ADVANCED ALARM SYSTEMS:
DISPLAY AND PROCESSING ISSUES

John M. O'Hara
Brookhaven National Laboratory
P.O. Box 5000
Upton, NY 11973-5000
(516) 282-3638, ohara@bnl.gov

Jerry Wachtel and J. Persensky
U.S. Nuclear Regulatory Commission
Office of Nuclear Regulatory Research
Washington, D.C. 20555
(301) 415-6498

ABSTRACT

This paper describes a research program sponsored by the U.S. Nuclear Regulatory Commission to address the human factors engineering (HFE) deficiencies associated with nuclear power plant alarm systems. The overall objective of the study is to develop HFE review guidance for alarm systems. In support of this objective, human performance issues needing additional research were identified. Among the important issues were alarm processing strategies and alarm display techniques. This paper will discuss these issues and briefly describe our current research plan to address them.

I. INTRODUCTION

The need to improve the human factors engineering (HFE) of alarm systems has led to the development of advanced alarm systems in which alarm data are processed beyond the one sensor - one alarm framework. While this technology promises to provide a means of correcting many known alarm system deficiencies and may be used in new plants as well as in upgrades to existing plants, there is general agreement in the literature that there is an "international lack of guidance and requirements for alarm systems" and new guidance for the review of advanced alarm system designs is needed.¹

To support the review of advanced alarm systems by the U.S. Nuclear Regulatory Commission (NRC), HFE review guidance was developed using a methodology described elsewhere.² The individual guidelines include the specific acceptance criteria to be used by an NRC reviewer and the technical basis upon which the guidelines were formulated.³

During guidance development, several human performance issues associated with advanced alarm systems were identified. The HFE 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. This approach was based on the approach used by the National Academy of Sciences in their review of human factors research needs in the nuclear industry.⁴ 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. The evaluation of expected review needs was conducted to determine the near-term and long range likelihood that the NRC staff would perform a safety review of an advanced alarm system design incorporating features addressed by the issues. Based upon this analysis, the issues associated with visual display of alarm information and simple alarm processing prioritization/filtering methods were rated as the highest priority issues.

The purpose of this paper is to discuss the alarm processing and display issues and to briefly describe the research underway to address these alarm system characteristics.

¹This work was performed under the auspices of the U.S. Nuclear Regulatory Commission.
II. ALARM PROCESSING

A. Alarm Processing Characteristics

The single most important objective in the design of advanced alarm systems is to reduce the avalanche of alarms 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.

1. Alarm processing techniques. Alarm processing techniques were developed to support operators by reducing the number of alarms, identifying which alarms are significant, and reducing the need to infer plant conditions.

Alarm signal processing refers to the process 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 signals from parameters that momentarily exceed the setpoint limits but are not indicative of a true alarm condition. Signal validation is a group of techniques by which signals from redundant or functionally related sensors are compared and analyzed 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 processing techniques have been developed. Each alarm condition processing technique affects the information provided to operators. For the purposes of this discussion, four classes of processing techniques are defined:

Nuisance Alarm Processing - These are techniques that essentially eliminate alarms that are not true alarms; i.e., have no operational importance. For example, mode dependent processing eliminates alarms that are irrelevant to the current mode of the plant, e.g., a low temperature signal that is an alarm in normal operating mode but is normal during startup.

Redundant Alarm Processing - These are techniques that analyze for alarms that are true/valid but are of less importance because they provide information that is redundant with other alarms and provide no new/unique information. For example, in causal relationship processing only causes are alarmed and consequences are considered redundant. However, beyond quantitatively reducing alarms, processing methods qualitatively 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 are techniques that analyze for alarms that are true/valid but are of less important in comparison to other alarms. For example, in an anticipated transient without scram event, alarms associated with certain minor disturbances on the secondary side of the plant are less significant.

Alarm Generation Processing - These are techniques that analyze the existing alarms and generate new alarms that (1) give the operator higher level or aggregate information, (2) notify the operator when "unexpected" alarms occur, and (3) notify the operator when "expected" alarms do not occur. Processing techniques that generate alarms present an interesting paradox. Alarm generation features may help mitigate problems that often reflect the overloaded operator's incomplete processing of information by directing the operator's attention to plant conditions that are likely to be missed. However, the most significant problem with alarm systems is the number of alarms and alarm generation creates additional alarms, thus potentially exacerbating the problem.

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. In addition, system complexity should be considered. Alarm processing systems often employ combinations of these techniques. The operator, as the system supervisor, must 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 the operators to take time-critical actions.

2. Alarm availability. 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
DISCLAIMER

Portions of this document may be illegible in electronic image products. Images are produced from the best available original document.
presented, which is alarm display). Three techniques have been used (note that the definitions of these terms are the author's; the terms "filtering" and "suppression" are often used interchangeably: 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 suppressed alarms 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).

There are clear tradeoffs between these approaches; thus an issue remains about what contexts the various options should be exercised. Filtering eliminates the possibility that unimportant alarms will distract the operators. However, the designer may be removing 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 potential distracting alarms. However, since they are accessible on auxiliary displays, additional workload may be imposed by requiring operator action to retrieve them. Prioritization, on the other hand, does not conceal any information from operators. However, the operator is required to perceptually "filter" alarms, e.g., to scan for red, high-priority alarms from the other alarms. Thus, there is a potential of distraction due to the presence of less important alarms.

B. Related Research

Several studies have examined the effects of alarm processing techniques on operator performance. 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 specific with respect to the plant transient. No significant difference was found for operator 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 with and without filtering during simulated transients were made in subsequent studies.\(^6\) The filtering system reduced the alarms by approximately 50 percent and the filtered alarms were not available to the operator. The performance measures were detection time and percentage, diagnosis time and percentage, percentage of checks, and percentage action. Process variables and subjective evaluations were also measured. Seven crews of two operators each used the three systems in 12 simulated scenarios. Filtering of alarms had little effect on observed 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 potential 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.

Although the operators expressed support for the alarm filtering system in another study using a verbal protocol analysis taken in real time from three operators during simulated malfunctions, no evidence was found that it had a positive effect on their performance.\(^7\)

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 alarm processing.\(^8\) Alarms were displayed on a combination of tiles and VDUs. The color was used to support operators in distinguishing between 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 two 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 research reported earlier where secondary event detection was not enhanced.

The Electric Power Research Institute (EPRI) conducted a study comparing tile and VDU-based alarm presentations.\(^9\) One of the experimental conditions included a VDU presentation of alarms where the typical alarms associated with reactor and turbine trip were suppressed.
The alarm suppression presentation reduced the number of "maverick" alarms (those not typically occurring during a plant trip) operators missed by 50 percent; although concern over suppression was expressed, since the timing of some normal trip-related alarms helps the crew's understanding of transients.

With respect to the filtering of alarm information, 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. The issue as to whether to include status indications in an alarm system is related to the criteria for alarm selection and the capabilities provided by other portions of the HSI for displaying plant status indications.

C. Summary

Two studies failed to find an effect of alarm processing. One study found no effect for the detection of initial disturbances, but improved performance in the detection of secondary malfunctions (which is a significant problem). Another study found a positive effect on detection of unusual alarms, but raised a question regarding possible trade-offs with the loss of information making the operator's understanding of events more difficult. The differences in results could be due to many factors such as type of processing used, degree of filtering achieved, method of data display, and familiarization of the users 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 are of interest as well although these effects have not been effectively addressed. Also, individual alarm processing methods have not been compared to determine which methods best support operator performance.

A key issue that must be resolved is the type and degree of processing needed. While it is clear that the number of unprocessed alarms is often overwhelming to operators and that processing techniques can reduce the number of alarms, the impact on operator performance is the most important variable of interest. An industry survey found that a typical objective of alarm filtering system development was to reduce the number of alarms by 50 percent. However, that amount of filtering may not significantly improve operator performance. In terms of operator processing of alarm information, it is probably inappropriate to specify alarm reduction in terms of absolute 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 depends rather on their rate, their recognizability as familiar patterns, their predictability, and the complexity of the operator's ongoing task. A design goal for improved performance needs to be established.

With respect to availability, the conditions under which alarms should be filtered, suppressed, or prioritized needs to be determined.

III. ALARM DISPLAY

A. Alarm Display Characteristics

The alarm systems in conventional plants tend to be stand alone systems. Operators consult other indicators for specific information. The general trends in visual display design, however, are for increased integration of information. This trend has extended to alarm information as well 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 work space providing significantly less display area (contrast the display area available in a conventional NPP with that provided by advanced control room designs). The net effect is that more information needs to be presented in less space. Thus, there is a need for greater integration of information, layering of information, and presentation of information at higher levels (aggregates of lower level information).

Second, it is thought that the cognitive processing of information is supported by integration of information into a single object or display. 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 permanently 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 - Traditionally, alarm data has been displayed through the use of lighted tiles. The tiles provided a visual display of alarm information in a permanent location. More recently, tile-like VDU displays have been used where operators are seated at a workstation.
**Temporary Alarm Displays** - Alarm message lists are a typical implementation 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 state or flashing of the pump icon. These types of displays may be 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 in the presentation of alarm information is an issue.

**B. Related Research**

EPRI investigated alternative systems for alarm presentation including (1) alarm tile display alone, (2) VDU display alone, and (3) combined tile and VDU alarms (additional display conditions were also evaluated). 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). 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, experienced operators evaluating an advanced control room design indicated that the VDU displays were sufficient when few alarms were presented but during accident or transient conditions, the problem identification was more difficult. The design was modified to include both tile and VDU-based display formats.

In a study examining parallel versus sequential 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. 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. 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 that they 'supplement'." 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 has been identified as a significant problem in Canadian plants. Operator problems with VDU-based message displays in high density situations have been noted in other field observations as well.

Operator preference for SDCV displays has been found in other NPP studies and chemical plants. Wickens found increased memory load for temporary message displays and a loss of spatial organization of information which facilitates information processing. One of the problematic issues associated with VDU alarm displays relates to difficulties operators have with alarm message lists, especially in systems where the alarm messages scroll. The effects of message rate on performance has been investigated. When the rate increased, the number of missed alarms increased. 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 more advanced, graphics-based VDU presentations. The Halden studies discussed in the previous section compared: (1) an unfiltered text-based version of a tile-like alarm display presented on a VDU, (2) a filtered text-based version of alarms presented on a VDU, and (3) a filtered text/symbolic-based version of alarms presented on a VDU. In the latter condition, top-level alarm schematic overview displays of the plant were presented on a VDU. When an alarm is activated, symbols representing the appropriate subsystems would
bloon (red if high priority and yellow if not). 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. The main findings with respect to displays were that 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 found to be 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.

Another study compared operator performance with an advanced display system to a tile-based display. Both systems used alarm filtering. The advanced display system provided process data on an overview display and a "forced-to-look" feature which prompted the operator to examine new alarming. 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. The authors concluded that in an advanced control room the alarm system should be integrated into the information system and that it would be disadvantageous to use a separate alarm system.

C. Summary

In summary, these studies show the importance of general alarm display properties. SDCV displays are preferred by operators and have a performance advantage under high alarm conditions. However, placing all alarms on such displays (potentially many thousands of alarms in advanced plants) is not practical and has been associated with the flooding problems identified in the past. 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 can play an important role in advanced systems but the allocation of alarm functions to each needs to be addressed.

IV. ALARM SYSTEM TESTS

In order to help resolve these processing and display issues, and to provide data to support the development of design review guidance, the impact of three alarm system design factors on plant and operator performance are currently being evaluated: (1) display type, (2) processing methods (alarm reduction and generation methods), and (3) availability of processing results. The effects of these design characteristics will be tested in three experiments:

- **Experiment 1: Display Types** - This experiment is evaluating the effects of display type on performance independent of alarm processing techniques.

- **Experiment 2: Alarm Reduction and Availability** - This experiment will evaluate the effects of alarm processing techniques which are oriented to alarm reduction and the availability of alarm processing results (and their interaction) on performance.

- **Experiment 3: Alarm Generation** - This experiment will evaluate the effects of alarm generation on performance.

Prior literature has shown that scenario effects may have led to inconsistencies between the available studies. Therefore, scenarios from two general categories will be sampled. The first category will be "rule-based" scenarios that are well defined by available procedures. The second category will be "knowledge-based" scenarios that are less-well defined by available procedures.

V. CONCLUSIONS

Guidance for the HFE review of alarm systems was developed. However, there was insufficient data to support NRC alarm design reviews for several aspects of alarm system design. The top priority research topics were identified as alarm processing and display. Tests are currently underway to address these issues. The results of these tests will contribute to the understanding of the potential safety issues associated with these issues and will provide information to support the development of design review guidance in these areas.

ACKNOWLEDGEMENTS

This research is being sponsored by the U.S. Nuclear Regulatory Commission. The views presented in this paper represent those of the authors alone, and not necessarily those of the NRC.
REFERENCES


---

**DISCLAIMER**

This report was prepared as an account of work sponsored by an agency of the United States Government. Neither the United States Government nor any agency thereof, nor any of their employees, makes any warranty, express or implied, or assumes any legal liability or responsibility for the accuracy, completeness, or usefulness of any information, apparatus, product, or process disclosed, or represents that its use would not infringe privately owned rights. Reference herein to any specific commercial product, process, or service by trade name, trademark, manufacturer, or otherwise does not necessarily constitute or imply its endorsement, recommendation, or favoring by the United States Government or any agency thereof. The views and opinions of authors expressed herein do not necessarily state or reflect those of the United States Government or any agency thereof.