What Constitutes a Well-Designed Alarm System?

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***Abstract*—Alarm systems play an important role in the operation of complex process control settings. A reliable and user-friendly alarm system developed according to the operators' conditions contributes to maintaining safe and efficient operation.**

Many projects performed within the power generation industries are modernisations of legacy systems. The guidelines compiled to aid engineers and system developers when developing alarm systems mainly focus on new designs and are therefore only partially applicable in modernisation projects.

Results and experience from seven theoretical and empirical research studies concerned with operator decision making and information needs in different working situations have been used to evaluate existing alarm system design guidelines (primarily NUREG-0700 and IEC-62241), in order to find out which alarm design guidelines are most important to consider in modernisation projects.

The results indicate that general guidelines (e.g., use of an alarm philosophy) are essential for modernisation projects. However, detailed guidelines (e.g., colour coding and text size) should be used more carefully and with consideration taken to the existing design in the control room. The main conclusion is that, in many cases, the need for consistency between the new system and the existing system overrides the need to follow ergonomic design guidelines. The operators should not experience that they are using another system but instead only an extension and improved version of the existing system they already have. This paper summarises the principal guidelines to consider when modernising one's alarm system in hybrid control rooms.

I. INTRODUCTION

Alarm systems play an important role in the maintaining of safe operation in complex process control settings. Well-designed alarm systems facilitate safe operation, whereas deficiencies can contribute to incidents. Furthermore, poor performance of alarm systems can result in financial losses, environmental consequences and hazards to people.

The human operator is still the last line of defence in many industries and the process relies on efficient operation by the operators. Since the safety and availability of a plant still relies on human operator performance (4), it is important to consider the operator's working situation when alarm systems are developed. Otherwise, the safety and efficiency of a plant may be jeopardized (2).

Over the years, many accidents have occurred in which the alarm system has been a contributing factor to the severity of the accidents, e.g., Three Mile Island, Union Carbide in Bhopal, and Texaco Refinery in Milford Haven (20). Since the demands on the operators are increasing (e.g., due to process operation close to maximum efficiency, lower safety margins, higher costs for process interruptions, more complex processes, and fewer operators) the potential for problems are not decreasing but increasing. This emphasises the importance of considering the operator's role when designing alarm systems.

Over the years, the knowledge about the importance of considering human factors has increased. Today, it is widely acknowledged that an operator-centred approach is desirable from the beginning of a design project. However, Nachreiner et al. (14) argue that human factors knowledge still does not play the important role it deserves. Improvements in alarm management work have commenced, but there is still much to better (20).

Control and alarm systems in nuclear power plants are updated and modernised regularly. However, much of the research performed within the area of alarm systems focuses on how new such systems should be designed. Few studies have been made on how control and alarm systems should be modernised in an existing control room to be compatible with the operators' experience and/or the other equipment already installed.

When upgrading control and alarm systems and adding features in hybrid control rooms a number of questions arise:

- How is the operator affected by the introduction of new technology?
- What design guidelines are important to consider?
- Are deviations from existing guidance justified? and if so, What are the deviations?
- What specific conditions does one need to consider in modernisation projects?

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- Which new ideas are applicable to use in modernisation projects as well?

This paper addresses the specific conditions of modernisation projects and tries to give guidance for how human factors aspects can be integrated in such projects.

II. OBJECTIVES

The purpose of the paper is to facilitate for control room designers to take the operator's perspective into account in modernisation projects and thereby to improve safety and efficiency.

The aim is to identify characteristics of good and well-designed alarms and alarm systems in upgraded Swedish nuclear power plants, and hence identify principal design guidelines to consider in modernisation projects.

III. METHOD

This paper is the outcome of an integration of theory about alarm systems and alarm system design guidelines, and evaluations of the guidelines with consideration to the results from seven theoretical and empirical studies (1, 11, 12, 19, 23-26).

Alarm guidelines from NUREG-0700 (17) and IEC-62241 (7) together with recommendations and lessons learned about alarm system from the Institute for Energy Technology in Halden, Norway (22) have been compiled and evaluated based on the results from the research studies.

All the alarm design guidelines in NUREG-0700 Chapter 4 (17), IEC-62241 (7) and Sørenssen et al. (22) have been compiled and grouped. Duplicates have been removed and the remaining recommendations have been evaluated by two researchers independently. Finally, the results have been compared to undertake the final evaluations.

In the evaluations, the researchers have grouped the guidelines into three main groups:

- General guidance that should be used as a design basis in all control room design projects.
- Guidelines to consider in modernisation projects, ranked into three categories.
- Guidance less applicable to modernisation projects.

IV. ALARM AND ALARM SYSTEMS

Alarms and alarm systems are needed in the management of large industrial processes. The operators cannot be observant all the time, they are not omniscient and they make mistakes. An alarm system should help the operator to diagnose faults and correct them.

An alarm is a signal indicating an abnormal or deviating condition, or a combination of conditions that require the operator's attention (5). Further, the alarm should require a physical or cognitive response (16, 21, 22).

The aim of an alarm system is to:

- Alert the operators about a deviation,
- Inform the operator about the nature of the deviation
- Guide the operator's initial response, and
- Confirm, in a timely manner, if the operator's response corrected the deviation.
- Four recurrent core principles in almost all alarm theory and alarm guidance are:
- Alarm systems should be designed to meet the operators' needs and operate within their cognitive and physical capabilities.
- The purpose of the alarm system and its contribution to protection should be clearly identified.
- The performance of the alarm system should be assessed during design and commissioning.
- The design of alarm systems should follow a structured methodology.

Further, an alarm system should be usable and effective under all operating modes and working situations. To be able to develop a usable alarm system, the alarms need to be justified. This implies that the role of the operator needs to be identified, including the changes of the role in different operating conditions. For a usable alarm system, the following characteristics of the output information need to be met:

- It is relevant to the operator's role at the time.
- It informs about the system state and the cause of the alarm.
- It indicates clearly what response is required.
- It is timely and is presented at a rate the operator can handle.
- It is easy to detect and understand. (5, 13, 22)

Several studies have been performed to set guidelines for an ideal alarm system. For example, EEMUA (5) has presented a number of important characteristics for an individual alarm.

- Timely – presented at the right time.
- Relevant – for the operators, not a false alarm.
- Unique – not a duplicate of another alarm.
- Prioritised – helps the operators to focus their attention.
- Understandable – speaks the operator's language.
- Diagnostic and advisory – indicates what has happened, what actions are needed.
- Manageable – not too many alarms.

These recommendations are important to consider in the design of an alarm system. However, general recommendations do not provide the alarm system designers with concrete help. Instead, the basic theory should be considered as a foundation and/or vision for the designers. Design guidelines provide better, clearer and more detailed support in the design projects.

V. ALARM SYSTEM GUIDELINES

Several guidelines both for the design process and the presentation and functionality of alarm systems are provided by international organisations. Well-known and often used guidelines for ergonomic design of control centres, human-system interfaces and alarm systems are e.g., IEC-62241 (7), ISO-11064 (8), NUREG-0700 (17), and NUREG-0711 (18). In addition, Sørenssen et al. (22) have compiled many years of experience and lessons learned about alarm system design and implementation at the Institute for Energy Technology in Halden, Norway.

The need to consider existing guidelines and to increase the importance of human factors and ergonomic aspects in the design of alarm systems has improved over the years. To facilitate for designers to integrate human factors aspects and ergonomic guidelines, the recommendations need to be adapted for each project individually. Many guidelines are general and hence are difficult to implement in development projects.

The existing alarm design guidelines can be divided into two main categories; guidelines for the design process, and guidelines for the presentation and functionality of the alarm system. This paper focuses on the specific requirements for the presentation, layout and functionality of alarm systems in hybrid control rooms. The delimitation does not indicate that the design process is of less importance. Instead, an ergonomic and operator-centred design process is a necessity if human factors aspects should be integrated in the alarm system design. Interviews with control room designers have showed that the guidance given on the design process is satisfactory (see e.g., NUREG-0711 (18) and ISO-11064: part 1-7 (8)). Instead there is a need to group and prioritise among the large amount of guidelines regarding alarm system presentation and functionality.

The alarm system guidelines used in the study are:

- NUREG-0700, Chapter 4 Human-System Interface Design Review Guidelines (17)
- IEC-62241 Nuclear power plants – Main control room – Alarm functions and presentation (7)
- Recommendations to alarm systems and lessons learned on alarm system implementation, Institute for Energy Technology. (22)

These guidelines are well-known and established and are used in control room modernisation projects within the Swedish nuclear industry.

The alarm design guidelines cover everything from general design aspects e.g., “base the design of the alarm system on an alarm philosophy”, to specific and detailed information about e.g., alarm tile flash rates, frequency of tonal signals and brightness levels of displays.

NUREG-0700 (17) is used for inspections of alarm systems, which is reflected in the level of detail of the guidelines. The guidelines in IEC-62241 (7) also give quite detailed information about the design. Specific and detailed guidelines can be difficult to use in early development stages. However, both documents include general sections with basic functional requirements or high-level functions.

The guidance given by the Institute for Energy Technology is based on experience of many years of alarm system research. The guidelines indicate functions for well-designed alarm systems rather than give detailed information about the layout and functionality. This makes the guidelines easier to use proactively. One main drawback is that the guidance tends to be quite general and difficult to apply.

In total, the number of alarm guidelines presented in the three documents is around 450. The number of guidelines and lack of prioritisation among them make them difficult for the designer to use. The focus of the alarm system design project might be lost in design details or the designer might get stuck on less relevant guidance.

Alarm system research has often taken its starting point from existing alarm problems with the aim of reducing the problem. However, identifying alarm system problems and resolving them is not the most efficient method of developing these system.. Prevention of alarms is better than cure (6).The motivation for this research project facilitate for the designer when integrating human factors aspects and the operator’s perspective into the design of alarm systems.

VI. PRECEDING STUDIES

Seven theoretical and empirical studies (1, 11, 12, 19, 23-26) have been performed within a research project with the aim to improve alarm system designs in Swedish nuclear power plants. The studies have been performed in Swedish nuclear control rooms and full-scope simulators. The units included in the studies have had different degrees of modernisation. Many of the control rooms have second generation technology as a basis but different modernisation projects have resulted in hybrid control rooms at all units.

The empirical studies have consisted of interviews of operators at site, observations of normal operation in control rooms and of disturbance management in simulators, different task analyses, risk assessments and workload assessments. The aims of the studies have been to investigate existing alarm systems, understand how operators manage disturbances and control the plant, identify expertise and to investigate how team members collaborate.

The results from the studies show that the alarm system is mainly used in normal operation and in minor disturbances. In these situations, the operators want all alarm information in order to optimise the process or handle the deviation such that the process is brought back to normal operation. On the other hand, during deviations, the operators follow handling procedures to keep the plant safe. The alarm system is used in a very limited fashion due to the huge amount of alarms presented. One way to reduce the number of alarms could be to evaluate if every alarm requires a response. A common problem in many alarm systems is the issue of alarm flooding in disturbances with many alarms of none or low value to the operator.

The difference between normal operation and disturbance management indicate that the operator has different roles and aims in different operational modes. For example, in steady-state operation the operators try to optimise the process and during large disturbances the operator wants to ensure safe shut-down. Consequently, the role of the operator is very important for the operator's behaviour and the processing of information. To meet the operator's varying needs, future alarm system should be adaptive.

Furthermore, the operators manage the process by being aware and pro-active. They actively monitor key parameters to be able to detect deviations early. To facilitate for the operators to evaluate parameter values, the value should be presented together with the setpoints and/or alarm limits.

The experience of an operator does not affect the decision making process to a large extent, but instead it affects which information the operator perceives. Experienced operators are more likely to use multiple information sources to verify information and an experienced operator also has a good ability to foresee possible outcomes of different situations. Therefore, the experienced operator has advantages in assessing situations correctly. On the other hand, if the less experienced operator is supported in the perception of information, he/she is very likely to reach the same decision. This is due to the fact that decision making in many situations is supported by checklists and procedures. This indicates that a main task for the alarm system is to reduce distracting stimuli and to guide the operator towards the important information. For example, use checklists in deviations, implement alarm prioritisation and implement alarm suppression techniques.

Furthermore, the results show that workload regulation is very important to maintain high overall performance. The operators regulate their workload by prioritising tasks according to available time and resources. They use external cues to decrease the workload. The supervisor has an important role in maintaining a manageable workload level for all operators. For future alarm systems, it is important to implement support functions for the operator to create and use external cues e.g., possibility to define personalised alarms and write comments in connection to objects and/or alarms. Furthermore, external cues can reduce the need for the operator to recall information when moving from one operation to another in a task sequence.

The level of expertise affects the information processing and the experienced workload. The expert operators were able to group information, evaluate values immediately, and could more easily plan their work and foresee possible outcomes of their actions than the novices could.

Furthermore, the operators need continuous information and feedback of the system's status. The operators need feedback regarding the results of their corrective measures and they should be informed when severe incidents occur. For example, it is important that safety-critical alarms are spatially dedicated and continuously visible. Given this, the operator can detect variations in the system's status fast.

One of the largest benefits with computer based technology, according to the operators, was the higher degree of integration. For example, instructions integrated in the interface were experienced as a support.

One important aspect to consider is that the work performed in a nuclear power control room is not the result of the performance of an individual operator, but a result of the operators working together. A central issue for the alarm system is therefore to facilitate for the natural collaboration in the control room. For example, a main shared overview display should be provided in the control room to support the operators to have a shared understanding of the situation.

VII. ANALYSIS

Many guidelines are applicable both for new systems and for re-designed systems. However, the same guideline can have different priority depending on the type of design project. The aim with this analysis was to prioritise among existing design guidelines to facilitate for designers in modernisation projects.

A. General guidance

Initially, the aim of the evaluation of existing guidance was to rank the importance of each guideline. However, it was quickly discovered that many guidelines should not be addressed during the design project, but should be defined before or at a starting point.

Hence, a category with important but not project specific guidelines was defined. The category includes guidelines that are of a general nature and should found the basis of the design projects. Examples of guidelines included in this category are:

- The design should be based on an alarm philosophy.
- Alarms should be prioritised.
- Alarm set points should be determined to ensure that the operating crew can monitor and take appropriate action for each category of alarms.
- The alarm system should be adaptable to different operational modes and the operator's varying role.
- Alarms which refer the user to another, more detailed display located outside the main operating area should be minimized.
- Definitions of alarms and objective criteria for the division of alarms into several levels of priority.
- Design the alarm system in connection to the overall control system.

Instead, these guidelines could be used to formulate an alarm philosophy. The guidelines consist of design basis requirements and should be a common basis for different modernisation projects to ensure compatibility and consistency between the systems introduced in different modernisation projects.

To use an alarm philosophy and to communicate that philosophy to the operators is very important in modernisation projects. The studies in nuclear control rooms showed that the operators occasionally did not understand the motivations behind certain design solutions. Hence, the operators did not utilise the full potential of the new systems. If the design aim and strategy is clear, the operators are more likely to relate individual projects to an overall vision of the control room. Consequently, they are more likely to understand the purpose of the new system and their disturbance management can improve since no doubts exist about e.g., alarm priorities.

The main problem with many alarm systems is a huge amount of alarms in disturbances (3, 22). With computer based technology, the number of alarms usually increases dramatically. This implies that one of the alarm system designer's main tasks is to evaluate each and every alarm in order to only implement relevant alarms. In order to develop a usable alarm system, each alarm needs to be justified (5). One question to consider is if the alarm requires a response. If the signal does not require a response, then it should not be categorised as an alarm. Furthermore, objective measures for alarm prioritisation categories should be documented.

A trend in the development of control and alarm systems is that the two systems are becoming more closely integrated. A closer integration better matches the way operators want to work. Instead of reacting to alarms, the operators try to be aware and to discover potential alarms and deviations before they occur. This emphasises the importance of designing the alarm system together with the control system. In addition, it is important to integrate setpoints and alarm limits so the operators easily discover deviations before the alarm is set off (1).

One of the challenges when developing new or modernised alarm systems is the need to make the systems more adaptable. Today, alarm systems are not flexible enough to cope with different operating modes (4). Since the role of the operator varies depending on the operating mode, an adaptable alarm system is necessary if the system is to support the operator.

B. *Guidelines for modernisation projects*

Detailed guidelines can be very helpful for designers in modernisation projects. However, one of the core or top-ten human factors principles is the principle about consistency (10, 15). Operators working with inconsistent systems are more prone to make mistakes, they feel less secure, and human errors are more common than with consistent systems. Therefore, this basic principle can override many detailed ergonomic guidelines. A number of guidelines were therefore considered as less important to follow in modernisation projects, e.g.:

- Flash rates should be from three to five flashes per second with approximately equal on and off times.
- An auditory signal should be used to alert the user to the existence of a new alarm, or any other condition of which the user must be made immediately aware.
- Manual disable or adjustment of auditory signal intensity (loudness) should be avoided.
- Centre frequencies should be widely spaced within a range of from 500 to 3,000 Hz.
- No more than three pulse repetition rates should be used for coding purposes.
- An alarm tile display matrix should contain a maximum of 50 alarms.

Instead it is recommended that the new design follows the layout and presentation of the old system. Important design features to follow are existing coding techniques, phrasing, abbreviations, colours, audible and visual cues, signs and symbols. To investigate the existing alarm systems and how operators work, situational analyses are necessary. Further, another aim of the situational analyses is to analyse the operators' previous experience and knowledge. The new design should consider the operators' experience and should also agree with exiting essential work procedures e.g., in disturbance management.

It is also important that the alarm system is not consistent only in itself, but that the requirement for consistency also applies to the overall control system, since the control and the alarm system are more closely integrated in new systems.

The remaining guidelines were divided into five groups:

- Operation
- Presentation
- Navigation
- Signal processing
- Instructions and training

The level of detail still varies between the guidelines and therefore another sub-division has been made. The level of detail is considered as a representation of when the guideline is applicable. General guidelines are more useful early in the design stages, whereas detailed design guidelines are used in the late stages. Influenced by the design of the evaluation checklists in CRIOP (crisis intervention and operability analysis) (9) the design guidelines have been grouped, presented in tables and marked to indicate when the guideline is applicable. Grey shading indicates a guideline which should be consulted early in the design process. A white box indicates that the guideline is applicable in the detailed design stages. See Tables 1 and 2 for examples.

TABLE I. EXAMPLES OF GUIDELINES IN THE CATEGORY "ALARM PRESENTATION".

No.	Guideline
2-2	The alarm presentations shall be controlled with functions designed to ensure that the operators have noticed each alarm.
2-2.1	The following alarm control functions should be provided: - Silence; - Acknowledge; - Ringback; - Reset; - Reflash.
2-3	Provide a common spatially dedicated continuously visible alarm display for safety critical alarms.
2-3.1	The alarm display for safety critical alarms should be visible from all operator work stations.
2-5	Alarms should be integrated in VDU process displays

TABLE II. EXAMPLES OF GUIDELINES IN THE CATEGORY "SIGNAL PROCESSING".

No.	Guideline
4-1	The alarm system should be context sensitive
4-2	Alarms should be defined in (three) priority levels
4-2.1	The priority of the alarm should be assessed primarily based on potential consequences and secondly on the time available to correct the alarm.
4-3	Include suppression techniques
4-3.2	The number of consequence alarms should be reduced by suppression.

VIII. DISCUSSION

The evaluation and division of existing guidelines on alarm presentation and alarm system functions provide a first step towards a more user-friendly support for the designers of control and alarm systems. Modernisation projects of nuclear control rooms tend to be large complex projects where many design recommendations and requirements need to be considered and met. Therefore, it is important to have a clear set of priorities from the beginning of the project.

The division of guidelines performed in this study are only based on theoretical evaluations by researchers. The results need validation. The plan for the future work to validate the design guidelines consists of two parts:

- Firstly, the design guidelines should be used in a research project with the aim to develop an improved version of an alarm system for the condensate and feed water systems of a boiling water reactor in Sweden.
- Secondly, control room designers from the different nuclear power plants should evaluate the guidelines according to their experience.

The evaluation has been performed to match the conditions of Swedish nuclear power plants. This implies modernisation and upgrades of legacy systems in existing control rooms. Other plants facing the same conditions could benefit from the results of this study. For other plants, with other conditions, other guidelines or a different classification and division might be more applicable and appropriate.

IX. CONCLUSIONS

Many alarm design guidelines are applicable both for new control and alarm systems and for modernisation projects.

General design guidelines should be used as a basis independently of the design project. The general design guidelines should be documented in an alarm philosophy applicable to all projects.

Modernisation projects set specific requirements in order to develop user-friendly, safe and efficient alarm systems. For example, it is important to consider the operators' previous experience and knowledge in order to maintain work procedures in disturbance situations.

The need to be consistent in the design is a fundamental human factors requirement. This requirement can e.g., override detailed guidance on audible and visual signalling. Consistency is very important in modernisation projects since the new system together with the existing technology in the control room should be experienced as one system.

Not only should the design of the control room and the human-system interfaces be considered, but also the development of instructions and training to ensure efficient operation and consistency.

ACKNOWLEDGMENTS

Financial support was given by the Swedish nuclear power inspectorate and the Swedish nuclear power plants; Forsmark, Oskarshamn and Ringhals. Furthermore, the work could not have been accomplished without the support and participation from designers and operators at the Swedish nuclear power plants.

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