ADVANCED ALARM SYSTEM DESIGN AND HUMAN PERFORMANCE: GUIDANCE DEVELOPMENT AND CURRENT RESEARCH

John M. O'Hara
Brookhaven National Laboratory
Upton, New York

ABSTRACT

This paper describes a research program sponsored by the U.S. Nuclear Regulatory Commission to address the human factors engineering (HFE) aspects of nuclear power plant alarm systems. The overall objective of the program is to develop HFE review guidance for advanced alarm systems. Guidance has been developed based on a broad base of technical and research literature. As part of the development effort, aspects of alarm system design for which the technical basis was insufficient to support guidance development were identified and prioritized. Research is currently underway to address the highest priority topics: alarm processing and display characteristics.

1. INTRODUCTION

The need to improve the human factors engineering (HFE) of alarm systems has led to the development of advanced systems in which alarm data are processed beyond the traditional "one sensor - one alarm" framework. While this technology promises to provide a means of correcting many known alarm system deficiencies, there is also the potential to negatively impact operator performance [1]. In addition, there is general agreement that an "international lack of guidance and requirements for alarm systems exists" and new guidance for the review of advanced alarm system designs is needed [2].

This paper describes a research program sponsored by the U.S. Nuclear Regulatory Commission (NRC) to address the HFE aspects of nuclear power plant alarm systems. The objective of the study is develop HFE review guidance for advanced, computer-based alarm systems. As part of the development effort, aspects of alarm design for which the technical basis was insufficient to support guidance development were identified and research to address the most significant issues was initiated. The paper will report on the status of these guidance development and research efforts.

2. DEVELOPMENT OF ALARM SYSTEM REVIEW GUIDANCE

The basic guidance development methodology is illustrated in Figure 1. The methodology places a high priority on establishing the validity of the guidelines in a cost-effective manner. Validity is defined along two dimensions. "Internal" validity is the degree to which the individual guidelines are based upon an auditable research trail. "External" validity is the degree to which the guidelines are subjected to independent peer review. The peer review process is considered a good method of screening guidelines for conformance to accepted human engineering practices. These forms of validity can be inherited from the source documents that form the technical basis for new guidance development or they can be established as part of the guidance development process itself. Primary source documents (see Figure 1) are those that already possess internal and external validity. However, existing primary source documents alone do not provide a sufficient basis on which to develop comprehensive advanced alarm system guidance, thus additional sources of information are necessary. For these sources, guidance validation has to be established.

Guidance development proceeds as shown in Figure 1. Primary source documents are considered first. Secondary source documents are those with either internal or external validity. While tertiary documents, such as HFE handbooks, provide good information for specific topics, they often do not possess internal or external validity. Guidelines are developed from tertiary documents with relatively little effort in comparison to the final three sources shown in Figure 1.

Basic literature and industry experience are used where guidelines cannot be obtained from the other sources. Results are evaluated from basic literature including articles from refereed technical journals, reports from research organizations, and papers from technical conferences. Industry experience is obtained from published surveys. It is a valuable information source for identifying performance issues and tested design solutions. Although information from industry experience may lack a rigorous experimental basis it does have the benefit of high relevance to the practical application of alarm systems within the nuclear setting.

In addition to alarm literature, guidance is also developed based upon the application of the high-level design review principles [3] to alarm system characteristics. These principles were developed based upon an assessment of the human-performance issues associated with advanced technology systems and on human-system interface (HSI) design and evaluation literature.

Using this guidance development method, draft alarm review guidance was developed based on all sources in the hierarchy of information listed in Figure 1 except the last category (original research). Original research is appropriate when the technical bases does not exist in the available literature or practice, or when additional experimentation is needed to provide supporting evidence. It has the advantage of being focused on specific issues of interest. Because these needs existed with regard to the introduction of advanced alarm systems in nuclear power plants, a program of original research was also deemed necessary. Such a program is currently underway and the guidance will be expanded when the results become available (See Section 3 below).

Each guideline contains the specific acceptance criteria to be used by the NRC reviewer and the source(s) of information upon which the guideline was established. The latter provides a basis for evaluating the internal validity of the individual guidelines. The technical bases vary for each guideline. Some guidelines are based on technical conclusions from a preponderance of empirical evidence, some on a consensus of existing standards and others on judgement that a guideline represents good practices based upon the information reviewed.

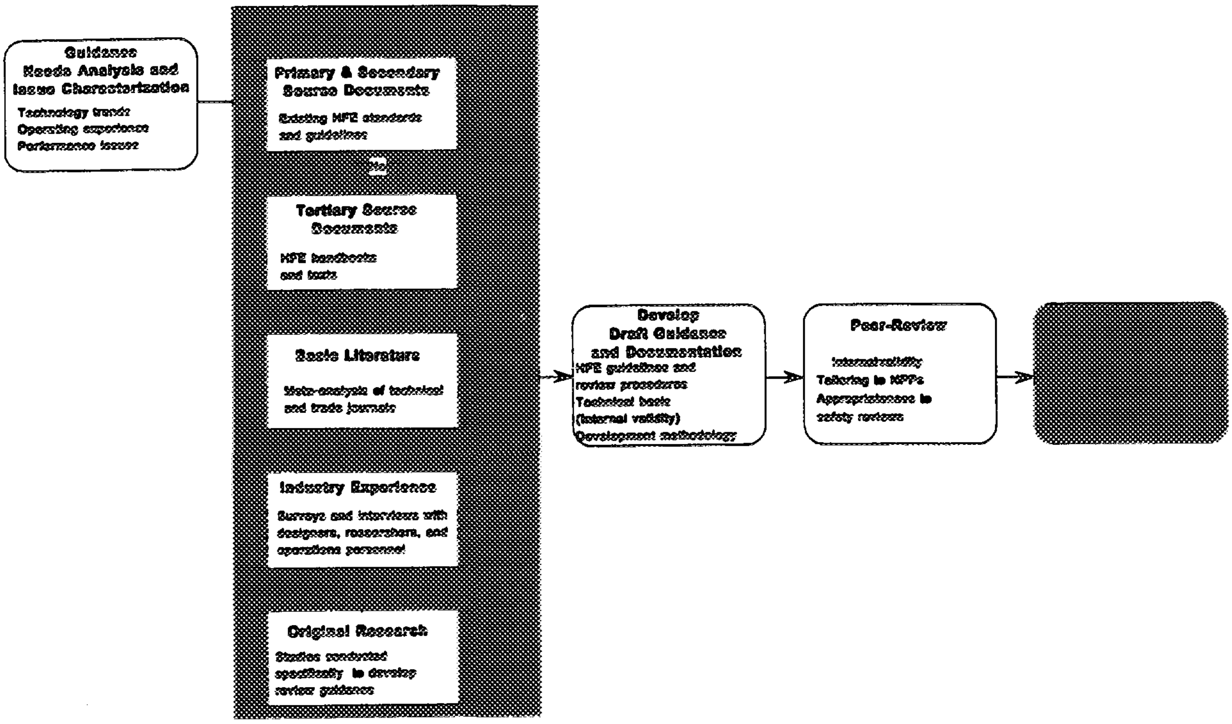

Figure 1. Guidance Development Methodology

The draft guidelines were then evaluated by several independent peer-reviewers who assessed: (1) the internal validity of the guidance, (2) the relevance of the guideline to the nuclear plant setting, and (3) the appropriateness of the guideline for NRC safety reviews. This peer review constitutes the external validation of the guidelines. A revision to the draft guidance based on the reviews was accomplished. The detailed guidance development methodology and technical basis is documented in NUREG/CR-6105 [3] and the guidance itself is integrated into NUREG-0700, Revision 1 [4].

2.1 Guideline Contents

The scope of the guidance includes both conventional and advanced alarm systems. The review guidelines are organized into the following ten sections:

General Guidelines - This section addresses the functional criteria for the alarm system and the general principles to which it should conform, such as consistency with the main control room HSI. Alarm system validation is also addressed.

Alarm Definition - This section addresses the selection of plant parameters and their setpoints.

Alarm Processing and Reduction - This section addresses the review of alarm processing, from simple processes such as signal validation to more complex alarm reduction processing strategies.

Alarm Prioritization and Availability - This section addresses alarm prioritization criteria and implementation, and alarm availability, i.e., the method by which the results of alarm processing are made available to the operating crew through filtering, suppression, and/or coded prioritization.

Display - This section addresses general alarm display guidelines, display of importance/urgency, display of alarm status, display of shared alarms, alarm message content and format, coding methods, and alarm organization.

Control - This section addresses controls including silence, acknowledge, and reset.

Automated, Dynamic, and Modifiable Characteristics - This section addresses the implementation of operator defined alarms and setpoints as well as other alarm features that may be modified.

Reliability, Test, Maintenance, and Failure Indication - This section addresses alarm system reliability to assure that (a) the alarm system provides alarm information to the operators in a reliable manner, (b) the crew can periodically test alarm functions and components, (c) the alarm system can be maintained with minimum interference to the operators' ability to receive and understand alarm messages, and (d) the system provides indication of alarm system failures.

Alarm Response Procedures - This section addresses the scope, content, and format of alarm response procedures (ARPs). In addition, operator access to ARPs is addressed.

Control-Display Integration and Layout - This section addresses the layout of control and display components, and their integration with other aspects of the HSI.

Individual guidelines are presented in a standardized format (see Figure 2). For many guidelines additional information (e.g., examples and clarifications) is provided to support use and interpretation of the review criterion. The additional information field may also contain a "discussion" regarding the technical basis and/or relevant research contributing to the guideline development. In such cases specific studies are cited that provide the supporting research. The discussions were removed from the additional information field when the alarm guidelines were incorporated into NUREG-0700, Revision 1.[4] Thus, when the guideline in Figure 2 was incorporated into NUREG-0700, the discussion section was deleted. It is available, however, in NUREG/CR-6105, which documents the technical basis to the alarm guidelines.

3. CURRENT RESEARCH

During guidance development, several human performance issues associated with advanced alarm systems were identified. They were organized into four topical areas: general issues, processing methods and related issues, display of alarm data, and alarm system controls. The issues were prioritized to determine which were most significant, using two dimensions: potential impact on operator performance and need for issue resolution to support near-term

NRC reviews. Estimates of each issue's impact on crew performance were obtained from the ratings of nine subject matter experts (SMEs) in nuclear plant systems, operations, and HFE. The SMEs rated (on three-point scales) the importance of the issues in terms of plant safety, human error, situation awareness, and operator workload. An evaluation of expected review needs was conducted to determine the near-term likelihood that the NRC staff would perform a review of an alarm system design incorporating features addressed by the issues. Based upon this analysis, those issues associated with alarm processing and display were given the highest priority. These issues are discussed in Section 3.1 below and the experiments currently underway to address them are discussed in Section 3.2.

4.2-3 Nuisance Alarm Avoidance

The determination of alarm setpoints should consider the trade-off between the timely alerting of an operator to off-normal conditions and the creation of nuisance alarms caused by establishing setpoints so close to the "normal" operating values that occasional excursions of no real consequence are to be expected..

ADDITIONAL INFORMATION: When determining setpoints, consideration should be given to the performance of the overall human-machine system (i.e., operator and alarm system acting together to detect process disturbances).

Discussion: Process control operators are in a monitoring environment that has been described in signal detection terms as an "alerted-monitor system" (Sorkin et al., 1985 and 1988). This is a two-stage monitoring system with an automated monitor and a human monitor. The automated monitor in a NPP is the alarm system which monitors the system to detect off-normal conditions. When a plant parameter exceeds the alarm criterion, the human monitor is alerted and must then detect, analyze, and interpret the signal as a false alarm or a true indication of a plant disturbance. Both the human and automated monitors have their own specific signal detection parameter values for sensitivity and response criterion. For the human monitor, both parameters are strongly affected by alarm system characteristics including set points, the presence of nuisance and false alarms, and alarm density. A significant issue associated with alerted-monitor systems is that optimal overall performance of the alerted-monitor system is a function of the interaction of both components. Optimizing the signal detection parameters for one component of the system may not optimize performance of the entire two-stage system. An alarm setpoint philosophy frequently employed is to attempt to optimize the detection of signals by the automated monitor subsystem. The response criterion is set to minimize missed signals. This, however, increases the false alarm rate, thus increasing the noise and lowering the operators' confidence in the alarm system. In addition, this guideline is consistent with the high-level design review principles of Cognitive Compatibility and Timeliness (see Appendix A).

SOURCE: NUREG-6105, NUREG-0700.

Figure 2. Example of an Alarm Guideline

3.1 Processing and Display Issues

3.1.1 Alarm Processing

3.1.1.1 Alarm Processing Characteristics

One of the most important objectives in the design of advanced alarm systems is to reduce the large number of alarms that typically occur during plant disturbances. Alarm processing is intended to accomplish this objective. The issues related to alarm processing fall into two general topics: alarm processing techniques and alarm availability.

Alarm signal and condition processing techniques were developed to support operators by reducing the number of alarms which may be encountered at one time, identifying which alarms are significant, and reducing the crew's need to infer plant conditions. Alarm signal processing refers to the method by which signals from plant sensors are automatically evaluated to determine whether any of monitored plant parameters have exceeded their setpoints and to determine whether any of these deviations represent true alarm conditions. Alarm signal processing includes techniques for analyzing normal signal drift and signal validation. Techniques for analyzing normal signal drift and noise signals are used to eliminate alarms that would occur because parameters momentarily exceed the setpoint limits. Signal validation is a group of techniques that compare signals from redundant or functionally related sensors to identify and eliminate false signals that may result from malfunctioning plant instrumentation such as a failed sensor. Alarm conditions that are not eliminated by the alarm signal processing may be evaluated further by alarm condition processing before they result in the presentation of alarm messages to the operator.

Alarm condition processing refers to the rules or algorithms that are used to determine the operational importance and relevance of alarm conditions. A wide variety of condition processing techniques have been developed and each affects the information provided to operators. For the purposes of this discussion, four classes of techniques are defined:

Nuisance Alarm Processing - These techniques essentially eliminate alarms that are irrelevant to the current mode of the plant. For example, a low temperature signal that is an alarm for a normal operating mode is irrelevant when it occurs during startup.

Redundant Alarm Processing - These techniques analyze alarms to determine which are less importance because they provide information that is redundant with other alarms. For example, in causal relationship processing only causes are alarmed and consequences are considered redundant. In addition to reducing the actual number of alarms, however, these processing methods may adversely affect the information used by the operator for confirmation that the situation represented by the "true" alarm has occurred, for situation assessment, and for decision-making.

Significance Processing - These techniques analyze alarms to determine which are less important in comparison to other alarms, e.g., in an anticipated transient without scram event, alarms associated with minor disturbances on the secondary side may be less significant.

Alarm Generation Processing - These techniques analyze existing alarms and generate new alarms that (1) provide higher-level information, (2) indicate when "unexpected" alarms occur, and (3) indicate when "expected" alarms do not occur. These techniques present an interesting paradox. Generation features may help mitigate problems that reflect the overloaded operator's incomplete processing of information by directing their attention to conditions that are likely to be missed. However, since additional alarms are created, the issue of alarm overload may be exacerbated.

The impact of the various processing methods and the degree of alarm reduction should be evaluated for their relative effects on operator performance. An understanding of this relationship is essential to the development of alarm system improvements and review guidance. System complexity should also be considered. The operator, as the system supervisor, should easily comprehend alarm information, how it was processed, and the bounds and limitations of the system. An alarm system combining multiple processing methods may be so complex that it cannot be readily interpreted by operators in time-critical situations.

Alarm availability refers to the method by which the results of alarm processing are made available to the operating crew (rather than *how* they are presented, which is alarm display). Three techniques have been used: *filtering* (alarms determined by processing techniques to be less important, irrelevant, or otherwise unnecessary are eliminated and are not available to the operators); *suppression* (alarms determined by processing techniques to be less important, irrelevant, or otherwise unnecessary are suppressed and not presented to the operators, but can be accessed by operators upon request or by the alarm system based upon changing plant conditions); and *prioritization* (all alarms are presented to operators based on prioritization schemes).[1]

There are tradeoffs between these approaches; thus an issue remains about when the various options should be employed. Filtering reduces the possibility that unimportant alarms will distract operators; however, it may remove information used for other purposes. In addition, the designer must be certain that the processing method is adequately validated and will function appropriately in all plant conditions. Suppression also removes potentially distracting alarms; however, since they are accessible on auxiliary displays, additional workload may be imposed by requiring operator action to retrieve them. Prioritization does not conceal any information from operators. However, the operator must perceptually "filter" alarms, e.g., scan for red alarms, and thus, a potential exists for distraction from less important alarms.

3.1.1.2 Related Research

Several studies examined the effects of alarm processing techniques on operator performance.

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[1] Note that the definitions of "filtering" and "suppression" are the author's; the terms are often used interchangeably in the literature.

The HALO (Handling Alarms with Logic) alarm system was developed by the Halden Reactor Project. In an initial study, inexperienced students were trained with the system and were asked to identify disturbances in a simulated pressurized water reactor [5]. Alarm information was presented as (1) unfiltered message lists, (2) filtered message lists, or (3) filtered message lists with an overview display. Alarm information was presented in static displays rather than dynamic simulation. Diagnosis time and accuracy were the primary dependent variables. The results indicated that accuracy was improved with filtering, but the benefit was transient specific. No significant difference was found for response times. Also no differences were observed between the filtered message list used alone and the filtered list used with the overview display.

Comparisons of performance using alarm systems with and without filtering during simulated transients were also made in subsequent studies [6-8]. The filtering system reduced the alarms by approximately 50 percent and the filtered alarms were not available to the operator. The performance measures included detection time/percentage and diagnosis time/percentage correct. Process variables and subjective evaluations were also measured. Seven two-operator crews used the three systems (listed above) in 12 simulated scenarios. Alarm filtering had little effect on performance. It was observed that the detection of events decreased from 81 percent to 51 percent when the event occurred late in a scenario rather than early in a scenario. None of the systems tested helped to mitigate the problem. One problem with interpreting the results of this study is that the display type and use of alarm filtering were experimentally confounded. Thus, no conclusions with respect to the *independent* effects of display mode or filtering can be made.

In another study using a verbal protocol analysis taken in real time from three operators during simulated malfunctions, no evidence was found that an alarm filtering system had a positive effect on their performance, although the operators expressed support for it.

In a test of the Dynamic Priorities Alarm System (DPAS), the number of high-priority alarms was reduced through mode, multi-setpoint, and cause-consequence processing [10-11]. Alarms were displayed on a combination of tiles and video display units (VDUs). Color was used to distinguish status and alarm information. Performance with and without the new system was compared. Nine crews of three experienced operators used the systems during simulated scenarios involving single and multiple failure events. Operator performance measures included time to identify initiating event, time to identify second malfunction, time to take control action, and alarm utilization frequency. No difference between the systems was found for initiating event identification; however, detection time for second malfunctions was significantly reduced in three of the four scenarios when the alarm handling system was available. DPAS significantly reduced the time required to take a control action in two of the four test scenarios. The finding that second malfunction detection time was reduced with the alarm system is not consistent with the findings from the HALO study reported earlier where secondary event detection was not enhanced.

The Electric Power Research Institute (EPRI) compared tile and VDU-based alarm presentations [12]. In one VDU condition the typical alarms associated with reactor and turbine trip were suppressed. The alarm suppression reduced by 50 percent the number of "maverick" alarms (those not typically occurring during a plant trip) operators missed. Operators expressed concern about suppression of alarms because their timing helps them understand the event.

With respect to filtering, several studies have found that operators use the alarm system to obtain status information and that under some conditions, they prefer to have status alarm information presented to them rather than to have status information eliminated [13-16]. The issue of whether to include status indications in an alarm system is related to the criteria for alarm selection and the capabilities provided by other HSIs for displaying status indications.

3.1.1 Summary

Two studies failed to find an effect of alarm processing [7,9]. One study found no effect for the detection of initial disturbances, but improved detection performance during a secondary malfunction [11]. Another study found a positive effect on detection of unusual alarms, and questioned the trade-offs between information loss and situation assessment [12]. These differences could be due to many factors such as type of processing used, degree of filtering achieved, method of data display, and user familiarization with the system. The effects could also be transient dependent, e.g., dependent on the specific scenario, on the operator's ability to recognize familiar patterns, or on plant type. While the focus of most research has been on alarm reduction, alarm generation effects on performance have not been completely addressed. Also, individual alarm processing methods have not been compared to determine which methods best support operator performance.

A key issue is the type and degree of processing. While it is clear that processing techniques can reduce the number of alarms [17-18], their impact on operator performance is the most important effect of interest. An industry survey found that a typical filtering objective was to reduce the number of alarms by 50 percent [18]. However, that amount of filtering may not significantly improve operator performance [6-7]. In terms of operator information processing, it is probably inappropriate to specify alarm reduction in terms of numbers of alarms (a metric often used to assess alarm reduction schemes). Operator information processing demands are not necessarily a function of the absolute number of alarms, but rather their rate, their recognizability as familiar patterns, their predictability, and the complexity of the ongoing task. A goal for improved operator performance needs to be established. With respect to availability, the conditions under which alarms should be filtered, suppressed, or prioritized needs to be determined.

3.1.2 Alarm Display

3.1.2.1 Alarm Display Characteristics

The alarm systems in traditional U.S. nuclear power plants tend to be stand alone systems; that is, the alarm information is not integrated with other plant information. Operators consult other plant indicators for specific information. General trends in display design, however, are for increased integration of information. This trend has extended to alarm information for two principal reasons. First, computer-based information systems can access and present a very large quantity of data. However, the information is presented in a compact display space providing significantly less display area (contrast the display area available in a conventional and advanced control room design). Because more information needs to be presented in less space, there is a need for greater integration and layering of information and for presentation of this information at higher levels (aggregates of lower level information). The second reason is that it is thought that the cognitive processing of information is supported by integration of information into a single object [19] or display [20]. Such displays are thought to enhance parallel processing (lowering cognitive workload), enable operators to better understand the relationships between display elements, and ultimately to develop a more rapid and accurate awareness of the situation.

Alarm displays can be considered as reflecting two dimensions: spatial dedication (whether an alarm is always displayed in the same physical location or in variable locations); and display permanence (whether an alarmed is always visible or visible only when in an alarmed state). These dimensions can be combined to produce a wide variety of alarm display formats, such as:

Spatially-Dedicated Continuously-Visible (SDCV) Alarm Displays - The presentation of alarms through lighted tiles is an example. Tile-like VDU displays have also been developed. The tiles do and the VDU may provide a display of information in a permanent location.

Temporary Alarm Displays - Many VDU alarm message lists are examples of a temporary alarm display. Messages only appear when the alarm is in a "valid" state. Depending on the design, temporary alarms may or may not appear in spatially dedicated locations.

Integrated Alarms - Alarm information can be presented as an integral part of other displays, such as process displays. For example, if alarms are built into a system mimic display, trouble with a component such as a pump can be depicted by a change in color or flashing of the pump icon. These displays may be in a fixed or variable location and are typically not permanent displays.

To serve the different functions of the alarm system, multiple display formats may be required. Thus the display format of alarm information in advanced systems and the degree to which that information is presented in separate or integrated fashion with other process information are important safety considerations. The role, relative benefits, and design of each type of alarm display format in the presentation of alarm information is an issue.

3.1.2.2 Related Research

EPRI investigated alarm system display characteristics incorporated into (1) alarm tile displays, (2) VDU displays, and (3) combined tile and VDU alarm display systems, (additional display characteristics were also evaluated) [12]. Fifteen licensed operators participated in the tests using an alarm system simulator. Performance measures included the speed and accuracy with which operators could extract information from the alarm system and operators' opinions on ease of use and other subjective parameters. The results indicated that the grouping of alarms by system and function improves performance (consistent with other finding) [21]. The tile display resulted in earlier, more rapid information acquisition. The VDU was best utilized as an adjunct to the alarm tile display to highlight alarms that were unusual for a given transient.

Similarly, in another study [22] experienced operators evaluated an advanced control room design and indicated that VDU alarm displays were sufficient when few alarms were presented but not during accident or transient conditions. As a result of this study, the control room design was modified to include both tile and VDU-based display formats.

In a study examining parallel versus sequential alarm presentation, three types of alarm displays were evaluated: (1) a tile display, (2) a VDU-based model similar to the tile display, and (3) a VDU-based sequential textual alarm presentation [13]. Chemical plant trainees served as participants in a laboratory study. Operator errors and difficulty ratings were the main dependent variables. The results indicated that the sequential presentation of alarms was inferior both in terms of operator performance and subjective ratings. The differences between presentation modes was greater during high alarm density conditions. The ability to recognize a pattern of alarms was offered as an explanation for the advantage of the parallel alarm presentation. In a survey of plants having both tile and VDU message alarm displays available, operators found the use of VDU alarms acceptable during normal power operations when the number of alarms is small, but preferred tile displays during plant disturbances when the number of alarms was large [15]. VDU alarm messages were difficult to manage during plant disturbances. In fact, the authors state that "there is clear evidence that VDU message lists are a poorer method of presenting alarms than the conventional annunciators." In the plants surveyed, while VDU-based displays were the primary method of alarm presentation, an increasing trend toward conventional alarm presentations was observed. More recently, VDU alarm message flooding (when many more alarm messages are coming in than can be presented on the VDU) has been identified as a problem in Canadian plants [16,25]. Operator problems with VDU-based message displays in high-density situations were noted in other field observations as well [26].

Operator preference for SDCV displays has been found in other NPP studies and chemical plants [27,12-13]. Wickens found increased memory load for temporary message displays and a loss of spatial organization of information which facilitates information processing [28]. One of the issues associated with VDU alarm displays relates to difficulties operators have with alarm message lists, especially in systems where the messages scroll across the screen. When the rate increased, the number of missed alarms increased [29]. This finding is, of course, dependent on the alarm display and types of message design implemented.

A major attraction of the VDU-based presentation is the flexibility to present alarm information in a wide variety of ways. Several studies have gone beyond message lists and examined graphics-based presentations. The Halden studies [6-7] discussed in the previous section compared: (1) an unfiltered text-based version of a tile-like alarm VDU display, (2) a filtered text-based alarm VDU display, and (3) a filtered text/symbolic-based alarm VDU display. In the latter condition, top-level schematic overviews of the plant were presented. When an alarm was activated, symbols representing the appropriate subsystems would blink. The operator could then move to a second-level display which was an enlarged schematic presented on a separate VDU. Flashing symbols indicated the problem system. Text-based alarm messages were provided. There were no significant differences between the three systems on measures of diagnosis, checks, and action, but detection time was faster with the textual presentation. While operators found the graphic displays helpful, navigating between the displays was slow and cumbersome. In addition, operators requested that process data be included in the overview display. Again, however, display type and processing were confounded in this experiment.

In another study, operator performance with an advanced display system was compared with a tile-based display [24]. The advanced display system provided process data on an overview display and a "forced-to-look" feature which prompted the operator to examine new alarms. A blinking alarm on the overview could only be accepted by calling up the appropriate process format. Ten subjects (four operators and six project staff volunteers) took part in the study. The systems were compared under a variety of transient conditions. The results indicated that although the advanced alarm display provided better performance in the selection of process displays, there was no clear advantage of either system for detecting abnormal events or for locating a deviant parameter. It was concluded that the alarm system should be integrated into the information system.

3.1.2.3 Summary

In summary, even though SDCV displays are preferred by operators and may have a performance advantage under high-alarm conditions, placing all alarms on such displays (potentially many thousands of alarms in advanced plants) has been associated with operator overload. VDU-displays have not been completely successful alternatives, however. Message lists have been demonstrated to be problematic in high-alarm conditions and, although the research is limited, integrated graphic displays have not been shown to improve performance. These findings emphasize the importance of display design, i.e., poorly designed VDU displays can have safety concerns that need to be understood so as to provide a basis for the development of regulatory guidance. It is likely that both SDCV and message list alarms can play an important role in advanced systems but the allocation of alarm functions to each needs to be addressed.

3.2 Alarm System Experiments

In order to help resolve these issues an experiment is underway to evaluate the impact of alarm system design characteristics on plant and operator performance in order to contribute to the understanding of potential safety issues and to provide data to support the development of design review guidance. Three alarm system design factors are being evaluated: (1) processing methods, (2) availability of processing results, and (3) alarm display format.

As stated earlier, prior research has produced no consensus regarding the effects of processing methods on operator performance. While industry objectives for alarm reduction often focus on the number of alarms reduced, relating degree of reduction to the type of alarm information that is processed has not been accomplished. The degree of alarm reduction achieved is a function of the alarm processing techniques that are applied. For this study, a variety of alarm processing methods are employed that are representative of near-term applications, and therefore, near-term regulatory review considerations. Alarm reduction is accomplished using two methods: one that minimizes nuisance alarms to achieve moderate alarm reduction; and one that employs redundant processing to achieve maximum reduction. In addition, a baseline condition of no alarm processing is being used to provide a basis of comparison.

The differential effect of two types of alarm availability is being evaluated: suppression and dynamic prioritization. As indicated, there are clear tradeoffs between these approaches; thus an issue remains about which method should be used or in what contexts the various options should be exercised. Suppression provides the potential benefits of removing alarm from the operators attention thereby reducing the need to process and respond to them. There are two potential drawbacks. First, since designers cannot anticipate all possible plant disturbances it is possible that some of the alarms suppressed may be important to decision making in certain contexts. Second, since suppressed alarms are accessible on auxiliary displays, additional workload is imposed by requiring operator action to retrieve them. When dynamic prioritization alone is used to present the results of alarm processing no alarms are concealed from operators. Instead, alarms that would have been suppressed are presented as low priority alarms. However, the potential limitation to this approach is that operator's are required to perceptually "filter" alarms, e.g., to scan for the red alarms. Thus, there is a potential that the detection of higher priority alarm is impaired by the distracting presence of less important alarms.

Alarm display design has been shown to have significant effects on operator performance but further research into the integration of SDCV displays and the design of alternative VDU display formats is needed. Three types of VDU-based alarm displays are being compared: a dedicated "tile-like" format, a mixed tile and message list format, and a mixed graphic and message list format. The graphic provides alarm information integrated into process display formats. These display formats enable the examination of two aspects of alarm display design: spatial dedication and degree of integration with process information.

Eight alarm system configurations, representing combinations of these alarm characteristics, are being evaluated during simulated nuclear plant transients. The tests are being conducted at the Human-Machine Laboratory (HAMMLAB) at the Halden Reactor Project in Norway. The plant model simulates a pressurized water reactor power plant with two parallel feedwater trains, turbines and generators. It is closely related to the plant model used in the large scale training simulator at the Loviisa nuclear power station in Finland. The participants are professional nuclear power plant operators from Loviisa. Six crews of operators are participating with two operators per crew.

The measurement of performance in the study is based upon a supervisory control model in which modifications to the human system interface (in this case the alarm system) effect plant safety through a causal chain from the operator's cognitive processes, to operator task performance, and ultimately to system and plant performance. Data related to plant/system performance, operator task performance, and operator cognitive processes (e.g., situation awareness and workload) is being measured. The subjective opinion of the operators is also being obtained.

The data will be analyzed to determine the effects, if any, on crew performance of the following alarm system characteristics:

- spatial dedication
- alarm integration
- alarm reduction
- type of alarm reduction
- alarm suppression
- scenario complexity.

In addition, the analysis will examine whether alarm availability interacts with processing type.

4. CONCLUSIONS

There are two major conclusions from this research program to date. First, the nuclear and human factors communities have developed a significant database upon which HFE review guidance for advanced alarm systems was developed. Information supporting guidance development came not only from available guidance documents, but also from published reports of research and operational experience. Further, advanced alarm systems, particularly those utilizing computer-based interfaces share many HSI characteristics in common with the rest of the control room. Thus HFE principles associated with VDUs, graphics displays, dialog structures (such as menus and command language) and computer input devices (such as touch screens, keyboards, and trackballs) are applicable to alarm systems. Second, there remain notable human performance issues. Research is underway to address the issues associated with alarm processing and display.

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