HUMAN RELIABILITY ANALYSIS IN LOW POWER AND SHUT-DOWN PROBABILISTIC SAFETY ASSESSMENT: OUTCOMES OF AN INTERNATIONAL INITIATIVE

by

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Since the beginning of the nuclear power generation, human performance has been a very important factor in all phases of the plant lifecycle: design, commissioning, operation, maintenance, surveillance, modification, and decommissioning. This aspect has been confirmed by the operating experience. A workshop was organized by the IAEA and the Joint Research Centre of the European Commission, on Harmonization of low power and shutdown probabilistic safety assessment for WWER nuclear power plants. One of the major objectives of the Workshop was to provide a comparison of the approaches and results of human reliability analyses for WWER 440 and WWER 1000, and gain insights for future application of human reliability analyses in Low Power and Shutdown scenarios. This paper provides the insights and conclusions of the workshops concerning human reliability analyses and human factors.

Key words: probabilistic safety assessment, low power and shutdown, human reliability analyses, WWER, human factors

BACKGROUND

The risk corresponding to Low Power and Shutdown (LPSD) operation of WWER NPP is comparable with the risk for at-power operation or even may exceed it, as pointed out by many PSA studies. Human factors play a major role in the LPSD operations, therefore the main contributors to the risk implied by the LPSD operations are related to human factors. By means of probabilistic safety assessment (PSA), weaknesses related to human performance and human factors can be identified and appropriate corrective actions can be taken with the aim of further enhancing nuclear safety.

The human reliability analysis of PSA for LPSD states has to consider specific features that may be different from those of the human reliability analyses (HRA) performed for at-power PSA. These features may impact both the operators' work and on the methods, and include: different time windows available for operators to mitigate consequences, the level of detail and completeness of the procedures used during shutdown, more requirements for manual manipulations with plant equipment in response to initiating event due to unavailability of some emergency interlocks, and very strong interaction between human-induced initiators and subsequent operator response.

In 2007, the IAEA launched a Regional technical co-operation (TC) Project RER9087 Harmonization of PSA & PSA Applications. In the framework of the above project, the IAEA organized in co-operation with the Institute for Energy of the Joint Research Center of the European commission (JRC-IE) a workshop on Harmonization of Low Power and Shutdown Probabilistic Safety Assessment for WWER Nuclear Power Plants. One of the key topics was the analysis of the impact of human factors on NPP safety. In particular, the workshop, with specific focus on human reliability, aimed at continuing the work on harmonization of PSA for WWER-type nuclear power plants for LPSD states that was started at the first workshop held at the same place in March 2007. More details concerning the results of the workshops, and the dominant human errors identified in the different PSA related to WWER reactors are given in the reports of the workshops [1, 2] and in a previous paper of the authors [3].

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METHODOLOGY USED FOR THE PSA STUDY

For collecting the data needed for the purposes of the Workshop, a questionnaire was developed and sent to the participants. The questionnaire aimed at collecting detailed information on initiating events frequencies, human errors, and modeling details for six selected initiators for WWER-440 and WWER-1000 plants. The selected initiators represent the major contributors to the core damage frequency (CDF) in PSA studies for respective WWER plant units. These have been identified at the first workshop [2]. The selected initiators were:

WWER-440:	WWER-1000:
(1) Human-induced loss of coolant accident (LOCA)	(1) Loss of offsite power (LOOP)
(2) Loss of non-essential service water	(2) Heavy load drops on primary circuit (into the reactor)
(3) Reactivity accidents including boron dilution	(3) Primary circuit leaks outside containment
(4) Loss of natural circulation	(4) Small LOCA from primary to secondary circuit
(5) Heavy load drops	(5) Loss of heat removal from reactor core via primary side
(6) Small LOCA 20-60 mm	(6) Primary leaks via pressurizer safety valves after opening during hydrotest

Eleven completed questionnaires were received form the participants representing different NPP as presented in tab. 1.

The original responses can be found in Annex III of ref [1]. During the Workshop, the collected data were processed in the PSA comparison activities which were carried out by two working groups (WG):
– WG 1, which carried out the comparison and harmonization of LPSD PSA for WWER-440 NPP, and
– WG 2, which carried out the comparison and harmonization of LPSD PSA for WWER-1000 NPP.

For both groups of WWER NPP the following information was collected for six initiators recognized to be the major source of differences in the risk profiles:
– contribution to the total CDF for the initiators [1, 2],
– twenty TOP minimal cut sets (MCSs)**, and
– human errors (HE) modeled.

Several main areas of analysis were covered in the discussions carried out in the working groups [1]; in particular, the achievement of insights on results and specific features of Human Reliability Analysis for PSA for LPSD states. While doing the comparison exercise, the design differences were analyzed and taken into account, as well as the fact that the original designs were not identical.

Table 1. Overview of Plants Contributing to the Questionnaire on LPSD PSA

Country	Plant	Basic design
WWER-1000 NPP		
Bulgaria	Kozloduy NPP units 5, 6	V-320
Russia	Kalinin NPP unit 2	V-338 (small series)
Russia	Novovoronezh NPP unit 5	V-187 (small series)
Ukraine	Rivne NPP unit 4	V-320
Ukraine	Khmelnytsky NPP unit 2	V-320
WWER-440 NPP		
Bulgaria	Kozloduy NPP units 3, 4*	V-209M Upgraded model of V-230
Czech republic	Dukovany NPP unit 1	V-213
Hungary	Paks NPP units 1-4	V-213
Slovakia	Bohunice V-1 unit 2	V-230
Slovakia	Bohunice V-2 unit 3	V-213
Slovakia	Mochovce NPP unit 1	V-213

*The plant units are shut down of December 31, 2006

OVERVIEW OF THE METHODS FOR THE HRA QUANTIFICATION

During the workshop, the emphasis was put on the comparison of the methodologies used for human reliability analysis in the LPSD PSAs for WWER-440 NPPs, in particular for what concerns the quantification of the probability of occurrence of human failure events. An overview of the methodologies is presented in tab. 2 (Additional information concerning the table can be found in reference 1).

Table 2. Methodologies used for analysis and quantification of human error probability (HEP) for the individual categories of human actions

Plant	Type of human failure event		
	Pre-accident	Initiator	Post-accident
Armenian 2	THERP [4, 5]	... (***)	HCR [6], ASEP
Bohunice V-1	THERP	THERP, ASEP	TRC, THERP
Bohunice V-2	THERP	THERP, ASEP	TRC, THERP
Dukovany	THERP	THERP, CREAM [7], HEART [8], Decision trees	Decision trees + ASEP
Mochovce	THERP, ASEP [9]	THERP, ASEP	SLIM [10]
Paks	ASEP	Decision trees	Decision trees
Kozloduy NPP Units 3,4	THERP	Information not available	HCR

*** Since the information has been taken from full power PSA, no human induced initiators were identified and no specific HRA method was deemed necessary therefore for this part of HRA

** A minimal cut set is a combination of an initiating event and component failures and/or human errors that could lead to undesirable consequences (*e. g.* core damage). It means that: (1) the given combination of events would cause core damage, and (2) if any event is selected and eliminated from the minimum cut set, the remaining subset of events does not cause core damage anymore. Each MCS has a frequency assessed by PSA technique.

With reference to tab. 2, the following considerations emerge. A set of different HRA quantification methods was used by the individual teams. In total seven methods had been used, if it is considered TRC and HCR to be the same. The THERP method is the most popular in the considered analyses; ASEP follows as second. Because ASEP can be seen as a shortened and up-dated version of THERP, THERP/ASEP were identified as the most used HRA methods for analyzing human errors occurring in the pre-accident phase. TRC (HCR) is the most popular method for post-accident human errors analysis.

SPECIFIC INSIGHTS REGARDING HRA IN LPSD PSA

This section is divided into two parts. In the first one, some general comments about LPSD HRA are made. In the second, some conclusions are presented, based on the analysis of the questionnaires provided by the teams involved into the harmonization effort for the PSA for WWER plants.

General considerations on LPSD HRA

The first comment stemming from the workshop is that the role of plant crew during low power and shutdown operation and, consequently, the importance of HRA for the LPSD of an integrated plant PSA model is even higher than in case of full power operation. This is summarized in tab. 3, which shows the importance of different types of human errors.

The importance of human actions for LPSD PSA of WWER reactors can also be considered with respect to the plant crew role in the most frequently analyzed LPSD accident scenarios. The high involvement of plant staff in these scenarios is pointed out by tab. 4.

The problem of LPSD HRA is that the enhanced role of human factors in LPSD accident conditions cannot be supported with adequately developed specific HRA methodologies. The potential of HRA methodologies to adequately support the analysis of specific types of human errors is summarized in tab. 5.

Some other specific aspects of HRA analysis can be also inferred by comparing full power and LPSD PSA. These comparisons are summarized in tab. 6.

The general conditions of crew work during plant LPSD status have to be addressed adequately in LPSD HRA. In tab. 7, an overview of basic categories of plant states during LPSD period of operation is given. Different Human Error Probabilities (HEPs) are derived for even the same human actions, when carried out under the different circumstances and dif-

Table 3. Importance of different types of human errors

HE category	Full power PSA	Low power PSA
Pre-accident	Low	Low
Contributing to initiating events	Very low	High
Post-accident	High	High
Recoveries	Medium	High

Table 4. Human related scenarios contributing to the initiating event occurrence during LPSD operation of WWER reactors

Scenario	Plant crew role in the initiation part of the scenario	Plant crew role in the response part of the scenario
Interruption of RHR circuit coolant flow	Almost completely caused by human actions	Important
Drainage of RHR circuit coolant	Almost completely caused by human actions	Important
Loss of natural circulation due to steam bubble	Partially	Critical
Loss of natural circulation due to primary circuit drainage	Completely caused by human actions	Important
Inadvertent closing of main isolation valves	Completely caused by human actions	Important, although playing relatively simple role
Man-induced LOCA	Completely caused by human actions	Very important
Reactivity transients	Depending on cases, may be crucial, may be unimportant	Important
Primary circuit cold over-pressurization	Completely caused by human actions	Important

Table 5. Potential of current methodologies for analysis of human action categories

Human failure type	Full power PSA	Low power PSA
Pre-accident	Medium	Medium
Contributing to initiating events (IE)	Almost irrelevant	Medium
Post-accident	Relatively high	Relatively low
Recoveries	Low to medium	Unclear
Human failure type	Full power PSA	Low power PSA
Altogether	Medium to high	Low to medium

Table 6. Some comparisons between full power HRA and shutdown HRA attributes

Attribute	Full power PSA	Low power PSA
Dependence analysis	Strong dependencies among human actions in one accident sequence typical	Less strong dependencies (long time, successive actions, change of crew, additional members of accident team)
Errors commission	Potentially important	Very important
Expert judgment use	Medium	Medium to high
Revision phase	Difficult	Very difficult
Relative uncertainty	Medium	High

Table 7. Five areas of human actions in LPSD PSA

Area	Conditions for crew work	From-to
Area 1 – Plant within the early stage of going to shut down status	Similar or at least similar to nominal power, dynamic changes in parameter values	From nominal power operation to initiation of residual heat removal (RHR) cooling
Area 2 – Plant at the end stage of going to shut down status	Significantly different from nominal power, dynamic changes, short period	From initiation of RHR cooling to start of reactor cover removal
Area 3 – Plant within the first part of shut down	Shut down specifics, medium dynamic, relatively long period	From the start of reactor cover removal to the start of fuel exchange
Area 4 – Plant in late shut down	Very long time windows for crew corrective actions, low residual heat	From fuel exchange to the start of unit power-up
Area 5 – Plant during start-up	Basically similar to AREA 2, but specific features must be addressed	From the start of unit power-up to niminal power

ferent plant states. The analysis of the most common HRA methods may differ for full-power and LPSD analysis significantly. Some methods that are quite suitable for full-power analysis may not address LPSD conditions sufficiently, whilst others may provide satisfactory or good results. In addition, in tab. 8, several comments concerning the applicability of different HRA methods for LPSD study are summarized and referred to five typologies of human actions.

DISCUSSION

Some specific insights regarding HRA in LPSD PSA have been gained on the basis of comparison of the results related to human reliability analysis provided by the individual plants in the questionnaires (see Annex III of ref. [1]). The comparison of the basic features of HRA performed within the individual WWER PSA is given in tabs. 9 and 10, one table for WWER-440 reactors and the other for WWER-1000 reactors. The WWER-440 table covers information about HRA for six NPPs; the WWER-1000 table is devoted to HRA information taken from five NPP. A few plants did not provide detailed information, because it was either not available or the LPSD study was not finalized yet.

In the tables, six selected emergency scenarios are defined, which were evaluated as most important from the point of view of the LPSD PSA results concerning WWER reactors. Some of the scenarios are the same for both types of reactors, some are different. Some scenarios had been found not to have significant impact on the PSA results for specific plants, which as a consequence have not been covered with the corresponding PSA. In this specific case, the note "not provided" or "screened out" is inserted in the tables.

Table 8. Comparison of quantification methods applicability for full power and LPSD HRA

Method	Conclusions
Absolute probability judgment	In LPSD PSA, the suitability of the method is even higher, considering that the application of "classic" methods may imply some problems
Time *vs*. reliability correlation (HCR)	Limited applicability, particularly in shut down scenarios. Often producing unrealistic and too low long time windows HEP
THERP, ASEP	Suitable for selected categories of actions, similarly to full power PSA (actions explicitly given in procedures, with low level of cognition, or local actions)
Decision trees	Good applicability in general, but not a very good transferability from full power PSA. Special decision trees may need to be developed for LPSD PSA applications
HEART	Similarly to full power PSA, the method may help in analyzing specific actions difficult to be processed with other methods. The method does should not be used as standalone HRA method
Simulator data, bayesian update	Limited applicability because a significant part of initiating event response activities may be performed out of the control room. Consequently, many important crew tasks related to low power operation and shut down are not covered by the training at full scope simular. The problem of simulator fidelity is even higher in case of the LPSD status
Generic data	Very limited applicability due to the highly plant specific character of measures preventing and responding to LPSD PSA accident scenarios
SLIM	Good applicability potential, provided that the time related issues are treated adequately. The method is one of the available good choices for LPSD PSA
CREAM	Very helpful when the cognition part of human actions must be taken into account (*e. g*. for the circumstances when the procedural support is missing and improvisation needed). Good choice for full power as well as LPSD PSA

Every plant specific HRA information consists of five items:

- "HEP range" – for every scenario, it is the range of HEP quantifying the human actions which are modeled as part of the technological and organizational processes forming the scenario. This couple of parameters can give some insights about the conservatism of the HRA study under consideration. However the used HEP cannot be taken as an absolute indicator, because the level of conservatism is reflected both in HEP values and in the approach used in the development of the scenario model,
- "HEP range typical" – the basis for this parameter is given in the previous row, but some fairly exceptional HEP values, from the set of all HEP values for the given scenario, are not taken into consideration. Sometimes, the "HEP range" parameter is not a good reflection of the scope of most of the values, because there is a couple of non-typical HEP

Table 9. Results of analysis of HRA related information provided in the questionnares developed for WWER-440 NPP

WWER-440 reactors	Scenario 1 – man induced LOCA (MIL)	Scenario 2 – loss of operational (non-essential) service water (LOSW)	Scenario 3 – reactivity accidents	Scenario 4 – loss of natural circulation	Scenario 5 – heavy load drops	Scenario 6 – small LOCA
Plant 1						
LPSD not finished yet						
Plant 2						
HEP range	5 10^{-5}-1.4 10^{-2}	5 10^{-5}-2.5 10^{-2}		5 10^{-5}-1.4 10^{-2}		5 10^{-5}-5 10^{-2}
HEP range typical	5 10^{-5}-5 10^{-5}	5 10^{-5}-2.5 10^{-2}		5 10^{-5}-1.4 10^{-2}		5 10^{-5}-4 10^{-4}
HE absolute CDF	1.33 10^{-6}	5.1 10^{-7}	Not provided	1.43 10^{-6}	Not provided	5.1 10^{-8}
HE relative CDF	0.29	0.85		0.66		0.046
LER	Not available	Not available		Not available		Not available
Plant 3						
HEP range	4 10^{-3}-2·10^{-1}		4 10^{-3}-6·10^{-2}	8 10^{-4}-2·10^{-1}	4 10^{-6}-5·10^{-6}	2.5 10^{-3}-3·10^{-1}
HEP range typical	1 10^{-2}-7 10^{-2}		1 10^{-2}-6·10^{-2}	5 10^{-3}-8·10^{-2}	4 10^{-6}-5·10^{-6}	1.75 10^{-2}-1·10^{-1}
HE absolute CDF	1.7 10^{-6}	Screened out	8.5 10^{-8}	8.5 10^{-6}	6.8 10^{-6}	5.17 10^{-6}
HE relative CDF	1		1	1	0.89	0.99
LER	0.59		0.84	0.90	0.86	1
Plant 4						
Information not provided						
Plant 5						
HEP range	2.5 10^{-5}-5·10^{-1}		8.36 10^{-6}-1.83·10^{-3}	5.27 10^{-4}-4.35·10^{-1}	3 10^{-2}-6.59·10^{-1}	4 10^{-3}-2·10^{-1}
HEP range typical	2.5 10^{-5}-5.6·10^{-2}		8.36 10^{-6}-1.20·10^{-4}	2.0 10^{-3}-4.35·10^{-1}	3 10^{-2}-2.64·10^{-1}	4 10^{-3}-2.64·10^{-1}
HE absolute CDF	6.48 10^{-7}	Screened out	1.7 10^{-6}	1.70 10^{-7}	1.95 10^{-8}	1.34 10^{-8}
HE relative CDF	0.96		1	1	0.07	0.955
LER	0.3		0.98	0.62	0.91	0.29
Plant 6						
HEP range	1.2 10^{-4}-1.2·10^{-4}	1.2 10^{-4}-5·10^{-1}	1 10^{-5}-1	1.2 10^{-4}-3.6·10^{-3}		1.18 10^{-4}
HEP range typical	1.2 10^{-4}-1.2·10^{-4}	1.2 10^{-4}-5·10^{-3}	1 10^{-5}, 1.44·10^{-1}	1.2 10^{-4}-2.6·10^{-4}		1.18 10^{-4}
HE absolute CDF	5.86 10^{-6}	1.7 10^{-6}	2.97 10^{-7}	1.05 10^{-5}	Not analyzed	6.11 10^{-10}
HE relative CDF	0.108	0.49	0.996	0.87		0.009
LER	0.63	0.71	0.96	0.96		0.88
Plant 7						
HEP range	2.1 10^{-5}-5·10^{-2}		1 10^{-5}-1	1 10^{-5}-1·10^{-5}		1 10^{-5}-5.2·10^{-5}
HEP range typical	5.9 10^{-4}-5·10^{-2}		1 10^{-5}-5·10^{-2}	1 10^{-5}-1·10^{-5}		1 10^{-5}-5.2·10^{-5}
HE absolute CDF	Not at disposal	Screened out	1.38 10^{-6}	1.1 10^{-7}	Not analyzed	Negligible
HE relative CDF	Not at disposal		1	0.079		Close to 0
LER	0.42		Not at disposal	0.89		0.013
Plant 8						
HEP range	4.12 10^{-4}-2·10^{-2}	2.5 10^{-5}-1.8·10^{-2}	2.5 10^{-4}-6.34·10^{-3}	1.39 10^{-4}-2.6·10^{-3}	To be specified	4.92 10^{-4}
HEP range typical	4.12 10^{-4}-2·10^{-2}	1.16 10^{-3}-1.8·10^{-2}	2.5 10^{-4}-6.34·10^{-3}	1.39 10^{-4}-2.6·10^{-3}	To be specified	4.92 10^{-4}
HE absolute CDF	2.71 10^{-6}	1.77 10^{-8}	1.16 10^{-9}	2.21 10^{-6}-1.19·10^{-8}	To be specified	2.4 10^{-9}
HE relative CDF	1	0.48	1	0.99	To be specified	0.13
LER	0.996	1	0.94	1, 1	To be specified	0.69

Table 10. Results of analysis of HRA related information provided in the questionnaires developed for WWER-1000 NPP

WWER-1000 reactors	Scenario 1 – loss of offsite power	Scenario 2 – heavy load drops	Scenario 3 – primary circuit leaks outside containment	Scenario 4 – small LOCA primary to secondary	Scenario 5 – loss of heat removal via primary side	Scenario 6 – pressurizer safety valve (PSV) primary leaks during hydro-test
Plant 9						
HEP range	$8\ 10^{-3}$-$1.6\cdot10^{-1}$		$1\ 10^{-5}$-$1.3\cdot10^{-3}$	$2.7\ 10^{4}$-$1.6\cdot10^{-2}$	$2.13\ 10^{-4}$-$2.3\cdot10^{-2}$	
HEP range typical	$8\ 10^{-3}$-$1.6\cdot10^{-1}$		$8\ 10^{-4}$-$1.3\cdot10^{-3}$	$2.7\ 10^{4}$-$1.6\cdot10^{-2}$	$8\ 10^{-3}$-$2.3\cdot10^{-2}$	
HE absolute CDF	$1.06\ 10^{-6}$	Not analyzed	$1.26\ 10^{-6}$	$1.03\ 10^{-6}$	$2.74\ 10^{-6}$	Not considered
HE relative CDF	0.22		1	1	0.36	
LER	0.39		0.81	0.8	0.29	
Plant 10						
Information not provided						
Plant 11						
HEP range	No HE	No HE	$1\ 10^{-3}$	$1\ 10^{-4}$-$2\cdot10^{-3}$	$1\ 10^{-4}$-$1\cdot10^{-4}$	No HE
HEP range typical	No HE	No HE	$1\ 10^{-3}$	$5\ 10^{-4}$-$2\cdot10^{-3}$	$1\ 10^{-4}$-$1\cdot10^{-4}$	No HE
HE absolute CDF	0	0	$4.89\ 10^{-12}$	$6.9\ 10^{-8}$	$3.7\ 10^{-7}$	0
HE relative CDF	0	0	0.82	0.98	0.31	0
LER	1	1	1	1	0.6	1
Plant 12						
HEP range	$6.2\ 10^{-4}$-$8.8\cdot10^{-2}$	No HE	$2.4\ 10^{-2}$-$2.4\cdot10^{-2}$	$1\ 10^{-4}$-$4.86\cdot10^{-2}$	No HE	$1.4\ 10^{-3}$-$3.7\cdot10^{-3}$
HEP range typical	$1.2\ 10^{-3}$-$6.6\cdot10^{-2}$	No HE	$2.4\ 10^{-2}$-$2.4\cdot10^{-2}$	$1.9\ 10^{-3}$-$4.86\cdot10^{-2}$	No HE	$1.4\ 10^{-3}$-$3.7\cdot10^{-3}$
HE absolute CDF	$3.06\ 10^{-6}$	0	$2.43\cdot10^{-6}$	$7.8\ 10^{-8}$	0	$1.9\ 10^{-8}$
HE relative CDF	0.24	0	0.66	1	0	0.02
LER	0.33	1	0.91	0.99	1	0.97
Plant 13						
HEP range	$2.3\ 10^{-3}$-$2.9\cdot10^{-2}$	$6.8\ 10^{-3}$-$1.5\cdot10^{-2}$	$4\ 10^{-3}$-$1.5\cdot10^{-1}$	$2.4\ 10^{-3}$-$1.5\cdot10^{-1}$	$4\ \ 10^{-3}$-$1.2\cdot10^{-2}$	$6.8\ 10^{-3}$-$2.9\cdot10^{-2}$
HEP range typical	$2.3\ 10^{-3}$-$2.9\cdot10^{-2}$	$6.8\ 10^{-3}$-$1.5\cdot10^{-2}$	$4\ 10^{-3}$-$4.9\cdot10^{-2}$	$2.4\ 10^{-3}$-$6.8\cdot10^{-2}$	$4.8\ 10^{-3}$-$6.8\cdot10^{-3}$	$6.8\ 10^{-3}$-$1.5\cdot10^{-2}$
HE absolute CDF	$6.3\cdot10^{-8}$	$9.4\cdot10^{-6}$	$1.37\ 10^{-6}$	$3\ 10^{-6}$	$1.7\cdot10^{-6}$	$1.07\cdot10^{-5}$
HE relative CDF	0.14	0.96	1	1	1	1
LER	0.21	0.94	0.96	0.21	1	1
Plant 14						
HEP range	$1.5\ 10^{-2}$-$1.5\cdot10^{-2}$	$2.3\ 10^{-3}$-$1.5\cdot10^{-2}$	$2.4\ 10^{-3}$-$1.5\cdot10^{-1}$	$4\ 10^{-3}$-$1.5\cdot10^{-1}$	$6.7\ 10^{-4}$-$1.5\cdot10^{-2}$	$2.35\ 10^{-3}$-$2.86\cdot10^{-2}$
HEP range typical	$1.5\ 10^{-2}$-$1.5\cdot10^{-2}$	$2.3\ 10^{-3}$-$1.5\cdot10^{-2}$	$2.4\ 10^{-3}$-$4.9\cdot10^{-2}$	$4\ 10^{-3}$-$1.5\cdot10^{-1}$	$1.2\ 10^{-2}$-$1.5\cdot10^{-2}$	$2.35\ 10^{-3}$-$2.86\cdot10^{-2}$
HE absolute CDF	$1.26\cdot10^{-7}$	$5.26\cdot10^{-6}$	$1.09\cdot10^{-5}$	$1.11\cdot10^{-5}$	$2.06\cdot10^{-7}$	$7.66\cdot10^{-6}$
HE relative CDF	0.15	0.91	1	1	1	0.99
LER	0.4	0.55	0.78	0.79	0.15	0.98

values falling significantly out of the "normal range". The aim of the "HEP range typical" is to eliminate these "remote observations" and to get more precise pattern of the HEPs used,

– "HE absolute core damage frequency (CDF)" – Total contribution of frequencies of all those minimum cut sets (MCS), belonging to the given scenario of the PSA model that contains the basic event representing the human failure in question. This information is suitable for comparison of absolute impact of human-factor issues specific for the given scenario on the evaluated risk,

– "HE relative CDF" – relative contribution of frequencies of all those minimum cut sets (belonging to the given scenario PSA model) that contain failure of some human actions, *i. e.* total contribution of the human error (HE) absolute CDF divided by the total sum of the first twenty MCS CDF contributions. In this way it is possible to see which part of risk connected with selected scenario has some

relation with human factor problems: small values of this parameter indicate that the response to the given initiating event is performed mostly automatically, without involvement of plant crew (what should not be the case for WWER NPP), and
- "Level or representativeness (LER)" – total contribution to CDF coming from the first twenty MCS related to the given scenario divided by the total CDF value derived for the scenario (coming from "all" scenario MCS). LER shows, how much representative are the previous results presented in the table, obtained on the base of the twenty most important minimum cut sets only, if the value is close to 1, where the first twenty MCS represent almost all the scenario risk.

A large quantity of information is presented in the tables. For the individual attributes, the range values are the following:

HEP range values
- extremely low – of magnitude 10^{-6}
- very low – of magnitude 10^{-5}
- low – of magnitude 10^{-4}
- medium – of magnitude 10^{-3}
- fairly high – of magnitude 10^{-2}
- very high – of magnitude 10^{-1}

Note 1: Low HEP values are desirable, high values undesirable. However, low HEP values may also be due to the presence of some bias in the analysis.

HE absolute CDF
- very low – of magnitude 10^{-8} and lower
- low – of magnitude 10^{-7}
- medium – of magnitude 10^{-6}
- high – of magnitude 10^{-5} and higher

Note 1 holds for this case, as well.

HE relative CDF
- very low – lower than or equal to 0.1
- low – from the interval (0.1, 0.4>)
- medium – from the interval (0.4, 0.7>)
- high – from the interval (0.7, 1>)

Note 2: High values of this parameter are expected, low values are seen as abnormal.

LER

The same rules are used as for "HE relative CDF" attribute.

Note 3: High values of this parameter indicate higher credibility of analysis results and vice versa.

Using tabs. 9 and 10, two kinds of useful comparisons can be basically made:
- the comparison of the parameters between different plants for the same scenario, and
- the comparison of the parameters between different scenarios for the same plant.

The following conclusions can be made on the basis of the table for the LPSD HRA (across scenarios) for the individual WWER-440 plants:
- the HEP values used in Plant 2 PSA are the most optimistic ones among all the values provided by the plants; in general, the risk contribution for human factors related issues is relatively low and a relatively significant part of MCS (for most of the scenarios) does not contain human failures,
- the HEP range typical for Plant 3 NPP HRA is rather conservative, except for heavy load drops, whilst the relative part of risk contribution connected with scenario segments controlled with human actions is rather high,
- some HEP values used in Plant 5 HRA are highly conservative, but still adequate, because the level of risk contribution related to human factors is quite low in those cases; the relative contribution to the risk level expected to be high (big influence of human factor) with an exception regarding heavy load drops,
- the HEP values in Plant 6 PSA study are relatively low in most scenarios taken into consideration; however, the absolute human related risk contribution is fairly high in several scenarios analyzed; a very low (both absolute and relative) contribution of human actions is typical for small LOCA scenarios,
- for Plant 7, the conclusions regarding HEPs ranges and human factor absolute contribution to the risk connected with the scenarios under concern are quite close to the conclusions made for Plant 6, with one significant difference in the value of relative contribution of human related segments to the scenario "Loss of natural circulation", and
- in the LPSD PSA of Plant 8 some HEP ranges are expected in typical up-to-date PSA; some ranges are relatively low, leading to lower total contribution of the corresponding scenarios to LPSD operation risk; the values of relative human related contributors are rather close to unity, which points out the high relevance of human factors in the scenarios, with an exception in the case of small LOCA.

For the HRA developed for plants with WWER-1000 reactors, the following general conclusions are made:
- rather conservative HEP values are used in general for Plant 9 HRA, leading to relative balanced, significant total contributions of human parts of all selected scenarios to plant risk; however, the relative human related contributions are small for the scenarios "loss of off-site power" and "loss of heat removal",
- in the case of Plant 11, the HEP values used are rather optimistic (typical values which can be used for longer time windows), but the absolute human related contributions to plant risk have been found to be very low; because the relative weight of these contributors was specified as high, the reason can not be incompleteness of human factor part in the modeling; moreover, it is worth to men-

tion that the information was provided only for half of the scenarios,

- rather high HEP are used in general in Plant 12 HRA, but still keeping low the values of most of the contributions of human related MCS,
- in Plant 13 HRA, the values of HEP are very high and the values of absolute and relative contribution of human related parts of the individual scenarios to plant risk are – probably as a direct consequence – rather high as well. The only exception is the scenario "loss of off-site power" with high HEP values, but a quite low total as well as relative contribution to plant LPSD risk, and
- finally, for Plant 14 HRA, a very similar spectrum of parameter values can be found as for Plant 13 HRA, and, consequently, very similar conclusions can be made about the level of conservativeness as well as of human reliability importance for PSA results.

CONCLUSIONS

The following conclusions stem from comparisons from the point of view of the individual scenarios across plants.

In general, it is difficult to identify some specific features of the individual scenarios regarding HEP values used in corresponding HRA. The whole spectrum of HEP ranges can be usually identified across plants, some exception from this conclusion are noted for the WWER-1000 scenarios "Loss of heat removal via primary side" and "PSV primary leaks during hydro-test", where lower HEP values significantly prevail.

Man-induced LOCA in operation of WWER-440 reactors is the only scenario showing a relatively good agreement among the total values of absolute human related CDF contributions derived in the individual studies; some level of agreement can be found also in case of WWER-1000 scenario "Loss of heat removal via primary side".

The WWER-440 scenario "Reactivity accidents" is typical with very high level of human factor involvement into the most important MCS, which is very close to unity or even equal to unity in most cases.

The WWER-440 "Small LOCA" scenario shows in several cases relatively low human factor contribution to the risk of twenty of the most important minimum cut sets.

Low relative contribution to CDF is typical for the human role in the WWER-1000 scenario "Loss of off-site power"; the level of agreement among the values presented in the table for the individual PSAs is surprisingly high.

In the WWER-1000 scenarios "Primary circuit leaks outside containment" and "Small LOCA from primary to secondary circuit", a very high portion of MCS includes primary events containing human actions, *i. e.* human involvement is a substantial contributor to the risk profile.

In general, it can be observed that the HEP values ranges explored in the WWER LPSD studies presented in the harmonization effort, are driven by the differences among HRA approaches much more than by the differences among the individual scenarios.

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АНАЛИЗА ПОУЗДАНОСТИ ОСОБЉА У ОКВИРУ ПРОБАБИЛИСТИЧКЕ ОЦЕНЕ СИГУРНОСТИ НУКЛЕАРНИХ ПОСТРОЈЕЊА У РЕЖИМУ МАЛИХ СНАГА И СТАЈАЊА ВАН ПОГОНА

– Резултати једне међународне иницијативе –

Од самог почетка ере коришћења нуклеарне енергије, људски фактор је разматран као један од кључних аспеката у свим фазама животног циклуса нуклеарног постројења: у пројектовању, пуштању у погон, током погона, одржавања, надзора, погонских измена и декомисије. Овакав став стално се потврђује искуствима из праксе. Међународна агенција за атомску енергију и Удружени истраживачки центар Европске комисије организовали су радионицу на тему хармонизације пробабилистичких анализа сигурности у режиму малих снага и стајања ван погона за нуклеарне електране WWER типа. Један од главних циљева радионице био је да се изврши поређење различитих приступа и резултата анализа поузданости особља код нуклеарних електрана типа WWER 440 и WWER 1000 и да се стекне увид у будуће примене анализа поузданости особља у разматрању сценарија у режиму малих снага и стајања ван погона. Овај рад сумира активности и закључке поменуте радионице који се односе на анализе поузданости особља и људског фактора.

Кључне речи: пробабилистичка анализа сигурности, режим малих снага и стајања ван погона, анализа поузданости особља, WWER, људски фактор