the famous nuclear and maritime accidents. A quantitative assessment of operators' performance on the base of thermo-hydraulic (T/H) calculations and full-scope simulator data for set of NPP design basic accidents with WWER is demonstrated. The last data are obtained on the 'WWER-1000' full-scope simulator of Kozloduy NPP during the regular practical training of the operators' teams. An outlook on the "evaluation system of main control room (MCR) operators' reliability" project, based on simulator data of operators' training is given.

Keywords: PET; MCR; Accident

1. Introduction

The technologies, which use hazardous materials, put the environment at risk. The complexity of technological systems is continuously growing. It makes them more difficult to be controlled and increases the need for automation. The actual reduction of technical component failure rates and the risk of their use is a successful step to meet higher demands for efficient and safe system performance. Unfortunately, these measures do not lead to a lower number of 'human errors' in accidents/incidents. In terms of relative values, their percentage increases. Therefore the study, description and evaluation of human–machine interaction are of great importance to safety investigation of accidents. It turns out that it is 'cheaper' to solve problems that have human rather than technological nature. Currently, a consensus seems to be reached that the contribution of "human errors" in accidents is about 80% [1]. This percentage is controversial because the attribution of 'human errors' as causes is based on expert opinion and judgments. There is no reliable methodology to distinguish between the contributions of human and machine. Anyway, these numbers cover not only the actual system operation, i.e. what happens in the control room, but include design and maintenance as well. The safety investigation of accidents and risk assessment of installations related to different industry and service sectors are unavailing without comprehensive evaluation of human–machine interaction and improvement of methods and concepts for finding human erroneous actions (HEA).

2. Human reliability analysis methods for safety investigation of accidents

In general, there are two principal approaches to human reliability assessment. When considering human performance reliability in accidents, the first dimension is time. The *temporal approach* uses time reliability curves (TRC). The "categories of human behaviour according to basically different ways of representing the constraints in the behaviour of a deterministic environment or system" (skill-, rule-, and knowledge-based levels) [2] are taken into account by adjusting the input parameters of probability distribution. This improved TRC version is called the human cognitive reliability (HCR) correlation. Though being justifiably criticised, it remains one of the most commonly employed human reliability analysis (HRA) methods. However, it is

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very ambiguous and with “less-than-adequate psychological realism” regarding its results [3].

That is why this *temporal approach* is usually complemented by *procedural*, *influential* or *contextual approach* to avoid “bareness in modelling”. The influence of situational, task, human and plant factors (context) are indicated by different influencing factors (IFs), according to the method: performance shaping factors (PSFs), performance influencing factors (PIFs), common performance conditions (CPCs), etc. This *contextual approach* is used as second dimension and manipulates PSFs in producing human error probability (HEP). Some of these methods such as THERP, HEART and CREAM use selected PSFs in adjusting basic HEP. Others, such as SLIM, IDA, etc. produce HEP by manipulating PIFs [4]. A third group of these methods downgrade time as just one of the PIFs that hampers their using for time-dependent accident analysis and quantification.

The study of human behaviour in emergency situation is mainly connected with the assignment of HEP. Usually, the operator’s performance is “fragmented” into separate actions in view of their presentation in the event tree (ET) and fault tree (FT) probability models. However, it is possible to employ a more realistic approach based on the description of the overall emergency context.

The second-generation HRA methods shift the problem from assignment of HEP to the emergency context description: the ATHEANA method determines the error-forcing context [5]; MERMOS considers the performance of human factor mission that depends on important characteristics of emergency operation (CICAs) that are ‘extremely contextual’ [6]; CREAM points out that: “ ... any description of human actions must recognise that they occur in context” and must account for “how the context influences actions” [1,3]. However, “the influential and contextual approaches may find themselves indistinguishable at the quantification stage because of the paucity of actual data” [7].

Thus, a prospective method for context identification, treatment and determination should not be only an expert tool for adjusting and manipulating of HEP by influence factors but also provide an opportunity to accumulate and process ‘explicit comparable’ context data of accident events. That implies comparison of the data on the base of explicit model not only for different accidents/incidents but also for all time periods of the accident (‘second-by-second’). As Moray [8] rightly points out, “the use of ‘expert judgement’ is a polite name for ‘expert guesses’, and we do not have data to validate the accuracy of the guesses ...”. The prospective method for context description would require the following:

- The human–machine system (HMS) is considered as a whole and its context depends both on humans and machine; the context is a function of time “on a second-by-second basis” [3], and can be quantified by taking into account mental or physical accessible states of HMS.
- The context quantification is not provided for individual HEA point probability, but it is necessary for assessment of any action of mental and physical processes at the time of the accident.

3. Performance evaluation of teamwork (PET) method

In the traditional probabilistic risk assessment (PRA) and HRA methods, unsafe system states are reached through a combination of hardware failures and/or errors of omission (EOOs) of required actions. The operators may, however, erroneously perform an action that will aggravate the scenario at any point in the scenario evolution. These actions are so-called errors of commission (EOCs). Therefore, the current efforts in the PRA event sequence analysis are addressed to previously unanalysed contributions due to EOC [9].

Regretfully, a proven methodology for systematical identification and analysis of potential EOC is not available and typical PRA do not treat them comprehensively. To overcome the HRA problem of identification and treatment of the potentially significant EOCs and EOOs, the procedure of performance evaluation of teamwork method distinguishes between three basic concepts which determine the reliability of human performance: violated, cognitive and executive erroneous actions. An important aspect of the PET method for analysis and prediction is the context quantification. It is essential to check current event situation and to ensure that the outcome could reflect all temporary and permanent influence factors.

The PET method consists of two reliability models represented as networks and solved by the analysis of topological reliability of digraphs (ATRD) method (see Figs. 1 and 2).

It distinguishes between three basic models determining the reliability of team performance: *individual cognition, team communication and leadership*. They are based on the quantification of event context probability (CP) and communication context probability (CCP) of team members by consecutive application of the violation of objective kerbs (VOK) method in the combinatorial context model (CCM). The results of quantification are used for obtaining the cognitive error probability (CEP) of individuals and team by the ATRD models of individual cognition and team communication processes [10].

3.1. Statistical description of accident context

As is well known from natural sciences, the quantitative approach to macroscopic systems is based on the calculation of the number of the accessible states. The context is a function of time “on a second-by-second basis”, and the mental or physical accessible states of HMS and human–human systems (HHS). That is why it has been proposed to distinguish between macro- and microscopic levels and to substitute equivalent subsets of macroscopic

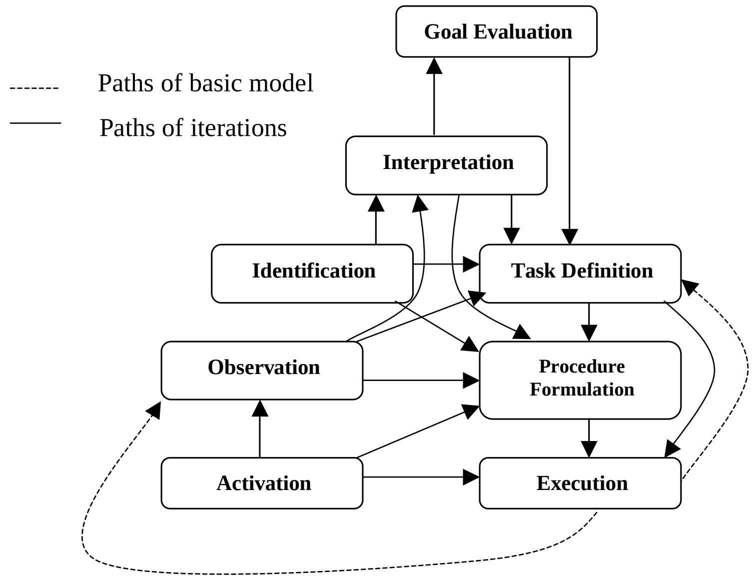

Fig. 1. Reliability of cognitive process by Rasmussen's Step-Ladder Model.

states for set of microscopic accessible states [11,12]. *Context quantification* includes description of HMS and HHS by counting identical macroscopic states.

3.2. Cognition and communication context quantification

3.2.1. Combinatorial context model

The CCM proposes to measure the context deviations by macroscopic contextual parameters denominated by context factors and conditions (CFC) [13]. It is based on the concept of "*human performance shifts*", i.e. it assumes that the 'context' rate in accident situation is proportional to the deviation in the operator's mental model objective image of past and future from the subjective one. They depend on machine and human, and take into account the total deviation rather than two separate types of deviation. In the aspect of past, the human performance shift is between objective (φ_{on}), occurred in fact, and subjective ($\varphi_{\text{s}n}$), considered to have occurred by human, scenario events (E), safety functions (F), upset trends (UT) of parameters, instrumentation indicated values, etc. In the aspect of future we deal with differences between objective (real) and subjective (recognised by human) safety goals (G), such as end states, transfers (T), human actions (HA), etc. [14].

3.2.2. Violation of objective kerbs

To trace the context image in time, it is necessary to know how the parameters change: $|\varphi_{\text{o}n}(t) - \varphi_{\text{s}n}(t)|$. For *the cognition process* $\varphi_{\text{o}n}(t) = \text{const}$ and $\varphi_{\text{s}n}(t)$ changes from the minimum $\varphi_{\text{s}n}(0)$ to the objectively expected value $\varphi_{\text{s}n}(\text{RT}) = \varphi_{\text{o}n}$ (RT is response time). The general case when $\varphi_{\text{s}n}(t) \neq \text{const}$ and $\varphi_{\text{o}n}(t) \neq \text{const}$ should be considered. But if the objective image changes from $\varphi^1_{\text{o}n}(t)$ to $\varphi^2_{\text{o}n}(t)$ because of any cause or reason, then a violation (V) takes place. The cognitive process is violated and the operator is motivated to achieve another objective goal [15]. For *the communication process*, if $\varphi_{\text{s}1n}(t) > \varphi_{\text{s}2n}(t)$, $\varphi_{\text{s}1n}(t) = \text{const}$ and $\varphi_{\text{s}2n}(t)$ changes from the minimum

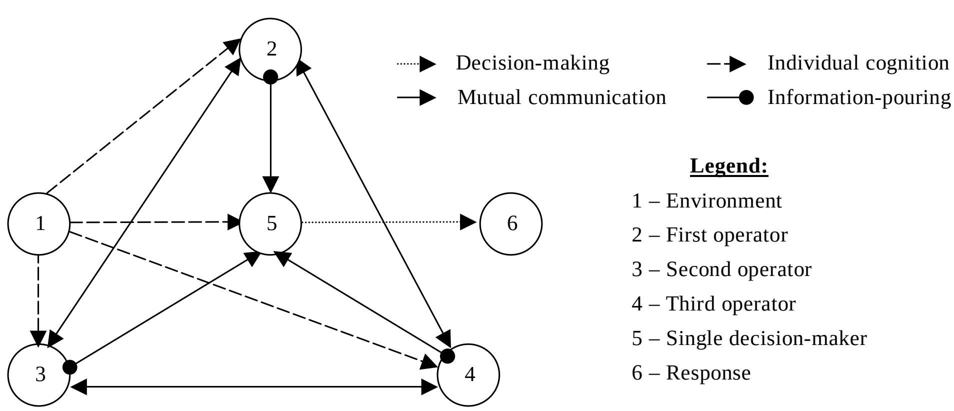

Fig. 2. Reliability of team from four operators by group communication model.

$\varphi_{s2n}(0)$ to the objectively expected value $\varphi_{s2n}(\text{CT}) = \varphi_{s1n}$ (CT is communication time). It means that the objectively expected value is changed to the subjective knowledge of the team partner and vice versa.

3.2.3. Human erroneous actions definitions

On the base of the Reason's [16] *qualitative definitions*, the CCM and VOK *quantitative definitions* of HEA are formulated:

Error: 'all those occasions in which a planned sequence of mental or physical activities fails to achieve its intended outcome'; *cognitive error* is probable when the $\varphi_{sn}(t) \neq \varphi_{on}(t)$, $n = 1, \ldots, N$.

Violation: 'aberrant action' (literally 'straying from the path' ...)'; *violation* occurs when the objective image of n-factor is changed from $\varphi^1_{on}(t)$ to $\varphi^2_{on}(t)$, n is number of CFC.

3.3. Reliability models of team decision-making process

The team decision-making process is a superstructure of the individual cognition. The decision-maker makes the correct decision when the situation is cleared up for him. In this case the group process is reduced only to the communication process. The models developed by means of ATRD include two overlapping networks: stochastic and control. The ATRD Step-Ladder Model (SLM) of cognition is based on the Rasmussen's Step-Ladder Model of cognitive process (see Fig. 1). The ATRD group communication model (GCM) is a model for K-member team with single absolutely reliable decision-maker (see Fig. 2) [10,17].

4. Retrospective human reliability analysis of accidents

The PET algorithm for retrospective HRA of accidents includes the following steps:

1. detailed 'second-by-second' description of the event by tracing a detailed time-line;
2. determination of HMS macroscopic parameters (CFC)—φ_n (φ_{sn} and φ_{on});
3. specification of initial and boundary conditions. For each situation and for each member the initial φ_{skn} (non-expert) or φ^{e}_{skn} (expert), and final φ_{okn} (non-violated) or φ^{v}_{okn} (violated) values of contextual parameters should be indicated, $k, j = 1, \ldots, K$, where K is the total number of team members;
4. calculation of cognition context and communication context deviations by the formula:

$$|\varphi_{okn} - \varphi_{skn}| = \Delta\varphi_{kn} \quad \text{or} \quad |\varphi_{skn} - \varphi_{sjn}| = \Delta\varphi_n, \quad n = 1, \ldots, N, \qquad k \neq j \tag{1}$$

5. enumeration of the HMS accessible states. C_i are all possible bit states mentally carried out in cognitive process, ($i = 1, \ldots, \Omega$), indicated as follows: $C_i = (\Delta\varphi_1, \ldots, \Delta\varphi_n, \ldots, \Delta\varphi_N)_i$;
6. calculation of cognition and communication context probabilities [10];
7. calculation of individual cognitive error probability (by the ATRD SLM Code);
8. calculation of team cognitive error probability (by the ATRD GCM Code). The decision-maker is absolutely reliable when his information is full.

In case of a retrospective HRA it is more important to have *a feedback* from the output to the each step of algorithm than to have only *a stop rule* [3]. By this iterative approach it is possible to check any situation and to ensure that the outcome could reflect all temporary and permanent influence factors. The PET method determines the set of acceptable macroscopic causes. It uses a one-step macroscopic quantification of context and team communication on the base of macroscopic parameters of HMS and HHS. That is why a detailed classification of microscopic causes is not the issue.

5. Applications

The PET method has been used for retrospective HRA of famous maritime and nuclear accidents. The PET results for "Grounding of the tanker 'Exxon Valdez"' [10,12], "Core melt of "Three Mile Island #2" [18] and "Chernobyl #4 disaster" [19] are shown on Figs. 3–5. For the nuclear accidents: (1) the non-violated process of cognition is not taken into account; (2) the generalised operator presents the shift and accident group of specialists ("fresh eyes") in "Three Mile Island #2"; (3) the generalised operator presents also the shifts of "Chernobyl #4".

The information for these analyses is extracted basically from the Internet sites. That is why the obtained results are strongly limited by data, especially for nuclear accidents. Nevertheless, they give a good opportunity for approbation and refining of the PET method. Moreover, some

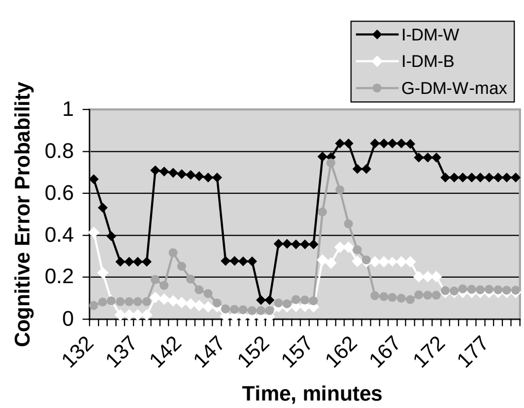

Fig. 3. Evaluation of Individual and Group Decision-Making CEP in "Exxon Valdez grounding" accident for Worst and Best context and max communication.

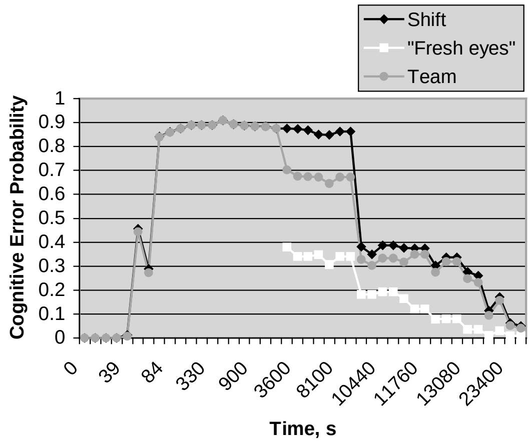

Fig. 4. Evaluation of shift, "fresh eyes" and team CEP in "Three Mile Island #2" accident.

generalisation, confirmation and proof of some conclusions and issues in accidents occurrence with essential human contribution are provided. It is of prime importance to recognise the need for additional theoretical underpinning of some HRA concepts. Without refining and development of these concepts the accident context and its potential for HEA (e.g. violations [18]) could not be correctly determined.

In this paper only two possible applications of the PET method for retrospective HRA of accidents are presented. The data for them are based on: the thermal–hydraulic calculations and full-scope simulator data for NPP design basic accidents with WWER (Soviet design pressure water reactor). Taking into account an opportunity to obtain sufficient information from these sources and construction of comprehensive models, it is obvious that these sources can play the most significant role for validation and verification of the PET method and its models. On the other hand, these applications can be easily used in a practical approach to safety management implementation and for database accumulation of HEA in accidents. This database could be integrated in the general framework of non-static PRA.

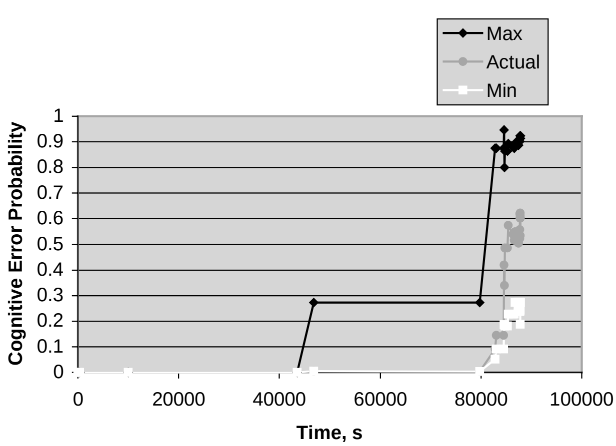

Fig. 5. Evaluation of maximum, actual and minimum team CEP in "Chernobyl #4" accident.

5.1. Integrated safety investigation of accidents

The pressurised thermal shock (PTS) PRA involves an integrated treatment of a variety of engineering disciplines within a PRA framework—"model of the world" [9].

The search for the probable causes of material shocks and human errors must clearly start from the observed event and the context, which characterises the event in particular. Event trees are used to model the event sequences relevant to PTS. Each PTS sequence is then analysed to estimate the expected time-dependent thermo-hydraulic (T/H) response of the plant and the operators' actions. The main focuses are on the minimum temperature of the primary coolant system (in particular, in the down-comer area of the reactor pressure vessel, RPV) and the maximum pressure (after the minimum temperature has been achieved). The T/H responses are then used (along with physical data on the RPV) in the probabilistic fracture mechanics (PFM) analyses to produce a frequency of through-wall cracks in the RPV. This will support the analysis of the proposed new limits on plant operation, e.g. a screening criterion for pressure vessel embrittlement or pressure–temperature (*P*–*T*) curves [20].

To achieve the goal of the 'maximum pressure and minimum temperature', the PTS analysts assume operator's actions of low probability or ignore the ones of high probability and in this way they "fix up" the appropriate PTS conditions.

Let us demonstrate an integrated PTS–HRA investigation of Large Break LOCA based on T/H calculations for WWER-440 [21]. The comparison of the traditional PRA and the integrated PTS–HRA HEP is shown on Fig. 6. The executive error probability is neglected.

Insights: The accident dynamics is the controlling factor in of the accident context and HEP. Therefore, the HEP of traditional HRA methods are not conservative approximation.

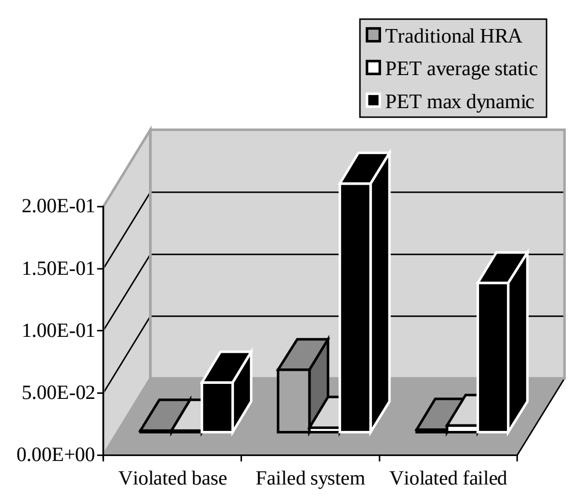

Fig. 6. Comparison of human error probability between traditional HRA, average static and max dynamic PET results.

5.2. Introducing an evaluation system of team and operator's reliability

5.2.1. Background

NPP process simulation has several-decade-tradition already. In many countries, regulatory authorities require to have plant specific simulators for training of all control room operators.

Since February 2000 Kozloduy NPP (units 5 and 6 with WWER-1000/V320) has a "full-scope" simulator (FSS-1000), implemented by GSE systems. "Full-scope" means that the FSS control room is a mock-up of the real referent unit (replica of unit 6) and the simulator load includes models of all plant systems and redundancies. In July 2000, the simulator was licensed. Since then it has been used for emergency exercises—training and retraining.

Efficient simulator configuration management and close co-ordination between Technical Support, Operational and Simulator Departments of Kozloduy NPP was established. As a result technological processes simulating has gradually become more accurate regarding to both normal and emergency operation modes.

The following results have been achieved:

- The simulator models have been upgraded in accordance with modernisation process on unit 6. The simulator has increased degree of realism;
- The operators' abilities for recovery actions were improved;
- Digital audio–visual system for team actions observation and registration was implemented and the effectiveness of simulator usage was substantially increased.
- A symptom based emergency operational procedures (SB EOPs) for accident management have been prepared, verified, and validated on the FSS-1000.
- A joint project of Kozloduy NPP and PNLL-DOE (USA) for simulator instructors training on SB EOPs is carried out.

So far, the full-scope simulator has been oriented mainly to operator training and procedures validation but it could be also used to collect more information essential for assessment of human reliability level of main control room (MCR) operators. This data can be used to improve human performance and enhance operational safety.

The Simulators Department of Kozloduy NPP and 'Risk Consult GP' have elaborated methodology based on 'Performance Evaluation of Teamwork' method for quantitative assessment of operators' team performance.

A pilot accident scenario model has been developed. The model data were obtained from Kozloduy NPP FSS-1000 training programs, operation instructions and emergency procedures of unit 6. All available tools of FSS-1000 made possible deducing behavioural information about registered events, controlled technological parameters and observed actions of operators and instructors. The capacities of the digital audio–visual system were used to check operators' behaviour, cognition and communication processes, to identify operators' response times and make hypotheses for probable influencing factors and their effect.

5.2.2. Project objectives and purposes

The main objectives and purposes of the project are:

- to strengthen the Kozloduy NPP operational safety and full-scope simulator management by control of ergonomics and efficiency of emergency procedures;
- to improve the safety culture of operators by introducing a modern human-centred control system in simulator training;
- to establish a new behavioural data collecting and processing system and integrate it into the simulator computer and digital audio–video system;
- to develop a comprehensive methodology for quantitative assessment of operators' team performance and retrospective analysis of accidents;
- to perform pilot application based on eight-selected accident scenarios of the operative teams' training of the 5 and 6 unit main control rooms;
- to provide conditions for applications of methodology by supplying advanced equipment for behavioural data collecting and processing;
- to tune and integrate the equipment into a network system for on-line tracking, processing and storage of operators' erroneous actions during simulation studies;
- to refine the methodology tools for quantitative assessment of operators' performance taking into account the system capacities;
- to establish an explicit quantitative standard for necessity and sufficiency of the simulator training;
- to evaluate the team synergism degree;
- to set up a feedback between the quantitative assessment of operators' performance and the necessity and workability of operational procedures.

5.2.3. Pilot study

The pilot study is based on a prepared PET model of 'Emergency Shutdown'. Results are obtained for equal conditions and durations before (165 s) and after (335 s) shutdown occurrence (totally 500 s). They are presented on Figs. 7 and 8. The individual and team CEP during the accident ('second-by-second') are evaluated. They depend on the accident context in HMS (environment) and HHS (team communication) and take into account technological and organisational requirements of emergency event-based and symptom-based procedures.

Indicators: To determine timeline and time-dependence of CFC and V, 160 technological parameters are tracked and archived for preparing a PET model of 'Emergency Shutdown'. However, only 132 of them are used in the current scenario. The capacity of simulator computer could be extended to more than 200 technological parameters.

Assumptions: (1) speed of cognition—all unknown CFC per 30 s; (2) specific durations of violations are determined

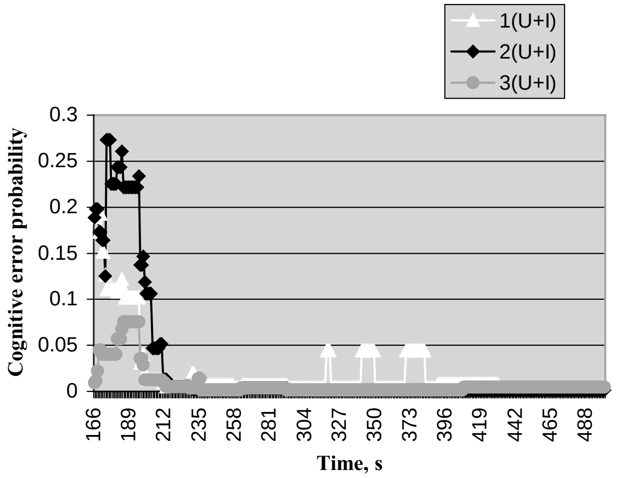

Fig. 7. Dynamic evaluation of CEP for three main control room teams. Pilot study "Emergency Shutdown": three training cases (1: 11/25/02; 2: 12/17/02; 3: 03/24/03) (U indicates the unknown, and I the incognizable HMS accessible states).

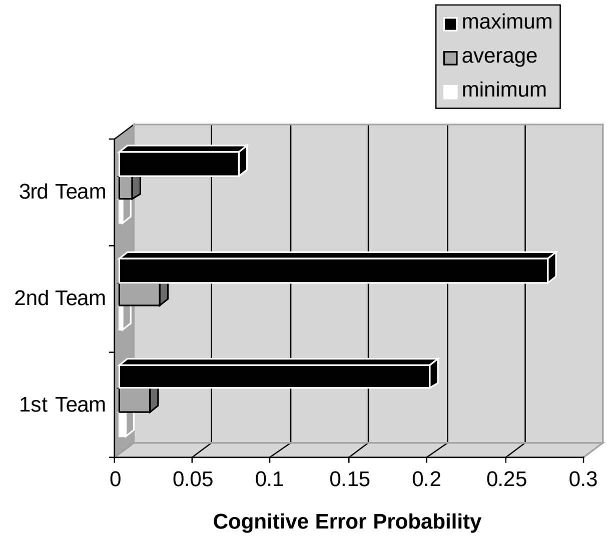

Fig. 8. Comparison of the minimum, average and maximum CEP for three team performances in three training cases of "Emergency Shutdown" for the interval 166–500 s.

on the base of the scenario timeline and inferred communication for each of the cases; (3) if the change of technological parameter is caused only by a physical process, then it is referred to trend of parameter (planned or unplanned); (4) if the change of technological parameter is caused by a physical process and/or logic protection/blockage system, then it is referred to scenario event; (5) the reliability model of team of five operators is shown on Fig. 9 where non-probable communication and information pouring are neglected; (6) decision-maker is absolutely reliable when all information is available for him.

5.2.4. Concluding remarks

The received quantitative results allow for using the models of basic scenarios for analysis of simulated and real accidents and incidents. The project purposes are related to the application of the PET method to:

1. sensitivity analysis of operator' and team performance;
2. optimum in: (a) configuration of control room teams (number of team members and team homogeneity), (b) operators actions, (c) operational procedures, (d) schedule of team substitutions, (e) the procedure of team substitutions, (f) man–machine interface in control room;
3. reliability monitoring of control room operators during accidents and incidents;
4. explicit quantitative standard for necessity and sufficiency of the simulator practical training;
5. evaluation of average reliability of all teams for basic and deviated scenarios;
6. upgrading of the NPP databases for reliability and safety assessments of the unit operation.

The current limitations are related to the equal weights of different V and CFC in accident and non-evaluation of executive error probability as well. However, they can be overcome by completion of the models of all basic scenarios, accumulation of statistics (sufficient sampling of simulator training evaluations). The project presumes determination of fundamental characteristics of decision-making: cognition and communication rates and the crucial role of decision-maker.

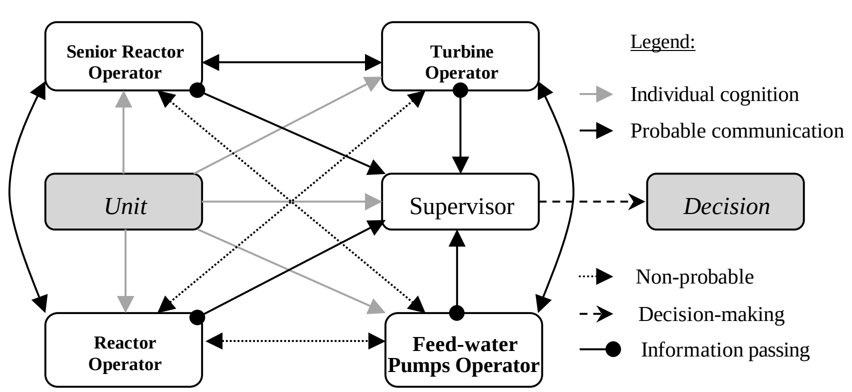

Fig. 9. WWER-1000 control room team communication model.

6. Conclusions

Safety investigation of team performance in accident should be based on dynamic context description of human–machine system.

In an effort to describe context, it is more important to classify and group the incompatible HMS accessible states rather than to look for independent performance shaping factors.

Development of a comprehensive system for monitoring, quantitative evaluation and management of operators' reliability based on their behaviour and performance during full-scope simulator training is one of the "hottest" areas in safety investigation of industrial accidents and incidents.

References

[1] E. Hollnagel, Human Reliability Analysis: Context and Control, Elsevier Science Ltd., London, 1993.
[2] J. Rasmussen, Skills, rules, and knowledge signals, signs, and symbols, and other distinctions in human performance models, in: Proceedings of the IEEE Transactions on Systems, Man, and Cybernetics, vol. SMC-13, no. 3, May/June 1983, pp. 257–266.
[3] E. Hollnagel, Cognitive Reliability and Error Analysis Method—CREAM, Elsevier Science Ltd., London, 1998.
[4] J. Kim, W. Jung, Proposal of performance influencing factors for the assessment of human error under accident management situations, in: Proceedings of the PSA'99, ANS, La Grange park, IL, USA, 1999, pp. 1119–1124.
[5] M.T. Barriere, D.C. Bley, S.E. Cooper, J. Forester, A. Kolaczkowski, W.J. Luckas, G.W. Parry, A.M. Ramey-Smith, C. Thompson, D. Whitehead, J. Wrethall, Technical Basis and Implementation Guidelines for a Technique for Human Event Analysis (ATHEANA), NUREG-1624, US Nuclear Regulatory Commission, Washington, DC, 1998.
[6] P. Le Bot, F. Cara, C. Bieder, MERMOS, A second generation HRA method: what it does and what doesn't do, in: Proceedings of the PSA'99, ANS, La Grange park, IL, USA, 1999, pp. 852–860.
[7] Ed. Dougherty, Context and human reliability analysis, Reliab. Eng. Syst. Safety 41 (1993) 25–47.
[8] N. Moray, Dougherty's dilemma and the one-sidedness of human reliability analysis (HRA), Reliab. Eng. Sys. Safety 29 (1990) 337–344.
[9] N. Siu, S. Malik, D. Bessete, H. Woods, Treating aleatory and epistemic uncertainties in analyses of pressurised thermal shock, in: Proceedings of the PSAM5, Osaka, Japan, 27 November–1 December 2000.
[10] G. Petkov, Quantitative assessment of operators' performance in accidents, in: Proceedings of the IFSES III, Tokoroazawa, Saitama, Japan, 10–11 January 2002.
[11] C. Shannon, A mathematical theory of communication, Bell Syst. Tech. J. 27 (1948) 379–423, 623–656.
[12] G. Petkov, P. Antao, C. Guedes Soares, Context quantification of individual performance in accidents, in: Proceedings of the ESREL'2001, Torino, Italy, 16–20 September 2001.
[13] G. Petkov, K. Furuta, Application of PN-based method for identification and classification of human actions in NPP TLRS, in: Proceedings of the PSAM4, vol. 2, Springer London Ltd., New York, USA, 3–17 September 1998, pp. 1136–1141.
[14] G. Petkov, Networked risk images in human action context, in: Proceedings of the Ct'99 Conference, San Francisco, USA, 1999, http://www.cogtech.org/CT99.
[15] G. Petkov, S. Petkov, Towards defense-in-depth of human–machine interaction, in: Proceedings of the PSAM5 Conference, Osaka, Japan, 2000.
[16] J. Reason, Errors, outcomes and circumventions: a reply to dougherty, Reliab. Eng. Syst. Safety 46 (1994) 297–298.
[17] G. Petkov, Identification and fitting of human cognition model, in: Proceedings of the ASME-PVP Conference, vol. 400, ASME-PVP, Seattle, USA, 2000, pp. 35–48.
[18] G. Petkov, Retrospective human reliability analysis by performance evaluation of teamwork method, in: Proceedings of the PSAM-VI Conference, San Juan, Puerto Rico, USA, 23–28 June 2002.
[19] B. Milev, G. Petkov, Evaluation of operators' actions in chernobyl accident, in: Proceedings of the EMF'03 Conference, Technical University of Sofia, Bulgaria, 30–31 October 2003.
[20] W.J. Galyean, N.O. Siu, H.W. Woods, et al., Integrated probabilistic safety assessment of pressurised thermal shock for US pressurised water reactors, in: Proceedings of the PSAM5, Osaka, Japan, 27 November–1 December 2000.
[21] G. Petkov, P. Groudev, Cognitive error probability in pressurised thermal shock event, in: Proceedings of the IAEA Technical Meeting on Risk Informed Aspects of NPP Life Management—Emphasis on Integrity of Primary Circuit Components, Budapest, Hungary, TWG-LMNPP-01/4, 8–10 October 2001, pp. 224–239.