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Nuclear Power Plant Alarm Systems: Problems and Issues

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Despite the incorporation of advanced technology into nuclear power plant alarm systems, human factors problems remain. This paper identifies issues to be addressed in order to allow advanced technology to be used effectively in the design of nuclear power plant alarm systems. The operator's use and processing of alarm system information will be considered. Based upon a review of alarm system research, issues related to general system design, alarm processing, display and control are discussed. It is concluded that the design of effective alarm systems depends on an understanding of the information processing capabilities and limitations of the operator.

The human engineering deficiencies associated with conventional (one sensor-one alarm) alarm systems in nuclear power plants (NPPs) are well documented (Malone et al., 1980; Banks and Boone, 1981; Rankin et al., 1983; Seminara et al., 1979; Pine et al., 1982; Fink, 1984; Kinkade and Anderson, 1984; MPR, 1985) and recommendations for improvements have been offered (Crouch et al; 1989; Fink, 1984; Kinkade and Anderson, 1984; MPR, 1985; Pine, 1982; U.S. NRC, 1981). However, the presentation of alarm information to operators continues to be a problem (Seminara, 1988). One reason may be that not all of the human factors issues (the number of alarms during major plant disturbances, and static prioritization capabilities, to cite two examples) can be effectively resolved through upgrades to conventional systems (Woods et al., 1987; Beltracchi, 1988).

The need to improve the human engineering 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. The processing can be simple, such as the filtering of plant mode dependent alarms, or complex, such as dynamically prioritizing alarms based upon unfolding events. The defining feature of an advanced system is the capacity to assist the operator by processing alarm data prior to its presentation. This technology promises to provide a means of correcting many known alarm system deficiencies. However, there is evidence to indicate that attempts made to date to develop such advanced alarm systems have been less than completely successful, and that operators tend to prefer conventional systems (e.g., Kraght, 1984; MPR, 1985, 1988). Thus, despite the application of advanced technology to NPP alarm systems, human factors problems remain.

This paper identifies issues to be addressed in order to allow advanced technology to be used effectively in the design of nuclear power plant alarm systems. First, the operator's use and processing of alarm system information is considered. Then, based upon a review of alarm system research, issues related to general system design, alarm processing, display and control are discussed.

OPERATOR PROCESSING OF ALARM INFORMATION

One of the operator's primary tasks is to detect and correct plant disturbances. The need for operator attention is conveyed by automated monitors, i.e., the alarm system. The role of an operator, then, is that of an "alerted monitor" (Sorkin and Woods, 1985). In an alerted-monitor system, both the human and the automated monitors are assumed to have their own signal detection parameters (Green and Swets, 1966). When the criterion of the automated monitor is exceeded, the operator is alerted. The operator's criterion for action may be influenced by several real-time factors, e.g., the expected probability that an event will occur, or the cost of taking (or not taking) action.

Operators recognize plant events by comparing the information received from the alarm system and other sources with the knowledge structures or schemata (Bartlett, 1932) which comprise a mental model of the plant. The accuracy of the mental model at a given time, i.e., "situation awareness" (Fraker, 1988), depends upon how consistent information is with the mental model and how much additional processing is required by the operator. The large number of alarms that typically occur during a major NPP transient may overload the operator's information processing ability. Under such high workload conditions, the operator's attentional resources are in short supply and the effective cost of making observations rises. As a result, operators may adopt inappropriate alarm sampling strategies which make the detection of system anomalies less likely (Moray, 1981; Sorkin, 1989).

High workload is also associated with human error. Reason (1987, 1988) has presented a model that views human error as a predictable result of a tendency to overutilize cognitive processes which serve to simplify complex information tasks. Operators under high workload conditions and lacking the data required to clearly identify appropriate schemata will employ two heuristics (called "similarity matching" and "frequency gambling"). These heuristics give rise to a number of "basic error tendencies" in human performance which account for many human errors. Similarity matching reflects the tendency for the operator to attempt to match a perceived information pattern (such as a pattern of alarm signals) with an already existing knowledge structure. The operator cognitively tries to establish a link with the stored knowledge structure since it contains a previously identified successful action sequence, thus saving the resource-intensive effort of knowledge-based reasoning. When the perceived information partially activates more than one schema, the discrepancy is resolved by selection of the schema most frequently used in the past. This is the "frequency gambling" heuristic.

NPP operators are confronted with what Reason refers to as a "complex multiple-dynamic configuration". The problem configuration changes as a result of both the operators' actions and the system's actions which can create high variability in the problem. This is the most difficult type of problem-solving situation and the one in which heuristics are most likely to be relied on. A typical problem solving sequence assumes the following structure: (1) scanning is initiated by signals from the alarm system and the operator's attention is split between a variety of data gathering activities, (2) the operator "homes in" on a specific group of indicators and makes an initial diagnosis, (3) the operator's attentional resources seek data confirming the hypothesis, and (4) the operator becomes fixated on the hypothesis and can fail to notice changes in the plant's state or subsequent new developments. The operator can become aware of subsequent changes, but the process is hampered by limited information processing resources. This sequence is likely followed even for NPP transients where symptom-based emergency operating procedures (EOPs) are involved, as a parallel activity to EOP execution.

Based on the foregoing characterization of the operator's task from an information processing perspective and a review of recent alarm system research, a number of human factors issues have been identified that may have a bearing on the success of future efforts to employ advanced technology in nuclear power plant control rooms. The following section summarizes the major findings. A more complete discussion can be found in O'Hara et al., (1991).

ALARM SYSTEM ISSUES

Goals and Functional Requirements

Operator-centered design goals. Design objectives for alarm systems are seldom specified in terms of the operator's information needs or performance. For example, many of the reports of advanced alarm system development efforts cite alarm filtering design goals on the basis of achieving some percentage of filtering, e.g., to reduce by a factor of two the number of alarms during major transients (Kennedy, 1989). Yet reduction by a factor of two might not necessarily improve performance (e.g., Baker et al. 1985a, 1985b). The filtering design goal would optimally be stated in terms of the degree of alarm filtering required to improve human performance. Other operator-centered design objectives might include minimizing the time required to take appropriate action by providing the cues required to activate the operator's mental model appropriate to the situation (support situation awareness) and thus minimize cognitive workload (the higher-level processing and information processing burden) and heuristics-related error. The system should support operator scanning patterns which may change as workload increases and should facilitate the detection of alarms occurring after an initially identified problem.

Hybrid vs. advanced control rooms. The role of alarm systems in hybrid control rooms (i.e., backfits of advanced alarm systems into existing conventional control rooms) may be different from that in advanced control rooms. In conventional plants, the alarm system exists as an independent system. Advanced control rooms will have superior data display, integration, and operator aids. This difference could suggest that more capability should be expected of advanced alarm systems in hybrid plants than needs to be expected of alarm systems in advanced plants.

Alarm and annunciator functions. The alarm system is the principle source of information for the detection of a specific off-normal condition. In conventional NPPs, it is also used for the annunciation of system/function status and in this role also supports a feedback function on the success of actions taken by the operator. Observations of operators in process control contexts have shown that the annunciation function of the alarm system is important to operators (Kraght and Bonton, 1983). However, the combining of annunciation and alarm functions in a single system has contributed to the difficulty operators have with the system under high alarm density conditions. The number of alarms the operator must deal with can be significantly reduced by separating these functions. In advanced control rooms, such a separation can be easily accommodated. In a conventional control room, replacement of the conventional with an advanced alarm system requires consideration of how to handle the annunciation functions of the system. Some of the problems encountered with early attempts to utilize advanced alarm systems in conventional control rooms may stem from the loss of the annunciation function.

General alarm characteristics. There is a limited empirical basis for recommending specific alarm system design features. However, analytical studies (Rankin et al., 1983; Crouch et al., 1989) evaluating the alarm characteristics required to meet the functional requirements of alarm systems have identified a number of features which are generally considered important for the reduction of human error-related plant risk. These include, for example, prioritization, alarm inhibit features, first-out alarms (for reactor and turbine trip), reflash, message legibility and intelligibility, and keying alarms to alarm procedures. Although these studies were directed to characteristics of conventional alarm systems, the features represent generic alarm system characteristics. A detailed description of these characteristics is beyond the scope of this paper, but may be found in Crouch et al. (1989).

Alarms and symptom-based emergency procedures. Symptom-based emergency operating procedures (EOPs) have changed the operators' response to significant off-normal conditions in that event diagnosis is no longer required as the initial response to accident initiators. One important role of the alarm system can be to clearly indicate the specific entry conditions to the EOPs and to clearly identify with alarms the branch points in the EOPs.

Context specific response characteristics. The response of the alarm system can be made context specific to assist operators, e.g., silencing the auditory warning for lower priority alarms or eliminating the auditory cue for alarm clearing (Fink, 1984) under high alarm density conditions.

Alarm Processing Methods Issues

Comparison of individual processing methods. A variety of methods (such as mode dependency, state dependency, etc.) have been developed for the processing of alarm data (see O'Hara et al., 1991 for a review). However, the relative merits of the individual methods have not generally been evaluated for their effects on operator performance. Alarm processing research to date has examined only filtering and prioritization.

Effects of filtering on performance. The results of research on the effects of alarm filtering on operator performance are equivocal. Baker et al. (1985a, 1985b) and Fujita and Sanquist (1988) found no effect; Fujita (1988, 1989) found no effect for the detection of initial disturbances, but improved performance in the detection of secondary malfunctions. Two studies observed interaction effects. Marshall (1982) found effects for some transients but not others; Reiersen et al. (1987) found effects for complex disturbances but not simple transients. In short, no clear conclusion emerges. The observed differences in results could be due to two primary factors: (1) alarm system design characteristics, such as type of processing used, degree of filtering achieved, method of data display, and familiarization of the subjects with the system; or (2) transient dependency, i.e., dependent on the specific scenario or on the operators ability to recognize a familiar pattern.

Filtering and prioritization. Sorkin et al. (1988) have shown that prioritization of alarms (by indicating those alarms for which a failure to respond would be costly) may enhance performance by allowing operators in demanding situations to "budget" their attentional resources more effectively. Thus, prioritization has the potential to reduce the operator's information processing workload without withholding information, as can be the case in filtering. The implications of these alternatives for operator performance need to be addressed. Should alarm information be withheld from operators? What is the effect of adding the "perceptual noise" imposed by a prioritization scheme as opposed to filtering the information? A related question is that of the dimension on which alarms should be prioritized, e.g., importance to safety, urgency of operator action, etc. The selection of one or more of these dimensions will impact the alarm system's characteristics and operator performance.

Alarm generation. In the presence of an array of active alarms and status annunciators, the process of verifying that systems are performing as expected and that no unusual conditions exist is both attentionally demanding and error-prone. Alarm systems may relieve operators of these information processing demands by calling attention to the presence of "unexpected" alarms and to the failure of an "expected" alarm to occur.

Alarm setpoints and alerted monitors. Sorkin and Woods (1985) have suggested that in an alerted monitor system the operator's criterion may be influenced by the criterion of the automated monitor (i.e., the alarm system). It is common to attempt to optimize the detection of signals by the alarm system. Thus, the set points are adjusted to minimize missed signals. This, however, increases the false alarm rate of the alarm, which in addition to increasing the level of "noise" may lower the operator's confidence in the alarm system and cause the operator's criterion for action to be raised. Sorkin and Woods show that under certain circumstances the performance of the combined automated/human system may be worse than that of either detector alone. Further research is needed to understand the optimal integration of these two components of the alarm system.

Processing complexity. To be effective supervisory controllers, operators must understand how alarms are processed, what alarms mean, and the limitations of the system. For short-term solutions, the processing logic should not be so complex that it cannot be readily understood.

Display of Alarm Data

Tile and CRT-based displays. Conventional tile (or window) displays have been found to be superior to CRT-based presentations during high alarm density conditions (MPR, 1988; Matsushita, 1988; Kraght, 1984). In conventional displays an alarm always occupies the same spatial position and remains present even when not activated. Display designers are aware of the desirability of providing a dedicated location for high-priority information. Furthermore, a "permanent" alarm provides status information when not activated, and feedback information upon moving from an active to inactive state (Kraght and Bonton, 1983). The fact that individual alarms are distributed in space also allows the identification of events by recognition of patterns. A related consideration is that, whereas CRT-based alarm data will be available to the operator at the primary workstation, it may not be readily available to the entire operating crew if CRT displays alone are used. The proper allocation of alarm functions to conventional and CRT-based displays needs to be investigated.

Organization of alarm displays. The organization of conventional alarms by system and function has been shown to be preferred by operators and to improve their performance (Fink, 1984; MPR, 1988). If displayed information is organized in a manner congruent with the operator's mental model of the plant, the processing required in order to incorporate the information is reduced. The attentional demands associated with searching the display for information are also reduced, since search is assumed to be guided by the mental model. Approaches to preserve this display approach in CRT alarm displays should be considered.

Information-rich displays. Most of the alarm signals that operators must detect are infrequent events, and some have extremely low probabilities. Consequently, operators require additional data prior to taking action. Research indicates that the integration into alarm displays of additional information to assist in the confirmation of alarm validity is beneficial. Candidate approaches include enriching alarm displays with information regarding signal validation, alarm likelihood, and/or parameter values.

Hierarchical displays. Alarm density may be addressed by providing alarm information in hierarchical displays, e.g., integrating lower level alarm information into higher-order alarms. The system must integrate alarms into units that are meaningful to operators and which represent units that the operator would have developed without the system, i.e., units that are congruent with the operator's mental model. However, hierarchical displays may be presented in layers which can increase interface management workload. Thus, more advanced display techniques for alarm data require further investigation.

Auditory cuing. The auditory characteristics of alarms have often been found to be problematic, i.e., startling and distracting (e.g., Banks and Boone, 1981). More appropriate methods of using tonal cues need to be identified. The operator's ability to extract information from auditory cues has not been fully exploited. For example, zonal auditory cuing (which is used in several plants) may facilitate the operator's location of alarms. Auditory cues may be used to convey other information, such as alarm priority or system, but this has not been studied in a NPP context.

Speech displays. While the role of speech displays has not been investigated in the nuclear industry, they have been found to be effective in aviation applications (e.g., Berson et al., 1981). There is evidence to indicate that operators respond faster to voice warnings than to visual warnings (Simpson et al., 1987; Sorkin, 1987). The number of alarms and the richer auditory environment in a NPP makes extensive use of speech displays impractical. However, there may be selected applications of speech displays that could serve to "off-load" the visual processing channel.

Alarm System Controls

Control complexity. The controls associated with advanced alarm systems are likely to become more complicated, and thus require investigation. While the separate silence-acknowledge-reset-test philosophy will likely continue to apply to advanced systems, additional controls may be required to provide control of features such as operator-defined alarms, set-point adjustment, and filtering control. These features need to be studied to assure their safe implementation.

Role of automation. In certain situations, selected operator controls may be automated, such as the silencing of lower priority alarms. The most appropriate control functions for automation remain to be determined.

CONCLUSION

The incorporation of advanced technology into nuclear power plant alarm systems has begun but has not resolved the problems that operators have interacting with such systems. The design of alarm systems must be based on an appreciation of the information that operators need in order to perform their tasks, an understanding of how they process that information, and a recognition that the operators' capability to process the information may change with changing plant conditions. Such an awareness will form the basis for a more effective application of advanced technology in order to improve operator performance.

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