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How do operators monitor a complex, dynamic work domain? The impact of control room technology

KIM J. VICENTE

Department of Mechanical & Industrial Engineering, Cognitive Engineering Laboratory, University of Toronto, 5 King's College Road, Toronto, Ontario, Canada, M5S 3G8. email: vicente@mie.utoronto.ca, URL: www.mie.utoronto.ca/labs/cel.

EMILIE M. ROTH

Roth Cognitive Engineering, Brookline, MA, U.S.A. email: emroth@mindspring.com

RANDALL J. MUMAW

Boeing Commercial Airplane, Seattle, WA, U.S.A. email: randall.mumaw@pss.boeing.com

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This article describes part of a research programme whose goal is to develop a better understanding of how operators monitor complex, dynamic systems under normal operations. In a previous phase, field observations were made at two older nuclear power plant control rooms (CRs) consisting primarily of analogue, hard-wired instrumentation. In this phase, additional field observations were conducted in a newer computer-based CR to determine the impact of CR technology on operator monitoring. Eleven different operators were observed *in situ* for a total of approximately 88 h. The findings indicate that there are many similarities in the monitoring strategies adopted by operators in the two types of CRs. However, in most cases, these same strategies are performed using different behaviours, thereby showing the shaping effect of the CR technology. A new way of conceptualizing the difference between traditional analogue CRs and modern computer-based CRs is proposed.

KEYWORDS: monitoring; supervisory control; cognitive engineering; process control; nuclear power plants; human-machine interface; control rooms.

1. Introduction

For some time now, the technology that is being used to design interfaces for complex, dynamic work domains (e.g. aviation, manufacturing, medicine, nuclear, petrochemical) has been changing. Traditionally, indications were often displayed using analogue indicators that were hard-wired, meaning that their appearance and location were fixed at the time of design. In some industries (e.g. nuclear power), the majority of existing control rooms in operation still rely primarily on this older technology, albeit to differing degrees. As newer designs are implemented and upgrades are made, however, more information in complex, dynamic work domains is being managed and displayed using digital, computer-based indicators that provide important forms of flexibility in data

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management. Specifically, data can be brought up on multiple CRTs as a function of the operators' information needs, and work domain variables can be viewed in the context of other variables to facilitate interpretation (Woods, 1991). Newer interface designs rely much more heavily on this advanced technology, although in some industries, a subset of information is still displayed using the traditional analogue technology.

The power and flexibility of computer-based technology introduces myriad new design possibilities. Nevertheless, new does not necessarily mean better. What impact does the introduction of computer-based technology have on operator performance in complex, dynamic work domains? We have been pursuing this question in the context of nuclear power plants. As far as we know, no comparative field studies have ever been conducted to investigate the impact of control room technology in this industry. The work described in this article is part of a research programme that addresses this gap in the literature. In particular, we have focused on the impact of control room (CR) technology on operator monitoring under normal operations.

In earlier work (Vicente and Burns, 1996; Mumaw, Roth, Vicente & Burns, 2000), we conducted field observations in two older plants whose CRs consisted primarily of analogue, hard-wired technology. A total of 27 operators were observed on day and night shifts at these plants over approximately 177 h. Those observations led us to a characterization of operator activities that facilitated monitoring—specifically, to monitor effectively in spite of the limitations of the analogue, hard-wired CR technology. In the work reported here, we conducted similar observations at a newer plant whose CR consisted primarily of computer-based displays (a detailed description is provided later). The nuclear reactor at this newer plant was of the same type (i.e. CANDU) as those that we had observed previously. Furthermore, the newer plant was owned and operated by the same electrical utility as the two older plants. Therefore, although there were differences in the level of automation in the three plants we studied, we were fortunate to be able to control for some factors (i.e. reactor type and utility) that might affect our results. As a result, this sequence of field studies can be viewed as a "naturalistic experiment" (cf. Vicente, 2000), allowing us to study the impact of CR technology on operator monitoring during normal operations.

The article is organized as follows. We begin by providing a brief summary of the findings from our previous work. Then, we describe the methodology that was adopted for this phase of research. Next, we describe the design of the CR that we observed in this phase. The results of the field study are presented, organized according to the following factors: the sources of information that are available for monitoring, the factors that make monitoring difficult and the strategies that operators adopt to make monitoring easier. A discussion of these results is presented, with the primary focus on how the CR technology impacts operator monitoring.

2. Summary of previous findings

To provide a baseline for interpreting the findings presented in this article, we first briefly summarize the findings that were obtained in the earlier field studies of monitoring that we conducted [see Mumaw *et al.* (2000) for more details]. Those studies were conducted in two older CRs that will be referred to as the older CR and the oldest CR since one was slightly older than the other. Both were based predominantly on analogue, hard-wired

TABLE 1
Sources of information for monitoring [*see Mumaw et al.* (2000) *for details*]

Shift turnover	Log
Testing	Alarm screens
Control room panels	CRT displays
Field operators	Field tour
Other units	

TABLE 2
Factors that make monitoring difficult [*see Mumaw et al.* (2000) *for details*]

System complexity and reliability	Alarm system design
Displays and controls design	Design of automation

technology. Table 1 summarizes the sources of information that operators had to monitor the status of the older and oldest plants. We were surprised by the number and diversity of these sources. Operators do not just rely on the CR panels and alarms, but use other media and other people as sources of information.

Table 2 summarizes the factors that make monitoring difficult for operators. Some of these could be improved through more attention to human factors principles in CR design (e.g. alarm system, displays and controls, automation). However, there is a host of factors pertinent to system complexity and reliability that seem to be unavoidable. Since each reactor unit is composed of so many parts, it is inevitable that, on any given day, at least a few components or indicators will not be functioning, will be functioning imperfectly, or will be in the process of being maintained, repaired or tested. It is important for operators to keep track of these activities and states because they provide the background context for monitoring. That is, what indications are considered "normal" depends on which components or indicators are functioning properly, being maintained, repaired or tested. The same set of indications can be normal on one day, but an indication of a problem on the next. This job of tracking the background context to generate accurate expectations for monitoring is complicated by two factors. First, there is a great deal of information to track. Second, the status of these components or indicators can change from day to day. Thus, the operators' understanding of the background context must be continually updated if it is to be accurate. This need for dynamic and comprehensive updating of a complex background context cannot be avoided and makes monitoring a very challenging cognitive activity, even under "normal" (i.e. non-fault) operations.

Despite the complexity just noted, operators are able to monitor the plant effectively because they have developed a set of strategies to facilitate monitoring. For example, operators seem to build and maintain a situation model that they use as a basis for monitoring. In addition, operators appear to frequently engage in top-down, knowledge-driven monitoring rather than wait for events to occur before interpreting them. Perhaps most interesting, we also found that operators adopted a number of ingenious strategies that compensate for limitations in the existing CR interface and thereby reduce

TABLE 3
Strategies that operators use to facilitate monitoring [see Mumaw et al. (2000) for details]

Strategies that enhance information extraction from available data
Reduce noise
Enhance signal
Document baseline or trend
Use other reactor units as referents
Exploit knowledge of the plant and the current context to guide monitoring
Exploit unmediated indications
Seek more information
Strategies that create information
Create a new indicator or alarm
Determine the validity of an indicator
Strategies to off-load cognitive demands
Create an external reminder for monitoring
Create external cues for action or inaction
Employ additional operators

the cognitive demands associated with monitoring. As shown in Table 3, we placed these strategies into three classes: (1) strategies designed to enhance information extraction by increasing the salience of important indicators and reducing the background "noise"; (2) strategies designed to create new information; and (3) strategies designed to off-load some of the cognitive processing onto the interface (e.g. creating external aids and reminders for monitoring). These strategies are largely passed from operator to operator informally (instead of through formal training).

How many of the findings summarized in Tables 1–3 change when computer-based technology is introduced into the CR? As far as we know, this question had yet to be addressed in the literature because no comparative field study of operator monitoring had been conducted in the nuclear industry. Consequently, we were in an excellent position to make a unique contribution to the research literature. Since information technology is being introduced into many complex, dynamic work domains, the lessons we extract from this research program on operator monitoring should be of great interest to many cognitive engineering researchers.

3. Field study methodology

The following questions drove our research:

- How do operators routinely monitor the plant?
- What factors contribute to monitoring difficulty and vulnerability to missing key indicators of a developing problem?
- What cognitive strategies have operators developed to facilitate early detection of a problem?
- How did the differences in user interface technology from the previous CR we observed impact monitoring demands and monitoring behaviour?

These questions could best be addressed through field observations of operator performance in the actual work context.

Field observations support a discovery process. They serve to draw attention to significant phenomena and suggest new ideas, the validity and generality of which can then be evaluated through additional studies. The field studies we performed served this role. They helped us to discover and characterize the cognitive complexities that operators confront during normal operations and the active, problem-solving activities that play a fundamental role in monitoring a complex, dynamic work domain, such as an NPP. The field study methodology that we adopted is similar in approach to ethnographic methods (e.g. Jordan and Henderson, 1995; Nardi, 1997) and the European field study tradition (De Keyser, 1990) in that we placed ourselves in the actual work context to observe and interview operators as opportunities arose.

The computer-based CR observed in this study will be referred to as the New CR because it is the most recent design operated by this utility. The study's objectives were to confirm the classes identified in the observations at the two older control rooms, identify additional examples of these classes and look for new classes that had not been observed before.

In general, one observer sat in most of a work shift to experience the various activities that occur over the course of the day (or night). Interviews were used to obtain general information about operator practice, to follow up on the monitoring actions that we observed and to test the representativeness of monitoring strategies that we observed or were told about. Particular attention was focused on documenting illustrative incidents that provided concrete examples for the kinds of complexities that can arise in the environment and the kinds of monitoring strategies and facilitating activities that operators use to handle these situations.

Initially, our observations in the New CR were made using an open-ended methodology. Three different operators were observed over 3 day shifts for a total of approximately 24 h of *in situ* observation. The goal of this initial phase of data collection was to get an overall understanding of the CR design and a preliminary assessment of the similarities and differences with the two plants that had been observed before. Additional observations were made at the New CR using the more structured, directed methodology used in the previous phase of this work (see Mumaw *et al.*, 2000). Four different operators were observed on four different day shifts for about 8 h at a time. The goal of this second phase of data collection was to get a more detailed understanding of operator monitoring activities at the New CR, with particular focus on understanding how the CR technology affected monitoring activities.

During this second phase two observers were in the control room at the same time, but worked independently, each at a different unit. The observers used a checklist of issues to guide observations: (1) plant or crew policy and procedures for guiding monitoring, (2) unit and control room staffing, (3) overview of the control room interface and information resources for the operator, (4) overview of the alarm system, (5) problems with control room technology or operation, (6) use of automation in the interface, (7) how monitoring can become difficult, (8) the motivations for monitoring, (9) operator interactions with the interface to support monitoring, and (10) monitoring strategies.

In summary, we were able to observe 11 of the 28 operators at the New plant for a total period of approximately 88 h, thereby providing a fairly representative sample of field observations.

There are a number of advantages to the methodology we adopted. The field observations afforded the opportunity to gain a realistic view of the full complexity of the work environment, which is not possible with other approaches. We were able to observe the broad range of operator duties, the distractions that arise, the need to time-share tasks, other demands on operator cognition or types of complexity and the interactions with other people both inside and outside the control room. The field observations also allowed us to observe the distributed cognitive system (Hutchins, 1995). We were able to examine how operators adapt the work environment in order to off-load cognitive demands and facilitate performance. Finally, field observations provided the opportunity to observe and document actual incidents that reveal the cognitive demands operating in the environment and strategies that have been developed by operators in response to these demands. We were able to collect a corpus of concrete incidents that illustrate the complexities in the environment and the monitoring and facilitating strategies that operators have developed.

4. Control room design

Since the primary purpose of this research was to determine the impact of CR technology on operator monitoring, it is important to describe the new plant and its CR in some detail. There are substantial differences in both plant design and CR design between the new and the older or oldest plants. The implications of these differences for operator monitoring will be discussed in subsequent sections.

4.1. PLANT DESIGN

Although all three plants observed in this research are of the same reactor type, the structure of the new plant is quite different from that of the oldest plant. Among the differences that were noted was that many dedicated analogue controllers have been replaced by digital automation. It should also be noted, however, that the design of the new plant is quite similar to that of the older plant. However, the CR designs of these two plants are quite different from each other (see later). Consequently, more weight should be given to the differences between the results obtained at the new plant and those obtained at the older plant rather than those obtained at the oldest plant, since the former set of differences is likely to be a result of the CR technology, not the design of the plant itself.

4.2. CONTROL ROOM LAYOUT

One obvious difference between the new CR design and both the older and oldest CR designs is the layout of the panels for the four units. The older and oldest CRs were similar to each other, with the panels for each unit facing each other in opposite corners of a relatively square-shaped room. As shown in Figure 1, the new CR has a linear layout with the panels for each unit along the same side of the room in a serial fashion. In this case, the unit panels do not face each other and the distance between units is generally longer than that with the older and oldest CR designs. Also, note that the thick lines represent control panels, whereas the thin lines indicate short workspace dividers that

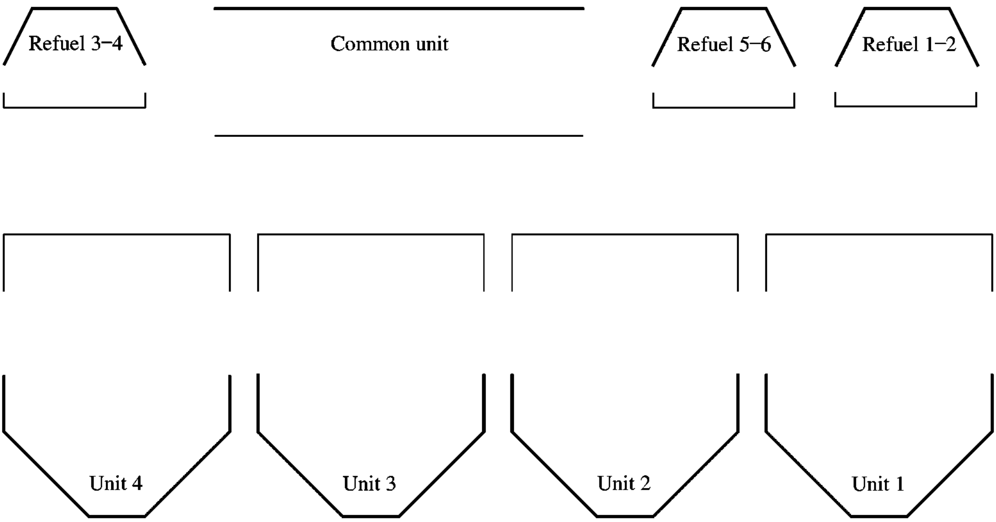

FIGURE 1. An approximate bird's eye view of the layout of all four reactor units in the new CR. Not to scale.

were added after the CR was built and the units had become operational. The implications of all of these characteristics for operator monitoring will be discussed in the next section.

4.3. UNIT WORKSPACE AND PANEL LAYOUT

Figure 1 shows the layout of the control panels for the different units at the new CR. Figures 2 and 3 illustrate the layout of instruments within any one of the four units. More specifically, Figure 2 provides an overhead view of the workspace for one unit. Aside from the panels themselves, there is one CRT to the far right of the panels, a PC on the extreme left of the operator's desk, a number of phones and wireless communication devices on the centre of the desk and four CRTs on the right of the desk.

Figure 3 illustrates the relative layout of the CR panels for one unit at the new plant. As is standard in the nuclear industry, the top row contains the alarms, the middle row contains the displays and the bottom row contains the controls. As indicated by the labels along the top, the panels are roughly grouped according to systems. Since we are primarily interested in the impact of computer-based CR technology on operator monitoring, the primary CRTs that are embedded in the panels are also identified in Figure 3 (see below for a more complete inventory). Along the top row, there are four CRT screens that are dedicated to presenting alarm information. Information has been allocated to these four alarms CRTs roughly according to systems. For example, the CRT that is the farthest to the right in the alarm row provides information about heat transport alarms. This top row also contains more traditional hard-wired alarm windows or tiles, although these are not shown in Figure 3. Referring now to the middle row containing displays, much of this space is allocated to analogue hard-wired instrumentation (not shown in the figure). However, as illustrated in Figure 3, there are also four

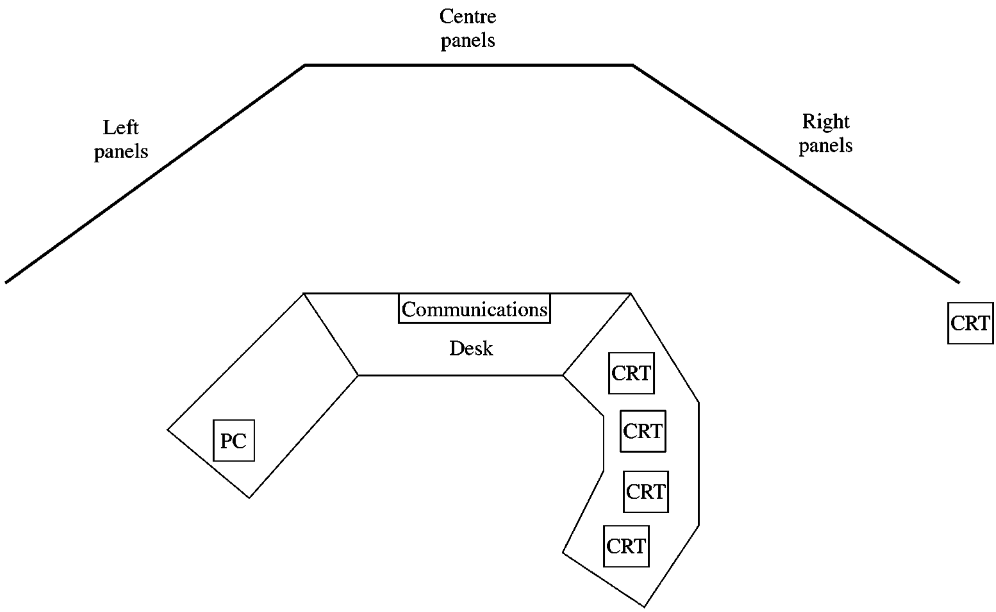

FIGURE 2. An approximate bird's eye view of the panels and workspace for one of the four reactor units in the new CR. Not to scale.

CRTs that are interspersed along the panels. These CRTs are flexible in that they can be used to display any of the numerous computer-based displays that are available to operators (see more detailed description below). Thus, unlike the alarm CRTs in the top row, these CRTs in the middle row are not dedicated. Finally, the bottom row contains the controls, including those that allow operators to select which screens to display in the four flexible CRTs in the middle row.

Although this is not shown in Figure 3, the new CR design has significantly fewer hard-wired instruments on the panels than the older or oldest CRs. In part, this is because some of the functions (e.g. refueling) have been moved to a separate area. There is, however, another reason why there are fewer hard-wired instruments on the panels at the new CR, namely that there are many more CRTs that can be used to bring up computer-based displays than at the oldest CR or even the older CR. In total, we counted 28 CRTs per unit.

- 1 PC on the LAN, shown on the extreme left of the desk in Figure 2.
- 1 CRT on the operator's desk that is used to display shut down system (SDS) information, shown at the bottom of Figure 2.
- 3 on the operator's desk that are completely flexible (the top 3 on the desk in Figure 2).
- 1 near the SDS panels to the far right in Figure 2. This CRT is slaved to the top desk CRT in Figure 2, and is used to monitor alarms during testing.
- 4 that are dedicated to displaying alarms (for the generator, electrical, nuclear, and heattransport systems), shown in the top row of Figure 3.
- 4 completely flexible CRTs embedded in the panels near the meters, shown in the middle row of Figure 3.

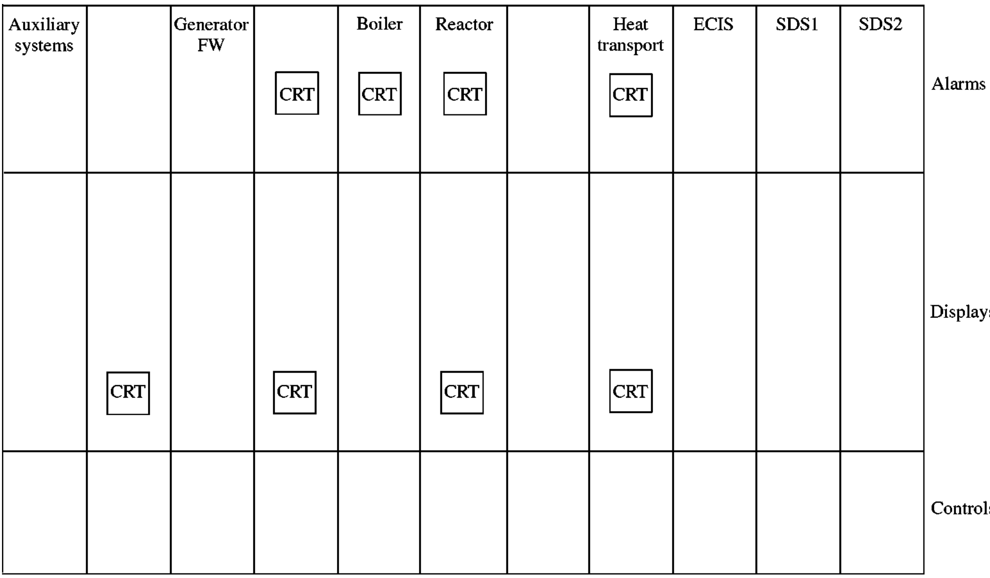

FIGURE 3. Front view of the panels for one of the four units in the new CR. Not to scale.

- 12 green CRTs embedded in the SDS panels.
- 2 small CRTs embedded in the panels. These are used primarily for testing purposes.

The flexible CRTs are controlled by light pen or dedicated push buttons.

In summary, the new CR design seems to have traded off hard-wired instruments for CRT-based displays.

4.4. CRT DISPLAY SYSTEM

Due to the more prominent role of CRT-based displays at the new CR, it is worthwhile describing them in more detail. The status displays have a hierarchical structure that is menu-driven. There are setpoint displays that can be brought up for each of the control systems for that unit. These displays provide information about the automation (i.e. the instrumentation and control system). There are also displays showing the status of the process. At the highest level in the hierarchy, there are approximately 45 system status displays. For each of these, a variety of sub-displays can be called up, including: more detailed equipment status displays; point data displays for specific variables; dedicated trend displays; bar chart displays; and bar trend displays (a hybrid of bar charts and trends). In addition, there is also a “dummy” graphical trend capability that allows operators to create and then view, customized trend plots consisting of combinations of operator-specified variables. These customized trend plots can be used to observe data that may not be available on the designer-specified trend displays. Up to 32 variables can be viewed in this way (4 pages $\times$ 4 variables $\times$ 2 digital computers). However, it is important to note that only some variables are stored in history. For these variables, previous values can be viewed when a dummy graphical trend is brought up. There is an option to put a limited number of variables for which history has not been stored into a historical mode. However, for the remainder of the variables, operators can only view their state beginning from the time that a dummy graphical trend is called up on the screen. When that dummy trend is no longer displayed on the CRT, the history for those variables is unrecorded and cannot be recovered.

4.5. SUMMARY

The computer-based display set at the new CR is both relatively comprehensive and flexible. It consists of many different display screens, many more than can possibly be viewed at any one time, even with the large number of CRTs available (see above). Also, the same display can be brought up on many different CRTs, and the same variable can be viewed in different ways. Furthermore, there is a provision for tailoring the presentation of trend displays, although there are constraints on the number of variables that can be viewed in this way at any one time and on which variables have stored history information. As we will see below, this comprehensiveness and flexibility have interesting implications for operator monitoring.

5. Sources of information for monitoring

In previous phases of this research programme, we identified a diverse set of sources of information that operators can consult to monitor the status of a unit in a traditional CR based primarily on analogue, hard-wired technology (Mumaw *et al.*, 2000). These are summarized in Table 1. Do operators at the new plant rely on the same set of information sources?

Our observations suggest that the answer is yes. We did not notice some major differences in the sources of information used by operators. One difference observed, more quantitative than qualitative, is that operators make much more use of computer-based displays at the new CR, which is expected of course, given the differences in CR technology described earlier. We also found that operators at the new plant do not seem to walk through the plant as frequently nor did they report relying on unmediated indications (cf. Vicente and Burns, 1996). Thus, the use of this type of information seems to differ from that at the oldest plant in particular. The reason for this difference is unknown, although it is possible that it takes years of experience to build up the episodic memory required to notice and effectively utilize informal information sources.

One pronounced similarity is that operators at the new plant rely heavily on the alarm CRTs to direct their attention to problems. This reinforces the pattern observed both at the older and oldest CRs.

6. What makes monitoring difficult?

In previous work, we identified a number of factors that make monitoring difficult in a traditional CR consisting primarily of analogue hard-wired technology. These factors are summarized in Table 2. Since the new plant was designed more recently, we would expect that at least some of these difficulties would be ameliorated because of improved design practices and additional operating experience. In the remainder of this section, we discuss the factors that make monitoring difficult from three complementary perspectives: improvements, new difficulties and remaining difficulties.

6.1. IMPROVEMENTS

6.1.1. System reliability. Nuisance alarms appeared with noticeably less frequency than at the older or oldest CRs. Also, operators seemed to have more trust in the indications they received from the panels. Thus, monitoring at the new CR seems to be slightly easier because there are fewer contingencies to take into account in creating and maintaining an accurate situation model (Mumaw *et al*., 2000).

6.1.2. Alarm system design. Although the design of the alarm system is very similar to those at the older and oldest CRs, it does seem to be improved in at least two ways. First, the new CR apparently has approximately 3000 alarms which is about 3 times more than at the oldest CR (we do not know how many alarms there are at the older CR). As a result, operators are provided with considerably more information that they can use to monitor the unit. Thus, the new CR alarm system design is more diagnostic or sensitive than that at the oldest CR at least.

Second, as illustrated in Figure 3, there are four different alarm CRTs at the new CR, each dedicated to displaying a particular category of alarms (e.g. generator, electrical, nuclear and heat transport systems). In contrast, at the older and oldest CRs, there were only two alarm CRTs for each unit, so the CRT alarm messages were not segregated physically in any way. All alarms were presented in a serial fashion on the same CRTs. Since the alarms are separated by type at the new CR, it is easier for operators to determine where the problem lies (e.g. in the heat transport system rather than the electrical system). They do not have to mentally categorize the alarms because the designers have done this job by allocating different alarms to different CRTs. Also, because each alarm CRT is located near the displays and controls that are pertinent to the system for which it displays alarms, the job of integrating information across alarms and displays is facilitated. For these reasons, we believe that the alarm system design at the new CR makes monitoring slightly easier than at the older and oldest CRs. However, as we discuss below, this does not mean that the alarm system does not have any limitations.

6.1.3. Displays and controls design. It was clear that the displays and controls in the new CR are better designed from a human factors point of view. Both the visibility and the layout seem to be improved over both the older and oldest CRs. These improvements facilitate monitoring because they make it easier for operators to extract information from the instruments. For example, each individual light bulb on the panel can be tested easily by pressing down on the bulb. This provides an enormous improvement over the older and oldest designs. Since operators can easily test the validity of these indications, they have a much better idea of which light bulbs are burnt out. As a result, they are much less likely to be misled by false instrument indications.

6.1.4. Radio communications. The new plant was constructed so that it is possible to use wireless radios to communicate between the CR and the field. This represents a distinct change, at least compared to the oldest plant. From what we could tell, this added information channel can facilitate coordination of activities across individuals distributed over the CR and the field. Thus, when monitoring requires coordination with personnel in the field, it can be made easier by these flexible and convenient communication devices.

6.1.5. Noise and distractions. Although we did not measure them, it seemed that there was less noise and fewer distractions at the new CR than at the other two CRs we had observed. This difference may be attributable to the CR layout (see below). Alternatively, it may be due to the fact that access to the CR is better regulated and thus there may be fewer people in the CR.

6.1.6. CR layout. As described earlier (see Figure 1), the new CR has a very different layout from either the older or the oldest designs. This seems to lead to some benefits, as well as some disadvantages (see below). The primary benefit is that sound is less likely to travel from one unit to another. As a result, there does not seem to be a problem with operators not being able to determine if an alarm is coming from their unit or an adjacent unit, as there sometimes was at the oldest CR for instance. Furthermore, the overall noise level seems lower than at the older or oldest CRs.

6.2. NEW DIFFICULTIES

6.2.1. Keyhole effect. There is another previously observed factor that makes monitoring difficult, but that is more pronounced at the new CR, so we have treated it as a new category. We are referring to the keyhole effect frequently associated with computer-based displays (Woods, 1984; Woods and Watts, 1997). In this case, the keyhole effect arises because of an interaction between several factors: (1) there are fewer analogue instruments on the panels at the new CR (e.g. there is only one strip chart recorder), so operators have to rely more on computer-based displays for monitoring than operators at the older and oldest CRs; (2) each CRT can only present a limited amount of information at a time; and (3) there are many more displays available than there are CRTs that can display them. In contrast, one of the advantages of a traditional hard-wired instrument CR design is that it presents all of the available data in parallel. Thus, operators merely have to move their eyes, or perhaps walk a little bit, to search for new information.

The computer-based displays at the new CR create a very different situation. Due to the factors listed above, operators either have to access information by serially bringing up different displays in sequence, or they have to be content to view only a subset of the available data at any one time in parallel (this subset being limited by the number of CRTs available for flexible data presentation).

An example can be offered to illustrate why the keyhole effect can make monitoring more difficult. As we discuss in the next section, operators dedicate the flexible panel CRTs to displaying valuable plant information to get an overview of the status of the unit. As a result, there are not enough CRTs to comprehensively monitor all of the control systems status displays. In fact, operators usually choose not to display the control systems status screens unless there is a specific reason to call them up. Operators therefore rely heavily on the alarm system to detect problems with the control systems (see below). Alternatively, if operators bring up a new display on a particular CRT, they lose the information that was represented on the display that was previously presented on that CRT. Of course, they could bring up that display on a different CRT, but then this would over-write a third display. This example illustrates that the keyhole effect makes it more likely that something is happening in the unit that the operator cannot see, given the displays that are currently up on the limited number of CRTs available.

Some operators we spoke to said that the keyhole effect does not impact their ability to monitor the unit effectively. They said that they only need a few displays to maintain an accurate overview of the unit, so even if several CRTs are being used for other purposes, they say that they can still keep an eye on "the big picture". Some operators also stated that, if at any time they need to monitor more displays than can be displayed on the number of CRTs available, then they will periodically cycle several displays through the same CRT. Further investigation would be required to determine how big of an impediment the keyhole effect is to monitoring at the new CR.

6.3. REMAINING DIFFICULTIES

6.3.1. System complexity. Although it seems that the new plant is in a better state of repair than the older or oldest plants, it is still the case that there are many components that contribute to the complexity of the plant. Thus, it is still not uncommon for equipment to have to be repaired, maintained or tested. As we noted in our previous article (Mumaw *et al.*, 2000), these activities temporarily cause the plant to be in a different state or even structure. As a result, the symptoms that are considered normal change accordingly. This change makes monitoring quite difficult because there is no single, fixed definition of what constitutes an expected set of indications. Operators must be able to update their situation model to be consistent with the current state of the plant, and then derive the appropriate referents for that particular state. Given the complexity of the unit (i.e. number of components and possible interactions), these cognitive activities can pose a significant demand on operators. These demands are particularly imposing for operators who are less experienced (see below).

6.3.2. Alarm system design. Although the alarm system design at the new CR does seem to represent an improvement over previous designs (see above), it also exhibits some of the same problems that we had observed at the older and oldest CRs. These limitations stem from the fact that the alarm system is not very context-sensitive. As a result, alarms that come in are frequently false positives in the sense that they are highlighting states that are expected given the current situation (e.g. operating mode, testing, maintenance, etc.). This situation can make monitoring challenging because it is up to operators to discriminate alarms that are normal for the current situation from those that are abnormal for the current situation. That is, it may be difficult for operators to detect a signal because of the large degree of noise generated by the alarm system. This is a particularly difficult task for less experienced operators (see below).

6.3.3. Displays and controls design. Although the displays and controls at the new CR are better designed than those at the older and oldest CRs, they still do not always conform to basic human factors design principles. Interestingly, problems exist with both the panel instruments and the CRT displays. Several examples are discussed by Vicente, Mumaw and Roth (1997). Thus, although it is a more modern design and represents an improvement over the older and oldest CRs, the new CR still has basic design limitations that make monitoring more difficult than it needs to be.

6.3.4. Automation design. Another remaining problem is the feedback offered by the automation (i.e. the control systems). With the replacement of many analogue controllers by digital controllers, the information available to monitor the state of the automation is increasingly provided in the form of computer-based displays. Aside from the rudimentary problems identified earlier, these displays also make monitoring difficult because they do not provide comprehensive information about the various factors that are needed to determine if a control system is operating correctly (i.e. as designed). More specifically, to uniquely distinguish automation failures from component failures, operators need to know the state of: the error signal being fed into the controller, the demand signal being sent from the controller to the component being controlled, and the actual state of that component [see Mumaw *et al.* (2000) for a more detailed discussion]. Some of this information is not provided on some of the control systems status displays. For example, some control systems displays show the demand signal but not the current state, whereas others show the current state but not the demand signal. Thus, it would be difficult for operators to detect an automation problem unambiguously by directly monitoring these displays.

Of course, eventually automation failures will lead to one or more alarms if the problem is serious enough. However, these indications can be indirect and can therefore occur at a different system or location in the unit, causing operators to have to trace back to find the root of the problem. Also, such indirect indications may happen only after a delay, which puts operators in a position where they are required to react to a problem rather than anticipate it.

Furthermore, the information that is available on control system status displays is presented in alphanumeric form, making it more difficult for operators to compare different values. This is an important point because, generally, automation faults can only be unambiguously detected by noticing that certain relationships between variables no longer hold, rather than by merely examining the value of individual variables in isolation. For these reasons, it is difficult to monitor the state of the automation directly.

Operators do not seem to be too concerned about this situation for two reasons. First, the automated systems seem to be quite reliable, so they rarely fail. Second, a failure in an automated system should generate one or more alarms. Thus, rather than regularly devoting a great deal of resources for monitoring the status of automated systems via the computer-based displays, operators instead rely extensively on the alarm system to notify them of an automation failure.

6.3.5. CR layout. As already mentioned, the new CR layout is different from those at the older and oldest CRs (see Figure 1). The linear sequencing of the unit panels makes it more difficult for operators on different units to communicate with each other, especially those who are not on adjacent units. For example, it is more difficult to determine if another operator is in need of help. Similarly, it is very difficult for operators to have an awareness of the state of, or the activities going on at, other units. For example, if one operator has to come over to help another during an abnormal event, it will be more difficult for him to keep an eye on his own unit. Both of these factors can make monitoring more difficult, although perhaps not substantially so. Thus, differences in CR layout seem to lead to a trade-off between noise level (see above) and ability to monitor other units.

6.4. CONCLUSIONS

As one would expect, the new CR is better designed in several respects than the previous generation designs at the older and oldest CRs, thereby facilitating some monitoring activities. Nevertheless, there are still design deficiencies, especially in the analogue and computer-based displays. These deficiencies are important because they make monitoring more difficult, not because the job itself is more difficult, but because the job has to be done with an interface that does not support monitoring activities as well as it could.

There is a similar “good news—bad news” story with respect to the knowledge required to develop and maintain an accurate situation model. On the positive side, the new plant and instrumentation seem to be more reliable and trustworthy than at either the older or oldest plants. Also, failures seem to occur less frequently. Consequently, the demands associated with monitoring are somewhat reduced. On the negative side, however, the plant is still very complex and the focus of training is more on the severe but infrequent events rather than on mundane but frequently encountered tasks (e.g. prioritizing work orders). As a result, the demands associated with maintaining an accurate situation model are quite substantial. That is, despite the noted improvements, monitoring is still a difficult task.

There is one new factor related to the change in CR technology that seems to add to the difficulty associated with monitoring, namely the keyhole effect. Although operators state that this is not a problem, the reduced visibility brought about by the keyhole effect is a potential threat to effective monitoring.

In summary, most of the factors that made monitoring difficult at the older and oldest CRs can also be found at the new CR. Some of these difficulties have been slightly ameliorated, but most of them remain. Monitoring is still a challenging task that requires extensive skill and experience to perform efficiently and reliably. Does the change in CR technology improve or inhibit operators’ abilities to deal with these challenging demands?

7. Strategies that operators use for monitoring

In the previous work, we outlined a number of clever strategies that operators have adopted to monitor the plant more effectively (Vicente & Burns, 1996; Mumaw *et al.*, 2000). Do operators at the new CR use the same or a different, set of monitoring strategies?

7.1. BUILDING AND MAINTAINING A SITUATION MODEL

At the older and oldest CRs, we noted that some of the operators' activities explicitly serve the purpose of building and maintaining an accurate situation model, which in turn directs their attention and sets their expectations during monitoring activities. These findings were replicated at the new CR. For example, the shift turnover serves as an important mechanism for operators coming on shift to update their situation model. Similarly, all operators take printouts at the beginning of a shift and then review these printouts to obtain a more detailed understanding of the current state of the unit. If operators are on an unfamiliar unit, or if they have been away for an extended period, then they will devote extra effort to these activities. For example, we saw an operator who had not been on shift for 10 days read all of the logs, take more detailed printouts, and conduct a more thorough turnover. It seems that the effort that operators devote to updating their situation model is a function of the time since they last worked on that unit.

While our observations in this category largely confirm our previous findings, there was one interesting change that can be attributed to a difference in CR technology. At the older and oldest CRs, we had observed operators walk down the control panels at the beginning of a shift to briefly familiarize themselves with the current state of the unit. In contrast, at the new CR we observed that some operators would instead cycle through a number of different computer-based displays at the start of the shift, essentially for the very same purpose. This example is simple but interesting because it shows that the task goals can be the same in CRs with different technology, but that the behavioural manifestations of these goals are shaped by the CR technology. This theme appeared several times in our observations.

7.2. KNOWLEDGE-DRIVEN MONITORING

Just as at the older and oldest CRs, we found that operators at the new CR frequently engage in knowledge-driven monitoring of the unit. Rather than merely reacting to stimuli in their environment in a data-driven fashion, operators actively seek out specific information, as a function of the current situation. Several examples of this type of activity were observed.

(1) During refuelling, status alarms are actively sought out to confirm that everything is going as planned. If the expected pattern of alarms is not obtained, then this is a sign that there is some sort of anomaly.
(2) After refuelling, we saw one operator compare the new thermal power value to the old value on a printout to confirm that the refuelling operation was successful.
(3) One operator regularly checks the primary heat transfer pump seals at the beginning of a shift because these seals are known to fail on his unit.

Many other similar examples of knowledge-driven monitoring were observed.

Again, we observed the shaping effect of the CR technology. For instance, if there is a reason to monitor a certain variable particularly closely, operators at the older and oldest CRs might open a strip chart recorder door or create an external reminder to monitor the variable. These strategies offload the operators' memory. At the new CR, operators might achieve the identical goal by temporarily bringing up a computer-based display on one of their desk CRTs. A frequently encountered example is the use of context-specific, dummy graphical trends during refuelling. Operators will customize a set of trends that are the most relevant to the channels being refueled so that they can closely monitor these variables during refuelling. Note, however, that by temporarily dedicating a CRT to knowledge-driven monitoring, operators have to remove another display from that CRT. Thus, they will not have access to this information (see the earlier discussion of the keyhole effect).

This contrast in the activities required to achieve the same objective with different CR designs is instructive because it reveals a lesson that may be generalizable. Analog hard-wired instruments are fixed in their location and grouping, so no degrees of freedom are intentionally provided in the design for tailoring the information to a particular local context. As a result, operators have to go outside of the means explicitly provided by the designer to tailor the displays to the task at hand. Usually, this involves using *ad hoc* methods (e.g. opening the door on strip chart recorders, creating external reminders). In contrast, computer-based displays offer a wealth of designed-in flexibility in terms of information content, location, grouping and form. Operators can exploit these built-in degrees of freedom to tailor the information presentation to the task at hand (e.g. creating a dummy graphical trend display to support monitoring during refuelling). Although these methods of tailoring were not anticipated by designers, they rely on interface functionality that was explicitly built into the CR. Whereas, in hard-wired CR designs, operators have to go outside of the means explicitly provided by designers, in computer-based CR designs, operators can work within the means provided by designers (if the designer had the foresight to provide the relevant degrees of freedom). This finding will be revisited below.

7.3. FACILITATING ACTIVITIES

In previous phases of this research (Mumaw *et al*., 2000), we observed that operators at the older and oldest CRs have developed an ingenious set of strategies that reduce the cognitive demands imposed by monitoring tasks (see Table 3). As this subsection shows, the same strategies can be used to capture the facilitating activities of the new CR's operators, although the manifestations of these strategies are again shaped by the CR technology in many cases.

7.3.1. Reduce noise. Operators at the new CR also exhibited many different strategies whose common goal is to facilitate monitoring by reducing the noise created by the CR interface.

Some of the strategies that operators used to reduce noise are identical to those exhibited by operators at the older and oldest CRs. For example, operators frequently cursor off nuisance alarms from the alarm CRT screens. This reduces the clutter on these screens by minimizing the number of uninformative alarm messages.

The shaping influence of the CR technology can also be seen in these strategies. At the older and oldest CRs, operators sometimes changed or jumpered alarm setpoints in cases where many annoying nuisance alarms were being generated by a particular variable. Many times, the change of alarm setpoints could be accomplished by taking advantage of the adjustable alarm setpoints on some of the analogue meters (a feature that was not explicitly designed for this purpose). At the new CR, there is only one analogue meter of this type on each unit, so operators change and jumper alarm setpoints from the CRTs instead. This provides another example showing how hard-wired instruments force operators to develop *ad hoc* facilitating activities, whereas flexible computer-based displays can provide built-in means that operators can rely on to facilitate monitoring.

7.3.2. Enhance signal. Several cases were observed where operators enhanced the signal available to them in order to facilitate monitoring. For example, when operators want to monitor a particular variable very closely (e.g. annulus gas system), they can change the range of the *y*-axis on a computer-based trend display. Reducing the range of the variable magnifies small changes in state, and thereby improves the saliency of the signal. This strategy shows how operators can exploit the flexibility provided by designers of computer-based displays to tailor information presentation to a local context.

7.3.3. Document baseline or trend. As in our previous studies, we found that operators at the new CR frequently document baselines or trends by writing down values or by printing out screen dumps. These activities facilitate monitoring by offloading operators' memory. If they want to see if a variable has changed and by how much, they can compare the current value to the documented baseline or trend instead of having to rely on their memory. For example, operators almost always print out baselines at the beginning of the shift or just before refuelling.

It is interesting to note that the paper medium is used, even though the history of many of these variables can be accessed in computer-based form. We believe that operators prefer to use printouts for two reasons. First, they can write on the printouts to highlight particular values or trends. Second, by comparing a printout with a computer-based display, only one CRT is used. Otherwise, two CRTs might have to be used to provide salient presentations of the current and previous values of a variable in parallel.

7.3.4. Create a new indicator or alarm. There were quite a few examples of operators exploiting the flexibility of the computer-based display systems to create new indications or new alarms. Perhaps the most important example was the creation of overview display information to compensate for keyhole effect of CRT-based systems. The 4 CRTs embedded in the unit panels (see Figure 3) were consistently used by all operators to display a set of plant variables that provide an overview of plant operational status. These CRTs are flexible in that they can be used to display any computer-based display available in the system. However, this flexibility was rarely employed. Instead, operators dedicated a specific display to each of these CRTs when at full power. Referring to Figure 3, the panel CRT on the far left near the generator panel was used to display trend graphs of output variables, such as megawatts out. The second panel CRT near the boiler panel was used to display boiler levels and setpoints. The third panel CRT near the reactor was used to display trend graphs of reactor power and zoning levels. Finally, the fourth panel CRT near the heat transport panel was used to display trend graphs of heat transport pressure control.

This dedicated use of CRTs has two significant features. First, the way in which operators decided to allocate these four displays to the four CRTs obeys human factors design principles. Each display was dedicated to the CRT that was closest to the alarms, meters and controls pertinent to the information represented in that display. For example, the reactor power and zoning levels display was dedicated to the CRT in the reactor panel. This system-based grouping is a good design practice because it causes the information displayed on the CRT to be well integrated with the associated alarms, meters and controls. This makes monitoring easier because it reduces the integration demands required of operators.

Second, the variables that the new CR operators have chosen to display on these four CRTs correspond quite closely to the variables that operators at the oldest CR monitor periodically in order to get an overview of the unit (Mumaw *et al.*, 2000). The difference is that operators at the oldest CR quickly consult this information on a regular basis simply by moving their eyes. At the new CR, on the other hand, operators can only do the same thing if they first dedicate the appropriate displays to the CRTs. Thus, the practice we observed at the new CR can actually be interpreted as a direct response to the keyhole effect mentioned earlier. Since computer-based information is presented serially rather than in parallel, operators select the displays that they need to get an overview and dedicate those displays to the four panel CRTs. In other words, operators have created a make-shift overview display because none was provided to them by designers. While the individual displays were already made available, the configuration used by operators was not. So in this sense, the practice we observed at the new CR can be categorized as creating a new indication (an overview display). All of the operators we spoke to have adopted this practice.

We also found examples of activities that create a new indication or alarm that were more similar to those observed at the older and oldest CRs.

(1) If an operator suspects that there is a problem with a particular variable, he may tighten up the alarm limits on that particular value. In this way, he will get a more sensitive "early-warning" alarm notifying him that the value is in fact drifting from where he expects it to be.
(2) Another example of creating a new alarm was observed when an outlet temperature on pump seals creeps up and exceeds the setpoint. In this case, the operator will use the computer-based display to move the setpoint up by 5°. Thus, the alarm system will notify him if there are further increases, thereby relieving him from having to remember to watch that variable periodically.
(3) Another example occurs when operators are draining the pressurizer, an operation that takes 10–12 h. In this case, the operator will move the setpoint alarm near to the fully drained level. As a result, he will receive an indication that the draining operation is almost complete rather than having to devote his scarce attention resources to periodically monitoring pressurizer level.
(4) A slightly different example of creating a new indication or alarm was observed when a variable that needs to be observed does not have its history stored in the computer. In this case, operators will take advantage of the fact that there is a second, related variable that does have history stored. A specific example involves two correlated variables, moderator cover gas pressure and moderator level. The former is stored with a history, but the latter is not. If the operator wants to get information about moderator level changes in the past, he can pull up the history on the cover gas

pressure trend to see changes that are related. Another example of the same technique was observed in a case where the operator wanted to view the history of a valve that was opening and closing. There was no history stored for this measure, nor was there history on the flow through valve. In some cases, there may be a history of pressure changes or temperature changes in the tank that this flow goes into. By using that history, the operator may be able to infer the number and timing of the valve openings.

These examples are interesting because they are analogous to strategies that we had observed at both the older and oldest CRs. The primary difference is that the strategies in the older and oldest CRs were frequently implemented using the adjustable alarm setpoints on the analogue meters rather than using the computer system. This difference is illustrative of the general point made earlier. With hard-wired instruments, operators have to go outside of the intended means provided by designers to tailor information presentation to the needs of a particular task (e.g. adjust the alarm setpoints on the analogue meters). With computer-based displays, on the other hand, it may be possible to tailor the information presentation by using the flexible features explicitly built in by the designers (e.g. changing alarm limits on the computer displays).

We observed several other examples of creating a new indication or alarm at the new CR that were implemented, not on the computer system, but with other media. For example, during refuelling, a manual valve needs to be throttled in the field. However, there is no computer-based display indication of the valve position. As a result, when that valve is throttled, a Panel Information Notice is placed on the board that indicates by how much the valve was throttled.

7.3.5. Create external reminder for monitoring. To reduce the demands on their memory, operators frequently create external reminders for monitoring. Several examples of this type of facilitating activity were observed at the new CR, just like at the older and oldest CRs.

(1) The simplest example is that operators frequently use a scratch pad as an external reminder to monitor one or more variables.
(2) When monitoring for LLDS (low-level drained state), operators need to consult a set of variables that are not typically monitored. Consequently, operators have created some special black plastic labels (like panel tags, and about 4" × 5") to place near the CRT to help remind them of the variables that need to be monitored.
(3) Another example is interesting because it is related to the CR technology. Since there are fewer CRTs than displays that the operator may want to consult at any one time, operators sometimes write themselves a reminder to pull up and monitor a particular display periodically. For instance, we saw a written note on a post-it reminding operators to periodically bring up a computer-based display so that they could monitor the ECI system.

7.3.6. Create external cues for action or inaction. Like the operators we observed at older and oldest CRs, operators at the new CR also facilitate monitoring by creating external cues for action or inaction, thereby reducing the cognitive demands placed on them. Many examples of this type of activity were also observed.

(1) A red printed plaque was used to warn operators that an approved work practice (AWP) was in effect, and that therefore certain activities should not be performed.
(2) Tags that are green (caution), yellow (work permit), or blue (op memo) are used as reminders for inaction.
(3) Paper signs are also sometimes put up as external cues for inaction. In one case, we saw a sign reminding operators not to remove a computer-based display from a particular CRT. In another case, we saw a sign put up on the reactor panel. This was a cue to indicate that fuel handling activity was going on in containment, and that certain activities such as changing power should not be performed.
(4) Interestingly, when discussing alarm management, one operator said he would sometimes keep a nuisance alarm up on the CRT rather than cursoring it off the screen. His rationale for doing so was that the alarm would serve as a reminder for him to take an action (e.g. to get the field maintenance people to fix the problem, to monitor the variable more closely or to periodically bring up a trend).
(5) Finally, operators sometimes also use field operators as cues for action or inaction. For example, one operator told us that when he is supposed to communicate with a field operator during a busy period of activity, he sometimes tells field operators to phone him back if they do not hear from him in 10 min. Just as the operators at the older and oldest CRs were using the alarm system to grab their attention, this operator was relying on other personnel to get his attention in case he became too occupied or overloaded.

7.3.7. Employ additional operators. Operators at the new CR also rely on additional operators to facilitate monitoring, just like operators at the older and oldest CRs. For example, it is not uncommon for an operator to direct an assistant to monitor a display or an instrument when the operator's workload is high.

7.4. NEW FACILITATING CATEGORY: CREATE EXTERNAL DESCRIPTOR

All of the types of facilitating activities described so far have been identified in previous phases of this research. Our observations at the new CR led to the identification of a new category of facilitating activities that had not been identified before. In some cases, operators create an external descriptor, whether it be of a variable label, variable limits or variable state. This descriptor is subsequently used as an external referent that aids in interpreting observations, thereby relieving the load on operators' memory. Several examples of this activity were noted.

(1) In one case, we saw an operator ask a field operator to make up a list of all of the nuisance alarms that could be brought in by the repair work that the field operator was going to be doing. The operator was then going to use this list as a referent for monitoring alarms. If an alarm came in that was on this list, then he would know that it was probably a nuisance alarm. On the other hand, if an alarm that was not on the list came in, he would know that it was probably caused by some other factor that might require further investigation.
(2) In another case, a post-it was being used to remind operators of what the limits were for a dummy graphical trend display. These limit values were also documented in an

operating memo, but the external descriptor served as an easier referent, saving the operator from having to look up the information in a binder.

(3) The dummy graphical trends display the code numbers of the variables on each trend, but they do not display verbal descriptions of those variables. Thus, operators use magnetic labels to indicate what variable label corresponds to the data being trended. This offloads the operator from having to look up or memorize, the code associated with each variable label. A similar example was found when monitoring heat transport header levels. When the operator puts up trend plots of the headers, he may not do so according to the order of header number. Thus, a magnetic sign is placed under the dummy trend to display the correspondence between the code number and header number.

Like the other facilitating activities we had already documented, these external descriptors reduce the cognitive burden on operators during monitoring.

7.5. CONCLUSIONS

The strategies that operators use at the new CR to make monitoring easier are largely the same as those that we had previously captured (i.e. building a situation model, knowledge-driven monitoring, and facilitating activities). However, in many cases, the same activities are performed using different behaviours, thereby showing the shaping effect of the CR technology. In particular, we saw several cases where the built-in flexibility of the computerized systems facilitated tailoring activities. Nevertheless, we observed new challenges raised by the computer-based technology. For example, the largely serial presentation of information on the CRTs can create a keyhole effect, and thus, a need for the secondary task of display management. Operators responded to these new demands by developing coping strategies. The creation of an overview display through the dedicated use of the four panel CRTs provides a good example.

8. Discussion

The most important differences between traditional and computer-based CRs seem to be localized to two factors: (1) procedural and declarative interface knowledge, and (2) strategies for creating or extracting information.

8.1. INTERFACE KNOWLEDGE

The impact of CR technology on operators' procedural and declarative interface knowledge is relatively straightforward. In a hard-wired CR, information is presented in a static, parallel form so the main requirement on operators for monitoring is to know where all of the different indicators are located. In a computer-based CR, however, there is a significant increase in the amount of knowledge required to operate the interface. Part of these demands arise from the fact that information is presented serially. Thus, operators need to know how to bring up the information they want to display on CRTs. The other part of the increase in knowledge demands arises from the fact that the computer-based displays are much more flexible than the hard-wired instruments. The same information can be displayed at different time scales, at different ranges, in different locations, in different forms and in different groupings. Consequently, the operator has to have much more knowledge about the interface (not the plant) to resolve the degrees of freedom offered by the flexible design of the interface. In summary, changes in CR technology have significant but relatively straightforward implications for procedural and declarative interface knowledge.

These differences in knowledge are intimately linked with differences in monitoring behaviour. In a hard-wired CR, much of the work is done with the eyes (i.e. visual scanning). In contrast, with a computer-based CR, more of the work needs to be done with the hands as well (i.e. interacting with the computer to search for and customize displays). An important question is whether these differences result in a net benefit or decrement in performance. On the one hand, one might argue that the flexibility provided by the computer-based medium should result in a performance improvement because it allows operators to view information in a form that is tailored to different types of contexts. This should reduce the need for the work-arounds in which operators engage in traditional CRs to facilitate monitoring. On the other hand, one could just as well argue that this flexibility comes at the price of an increase in the time and effort that operators spend manipulating the interface rather than monitoring the unit. Deeper insight can be gained into this issue by comparing the strategies that operators use to create and extract information in hard-wired vs. computer-based CRs. As we will see, differences in strategies turn out to be more subtle and more interesting than the differences in knowledge.

8.2. STRATEGIES FOR CREATING/EXTRACTING INFORMATION

Figure 4 tries to capture the implications of CR technology for monitoring strategies by comparing the degrees of freedom in hard-wired instruments vs. computer-based displays. There are two diagrams, each with a polygon that funnels in from top to bottom. The width of each polygon is intended to represent the degrees of freedom for display presentation, so that a broad width represents many possibilities and a narrow width represents few possibilities. The diagram on the left represents the intended degrees of freedom that a designer builds into a CR based on hard-wired instruments. With this technology, the designer is required to make numerous decisions that are then frozen into the design (e.g. what variables to display, which variables to trend, where each variable should be located, how variables should be grouped together, in what form the variables should be presented and so on). As a result, the intended design leaves no degrees of freedom for information presentation—everything is specified ahead of time. This is indicated on the left side of Figure 4 by the funnelling down of degrees of freedom to a single point where no choices remain. One way to think of this is that the CR is intended to have only one "look", which does not change as a function of context.

The word "intended" is used because, as we have seen throughout this research, in practice things are quite different. Since the CR is not tailored to operators' activities, monitoring can be a very difficult and demanding task. To reduce these demands to a manageable level, operators will adopt facilitating activities that essentially contextualize the CR to make it fit their needs at the time. These facilitating activities, illustrated on the left of Figure 4 by a dotted triangle, have two important characteristics. First, they are accomplished by using means that are outside of those that are intentionally

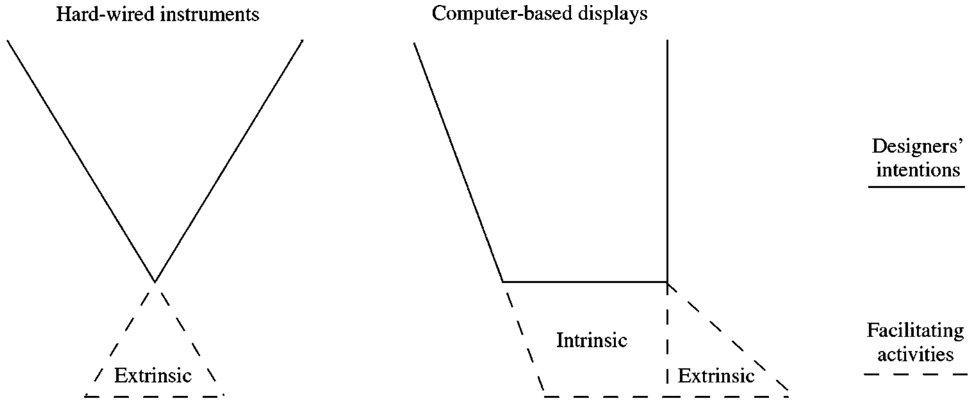

FIGURE 4. A graphical depiction of the impact of CR technology on monitoring based on the number of degrees of freedom in hard-wired instruments vs. computer-based displays. See text for description.

provided by the designer. At the oldest CR, for instance, we frequently saw operators using post-its, creating external reminders, opening up strip chart recorder doors and manipulating alarm setpoints on analogue meters. *None of these means were anticipated or intentionally provided by the CR designers*. We will refer to these as *extrinsic* facilitating activities. Second, these facilitating activities have the effect of opening up the degrees of freedom in the CR. Different facilitating activities are adopted at different times, so the CR no longer has one "look". Rather, it is made to have different looks depending on what the operator is currently doing. The significance of these two points can be made clearer by examining the degrees of freedom associated with computer-based displays.

The graphic on the right-hand side of Figure 4 shows a very different pattern. Due to their flexibility, computer-based displays intentionally leave a considerable number of degrees of freedom to the operator. For example, at the new CR, operators can decide: on which CRT to put a given display, what the time scale on a trend graph is, what the range on a trend graph is, what form to present a variable in (e.g. trend, bar, bar-trend, digital), what variables are to be graphed together and so on. Not only can operators make these decisions, but they can make them over and over again in the sense that these presentation parameters can be readily changed in a moment. This situation is indicated on the right-hand side of Figure 4 by the funnelling down of degrees of freedom to a line (rather than a point), indicating that many choices remain.

There are several interesting implications that follow. First, when operators are required to perform a particular monitoring task, they now have flexibility that they can exploit to present information in a way that makes monitoring easier. When this occurs, the operator is using means that were intentionally provided by CR designers. For example, the fact that the computer-based display allows operators to change the range on a trend graph is a result of a deliberate decision on the part of a designer. Facilitating activities that are performed using such means can be said to be *intrinsic*. Interestingly, we observed that facilitating activities had a tendency to reduce the degrees of freedom, relative to the degrees of freedom provided by the technology. Operators do not use all of the flexibility offered by the interface. In the new CR, for instance, there are at least thousands of different "looks" that the CR can have depending on which displays are brought up on which CRTs, and how those displays are configured. Intrinsic facilitating activities pick out one useful display configuration from myriad available possibilities, a configuration that makes the task at hand easier to perform.

So far, the discussion of the degrees of freedom in a computer-based CR has proceeded under the assumption that the flexibility offered by the designer is sufficient to tailor information presentation to facilitate monitoring. But as the examples we cited earlier reveal, this is not always the case. As shown in Figure 4, operators using a computer-based display sometimes also have to resort to extrinsic facilitating activities because they cannot make monitoring easier within the capabilities afforded by the designer. In these situations, we see operators resorting to post-its, tags and paper messages, just like the operators at the older and oldest CRs. Even in computer-based CRs, extrinsic facilitating activities have the role of opening up the degrees of freedom intentionally provided in the design to reduce the demands associated with monitoring.

8.3. IMPLICATIONS

1. Designers of complex, dynamic work domains should acknowledge that they cannot comprehensively anticipate operators' monitoring needs, and so facilitating activities will always be needed. However, it seems preferable to create interfaces that systematically support such local decision-making than to just expect such operator adaptation to occur in an informal manner (Vicente, 1999). The interface designed by Guerlain and Bullemer (1996) provides a good model for this type of design approach.
2. As a step towards designing such adaptive systems, valuable information can be collected by observing the extrinsic and intrinsic facilitating activities in which operators are currently engaged.
3. As a further step in this direction, the unique ways in which software media can be manipulated in the service of facilitating activities needs to be better understood (see Gaver, 1996). New insights in this area could provide designers with ideas for how to turn extrinsic facilitating activities into computer-based intrinsic facilitating activities.
4. Examples of facilitating strategies of the type we have collected in this, and previous, research could be compiled and used as a training device for new operators. This would be particularly valuable at plants where a significant number of experienced operators will be retiring at the same time, as is the case at the new plant studied here.
5. More attention should be paid to basic human factors issues in the design of CRs, whether they be based on hard-wired instruments or computer-based displays. There is still considerable room for improvement.

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