HUMAN FACTORS QUESTIONNAIRE AS A TOOL FOR RISK ASSESSMENT

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ABSTRACT

The human factors engineering (HFE) as a discipline, and as a process, seeks to discover and to apply knowledge about human capabilities and limitations to system and equipment design, ensuring that the system design, human tasks and work environment are compatible with the sensory, perceptual, cognitive and physical attributes of the personnel who operates systems and equipment. Risk significance considers the magnitude of the consequences (loss of life, material damage, environmental degradation) and the frequency of occurrence of a particular adverse event. The questionnaire design was based on the following definitions: the score and the classification of the nuclear safety risk. The principal benefit of applying an approach based on the risk significance in the development of the questionnaire is to ensure the identification and evaluation of the features of the projects, related to human factors, which affect the nuclear safety risk, the human actions and the safety of the nuclear plant systems. The human factors questionnaire developed in this study will provide valuable support for risk assessment, making possible the identification of design problems that can influence the evaluation of the nuclear safety risk.

1. INTRODUCTION

A nuclear control room is a complex system that controls a thermodynamic process used to produce electrical energy and to provide research and development activities. The operators interact with the control room through systems and human-system interfaces that have significant implications for the nuclear plant safety.

NUREG 711 [1] determines that the HFE aspects of a nuclear plant should be developed, designed and evaluated based on the basic structured analysis using accepted HFE principles. After the accident at Three Mile Island (TMI) a critical review of plant design in several countries, with respect to control room, was conducted by the International Atomic Energy Agency (IAEA). Human factors were considered in a much broader sense and a chapter 18 was included in the Final Safety Analysis Report (FSAR) of the nuclear power plants, addressing the human factors engineering (HFE).
A control room is defined as a functional entity with an associated physical structure, where the operators carry out centralized control, monitoring and administrative responsibilities [2]. In the control room of a nuclear reactor, the operators monitor the nuclear process, control the technological systems, recognize disturbances that affect safety systems and maintain the plant in safe conditions [3]. The control room is a complex environment, where the tasks and actions of the operators change dynamically as a function of the interaction between operators and the human-system interfaces. The operators must have access to control devices, safety systems, alarm systems and procedures [4]. During a verification process, the control room design is evaluated to determine whether it acceptably satisfies the needs of the operator tasks and the human factors requirements [1]. The validation process identifies potential design problems that should be corrected if the design does not meet performance requirements of the control room [5].

The evaluation of the nuclear control room requires the selection of appropriate measurements techniques. It depends on the purposes of the overall situation and of the practical constraints [6]. Survey techniques, such as questionnaires and interviews, can be used to assess potential user’s needs, opinions, beliefs, perceptions, expectations and reactions. There are many ergonomics tools, such as rating scales and questionnaires, that have been used for the evaluation of systems performance [7].

According to Hollnagel [8], it is necessary to use a classification based on the representation of the system performance, to provide a reasonable overview of the evaluation methods. There are four types. In the first type, the system is represented by a description of its functional characteristics. It is the conceptual evaluation. In the second type, the system is represented by samples taken from preliminary performance recordings, using results of runs with the real system or prototype. It is a static evaluation. In the third type, the entire process is simulated, the operators have a degree of psychological involvement and they react to the simulated process in a realistic manner. In the fourth type, the evaluation is done in the real system, factory acceptance tests and commissioning tests in the plant site. For the purposes of this study, an conceptual evaluation has been carried out by two human factors experts and two licensed operators, using a human factors questionnaire with questions based on the guideline NUREG 700 [1].

Virtual Reality (VR) is a visualization tool which can be used to help designers, to train maintenance personnel and to illustrate functions of an industrial plant. The advantage of the virtual reality is that the people can be immersed in the simulated environment, often not feasible, due to cost, safety, or perceptual restrictions in the real environment.

Virtual reality can offer a tool for verification and validation during the design process of a nuclear control room. Iguchi et al. [9] used the virtual reality technology to support the dismantling process of a nuclear power plant. It was possible to evaluate the exposure dose more accurately and to estimate the workload of dismantling work in the radiation environment. The results of application of the interactive capability of 3D computer aided design (CAD) work for construction, evaluation and improvement of a workplace, showed that this tool should be employed by the ergonomists to assess the workers risks [10].

The aim of this paper is to present a comprehensible and useful questionnaire for the verification of human factors requirements in the nuclear control desk design. A case study is described in which the human factors questionnaire was used to evaluate a real and a virtual
control desk of a research nuclear reactor. The human factors questionnaire provided support for the identification of the human factors issues that were not included in the design of Argonauta Reactor control desk and that should influence the nuclear safety risk.

2. STUDY SETTING

This paper focuses on the implementation of a human factors questionnaire to directly verify the inclusion of the human factors issues in the design of a nuclear control desk. We describe a case study in which the human factors evaluation of a real and a virtual control desk of the Argonauta Reactor (Fig.1 and Fig.2) was carried out by four experts, using the human factors questionnaires. This paper addresses the aspects of the experimental validation of the human factors questionnaire by means of statistical tools, and the use, as an aid tool, of the virtual model of a nuclear control desk to determine that the final design conforms to HFE design principles.

The recruitment of the participants in the study was based on the following criteria:

- Two participants with more than 10 years experience in nuclear instrumentation and control desk design and with at least 5 years experience in the ergonomics evaluation of control rooms were recruited.
- Two participants with more than 10 years experience in the operation of research nuclear reactors were recruited.
- The total number of participants was defined in function of the available number of operators. There are only two licensed operators in the staff of the Division of Reactors of the Nuclear Engineering Institute.

Four experts participated of the study case and answered the human factors questionnaire. The two human factors experts are engineers with 15 years of experience in nuclear instrumentation design and eight years of experience in evaluation of the control room. The other two experts are licensed operators with fifteen years of experience in the operation of research nuclear reactors.

Simultaneously, the two human factors experts evaluated the Argonauta control desk and the two licensed operators evaluated the virtual control desk, using the same human factors questionnaire. A month later, simultaneously, the two human factors experts evaluated the virtual control desk and the two licensed operators evaluated the real control desk.
3. HUMAN FACTORS QUESTIONNAIRE

Risk significance considers the magnitude of the consequences (loss of life, material damage, environmental degradation) and the frequency of occurrence of a particular adverse event. The standard MIL 1629A [11] classifies the risk into five levels and five scores: (1) extremely unlikely, (2) minor, (3) moderate, (4) serious and (5) critical. According to NUREG 1764 [12], the principal factors that should influence the determination of risk significance of a nuclear plant are nuclear safety risk, commercial risk and personnel safety risk. When a combination of factors (nuclear safety risk, commercial risk and personnel risk) is considered, a conservative assessment of the level of human factors evaluation can be obtained using the highest grading level. NUREG 1764 [12] assigns the nuclear risk significance into three levels (high, moderate or low) associated to the human actions impacted by the modifications in the control room design without considering human factors issues.
The principal benefit of applying an approach based on the risk significance in the development of the questionnaire is to ensure the identification and evaluation of the features of the control desk, related to human factors, which affect the nuclear safety risk, the human actions and the safety of the nuclear plant systems.

3.1. Questionnaire development

The human factors questionnaire consisted of fifty questions about panel layout, panel label, information displays, controls and alarms (Table 1) [13]. Sixteen questions were related to panel layout (control and display arrangement, control-displays relationships and demarcation of panel layout), ten questions were related to panel label (labels formats, identification of units, consistent wording and separation), six questions were related to information displays (scaling conventions, numbering of scales and uniformity of units of measurements), seven questions were related to controls (pushbuttons, continuous adjustment controls, thumbwheels, toggle switches, size uniformity and indication of actuation) and eleven questions were related to alarms (indication, location and configuration). The questions are based on NUREG 700 guideline [1].

3.2. Questionnaire scoring

The questionnaire design was based on the following definitions: the score and the classification of the nuclear safety risk. The score of the human factors questionnaire is defined as the value of the conformance scale multiplied by the importance weights, as Eq. (1).

\[
\text{score} = \text{conformance scale} \times \text{importance weights} \tag{1}
\]

The values of the conformance scale and of the weights of the human factors questionnaire were determined using the human factors guidance for control room and human-system interface design from Electric Power Research Institute [14] as a reference. Each feature of the control desk related to the panel layout, panel label, information display, controls and alarms, is rated on a conformance scale, shown below:

0 - the requested design feature is available or completely complied with the human factors guideline.
1 - the requested design feature is partially available or somewhat complied with the human factors guideline.
2 - the requested design feature is not available or not complied with the human factors guideline.

Since some features may be more important than others, importance weights can be assigned. The importance weights are:

3 - the feature is mandatory
2 - the feature is desirable
1 - the feature is not important
The classification of the nuclear safety risk was defined as high (H), moderate (M) and low (L), using NUREG 1764 [12] standard as a reference. The questionnaire score was grouped into five scores, using MIL 1629A [11] standard as a reference. The objective was, firstly, to get a score for each question related to the panel layout, panel label, information displays, controls and alarms of the nuclear control desk. Secondly, the score obtained for each question was used to assign the nuclear safety risk. The score equals zero or 1 is related to low risk, 2 or 3 is related to moderate risk, and 4 or 6 is related to high risk (Table 2). The results were used to identify the questions evaluated as high risk that will be corrected with a higher priority.

**Table 1. The questionnaire framework**

<table>
<thead>
<tr>
<th>Item</th>
<th>Sub item</th>
<th>Elements</th>
<th>Number of questions</th>
</tr>
</thead>
<tbody>
<tr>
<td>Information displays</td>
<td>Design principles</td>
<td>• Simplicity, size uniformity • Scaling conventions • Numbering of scales • Uniformity of units of measurements</td>
<td>6</td>
</tr>
<tr>
<td>Panel layout</td>
<td>Control-display integration</td>
<td>• Arrangement and grouping of controls • Arrangement and grouping of displays • Control-display relationships • Demarcation of panel layout</td>
<td>16</td>
</tr>
<tr>
<td>Panel label</td>
<td>Design principles</td>
<td>• Identification of units of measurements • Labels formats • Uniformity of position • Consistent wording labels • Normal orientation of labels • Labels separation</td>
<td>10</td>
</tr>
<tr>
<td></td>
<td>Labeling of displays</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Labeling of controls</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Controls</td>
<td>Design principles</td>
<td>• Scaling conventions • Size uniformity • Indication of actuation</td>
<td>7</td>
</tr>
<tr>
<td></td>
<td>Control devices: Pushbuttons, continuous adjustment, key-operated, thumbwheels, toggle switches</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Alarms</td>
<td>Design principles</td>
<td>• Indication of alarms • Controls • Location and configuration</td>
<td>11</td>
</tr>
</tbody>
</table>

**Table 2. Nuclear safety risk**

<table>
<thead>
<tr>
<th>Risk classification (MIL STD 1629A)</th>
<th>Human factors questionnaire: Score of the nuclear safety risk</th>
<th>Nuclear safety risk</th>
</tr>
</thead>
<tbody>
<tr>
<td>Extremely unlikely</td>
<td>0</td>
<td>Low (L)</td>
</tr>
<tr>
<td>Minor</td>
<td>1</td>
<td></td>
</tr>
<tr>
<td>Moderate</td>
<td>2 or 3</td>
<td>Moderate (M)</td>
</tr>
<tr>
<td>Serious</td>
<td>4</td>
<td></td>
</tr>
<tr>
<td>Critical</td>
<td>6</td>
<td>High (H)</td>
</tr>
</tbody>
</table>

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3.3. Data analysis

In the first phase of the case study, two human factors experts carried out the evaluation of the Argonauta control desk and two licensed operators evaluated the virtual control desk, using the same human factors questionnaire. In the second phase of the case study, two human factors experts carried out the evaluation of the virtual control desk and the two licensed operators evaluated the real control desk. Before the experiment, the evaluators were trained on the use of the human factors questionnaire, focusing on the familiarization with the questions framework. The evaluators were asked to fill in the answers for the questions related to the information displays, panel layout, panel label, controls and alarms.

The Cohen’s kappa test is a measure for comparing the level of agreement when two observers are classifying the same set of specimens into two or more exclusive categories (e.g., high, moderate, low). The level quantified by the Cohen’s kappa test is a measure of agreement that two observers have between them (inter-rater agreement), when they perform an evaluation on the same set of specimens using the same tool. In this paper, the tool is the human factors questionnaires and the specimens are the real and the virtual control desk. The level of agreement of the evaluation of the nuclear safety risk (high, moderate, low), among the operator 1 and operator 2 (O1/O2), operator 1 and expert 1 (O1/E1), operator 1 and expert 2 (O1/E2), operator 2 and expert 1 (O2/E1), operator 2 and expert 2 (O2/E2), expert 1 and expert 2 (E1/E2), was quantified using the Cohen’s kappa statistics. This analysis was made separately for the real control desk and for the virtual control desk.

The test of significance involving the sample average is related to two possibilities. If one occurs, the other does not. In this study, the objective is to show that there is no statistical difference between the score average of the fifty questions related to the evaluation of the real control desk and the score average of the fifty questions related to the evaluation of the virtual control desk. If the averages are significantly equal, then the use of the virtual model of the control desk may provide a good support for the human factors verification process in the design of nuclear control desk. The \( \mu_{oir} \) (i = 1 and 2) and \( \mu_{eir} \) (i = 1 and 2) are defined as the score mean of the fifty questions related to the evaluation of the real control desk, answered by the operators 1 and 2, and answered by the experts 1 and 2, respectively. The mean \( \mu_{oiv} \) (i = 1 and 2) and \( \mu_{eiv} \) (i = 1 and 2) are defined as the score mean of the fifty questions related to the evaluation of the virtual control desk, answered by the operators 1 and 2, and answered by the experts 1 and 2, respectively. The mean score average of the fifty questions related to the evaluation of the real control desk, answered by the operator 1, operator 2, expert 1 and expert 2, is represented as Eq. (2). The mean score average of the fifty questions related to the evaluation of the virtual control desk, answered by the operator 1, operator 2, expert 1 and expert 2, is represented as Eq. (3).

\[
\mu_1 = \left( \sum_{i=1}^{2} \mu_{oir} + \sum_{i=1}^{2} \mu_{eir} \right) / 4 \tag{2}
\]

\[
\mu_2 = \left( \sum_{i=1}^{2} \mu_{oiv} + \sum_{i=1}^{2} \mu_{eiv} \right) / 4 \tag{3}
\]
4. RESULTS

The results of the Cohen’s kappa test (K) were greater than 0.70 (Table 3). It means that the degree of agreement among the evaluators was good [15]. It gives an indication of the consistency of the evaluation results and that the use of the human factors questionnaire in two different context, the real and virtual environment, made possible the identification of an identical set of design problems that could influence the nuclear safety risk.

For the student’s t-distribution, the critical value was 2.447 (p = 0.025 and 6 degrees of freedom). For the test of significance involving the mean score average, the calculated value was 0.372 (Table 4). It means that the evaluation of the nuclear control desk may be carried out by the evaluators, using the virtual model. The context of the case study, virtual or real model, did not alter significantly the total score of the human factors questionnaire.

The percent of identical responses by evaluators, associated to the nature of the nuclear safety risk (low, moderate or high), was calculated for each question of the panel layout, panel label, controls, information displays and alarms. For the real control desk, the percent of identical responses ranged from 0.75 to 0.91. For the virtual control desk, the percent of identical responses ranged from 0.69 to 0.82 (Fig. 4). The results showed that the human factors verification using a virtual model of control desk can be done with satisfactory results for the following topics: panel layout, panel label and information display.

<table>
<thead>
<tr>
<th>Table 3. The kappa value (K)</th>
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<tbody>
<tr>
<td></td>
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<tr>
<td>Real Control Desk (K)</td>
</tr>
<tr>
<td>Virtual Control Desk (K)</td>
</tr>
<tr>
<td>O1/O2</td>
</tr>
<tr>
<td>O1/E1</td>
</tr>
<tr>
<td>O1/E2</td>
</tr>
<tr>
<td>O2/E1</td>
</tr>
<tr>
<td>O2/E2</td>
</tr>
<tr>
<td>E1/E2</td>
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<table>
<thead>
<tr>
<th>Table 4. The test of significance involving the mean score average</th>
</tr>
</thead>
<tbody>
<tr>
<td>Real control desk</td>
</tr>
<tr>
<td>Expert 1 (μ₁ₑ₁) 3.533</td>
</tr>
<tr>
<td>Virtual control desk</td>
</tr>
<tr>
<td>Expert 1 (μ₁ₑᵥ) 3.707</td>
</tr>
</tbody>
</table>

Score mean 3.849 (μ₁) 3.909 (μ₂)

Average score mean
5. CONCLUSIONS

In this study the human factors questionnaire was used to evaluate a real and a virtual control desk of a research nuclear reactor. The results of the Cohen’s kappa test ($K \geq 0.70$) indicated the good level of agreement among the evaluators and showed the validity of the human factors questionnaire.

The results of the test of significance showed that the virtual reality may be a powerful visualization tool to review human factors requirements in the design process. The virtual reality may be used as an alternative approach, because the evaluators would not need to be in the real environment of work, the control room, to carry out this kind of ergonomics evaluation. It may be not feasible in some cases, because nor always the access to the control room would be available.

The trends in the graphic data indicated limitations in the evaluation of the virtual control desk for the alarms and controls topics (Fig. 4). The conclusion was that it requires further development and use of better computational tools with higher resolution.

The use of the human factors questionnaire provided valuable support for the identification of the features of the Argonauta control desk, related to the panel layout, panel label, information displays, controls and alarms, that were not in compliance with NUREG 700 [1] standard. The questions evaluated as being of high safety risk were selected with a higher priority to be corrected and were identified as being the most severe problem. The questions evaluated as being of moderate safety risk were selected with a medium priority to be corrected.

In this study, the human factors questionnaire made possible the identification of design problems related to the alarms, the controls and the panel label, such as the alarm system do not inform the operator about the priority and the nature of the deviation; the alarm system is not grouped by function and is not clearly identified; separate controls are not provided for alarm silence, acknowledgement and reset; the direction of controls motion (increase, decrease) is not identified for continuous motion rotary controls; there is not descriptive label for the chart recorders; and there are not labels identifying the access to the rear panels of the control desk. Although the use of the human factors questionnaire has been essential for the
identification of the design problems of the nuclear control desk related to the high risk, more studies are needed.

Future plans include the development of a computational system, with a structure based on the human factors questionnaire, incorporating the fuzzy logic and the AHP technique. The fuzzy logic will be used to rank the experts based on professional experience and knowledge in the nuclear area. The AHP will be used to identify among the design problems evaluated as high risk, which will be corrected with a higher priority.

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