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Human reliability analysis data obtainment through fuzzy logic in nuclear plants

C.S. do Nascimento[a,*], R.N. de Mesquita[b]

[a] Centro Tecnológico da Marinha em São Paulo (CTMSP), Av. Professor Lineu Prestes 2468, 05508-000 São Paulo, SP, Brazil
[b] Instituto de Pesquisas Energéticas e Nucleares (IPEN/CNEN – SP), Av. Professor Lineu Prestes 2242, 05508-000 São Paulo, SP, Brazil

HIGHLIGHTS

- Human Error Probability estimates from operator's reactions to emergency situations.
- Human Reliability Analysis input data obtainment through fuzzy logic inference.
- Performance Shaping Factors evaluation influence level onto the operator's actions.

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ABSTRACT

Human error has been recognized as an important factor for many industrial and nuclear accidents occurrence. Human error data is scarcely available for different reasons among which, lapses in historical database registry methodology is an important one. Human Reliability Analysis (HRA) is an usual tool employed to estimate the probability that an operator will reasonably perform a system required task in required time without degrading the system. This meta-analysis requires specific Human Error Probability estimates for most of its procedure. This work obtains Human Error Probability (HEP) estimates from operator's actions in response to emergency situations hypothesis on Research Reactor IEA-R1 from IPEN, Brazil. Through this proposed methodology HRA should be able to be performed even with shortage of related human error statistical data. A Performance Shaping Factors (PSF's) evaluation in order to classify and estimate their influence level onto the operator's actions and to determine their actual state over the plant was also done. Both HEP estimation and PSF evaluation were done based on expert judgment using interviews and questionnaires. Expert group was established based on selected IEA-R1 operators, and their evaluation were put into a knowledge representation system which used linguistic variables and group evaluation values that were obtained through Fuzzy Logic and Fuzzy Set theory. HEP obtained values show good agreement with literature published data corroborating the proposed methodology as a good alternative to be used on HRA.

1. Introduction

One of the main lessons about nuclear and industrial plant accidents is that them, most of the time, are consequence of incorrect human action. The global conscience about human factors and human reliability has been growing significantly in the last ten or fifteen years, mainly due the fact that some of these severe accidents (nuclear and non-nuclear) had important human error contribution. In a world scale, the severe accidents caused by human error percentage are estimated between 40% and 50% (IAEA TECDOC-1048, 1998).

Inside nuclear area Three Mile Island (TMI) in 1979 and Chernobyl in 1986 accidents, in which human had significant part, brought valuable information about human reliability.

Inside process industries scope, human actions have been great contributors to accidents since human error has been considered as the main accident cause in the majority of described severe accidents as Bhopal, 1984 and Piper Alpha, 1988.

A human error is characterized as a divergence between the realized action and the action that should have been taken. Human Error Probability (HEP) is defined as the ratio between the number of performed errors and the number of given opportunities for error to occur. Human reliability is the probability that an operator will reasonably perform a system required task in a determined time, without performing any other action that should degrade the system (Swain and Guttmann, 1983). The usual tool employed to measure human reliability is Human Reliability Analysis (HRA) which has as its goal to perform a human performance prediction and evaluation, using Human Error Probability (HEP)

* Corresponding author. Tel.: +55 11 31339420.
E-mail addresses: claudio.souza@ctmsp.mar.mil.br (C.S. do Nascimento), rnavarro@ipen.br (R.N. de Mesquita).

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(Reason, 1990). There are factors that act on human performance (Performance Shaping Factors – PSF's) especially when related to human–machine environment. Among these, the external factors are equipment, procedures or environment. Internal factors are individual operator characteristics, motivations, abilities and dexterity. These factors have direct effect on behavior and shape HEP for the specific analyzed situation characteristics. The PSF's, depending on their nature, had the property of increase or diminish HEP (Swain and Guttmann, 1983).

Human actions are present during all life cycle of a system from project till its disposition. This human contribution can be better understood and evaluated through HRA techniques which have been taken as essential part of nuclear and industrial plants PSA's (IAEA 50-p-10, 1995).

The Probabilistic Safety Assessment (PSA) is an important tool for quantifying the existent operational risk on nuclear reactors or other potentially risky installations. Using this analysis, the actual accidents occurrence probabilities are obtained and their consequences are evaluated in order to get a numerical estimate of how safe that installation is (Henley and Kumamoto, 1992). PSA are modeled based on Event Tree and Fault Tree which are analyzed to obtain the basic events which may have as cause: a component failure and/or human error. Human error events inside PSA analysis are detailed in Hirschberg (2004) and AIChe (1994).

The quantification of HRA leads to a consequent need of Human Error Probability data of basic actions for different tasks and a quantitative representation of possible influence of PSF's on these actions (Gertman and Blackman, 1994). Unfortunately it is not possible to find human error data as easily as is to find component faults data (all usually tabled). The scarce available human error databases are usually or very specific or generic due to PSF peculiarities. Besides that, few plants keep regular registry of human error occurrence historical data (Subramanian, 1999). In this context, expert judgment taken as subjective probability evaluation has been an important tool to develop a human error database for HRA. Subjective judgment is necessary due to an impossible precise and objective evaluation. This judgment is done based on natural language (linguistic expressions) evaluations (Clemen and Winkler, 1999; Onisawa, 1988, 1995).

Many studies, as the ones made by Clemen and Winkler (1999), Onisawa (1995), Onisawa and Kacprzyk (1995) and Yuhua and Datao (2005), have shown that fuzzy logic can provide an exclusive method for translating common human expressions (vague and imprecise) into mathematical and logical variables. In order to overcome these intrinsic barriers on HEP and PSF determination, this work uses a methodology based on Fuzzy Logic combined with expert judgment to determine human error occurrence probabilities and to evaluate Human Performance Shaping Factors (PSF's) on performed actions in a nuclear power plant.

In order to demonstrate the employed methodology effectiveness, IEA-R1 (Ipen-Cnen, Sp, Brazil) nuclear reactor was chosen as scenery for a study of nuclear reactor operator actions based on their response to an emergency situation described in their Local Emergency Plan. This work initial development was discussed in INAC 2009 (do Nascimento and de Mesquita, 2009) and was implemented as a master degree dissertation (do Nascimento, 2010).

2. Method

2.1. Expert group formation

Expert group formation in order to obtain HEP data was based on the following method. Both to obtain HEP as to evaluate PSF it was necessary to elicit experts knowledge through interviews and questionnaires. A group of experts was selected among IEA-R1 actual operators. These experts were asked to make their evaluations based on their own experience and knowledge. As these attributes have considerable variation among different experts, an Expert Importance Grade (EIG) was introduced to weight their answers on evaluating their relative importance to overall reliability analysis (Bolado and Devictor, 2005; Clemen and Winkler, 1999; Pan, 2006). EIG factor was based on educational level and operation experience time as can be seen in Table 1.

Table 1
EIG criteria.

Educational level	Points (P1)	Time of experience (years)	Points (P2)
PhD	5	28–35	5
Master	4	21–27	4
Specialist	3	14–20	3
Graduate	2	7–13	2
Medium degree	1	1–6	1

Effectively eleven IEA-R1 operators' questionnaires were taken into account on this work. An evaluation score (P1) was attributed to each one according with their educational level and P2 points according to professional experience time. The selected group used for evaluations was composed of the seven higher EIG scores operators as shown in Table 2.

EIG factor was evaluated based on Eq. (1) as follows:

$$\mathrm{EIG}_i = \frac{\mathrm{PE}_i}{\sum_{i=1}^{7} \mathrm{PE}_i} \quad (1)$$

Table 2
Expert Importance Grade (EIG).

Expert (E_i)	Educational level	P1	Experience (years)	P2	PE_i(P1 + P2)	Factor (EIG)
E1	Master	4	30	5	9	0.25
E2	Graduate	2	32	5	7	0.20
E3	Graduate	2	27	4	6	0.17
E4	Medium degree	1	18	3	4	0.11
E5	Graduate	2	10	2	4	0.11
E6	Medium degree	1	12	2	3	0.08
E7	Medium degree	1	10	2	3	0.08
	Total = $\sum PE_i$				36	1

2.2. Human Performance Shaping Factors evaluation

Evaluation was done with two main purposes: determine PSF influence level on operator performance when action happens in response to an emergence situation and identify how the expert (operator) perceives each related factor actual situation, both related to activity local environment as those related exclusively to themselves.

The questionnaires were constructed firstly by describing all possible PSF's that should have influence on actions under evaluation. This step was done based on Swain and Guttmann (1983) classification in which these factors are grouped in two main classes: internal factors and external factors, as cited on Section 1 of this work. Based on this exhaustive PSF's list, the more representative factors to this work were selected, as presented in Table 3. The one to twenty seven numbered PSF's set constitute the group of external factors and the one to seventeen numbered PSF's set constitute the internal factors group.

Two questionnaires were constructed based on a wider range of linguistic options in order to extract maximum discrimination on their probability estimate opinion. Their subjective evaluation was based on the following linguistic terms: *PSF influence level*: N – no influence, L – little influence, M – moderate influence and G – great influence; *PSF actual situation*: TBD – too bad situation, BD – bad situation, R – regular situation, G – good situation and

Table 3
PSF – expert group evaluation.

Expert group evaluation															
PSF		Influence level							Actual situation						
		E1	E2	E3	E4	E5	E6	E7	E1	E2	E3	E4	E5	E6	E7
External	1	G	M	G	L	G	L	G	G	R	G	G	VG	G	G
	2	G	L	M	N	G	N	M	G	R	G	R	VG	G	G
	3	M	L	M	N	G	N	M	G	R	G	R	VG	G	G
	4	G	M	G	N	G	L	M	G	G	G	G	VG	G	G
	5	M	M	M	N	G	N	M	G	R	G	G	G	G	G
	6	M	M	M	M	G	N	L	G	BD	G	G	G	R	R
	7	M	M	M	L	G	N	L	G	BD	G	VG	G	R	R
	8	M	L	M	L	G	N	L	G	R	G	G	VG	VG	R
	9	G	M	G	M	G	L	M	G	R	G	R	G	G	G
	10	M	M	G	L	G	L	G	G	G	R	R	R	G	G
	11	G	M	G	L	G	L	G	G	G	G	G	G	G	G
	12	G	G	G	L	G	L	M	G	R	G	G	G	G	G
	13	G	M	M	L	G	L	M	G	R	R	G	G	G	R
	14	M	G	G	M	G	L	G	G	G	G	R	R	G	G
	15	G	M	G	M	G	N	G	R	G	G	R	G	G	G
	16	G	G	G	M	G	N	M	R	G	G	R	G	VG	G
	17	M	G	G	M	G	N	M	G	R	G	BD	G	G	R
	18	M	M	G	M	G	N	N	G	G	G	R	BD	G	G
	19	M	M	G	G	G	N	N	G	G	G	R	R	G	G
	20	M	M	G	G	G	L	N	G	G	G	R	R	G	R
	21	G	G	G	M	G	N	G	G	G	G	R	VG	VG	R
	22	G	G	G	M	G	N	L	G	R	G	G	VG	G	G
	23	G	G	G	G	G	L	L	R	R	G	R	R	G	R
	24	G	M	G	M	G	L	G	G	G	G	G	G	G	R
	25	M	M	M	M	G	N	G	R	G	R	R	VG	R	R
	26	G	M	G	M	G	N	M	G	R	G	R	VG	G	G
	27	G	L	G	L	G	L	G	G	G	G	R	R	G	R
Internal	1	G	G	G	M	G	N	M	G	VG	VG	G	VG	R	G
	2	G	G	G	G	G	N	M	G	VG	VG	G	VG	R	G
	3	G	G	G	G	G	N	G	G	G	VG	G	VG	G	R
	4	G	M	G	G	G	N	G	G	G	VG	G	VG	G	G
	5	G	M	G	G	G	L	G	G	G	VG	R	VG	G	G
	6	G	M	G	M	G	L	G	G	G	VG	R	VG	G	R
	7	G	G	G	M	G	L	G	G	G	R	G	G	G	G
	8	G	G	G	M	G	N	G	G	VG	VG	G	VG	G	G
	9	G	M	M	L	G	M	G	G	G	G	R	G	G	R
	10	M	M	M	L	G	L	M	G	G	G	R	R	G	G
	11	M	M	M	M	G	N	M	G	G	G	R	G	G	G
	12	M	M	M	M	G	L	M	G	VG	G	R	VG	G	G
	13	M	M	M	L	G	L	M	R	G	G	R	R	R	G
	14	M	M	M	L	G	N	M	R	VG	G	R	VG	R	R
	15	M	M	M	L	G	N	G	R	R	G	R	R	R	R
	16	M	M	M	L	G	N	M	G	VG	G	G	G	G	G

VG – very good situation. PSF evaluation performed by expert group is shown in Table 3.

The one to twenty seven numbered PSF's constitute the group of external factors and the one to seventeen numbered PSF's constitute the internal factors group.

2.3. Human Error Probability evaluation

HEP evaluation took into consideration actions described to contain the event: "Transient requiring the SCRAM system activation and with this activation failing on turning reactor off", classified on IEA-R1 Local Emergency Plan as "Open Emergency". Each action to contain the event is described in an appropriate procedure, for which operator error occurrence hypotheses were elaborated and for which probabilities were subjected to evaluation.

Inside the formulated questionnaire, error occurrence probability was to be classified into one of five different levels: Z – zero error occurrence probability, VL – very low occurrence probability, L – low occurrence probability, M – moderate occurrence probability, H – high occurrence probability, VH – very high occurrence probability. HEP expert group evaluation is shown in Table 4.

2.4. Fuzzy modeling of evaluations

Fuzzy theory was introduced in 1965 by L.A. Zadeh as a tool to deal with imprecision and to enable computing logical inference based on linguistic terms estimates (Zadeh, 1965). This tool is implemented though the called Fuzzy Logic System (FLS) which generally performs a nonlinear mapping of input data (feature) vector into a scalar output. The FLS evaluates suitable rules based on linguistic terms in order to obtain the decision values as output. Fuzzy evaluation is based on Fuzzy Set Theory which enables "if-then" similar rules creation and consequent fuzzy reasoning (Mendel, 1995).

A fuzzy set is defined by a group of elements of a Universe of Discourse $\boldsymbol{X}$ in which each element pertains to a certain set with a "membership grade". The characteristic function which associates each element with this membership grade is called "membership function" (μ) and it is usually normalized with real values varying

Table 4
Expert group evaluation of HEP.

Action	Hypothesis	E1	E2	E3	E4	E5	E6	E7
		Expert group evaluation						
Diagnosis	a	M	VL	L	L	L	Z	VH
	b	M	L	L	M	Z	VL	H
	c	L	L	L	M	VL	VL	H
	d	L	VL	Z	M	Z	VL	H
1	a	M	VL	VL	VL	L	Z	L
	b	VL	VL	VL	Z	Z	Z	L
	c	VL	L	VL	L	Z	Z	L
	d	VL	VL	VL	Z	VL	Z	VL
	e	VL	L	VL	Z	L	Z	M
	f	VL	L	L	VL	L	Z	VH
	g	VL	VL	VL	Z	M	VL	VL
2	a	VL	M	VL	VL	L	VL	L
	b	VL	L	VL	VL	L	VL	L
	c	VL	VL	VL	Z	L	VL	VL
3	a	VL	VL	L	VL	L	VL	L
	b	VL	VL	VL	VL	L	VL	VL
	c	VL	VL	VL	Z	L	VL	VL
4	a	VL	M	VL	VL	L	VL	L
	b	VL	H	VL	L	M	VL	M
	c	VL	L	VL	L	L	VL	M
5	a	VL	VL	VL	VL	Z	VL	M
	b	VL	VL	VL	L	L	VL	H
	c	VL	H	VL	M	L	VL	M
	d	VL	H	L	L	L	VL	M
6	a	VL	L	VL	L	L	VL	L
	b	VL	L	L	M	L	VL	M
7	a	VL	VL	L	VL	VL	Z	H
	b	VL	L	Z	Z	VL	Z	M
8	a	VL	VL	VL	VL	L	VL	M
	b	VL	L	M	VL	VL	VL	M
	c	VL	L	VL	M	L	VL	H
	d	VL	L	M	M	L	VL	M
	e	VL	M	VL	Z	Z	VL	M

between 0 and 1, and is formally described by: $\mu A: X \rightarrow [0.1]$, where $\boldsymbol{A}$ is a fuzzy subset and $\boldsymbol{X}$ is the universe of discourse.

Three different FLS's were implemented in this work:

- PSF influence level (INFL_PSF).
- PSF actual situation (SIT_PSF).
- Human Error Probability (HEP).

The dimension of a FLS is exponentially proportional to the number of input and output variables, and some optimization of global inference is necessary to obtain final estimates.

Fuzzy inference was performed in two steps using two FLS's following a hierarchical structure as described below:

First inference phase

The opinions from the operators with smaller EIG factors (E4, E5, E6 and E7) were aggregated into the first FLS estimating an output value $R_{(E4-E7)}$ for INFL_PSF, SIT_PSF and HEP representing this subset opinion.

Second inference phase

The previous aggregated opinion $R_{(E4-E7)}$ was used as input to the second FLS where higher score (higher EIG factors) operators opinions were used as inputs also. Second phase FLS were evaluated using E1, E2, E3 and $R_{(E4-E7)}$ as inputs.

2.4.1. Linguistic variables definition (fuzzy sets)

Universe of discourse parameters and reference values used as FLS linguistic input and output variables were based on recommended values (Swain and Guttmann, 1983; Reason, 1990; Kletz, 2001). Tables 5–7 show these values for each phase in each implemented FLS.

An important aspect of the FLS shown on above tables is that the effective values used as input on each FLS are based on input reference values and each expert's general consensus. They are classified into an output reference value range to obtain the correspondent

Table 5
Linguistic variables – FLS-INFL_PSF.

Type	Variables: 1st phase	Variables: 2nd phase	Universe of Discourse	Linguistic values	Reference values
Input	E4, E5 E6 and E7	E1, E2, E3 and $R_{(E4-E7)}$	0–10	N – no influence L – little influence M – moderate influence G – great influence	0 2 5 10
Output	$R_{(E4-E7)}$	INFL_PSF	0–10	N – no influence L – little influence M – moderate influence G – great influence	INFL_PSF < 1 1 ≤ INFL_PSF < 3 3 ≤ INFL_PSF < 7 7 ≤ INFL_PSF < 10

Table 6
Linguistic variables – FLS-SIT_PSF.

Type	Variables: 1st phase	Variables: 2nd phase	Universe of Discourse	Linguistic values	Reference values
Input	E4, E5, E6 and E7	E1, E2, E3 and $R_{(E4-E7)}$	0.1–10	VG – very good situation G – good situation R – regular situation BD – bad situation TBD – too bad situation	0.1 0.5 1 5 10
Output	$R_{(E4-E7)}$	SIT PSF	0.1–10	VG – very good the situation G – good the situation R – regulate the situation BD – bad the situation TBD – too bad the situation	0.1 ≤ SIT_PSF < 0.4 0.4 ≤ SIT_PSF < 0.8 0.8 ≤ SIT_PSF < 3 3 ≤ SIT_PSF < 7 7 ≤ SIT_PSF < 10

Table 7
Linguistic variables – FLS-HEP.

Type	Variable		Universe of Discourse	Linguistic values	Reference values
	1st phase	2nd phase			
Input	E4, E5, E6 and E7	E1, E2, E3 and $R_{(E4–E7)}$	0–1	Z – zero	0
				VL – very low	0.0001
				L – low	0.001
				M – moderate	0.01
				H – high	0.1
				VH – very high	1
Output	$R_{(E4–E7)}$	HEP	0–1	Z – zero	HEP ≤ 0.00005
				VL – very low	0.00005 ≤ HEP < 0.0005
				L – low	0.0005 ≤ HEP < 0.005
				M – moderate	0.005 ≤ HEP < 0.05
				H – high	0.05 ≤ HEP < 0.5
				VH – very high	0.5 ≤ HEP < 1

linguistic output value. Therefore all input values and expected output values on FLS are treated as “Reference Values”.

2.4.2. FLS implementation

The FLS implemented in this work were done based on MATLAB® Version 7.0.1 Fuzzy Logic Toolbox. All FLS’s were implemented base on Mamdani’s inference system with centroid defuzzification method. Inference system is based on fuzzy implication evaluation of classical logical proposition: “if x is A then y is B”, where A and B are linguistic values defined by fuzzy sets on the X and Y ranges (Universes of discourse) respectively. The “if-part” of the rule “x is A” is called the *antecedent* or premise, while the “then-part” of the rule “y is B” is called the *consequent* or conclusion (Mendel, 1995).

Three different fuzzy values for each linguistic variable were defined. Membership functions were triangular shaped as shown in Fig. 1.where $\mu_A(x)$:

$$\mu_A = \begin{cases} 0 \quad \text{for}\, x \le a_1 \\ \dfrac{x-a_1}{a-a_1} \quad \text{for}\, a_1 \le x \le a \\ \dfrac{b_1-x}{b_1-a} \quad \text{for}\, a \le x \le b_1 \\ 0 \quad \text{for}\, b_1 \le x \end{cases} \tag{2}$$

The rules set established for each FLS phase was implemented through possible combinations of defined linguistic values inputs. Expert Importance Grade (EIG) (Eq. (1)) was considered on rules implementation for each FLS, where each linguistic expression evaluated by an expert (ex. VL, H, VH, M,. . .) was weighted with its correspondent EIG value. Based on the rules the linguistic value with bigger EIG sum was taken as output to the rules set.

3. Results and discussion

The linguistic values associated with expert evaluations presented in Tables 3 and 4 were rewritten according to their

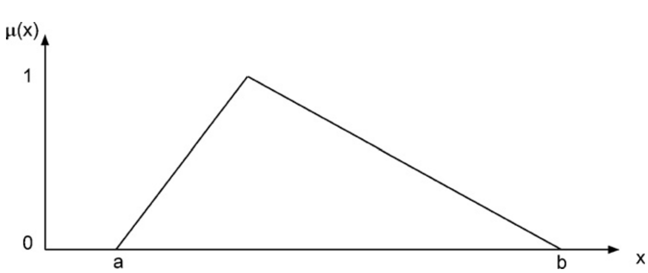

Fig. 1. Triangular membership function.

Table 8
Final results of evaluations of PSF.

PSF		1st phase Consensus (E4–E7)		2nd phase General consensus			
		INFL PSF	SIT PSF	INFL PSF		SIT PSF	
		(1)	(1)	(1)	(2)	(1)	(2)
External	1	1.83	0.65	8.20	G	0.56	G
	2	1.63	0.65	1.83	L	0.56	G
	3	1.63	0.65	1.83	L	0.56	G
	4	1.83	0.65	8.20	G	0.56	G
	5	1.63	0.56	5.00	M	0.56	G
	6	1.83	0.65	5.00	M	0.65	G
	7	1.83	0.65	5.00	M	0.65	G
	8	1.83	0.65	1.83	L	0.56	G
	9	5.00	0.56	5.00	M	0.56	G
	10	1.83	0.56	5.00	M	0.56	G
	11	1.83	0.56	8.20	G	0.56	G
	12	1.83	0.56	8.20	G	0.56	G
	13	1.83	0.56	5.00	M	0.61	G
	14	1.83	0.56	8.20	G	0.56	G
	15	8.37	0.56	8.23	G	0.61	G
	16	5.00	0.65	8.37	G	0.67	G
	17	5.00	0.65	5.00	M	0.56	G
	18	1.63	0.65	5.00	M	0.56	G
	19	1.63	0.56	5.00	M	0.56	G
	20	1.83	1.00	5.00	M	0.56	G
	21	8.37	1.00	8.23	G	0.56	G
	22	1.83	0.65	8.20	G	0.56	G
	23	1.83	1.00	8.20	G	1.00	R
	24	8.17	0.56	8.20	G	0.56	G
	25	8.37	1.00	5.00	M	1.00	R
	26	5.00	0.65	5.00	M	0.56	G
	27	1.83	1.00	1.83	L	0.56	G
Internal	1	5.00	0.65	8.37	G	0.65	G
	2	5.00	0.65	8.37	G	0.65	G
	3	8.37	0.65	8.23	G	0.65	G
	4	8.37	0.65	8.23	G	0.65	G
	5	8.17	0.65	8.23	G	0.65	G
	6	8.17	1.00	8.23	G	0.65	G
	7	8.17	0.56	8.20	G	0.56	G
	8	8.37	0.65	8.23	G	0.65	G
	9	8.17	1.00	8.20	G	0.56	G
	10	1.83	0.56	5.00	M	0.56	G
	11	5.00	0.56	5.00	M	0.56	G
	12	5.00	0.65	5.00	M	0.65	G
	13	1.83	1.00	5.00	M	1.00	R
	14	1.83	1.00	5.00	M	1.00	R
	15	1.83	1.00	5.00	M	1.00	R
	16	1.83	0.56	5.00	M	0.65	G
	17	1.83	0.65	5.00	M	0.65	G

(1) Reference values;
(2) Linguistic values.

Table 9
Final results of HEP evaluations.

Action	Hypothesis	1st phase Consensus (E4–E7)	2nd phase General consensus (1)	2nd phase General consensus (2)
Diagnosis	a	0.00210	0.00158	L
	b	0.00030	0.00132	L
	c	0.00030	0.00132	L
	d	0.00030	0.00058	L
1	a	0.00007	0.00008	VL
	b	0.00006	0.00008	VL
	c	0.00210	0.00008	VL
	d	0.00007	0.00008	VL
	e	0.00006	0.00008	VL
	f	0.00007	0.00008	VL
	g	0.00007	0.00008	VL
2	a	0.00007	0.00008	VL
	b	0.00007	0.00008	VL
	c	0.00007	0.00008	VL
3	a	0.00007	0.00008	VL
	b	0.00007	0.00008	VL
	c	0.00007	0.00008	VL
4	a	0.00007	0.00008	VL
	b	0.00320	0.00008	VL
	c	0.00210	0.00008	VL
5	a	0.00007	0.00008	VL
	b	0.00210	0.00008	VL
	c	0.00320	0.00008	VL
	d	0.00210	0.00158	L
6	a	0.00210	0.00008	VL
	b	0.00320	0.00158	L
7	a	0.00007	0.00008	VL
	b	0.00007	0.00008	VL
8	a	0.00007	0.00008	VL
	b	0.00007	0.00008	VL
	c	0.00320	0.00008	VL
	d	0.00320	0.00158	L
	e	0.00007	0.00008	VL

(1) Reference values;
(2) Linguistic values.

respective reference values shown in Tables 5–7 and appropriately formatted as inputs to its correspondents FLS, generating the results in each phase presented in Tables 8 and 9.

At first, the global results show clear coherence based on the linguistic terms used as shown in Tables 8 and 9 using initial evaluations obtained from the expert group shown in Tables 3 and 4. These results clearly represent the majority manifested opinions.

The numeric values presented in these Tables 8 and 9 are system final resultants and can be directly employed on HRA quantification. The linguistic values were obtained through adjustments based on reference values output ranges shown in Tables 5–7.

The king of information obtained in Table 8 is very important to situations in which better work conditions are necessary and desirable, enabling highlighting the more influent PSF's. It is possible to observe more than 90% of PSF factors to have good evaluations (*G*). This result may indicate that most specialists evaluate that improvements are necessary on the other 10%. SIT_PSF final results can be directly applied to HEP.

These HEP estimates were compared with data from Tables 20-18, 20-19, 20-23, 20-25, 20-26 and 20-32 from classical Handbook (Swain and Guttmann, 1983) and from Table 7.3 de (Kletz, 2001) and were consistently similar for similar actions. It was observed however, that some of the values presented by Swain and Guttmann (1983) were slightly larger than the obtained in this work. This fact is probably due to specific plant characteristics. This work was based on a research reactor while Swain and Guttman's values were based on power reactors, where responsibility and psychological tension involved on these tasks are much stronger. Swain and Guttmann (1983) provide a nominal PEH database recommended to nuclear area, which is based on both empirical evidence and specialist's evaluation.

A significant application to the obtained HEP's could be the estimation of reactor's Core Damage Frequency (CDF). The analyzed event on this work would lead to a Loss-of-Coolant Accident (LOCA). Based on the obtained HRA's and the pertinent PSF's would be possible to perform a HRA, resulting on a HEP for the global task. This result could be part on a Probabilistic Safety Assessment (PSA) through which the correspondent CDF could then be evaluated.

4. Conclusion

HEP data shortage can be efficiently and reliably overcame by applying methodology exposed on this work. This methodology enables solid mathematical treatment for subjective and uncertainty subject measurements through fuzzy logic variables implementation based on expert evaluation.

HEP and PSF obtained values are ready to be applied on HRA for this installation enabling possible important improvements to the system. Expert's judgment use is justified by the already mentioned highlighted human behavior dependence on PSF's which model it. These PSF's are specific and strongly dependant on local factors and on personal and environment characteristics.

The developed methodology shows some potential installation benefits:

- Appropriate guidelines for classification and data collection based on human errors.
- Possible HEP application on Probabilistic Safety Assessment – PSA, which could reduce accident risks through feedback information availability to project and maintenance analysis.
- Environmental conditions improvement by evaluation of PSF's actual situation which can contribute to find specific errors.
- Detection of potential operational procedure improvements by identification of the probable human errors.

Therefore this methodology widens the usual "yes" or "no" binary restriction in which HEP estimates are done. This evaluations are transformed into "high" or "low" probability fuzzy values for HEP, or "little influence" for PSF evaluation. This approach enables a more wide and profound answers quantification analysis.

The presented methodology, with appropriate changes can be adapted to other installations where human errors registry maybe scarce using other experts and environment references.

Introducing small changes the implemented FLS can be applied to evaluate other installations enabling similar tools for future application where database can be organized and structured based on HEP inference results.

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