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Aspects of the nuclear power plant control room system contributing to safe operation

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Abstract

The performance of a nuclear power plant's operational steering entity, the control room system, has a major impact on operational safety. The construction and modernization of nuclear power plants create a need to evaluate control room systems to assess if they fulfil their purpose to support safe operation. The aim of this study was to identify a foundation for evaluation measures, i.e. to find aspects of the control room system that contribute to safe operation from a human factors perspective. A number of professionals in roles influencing the operation and/or design of Swedish nuclear power plants were interviewed: reactor operators, shift supervisors, instructors, human reliability analysis specialists, human factors specialists, and personnel from the Swedish Radiation Safety Authority. A number of aspects contributing to safe operation were identified and categorised in six overall themes: *situations*, *functions*, *tasks*, *structural elements*, and *characteristics*. Situations describe states of and/or events in the surrounding environment that the control room system must be able to handle. Functions are the abilities the control room system must have, and tasks are what operators or technical systems in the control room system must be able to perform. Structural elements are the entities that constitute the control room system, and the characteristics of the structural elements establish conditions for the design of artefacts as well as the behaviours and abilities of personnel. These aspects are examples of what is required for controlled performance of the control room system, a prerequisite for safe operation. Together the themes serve as a structure for defining evaluation measures. The themes can be considered variables or constants when deciding on control room system evaluation measures, a choice that must be made for each evaluation. User experience aspects contribute to safe operation, but the operators' well-being has a value in its own right and should be considered as an additional goal when designing and evaluating control rooms.

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Keywords: Control rooms; Safe operation; Design; Evaluation; Nuclear power

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1. Introduction

Safe operation is crucial for a nuclear power plant, which should produce as much electricity as possible while avoiding damage to humans and the environment. Nuclear power, as an industry whose operation has potentially harmful consequences, is regulated at the governmental level. This regulation is meant to ensure that profitability requirements do not jeopardize system safety; the regulations must be satisfied before the plant can manage its operations with productivity in focus [1]. As an example, Swedish regulations state that the plants should have clearly defined “Operational Limits and Conditions” which, together with procedures, provide personnel with necessary guidance to ensure that operations are conducted in accordance with the conditions stated in the plant’s safety analysis report [2]. The safety analysis report documents what the plant is designed to handle, and operating in accordance with what it states can thus be considered safe operation. A design and operational principle used for nuclear power plants is the defence in depth principle [3]. The five levels of defence in depth range from preventing abnormal operation and failures to mitigating radiological consequences of significant releases of radioactive materials. This principle emphasises that safe operation is not merely about keeping operational limits from being directly threatened and mitigating consequences, it is also about acting proactively.

The functional entity responsible for operational control of the plant is the control room system. The control room, including its associated physical structure, is where the operators carry out centralized control, monitoring and administrative responsibilities [4]. The control room system is a socio-technical system including technology, human operators and organizational elements. The actual control room with operator interfaces is not enough to achieve proper control; components such as the operators’ competence, procedures, roles in the shift team, and work routines are also important parts. Any design changes of the control room system will have potential safety consequences [5] and thus also have an impact on production.

Today, there is an on-going process of modernization of old nuclear power plants and completely new plants are also being built. In this process it is important to continuously evaluate if the design of the control room system fulfils its purpose to support safe operation. Such an evaluation requires relevant measures, that is to say the purpose must be operationalised into factors that are possible to measure. The aim of this study was to identify a foundation for evaluation measures, i.e. to find aspects of the control room system that contribute to safe operation from a human factors perspective.

2. Method

The performance of the control room system depends largely on its design and the way it is operated, which makes personnel responsible for design and operation a valuable source of information. In order to utilize the experience of professionals within the Swedish nuclear power industry an interview study was conducted to investigate control room system contributions to safe operation. The professional roles chosen were those influencing human factors-related aspects rather than technical aspects. Table 1 shows the characteristics of the interviewees.

Two representatives of each role were interviewed (14 in total), twelve males and two females. The interviewees’ experience in their specific role ranged from 0.5 to 20 years. The representatives with the shortest experience had previous experience from work within the same field but with different responsibilities. Eight of the interviewees had an operational background and six had an academic background in behavioural science or engineering. In the groups with operational background half the interviewees had experience from boiling water reactors, and the others had experience from pressurized water reactors. The exception was the inspectors from the Swedish Radiation Safety Authority who primarily had experience from boiling water reactors.

Table 1. Characteristics of the different groups of interviewees in the study.

Role	Description	Background	Reactor type experience
Reactor operator	Responsible for operation of safety-related systems	Operation	Half the group had experience of boiling water reactors, the other half had experience of pressurized water reactors
Shift supervisor	Operatively responsible for all work in the control room	Operation	See above
Instructor	Responsible for implementing training of operators	Operation	See above
Human factors specialist working for the plant owner (licensee)	Responsible for human factors issues in plant modification projects	Behavioural science and/or engineering	N.a.
Human reliability analysis specialists	Performing human reliability analyses as part of the probabilistic safety analyses	Behavioural science and/or engineering	N.a.
Human factors specialist, Swedish Radiation Safety Authority	Responsible for reviewing the fulfilment of safety requirements	Behavioural science and/or engineering	N.a.
Inspector, Swedish Radiation Safety Authority	Responsible for reviewing the fulfilment of safety requirements	Operation	Boiling water reactors, one also had limited experience of pressurized water reactors

The interviews were semi-structured, held at the interviewees' workplace and took about 1-1.5 hours each. They were held by the same interviewer (the first author) and documented with audio recordings and written notes. The interviews started with an introduction of the purpose of the study. Emphasis was put on explaining to the interviewees that their view of what contributes to safe operation was sought, not 'the right answer'. It was also explained that they should not only consider the actual control room design when answering the questions, but include items such as procedures and personnel as well. The interviewees were asked about their role, the duration of their experience in that role, and their previous experiences regarding employment and education.

The second part of the interview contained broad questions on what contributes to safe operation and what contributes most, as well as what in the control room system needs to be evaluated to assess if it supports safe operation. Interviewees with an operational background were also asked if they could remember a real-life or simulator-set event with negative/potentially negative consequences, and what aspects had saved the situation or mitigated the effects.

The third part of the interview used different angles to trigger the interviewees' thoughts to obtain more extensive answers. It discussed what must be possible to perform in the control room, what sub-functions must exist, what characteristics the control room system should have and what parts it should consist of. These trigger questions were chosen to investigate the applicability of four different approaches to the problem. The first approach was to look at the human-machine system from a task point of view, to consider the control room system as a performer of tasks (something the system does). The second approach was to look at the system from a functional point of view, to consider the control room system as a compilation of abilities (something the system has the capacity to do). The third approach was to look at the system from a structural point of view, to consider the control room system as a collection of physical parts (structural elements give the system physical form). The fourth approach concerned the necessary properties of the structural elements, to discuss the control room system in terms of characteristics of the physical form.

Finally, the interviewer provided a summary of the interviewee's answers to give an opportunity to correct misunderstandings. The interviewee was again asked what contributes most to safe operation, since the interview might have led the interviewee to think more specifically about this issue. They were also asked about what they thought contributed least to safe operation. The purpose of the 'contributes most/least'-questions was to explore the interviewee's prioritisation of the different aspects expressed.

Thematic analysis was used to analyse the qualitative material from the interviews, which is a primarily descriptive approach to defining broad categories (themes) that describes significant features of data [6]. The thematic analysis procedure consists of six steps: data familiarisation, initial coding generation, search for themes based on initial coding, review of the themes, theme definition and labelling, and report writing. Going through these steps is not a linear process but rather an iterative one [6].

Data familiarization was achieved through both data collection and transcription (in full) of the interviews. In the initial coding generation statements regarding aspects of the control room system contributing to safe operation were marked and the content of each statement was summarized into one or a few words. Most of these initial codes were assembled for a search for patterns that indicated themes and sub-themes. The approaches adopted in the third part of the interview were used to structure the initial coding, but were modified to better fit the data.

3. Result

Five overall themes were identified from the interviews: *situations*, *functions*, *tasks*, *characteristics* and *structural elements*. Situations describe states of and/or events in the surrounding environment that the control room system must be able to handle. Functions are the abilities the control room system must have, and tasks are what operators or technical systems in the control room system must be able to perform. Structural elements are the entities that constitute the control room system, and the characteristics of the structural elements establish conditions for the design of artefacts as well as the behaviours and abilities of personnel. The aspects belonging to the five overall themes were further arranged in sub-themes. The statements in the situations theme were more general in nature, whereas the other themes were discussed in a more detailed manner by the interviewees.

The themes found in the interviews mirrored to a large degree the approaches used in the third part of the interview. This correspondence was however not evident when looking at the answers to separate questions. For example, the interviewees' answers covered all themes when asked about the sub-functions needed. The situations theme did not correspond to any of the approaches used in the interview, but was included to denote the statements emphasising the importance of considering the environment of the system being studied. A number of interviewees expressed the importance of having a systems view of the control room system, i.e. that aspects must be regarded jointly and not in isolation. All interviewees stated aspects belonging to all themes, except situations (Table 2).

Table 2. Themes identified in the answers of each interviewee. The roles shaded in grey have an operational background, the roles not shaded have a background in behavioural science or engineering.

Role	Theme				
	Situations	Functions	Tasks	Characteristics	Structural elements
Shift supervisors	x	x	x	x	x
	-	x	x	x	x
Reactor operators	-	x	x	x	x
	-	x	x	x	x
Instructors	x	x	x	x	x
	x	x	x	x	x
Inspectors, Swedish Radiation Safety Authority	x	x	x	x	x
	-	x	x	x	x
Human factors specialists, Swedish Radiation Safety Authority	x	x	x	x	x
	-	x	x	x	x
Human factors specialists	-	x	x	x	x
	-	x	x	x	x
Human reliability analysis specialists	x	x	x	x	x
	x	x	x	x	x

3.1. Situations

The statements of the situations theme were categorised in the two sub-themes: different operational modes (startup, power operation, shutdown, and outage) and different types of disturbances. All levels of disturbances were mentioned, from simple ones possible to correct using ordinary regulation of process systems to larger ones requiring the involvement of safety systems and barriers. The interviewees mostly stated that the control room system must be able to handle the different operational modes and disturbances, but did not elaborate more on the issue.

3.2. Functions

The statements of the functions theme were grouped into eleven sub-themes: presentation of information; possibility to of operating the plant; providing centralized supervision and operation of the plant; having personnel present locally in the plant; managing personnel; having established codes of conduct (rules); having a distribution of responsibility (roles); providing external support to the shift team; having redundancy and backup systems; provision of security; and being prepared for the unexpected.

According to the interview data the presentation of information must have the ability to: support problem-solving (for instance by providing analysis tools such as event history); support decision-making; provide a correct view of the status of the process; support the operators in knowing what to do and how to do it; provide an overview of the status of the process (knowledge "at a glance"); provide detailed information when needed; support prediction of the plant’s status in the future (for example by providing trend curves); support knowing the plant’s status in relation to what it should be; alert the operators when parameters deviate from normal/expected value (alarms); help the operators in prioritising the order in which to handle deviations; and provide response on performed actions (feedback).

In addition to presenting information the control room system must also have the ability to operate the plant. The overall function of the control room is hampered if important actions only can be performed in close relation the process objects in question, making centralized supervision and operation of the plant important. It is important however, to have personnel present locally in the plant as well, to monitor and analyse information that otherwise would go unnoticed, for instance smell and sound (sub-theme having personnel present locally in the plant).

The control room system must also have the ability to manage the people within the system (sub-theme managing personnel) and there must be established codes of conduct (rules) for how the personnel should act and how the plant is allowed to be operated. Having a clear distribution of responsibility (roles) in the shift team is another contributing factor. The next sub-theme, providing external support to the shift team, contains statements that the shift team in some situations must be able to get help from other people in the organisation, both by bringing them into the control room and by communicating over the phone.

The importance of having redundancy and backup systems in the design of the plant, as well as the provision of security (protection against sabotage, for example) for the control room was mentioned. Also, since not all events can be anticipated, the importance of being prepared for the unexpected was highlighted, that is to say having margins to allow the handling of unexpected events.

3.3. Tasks

The tasks theme was divided into four sub-themes: primary tasks, way of working, communication, and cooperation. Primary tasks were tasks directly related to operating the process (*what* tasks to do); e.g. handle disturbances, testing, and checking readiness for operation. *How* to do tasks, the way of working, included for example minimizing administrative tasks to allow focus on primary tasks and how personnel not in the shift team should behave in the control room so as to not disturb the operators. Communication and cooperation within the shift team as well as outside the team was stated as important.

3.4. Characteristics

The characteristics theme was split into the two sub-themes characteristics of the design and characteristics of the operators. Characteristics of the design included different traits of the design: transparency; clarity; consistency; error tolerance; contributing to a balanced workload for the operators; compatibility between interface and procedures; complexity in the design; providing time to act; robustness and technical reliability; and that information should be reliable, sufficient, correct, easy to understand, easy to access, and flexible in its presentation. The more overall characteristic usability was also often stated. Characteristics of the operators included different traits of the operators: competence (especially understanding the plant and its process); curiosity; stubbornness; flexibility; satisfaction with their job; confidence; calmness; and culture (values and attitudes).

3.5. Structural elements

The statements of the structural elements theme were categorised in five sub-themes: operator interfaces; physical control room design; process and instrumentation and control (I&C) systems; support systems; and personnel. Operator interfaces were parts where information from the process is shown and the plant can be operated. Physical control room design included the parts of the control room system that were not operator interfaces, such as layout. Process and I&C systems concerned the design of process and I&C systems, that is to say the origin of what is shown in the operator interfaces. Support systems were other means needed to support the tasks (for example procedures). The personnel sub-theme included the humans within the control room system.

3.6. Contributing most and least to safe operation

The interviewees' answers had little in common regarding what in the control room system they considered contributed most to safe operation. Aspects concerning overview and understanding of plant status and the medium for conveying this, that is to say the operator interface, were expressed by half the interviewees. Other aspects mentioned were the competence of the operators, cooperation, automation, construction of the plant and having a learning and questioning attitude.

Most interviewees found it difficult to specify what contributed least to safe operation. Things like non-safety critical objects and formalities concerning meeting routines (important, but should not steal focus from performance and technical aspects) were pointed out by a few. Some interviewees stated that flaws in the design of structural elements (such as operator interfaces and layout) could to some extent be compensated by a competent and apt operator, but not vice versa, indicating that they thought competence contributed more than design.

4. Discussion

The approach that aspects contributing to safe operation can be divided into functions, tasks, characteristics, and structural elements was confirmed by the interview data, with the addition of the situations theme. This division did not seem to be something the interviewees used consciously since their answers to specific questions did not follow the questions' themes. For example tasks were given as an answer when the question viewed the system from a functional perspective, and structural elements were suggested when the question regarded characteristics. Prioritising between aspects that contributed to safe operation proved to be difficult for the interviewees. Aspects concerning plant status (overview, understanding, and the operator interface presenting it) were expressed by half the interviewees as contributing most to safe operation. Apart from that, their answers had little in common. Nor was there clarity about which aspects were regarded as contributing least to safe operation. This is in agreement with the systemic view of complex socio-technical systems, that the control room system must be viewed as a whole and that the importance of different aspects depends on the situation. A complex system is by definition not fully understood, thus making the consequences of prioritising aspects in design and evaluation hard to foresee.

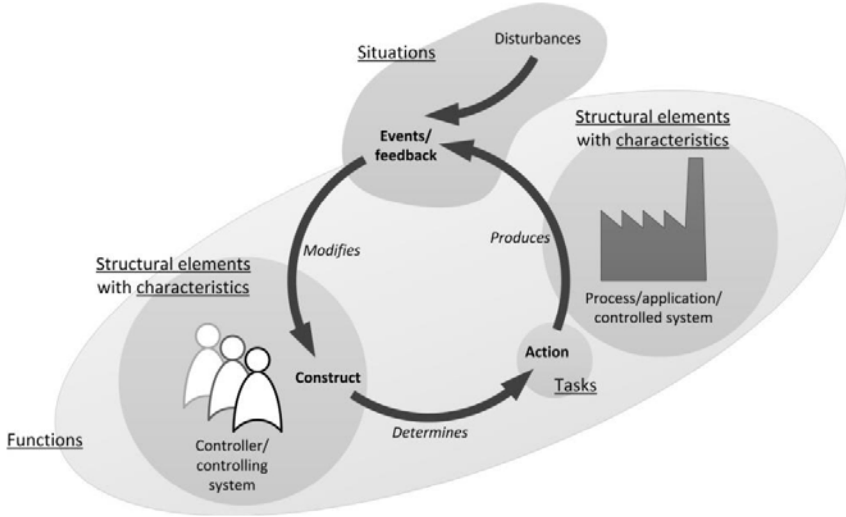

Fig. 1. The themes identified in this study (underlined) included in the basic cyclical model. Figure of original model adapted from Hollnagel et al. [7].

The relationship between the themes can be discussed in relation to Hollnagel and Wood's basic cyclical model [7] (Figure 1). This model describes the necessary steps in controlled performance, i.e. how a joint cognitive system maintains control. A cognitive system is defined as a system that can modify its behaviour on the basis of experience so as to achieve specific antientropic ends. The theme situations correspond to disturbances and events/feedback in the basic cyclical model. Both the controlling and the controlled system in Hollnagel and Wood's model are made up of structural elements, with specific characteristics. The controlling system performs actions, which corresponds to the theme tasks. Functions are the inherent potential of the joint cognitive system, hence the potential of the controlling and the controlled system together. Controlled performance in the control room context is a condition for safe operation, and the contents of the themes identified in this study provide examples of aspects in the nuclear power plant control room system that are required to achieve this.

This study was conducted with the purpose of identifying a foundation for control room system evaluation measures. The themes serve as a structure for defining evaluation measures, and the themes' roles in control room system evaluation depend on if they are considered to be variables or constants in the system to be evaluated. A minor exchange of outdated control room equipment might not justify changing the situations the control room must be able to handle and the tasks that must be possible to perform. These can thus be considered constants. The evaluation in this case should instead focus on the variables, that is to say if the structural elements have the correct functions and characteristics to handle situations and support tasks. The opposite is also possible, that the tasks performed in an existing control room need to be evaluated to assess if the manner of operation is effective and efficient. No assessment can be made if all themes are considered variables, which means that each evaluation must include a choice of what should be considered as variables and what should be considered as constants.

In the planning of this study the overall purpose of the control room system, i.e. safe operation, was seen as a performance and safety issue. User experience aspects, for example contributing to a balanced workload for the operators, was included in the characteristics of the design sub-theme since the desired experience of the operators forms conditions for the design. User experience aspects contribute to the performance and safety of the system, but this is not the only gain. Savioja et al. [8] described work as not only something individuals do in order to make money and survive, but rather as something that enables self-fulfilment and development as manifestations of the individual's well-being. They proposed that tools (for instance the operator interfaces in a control room) play a role in how satisfying, exciting and meaningful the work activity is to the worker. This reasoning shows that the operators' well-being has a value of its own, and should therefore also be considered a goal when designing and evaluating control rooms.

A planned continuation of this work is to use the identified themes and aspects as a foundation for selecting evaluation measures that assess if the control room system fulfils its purpose to support safe operation. Other researchers have presented frameworks for selection of evaluation measures, such as Braarud et al. [9] and Savioja [10]. A comparison with these, and other, measurement frameworks would challenge the results of this study and make it possible to develop the selection of measures further.

5. Conclusion

The result of this study can be summarized in three implications for the evaluation of nuclear power plant control room systems:

- Aspects contributing to safe operation can be divided into the themes situations, functions, tasks, characteristics, and structural elements. The aspects identified in this study are examples of what is required to achieve controlled performance of the control room system, which is a prerequisite for safe operation. The control room system must be viewed as a whole and the importance of different aspects depends on the situation. Together the themes serve as a structure for defining evaluation measures.
- When deciding on control room system evaluation measures, the themes play different roles depending on if they are considered to be variables or constants in the system to be evaluated. All evaluations must include a choice of what should be considered as variables and what should be considered as constants.
- User experience aspects contribute to the performance and safety of the system, but the operators' well-being has a value of its own as well. Thus should operator well-being, as well as safe operation, be considered as a goal when designing and evaluating control rooms.

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