Cognitive Engineering Laboratory

Cognitive Functioning of Control Room Operators: Final Phase

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Final Contract Report for Contract 96-175

"Cognitive Functioning of Control Room Operators - Final Phase"

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EXECUTIVE SUMMARY

This report describes the final phase of a three-phase research program conducted for the AECB. The overall goal of the program was to develop a better understanding of operator cognitive monitoring under normal operations. In previous phases, observations were made at the Pickering B and Bruce B control rooms. A preliminary model of operator monitoring was developed, describing: the sources of information available for monitoring; factors that make monitoring difficult; cognitive and behavioral activities associated with monitoring; and strategies that operators have developed to facilitate monitoring. This final phase consisted of two main research activities. First, a review of the literature on the impact of computer-based technology on operator cognitive monitoring in the nuclear industry was conducted. Second, observations were conducted in the newer computer-based control room at Darlington to: a) evaluate the generalizability of the preliminary model developed in previous phases; and b) determine the impact of computer-based control room technology on operator monitoring. Eleven different operators were observed for a total of approximately 88 hours.

The literature review revealed virtually no research directly on the topic of interest. This highlights the importance of the work presented in this report. As far as we know, it is the only systematic set of field studies investigating the impact of control room technology on operator monitoring under normal operations in the nuclear industry.

The field study observations led to the following set of findings:

1. The sources of information available for monitoring at Darlington are essentially qualitatively the same as those at Pickering B and Bruce B, although there are obvious quantitative differences.
2. Most of the factors that made monitoring difficult at Bruce B and Pickering B can also be found at Darlington. Some of these difficulties have been slightly ameliorated, but most of them remain. Monitoring is still a challenging task requiring extensive skill and experience.
3. The strategies that operators use at Darlington to make monitoring easier are largely the same as those previously captured in our model. However, in many cases, the same activities are performed using behaviours, thereby showing the shaping effect of the control room technology.

4. The most important addition to our preliminary model is the workload regulation activities that operators use to improve the reliability of monitoring.

Based on these findings, a revised model of operator monitoring is described. This model accommodates both the differences and similarities that were observed in the three plants that were studied during this research program. Therefore, it can be used to characterize the influences of the control room technology on monitoring.

INTRODUCTION

This document is a final contract report describing the work conducted under AECB contract 96-175, "Cognitive Functioning of Control Rooms Operators - Final Phase".

Background

In the previous phases of this series of contracts (2.376.1, 2.76.2, 2.376.3), control room operators at Pickering B and Bruce B nuclear generation stations (NGSs) were observed for their cognitive behaviour during normal operations (Mumaw, Roth, Vicente, & Burns, 1995, 1996; Vicente & Burns, 1996). Data were collected and the results of these phases indicated that experienced control room operators have developed a variety of informal effective strategies that are "passed along by word of mouth". It was also found that a high level of reliability is achieved because of these strategies, and that monitoring is influenced considerably by cognitive resource limitations. These findings have practical implications for systems integration, training, and interface design.

In this final phase, observations were made at Darlington NGS, a more highly automated plant than either Pickering B or Bruce B, to determine whether the model developed in the previous phase of work is still valid for more advanced plants. In addition, we were interested in determining whether increased automation has any impact on the strategies employed for operator monitoring.

Objective

The objective of this phase of work was to assist the AECB staff in completing the development of a model of operator monitoring activities to provide an improved understanding of current operator behaviour in normal plant operations with a high degree of systems automation.

Scope of Work

A human factors engineering analysis of activities was conducted to assess the degree to which the control room interfaces support monitoring and situation assessment functions, as defined below. To do so, the data collection methodology based on experience gathered during previous projects was adopted to collect data from Darlington NGS by observing control room

operators' monitoring activities. The process model derived from these analyses is related to human system interfaces and task demands in the CANDU control room.

LITERATURE REVIEW

Purpose

In order to put our work into context, we conducted a review of the literature on the impact of changes in control room technology on operator cognitive monitoring in NGSs. This highly-focused literature review is intended to complement, not expand, the broader review of operator monitoring behaviour conducted in the first phase of this project (Mumaw et al., 1995). By compiling the existing findings of how computer-based control room designs have been found to impact cognitive monitoring, we can determine to what extent the findings at Darlington NGS are generalizable or typical.

Sources Consulted

A number of different sources were consulted to perform this review. Particular emphasis was placed on searching conference proceedings that were more likely to contain papers by corporate authors in the nuclear industry. Specifically, the following sources were consulted:

- Proceedings of CSEPC 96: Cognitive Systems Engineering in Process Control. Kyoto, Japan: Kyoto University, 1996.
- Proceedings of NPIC & HMIT '96: The 1996 American Nuclear Society International Topical Meeting on Nuclear Plant Instrumentation, Control, and Human-Machine Interface Technologies. La Grange, Park, IL: ANS, 1996.
- Proceedings of the Topical Meeting on Nuclear Plant Instrumentation, Control, and Man-Machine Interface Technologies. La Grange, Park, IL: ANS, 1993.
- Advances in Human Factors Research on Man/Computer Interactions: Nuclear and Beyond. La Grange Park, IL: ANS, 1990.
- Proceedings of the Fourth European Conference on Cognitive Science Approaches to Process Control. Birkerød, Denmark: CRI, 1993.

- Proceedings of the Third European Conference on Cognitive Science Approaches to Process Control. Cardiff, Wales: University of Wales, 1991.
- Proceedings of the Second European Conference on Cognitive Science Approaches to Process Control. Siena, Italy: University of Siena, 1989.
- Proceedings of the First European Conference on Cognitive Science Approaches to Process Control. Marcoussis, France: University of Paris, 1987.
- Proceedings of the Third Annual Symposium on Human Interaction with Complex Systems: HICS '96. Piscataway, NJ: IEEE, 1996.
- Proceedings of the 1994 Symposium on Human Interaction with Complex Systems. Greensboro, NC: North Carolina A&T State University, 1994.
- Mouloua, M., & Parasuraman, R. (1994). Human performance in automated systems: Current research and trends. Hillsdale, NJ: Erlbaum.
- Proceedings of the 6th IFAC/IFIP/IFORS/IEA Symposium on Analysis, Design and Evaluation of Man-Machine Systems. Cambridge, MA: MIT, 1995.

A modest library search was also conducted within the resources available for the contract.

Findings

Despite the efforts just described, we found virtually no research directly on the topic of our review except for our own papers describing previous phases of this project (Vicente, Burns, Mumaw, & Roth, 1996; Vicente, Mumaw, Roth, & Burns, 1996). We did find several papers describing instrumentation & control upgrades (e.g., Colin, 1996; Yoder et al., 1996), experiences with advanced control rooms for fossil fuel plants (e.g., Gaddy et al., 1993), and experiences with digital control room designs (e.g., Chou et al., 1993). One might think that each of these efforts would include information about how advanced technology in the control room impacts operator cognitive monitoring, but unfortunately this is not the case. Instead, these papers focus primarily on hardware, software, financial, or scheduling issues associated with the implementation of advanced technology. When they do refer to human factors issues, the discussions tend to be quite brief, not very informative, and not centred on monitoring. Most importantly of all, these papers

do not present any detailed empirical evidence, whether it be experimental or observational, on how control room technology impacts operator monitoring activities.

One exception to this general pattern was a study reported by Heslinga and Herbert (1995), who presented designers, managers, and operators of conventional power plants with a questionnaire to determine their experiences with the introduction of advanced human-machine interface (HMI) designs. The questionnaire consisted of 143 questions in total, and was distributed to participants in eight European countries who had experience either with new plants or with retrofits. A total of 57 interviews were conducted using the questionnaire, with an average duration of approximately 2 hours.

The results revealed several findings that are pertinent to operator cognitive monitoring. First, in advanced control rooms where conventional instruments are still available, operators tend to return to these more familiar sources of information, especially in abnormal situations. The traditional instruments seem to provide a better overview and more direct access, so operators are able to find information more efficiently than with the newly-introduced computer-based displays. Second, computer displays that are based on plant systems do not provide the information operators need in non-routine situations, where there is little time to search for controls or information across a suite of hierarchically-arranged displays. Third, information should be provided so that operators can become familiar with the status of automation at all times. Fourth, and perhaps most importantly of all, "the current advanced HMI systems do not always have an overview panel or overview display presenting essential information. Such an overview feature was seen as an important aspect of the new HMI by the users" (Heslinga & Herbert, 1995, p. 257). It is important to point out that these limitations may not be inherent disadvantages associated with all advanced control rooms. Instead, they may be specific to the designs used by the respondents in Heslinga and Herbert's study.

In fact, there is additional evidence to support this interpretation. Kawano et al. (1996) conducted a full-scope simulator evaluation of the A-PODIA advanced control room designed by Toshiba. It was designed according to sound human factors practices and principles, and contains

several features which are markedly different from traditional control room designs, including: a hierarchical alarm display, a large flexible wall projector that can be used to present any computer-based display, advanced automation, CRT-based main console displays, and a wall panel display showing a fixed mimic overview of the plant (Makino et al., 1993, 1996). A-PODIA is perhaps the most advanced nuclear power plant control room currently in operation, with the first unit having come on-line late last year at the Kashiwazaki-Kariwa plant in Japan. Thus, the experiment conducted by Kawano et al. is very important because it is one of the few, if not the only, comprehensive and representative empirical evaluations of advanced control room designs.

The A-PODIA design was compared against the existing previous-generation control room design which consists of a combination of hard-wired instruments and CRT-based displays. Objective and subjective performance data were obtained from crews who were in for retraining on the conventional design and for transition training on the A-PODIA design. Two scenarios were selected: a typical scram event, and a very challenging multiple failure event (all CRTs down, plus loss of feedwater, plus failure in the high-pressure emergency core cooling system). Only a preliminary analysis of the data is presented by Kawano et al., so the conclusions that can be derived from that paper are limited. The results discussed suggest that, despite the lack of familiarity with the new design, operator acceptance was high. Also, the large wall display panel in particular seemed to be effective in assisting operators in the multiple malfunction scenario. This advantage was attributed to improved communication and coordination among the crew members, and a better overview of plant status. In general, the results indicated that the A-PODIA design provided better support for operator activities than the traditional design. This finding suggests that it is possible to design advanced control systems that enhance operator monitoring, if the proper design practices and principles are followed (see Makino et al., 1993, 1996).

Conclusions

Given the paucity of work in this area, we cannot provide any definitive conclusions. However, the following points can be put forward as hypotheses to be evaluated in future work:

1. Computer-based HMIs can make it more cumbersome for operators to find information and act on the system in an efficient manner compared with traditional control rooms.
2. Computer-based HMIs can make it much more difficult for operators to get an overview of the plant compared with traditional control rooms.
3. It is important that operators be provided with rich information that they can use to become familiar with the status of automation at all times.
4. It seems that it is possible to overcome these limitations by designing computer-based HMIs according to sound human factors practices and principles.

This list of issues will be revisited below within the context of our findings at Darlington NGS.

The fact that we found very little relevant literature investigating the impact of advanced control room technology on operator cognitive monitoring does not mean that such research has not been conducted. It is possible that papers on this topic exist in sources that we did not consult or do not know about. Furthermore, it is also quite likely that this type of research has been conducted by corporate design or research groups, but that the results have not been publicly released because of their proprietary and sensitive nature, especially if the results were not flattering to the organization in which the work was conducted. Although each of these factors may be at work, we also suspect that one of the main reasons why our literature review was not very successful is that the nuclear industry does not have very much operating experience with computer-based control rooms and highly-automated plants. Most plants in operation today are based on more traditional designs, using hard-wired control room instrumentation. It is only in the last few years that control rooms based more on computer-based interfaces, such as that at Darlington NGS, have become operational. And because of industry pressures to focus on immediate problems, the need to examine in a systematic way how advanced technology impacts operator monitoring may not be perceived as a top priority. If so, then it would not be surprising to find that few efforts have been made in this direction.

While perhaps disappointing, the findings from this literature review emphasize the importance of the present project. By investigating operator monitoring at Darlington NGS and

comparing our findings with those obtained at Pickering B and Bruce B, we are in an excellent position to make a unique contribution to the research literature and to the nuclear industry as a whole. Since virtually all major NGS vendors are designing advanced control rooms based on computer technology for next-generation plants (Vicente, 1992a, 1992b), the lessons we extract from this sequence of studies on operator cognitive monitoring should be of great interest, not just to the AECB, but to the international nuclear power community as well.

FIELD STUDY METHODOLOGY

Initially, observations were made using an open-ended methodology. Three different operators were observed over three day-shifts for a total of approximately 24 hours of observation. The goal in this initial phase of data collection was to get an overall understanding of the control room design, and a preliminary assessment of the similarities and differences with the two plants that had been observed in previous phases of this work. Additional observations were made at Darlington NGS using the more structured, directed methodology used in the previous phase of this work (see Mumaw et al., 1996). Four different operators were observed on four different day shifts for about 8 hours at a time. The goal of this phase of data collection was to get a more detailed understanding of operator monitoring activities at Darlington NGS. In particular, the focus was on understanding how the control room technology impacted monitoring activities, and on how well the preliminary model of cognitive monitoring accounted for the behaviours observed. In summary, we were able to observe 11 of the 28 operators at Darlington NGS for a total period of approximately 88 hours, thereby providing a comparatively representative sample of observations.

DARLINGTON NGS

Since the primary purpose of this contract is to determine the impact of automation and control room technology on operator monitoring, it is important to describe the Darlington NGS plant and control room in some detail. As we will see, there are substantial differences in either plant design or control room design between Darlington and Pickering B or Bruce B. The implications of these differences for operator monitoring will be discussed in subsequent sections.

Plant Design

Some attempt was made to understand the differences between the design of the Darlington plant (independent of the control room design) and those at Pickering B and Bruce B, since these differences could account for differences in operator monitoring behaviours and strategies. Ideally, we would have spoken to plant design engineers to develop a detailed understanding of this issue but this was not possible. Thus, only a few high-level similarities and differences were noted.

Although all three plants observed in this project are CANDU designs, Pickering B is the oldest of the three. Furthermore, Pickering B was based on the older design of Pickering A, which makes it even more dated. It was pointed out that the structure of the Darlington plant is quite different from that of Pickering B. Some of the differences that were noted were: many dedicated analog controllers have been replaced by digital automation; refueling is done in an entirely different way (3 trolleys that can each access any unit, rather than one dedicated refueling station for each unit as at Pickering B). It should also be noted, however, that the design of the Darlington plant is quite similar to that of Bruce B. However, as we will see below, the control room designs of these two plants are quite different from each other. Consequently, more weight should be given to the differences between the results obtained at Darlington and those obtained at Bruce B rather than those obtained at Pickering B, since the former set of differences is likely to be a result of the control room technology, not the design of the plant itself.

Control Room Layout

One obvious difference between the Darlington control room design and those at both Pickering B and Bruce B is the layout of the panels for the four units. The Pickering and Bruce control rooms were similar to each other, with a symmetrical layout of the panels for each unit facing each other in opposite corners of a relatively square-shaped room. As shown in Figure 1, Darlington has a sequential 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 with the Pickering and Bruce designs. Also, note that the thick lines represent control panels, whereas the thin lines indicate short workspace dividers that were added

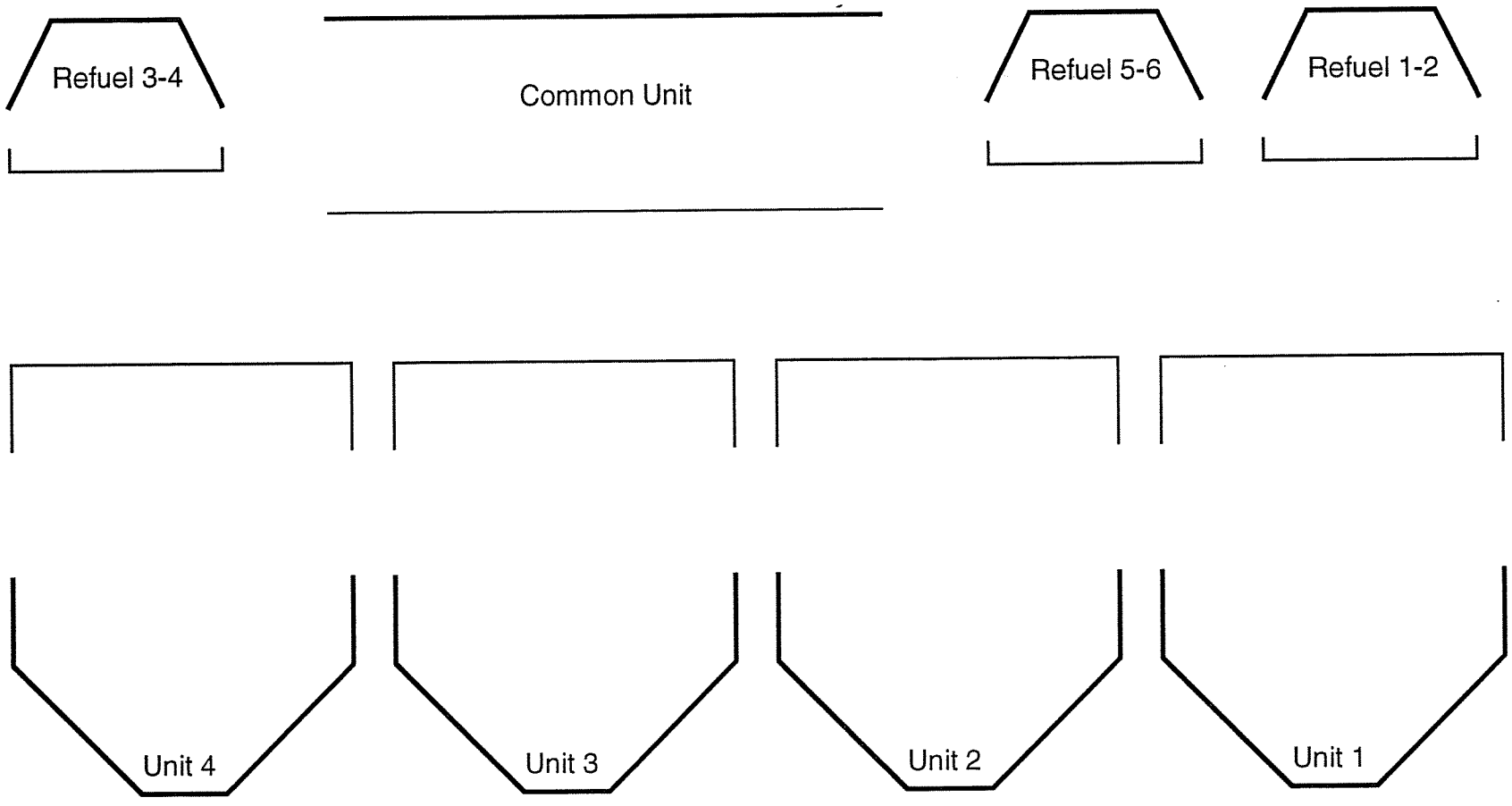

Figure 1. Approximate layout of Darlington NGS control room (not to scale).

after the control room 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.

Unit Workspace and Panel Layout

Whereas Figure 1 shows the layout of the control panels for the different units, Figures 2 and 3 illustrate the layout of instruments within any one of the four units. More specifically, Figure 2 provides a top 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. There are also three laser printers, not shown in this figure.

Figure 3 illustrates the relative layout of the control room panels for one unit at Darlington. 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. Because we are primarily interested in the impact of computer-based control room 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 analog hard-wired instrumentation (not shown in the figure). However, as illustrated in Figure 3, there are also four 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.

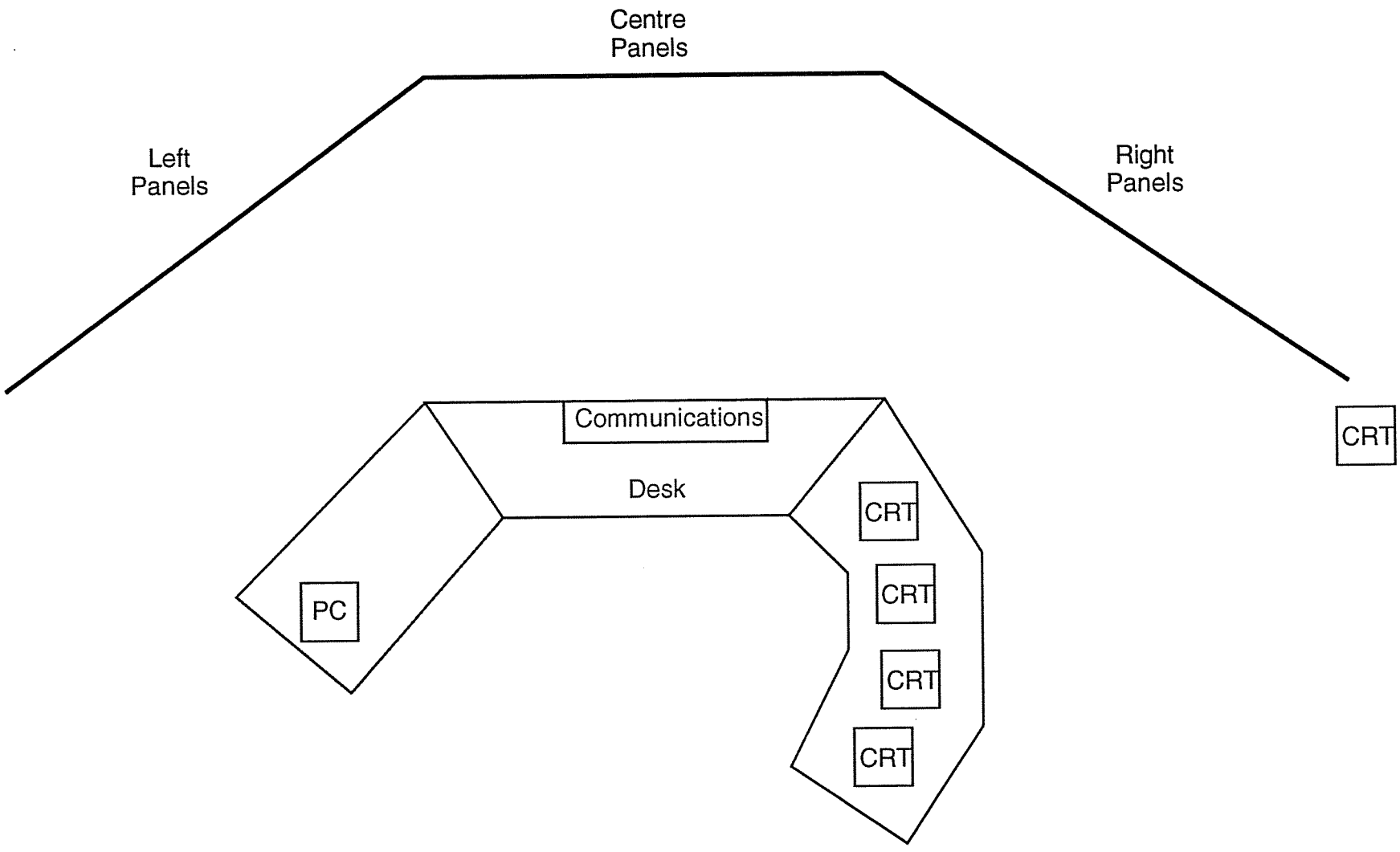

Figure 2. Top view of panels and workspace for one unit at Darlington NGS (not to scale).

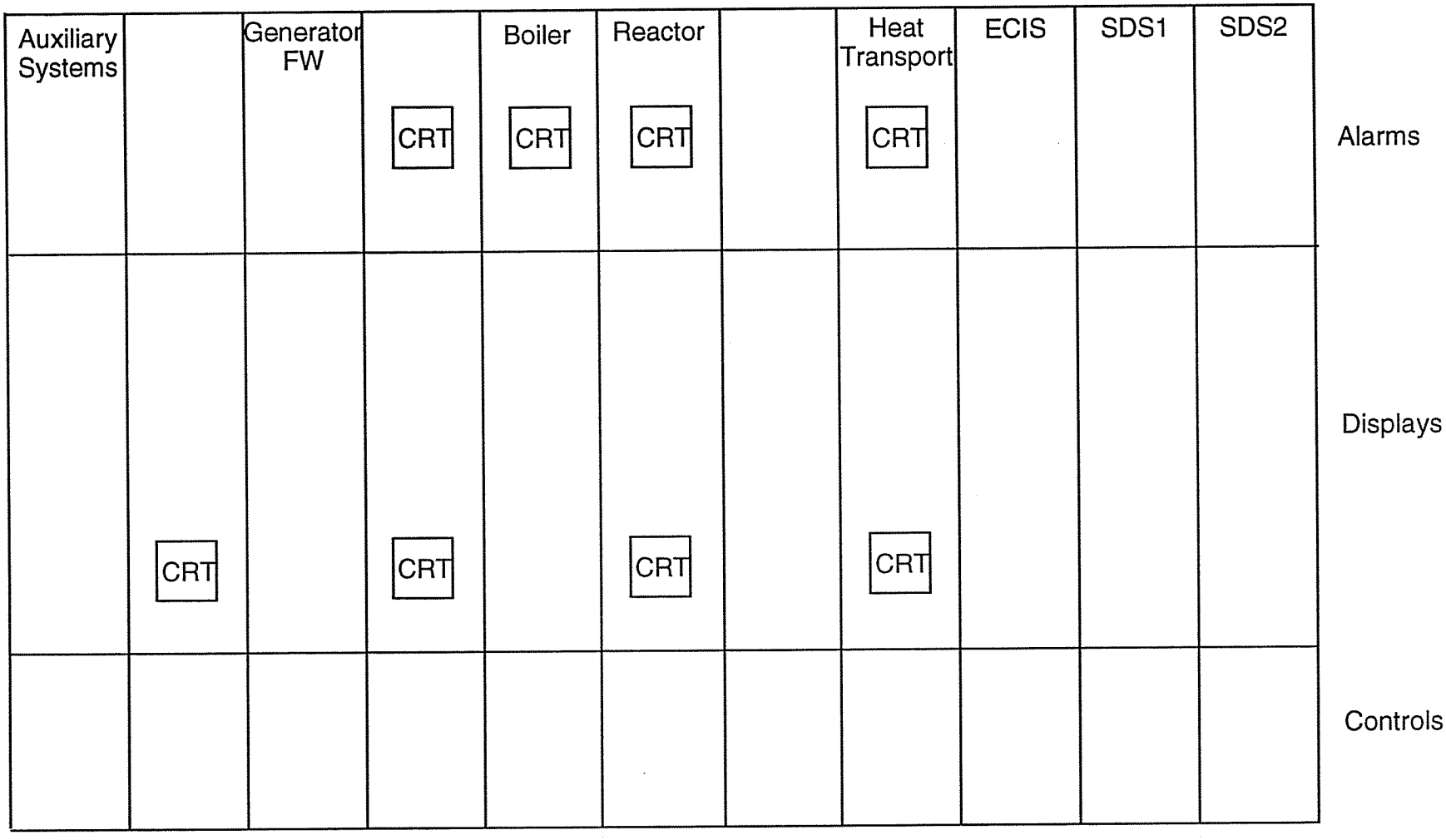

Figure 3. Front view of control room panels for one unit at Darlington NGS (not to scale).

Although this is not shown in Figure 3, the Darlington control room design has significantly fewer hard-wired instruments on the panels than the Pickering B or Bruce B control rooms. In part, this is because the refueling panels are separate from the unit panels, as shown in Figure 1. And as also shown in Figure 1, unit 0 which displays information for the containment, ECI controls, and electrical bus is located on a separate set of panels, away from the unit panels. There is, however, another reason why there are fewer hard-wired instruments on the panels at Darlington, namely that there are many more CRTs that can be used to bring up computer-based displays than at either Pickering B or even Bruce B. 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 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 (generator, electrical, nuclear, heat transport), 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.
- 12 green CRTs embedded in the SDS panels (2 SDSs x 3 channels x neutronics/other).
- 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 Darlington control room design seems to have traded off hard-wired instruments for CRT-based displays.

CRT Display System

Because of the more prominent role of CRT-based displays at Darlington, 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 showing 4 variables on one screen; bar chart displays showing 4 variables on one screen; and bar trend displays (a hybrid of bar charts and trends) showing 4 variables on one screen. 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 trends 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 x 4 variables x 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 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. And once that dummy trend is no longer displayed on the CRT, the history for those variables is deleted and cannot be recovered.

In summary, the computer-based display set at Darlington NGS 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.

SOURCES OF INFORMATION FOR MONITORING

In previous phases of this work, we identified a diverse set of sources of information that operators can consult to monitor the status of a unit (Mumaw et al., 1996), including: hard-wired panel instruments, computer-based status displays, hard-wired alarm tiles (or windows), computer-based alarm displays, logs, check forms, work reports, operating memos, long-term status binders, field operators, control room operators for other units, and unmediated indications. Do operators at Darlington rely on the same set of information sources?

From our observations, we did not notice any major differences in the sources of information used by operators. One small difference is that Darlington operators can rely on wireless radios to communicate with field operators and technicians outside of the control room. This was also observed at Bruce B, but not at Pickering B. Another difference, more quantitative than qualitative, is that operators make much more use of computer-based displays at Darlington, which is expected of course, given the differences in control room technology described above. We also found that operators at Darlington do not conduct field tours very regularly (at least on day shift), nor did they report relying on unmediated indications. Thus, the use of this type of information seems to differ from that at Pickering B 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. This may be why operators at the older Pickering B plant seem to rely more on this type of information. One similarity that is worth making explicit is that operators at Darlington NGS rely heavily on the alarm CRTs to direct their attention to problems. This reinforces the pattern observed both at Pickering B and at Bruce B.

Although there were no qualitative differences observed in terms of sources of information for monitoring, these additional observations did help us refine some of the categories of monitoring activities we had described in our preliminary report (Mumaw et al., 1996). In particular, two changes are warranted given our new observations. First, the printer should be added as a distinct resource for monitoring activities since it provides a means of displaying historical information. Second, the previous category labeled "communicate with operators from other units" should actually be divided up into two distinct categories: a) monitor indications from

another unit, and b) communicate with operators from other units. These are conceptually distinct activities that were previously confounded together. These two changes do not substantially alter our model but they do make it more precise than before.

WHAT MAKES MONITORING DIFFICULT?

In previous work, we had identified a number of factors which make monitoring a very challenging task (Mumaw et al., 1995, 1996; Vicente & Burns, 1996), including: system complexity and reliability; alarm system design; displays and controls design; automation design; insufficient training/experience with mundane but frequently-encountered tasks; increased demands associated with a shut down unit; increased demands associated with a call-up unit; noise and distractions; and control room layout. Because Darlington NGS was designed more recently than Bruce B and especially Pickering B, 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 perspectives: improvements, new difficulties, and remaining difficulties.

Improvements

System reliability. Nuisance alarms appeared with noticeably less frequency than at Pickering B or Bruce B. Also, operators seemed to have more trust in the indications they received from the panels. Thus, monitoring at Darlington 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., 1996).

Alarm system design. Although the design of the alarm system is very similar to those at Pickering B and Bruce B, it does seem to be improved in at least two ways. First, Darlington apparently has approximately 3,000 alarms which is about three times more than at Pickering B (we do not know how many alarms there are at Bruce B). As a result, operators are provided with considerably more information that they can use to monitor the unit. Thus, the Darlington alarm system design is more diagnostic or sensitive than that at Pickering B at least.

Second, as illustrated in Figure 3, there are four different alarm CRTs at Darlington, each dedicated to displaying a particular type of alarms (e.g., generator, electrical, nuclear, heat transport). In contrast, at Pickering and Bruce, there were only two alarm CRTs for each unit, so the alarms were not segregated physically in any way. All alarms were presented in a serial fashion on the same CRTs. Because the alarms are separated by type at Darlington, 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 Darlington makes monitoring slightly easier than those at Pickering B and Bruce B. However, as we will discuss below, this does not mean that the alarm system does not have any deficiencies.

Displays and controls design. It was clear that the displays and controls in the Darlington control room are better designed from a human factors point of view. Both the visibility and the layout seem to be improved over both Pickering B and Bruce B. 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 simply by pressing down on the bulb. This action closes the circuit, thereby lighting the bulb while it is depressed. If the bulb does not light, it is because it is burnt out. This provides an enormous improvement over Pickering B and Bruce B. Because 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. These improvements in control room design probably result from advances in technology and from the fact that much more attention was paid to human factors principles during the design of the Darlington control room than that of older control rooms. Nevertheless, as we will discuss below, there is still substantial room for improvement.

Radio communications. Darlington NGS was constructed so that it is possible to use wireless radios to communicate between the control room and the field. This represents a distinct change, at least compared to Pickering B. From what we could tell, this added information channel can facilitate coordination of activities across individuals distributed over the control room 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.

Increased demands associated with a call-up unit. At Darlington NGS, the call-up unit designation is not used. Instead of a particular crew being in charge of the routine maintenance on one particular unit, responsibility for all units is divided uniformly across all crews. As a result, the demands associated with monitoring are more evenly distributed across the operators in a crew.

Noise and distractions. Although it is difficult to be certain, it seemed that there was less noise and distractions at Darlington than at the other control rooms we had observed. This difference may be attributable to the control room layout (see below). Alternatively, it may be due to the fact that access to the control room is better regulated and thus there may be fewer people in the control room. Additional observations would be required to analyze this issue in more detail and obtain a more definitive assessment.

Control room layout. As described earlier and as shown in Figure 1, the Darlington control room has a very different layout from either Pickering B or Bruce B. 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 Pickering B for instance. Furthermore, the overall noise level seems lower than at Pickering B and Bruce B. This could be because of the control room layout, or it could be a result of the fact that the control room has been carpeted relatively recently and dividers have been installed in the control room (see Figure 1). These latter two changes may be responsible for the perceived attenuation in the noise level.

New Difficulties

Keyhole effect. There is another previously observed factor that makes monitoring difficult, but that is more pronounced at Darlington, so we have treated it as a new category. We are referring to the keyhole effect frequently associated with computer-based displays (Woods, 1984). In this case, the keyhole effect arises because of an interaction between several factors: a) there are fewer analog instruments on the panels at Darlington (e.g., there is only one strip chart recorder), so operators have to rely more on computer-based displays for monitoring than operators at Pickering or Bruce; b) each CRT can only present a limited amount of information at a time; and c) 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 control room 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 Darlington create a very different situation. Because of the factors listed above, operators either have to serially access information by bringing up different displays in sequence, or they have to be content to view only a small subset of the available data set at any one time in parallel (this subset being limited by the number of CRTs available for flexible data presentation).

Two examples can be offered to illustrate why the keyhole effect can make monitoring more difficult. As we will discuss below 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, the control systems status displays are not usually displayed 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 CRTs.

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 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 a CRT thorough several displays. Further investigation would be required to determine how big an impediment the keyhole effect is to monitoring at Darlington NGS.

Remaining Difficulties

System complexity. Although it seems that the Darlington NGS is in a better state of repair than Pickering or Bruce, it is still the case that there are many components which 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 observed in our previous reports, these activities temporarily cause the plant to be in a different state. As a result, the symptoms that are considered normal change accordingly. This makes monitoring quite difficult because there is no single, static 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 (number of components and possible interactions), these cognitive activities can pose a significant demand on operators. These demands are particularly imposing for operators who have recently obtained their license (see below).

Alarm system design. Although the alarm system design at Darlington does seem to represent an improvement over previous designs (see above), it also exhibits some of the same deficiencies that we had observed at Pickering B and Bruce B. 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 recently-licensed operators (see below).

Displays and controls design. Although the displays and controls at Darlington are better designed than those at Pickering B and Bruce B, they still exhibit some design deficiencies. Interestingly, problems exist with both the panel instruments and the CRT displays. A few examples will give an indication of the nature of the difficulties and the implications for monitoring.

One rudimentary case is the design of the four analog meters displaying boiler levels. The boilers themselves are physically located according to quadrants and have been numbered in a left-to-right, top-to-bottom fashion using a north-up frame of reference (i.e., northwest - boiler 1, northeast - boiler 2, southwest - boiler 3, southeast - boiler 4). Unfortunately, the four meters are arranged in a linear sequence. Thus, there is a poor mapping between the spatial layout of the displays and the spatial layout of the boilers themselves. To make matters even worse, however, the four level meters have been sequenced in the following linear order, reading from left to right: boiler 1, boiler 3, boiler 2, boiler 4. Therefore, not only does this layout have a poor mapping, but it also violates the population stereotype of numbering items in increasing order from left to right. The four analog meters displaying the boiler pressures suffer from the very same design deficiencies. So while the design is a poor one, it is consistent. Nevertheless, monitoring is made more difficult than it needs to be because operators have to deal with, and compensate for, an unnatural layout of analog meters.

A second example illustrates that these design problems are not restricted to the analog instruments. Figure 4 is a printout of one of the computer-based displays that operators can bring up on CRTs. The top part of the display provides a piping and instrumentation diagram representation of two heat exchangers, HX1 and HX2. HX2 is the east heat exchanger and is located on the left side of Figure 4. HX1 is the west heat exchanger and is located on the right side

1Y 12:30:44 13-MAR-97

STEAM GENERATOR PRESSURE
CONTROL STATUS

UNIT CONTROL MODE: ALTERNATE

DESCRIPTION	CURRENT STATUS
SG PRESSURE SETPOINT	4964 KPA
SG PRESSURE	4962 KPA
SG PRESSURE ERROR	1.90 KPA
SGP CONTROLS TURBINE	YES
SGP REACTOR POWER SETPOINT	100 %
LINEAR REACTOR POWER	1.00 FFP
TURBINE LOAD	101 %
TOTAL ASDV/CSDV LOAD	-.12 %
# OF ASDVS/CSDVS ON MANUAL	0
POISON PREVENT MODE	OFF
PSEUDO POISON PREVENT MODE	OFF
SGP MODE	HOLD
SETPOINT RATE CHANGE	0 DEG C/MIN

MENUS RECALL

Figure 5. An example of a poorly designed control system status display (see text for details).

674

of Figure 4. Right away there is a problem because the population stereotype (in North America at least) is based on a north-up frame of reference, so west should be on the left and east should be on the right. However, matters get worse when we examine the sumps for these two heat exchangers, shown at the very bottom right of Figure 4. Here, west is now on the left and east is now on the right. Thus, the relative spatial layout has been completely reversed, causing a poor mapping within a single display. Again, this makes monitoring more difficult than it needs to be because operators have to think in ways that are unnatural and counterintuitive.

A third example shows that the types of deficiencies we have been pointing out are not just limited to the equipment status displays but can be found in one control systems status display as well. Figure 5 is a printout of the steam generator (SG) pressure control status display. Note, at the top of the figure, that the SG pressure setpoint was set at 4964 Kpa at the time. The then current value of SG pressure was approximately 4962 Kpa. The standard way to calculate the error signal used in all control theory textbooks is to subtract the current value from the setpoint. Thus, if the current value is greater than the setpoint, the error signal is positive, and vice versa. This convention also has the advantage of being consistent with common sense. However, one can observe in Figure 5 that the error signal is being calculated in a different way on this display page. The setpoint is being subtracted from the current value, causing a reversal in the sign of the error signal. Thus, if the current value is too low, as it is in Figure 5, a <u>positive</u> error signal is shown.

There are two additional factors which make this design deficiency even more worrisome. Sometimes, operators need to regulate the generator governor valves manually. When this task needs to be done (about twice a year, we were told), the SG pressure error signal is used as the feedback signal for the manual control actions. Therefore, operators must remember to switch the sign on the error signal when performing this task. This load on memory is particularly error-prone because all of the other control systems status displays calculate the error signal in the conventional fashion. Thus, not only is the display in Figure 5 not intuitive, but it is also inconsistent with the other control systems status displays. This is a particularly noticeable

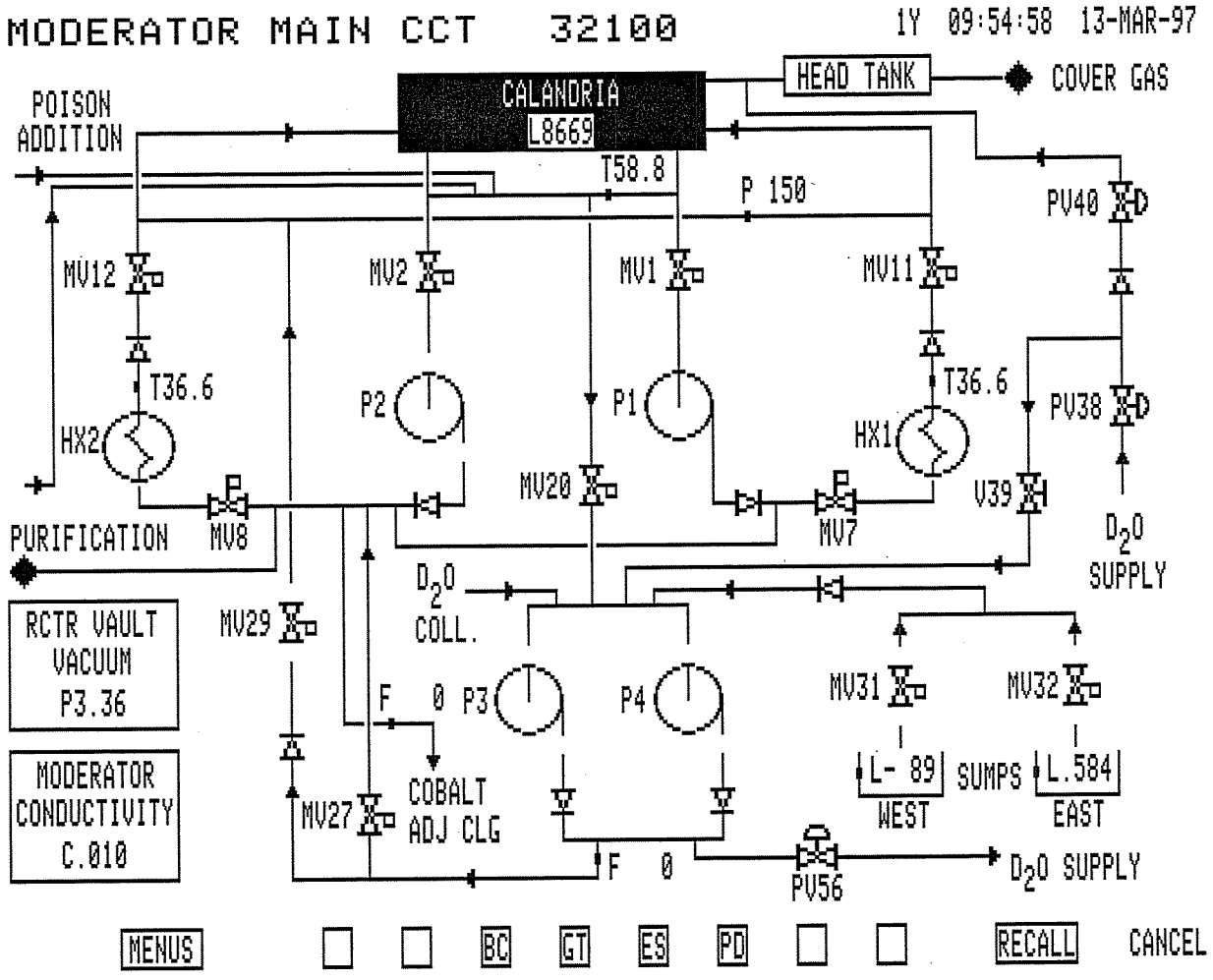

Figure 4. An example of a poorly designed equipment status display (see text for details).

634

example of a faillure to follow, not just basic human factors principles, but also control theory standards, not to mention common sense.

Finally, the controls on the Darlington panels also suffer from basic human factors deficiencies. For example, some handswitches are connected by flow paths shown on the panels (e.g., those for the reactor), whereas others do not (e.g., those for the moderator). The latter are more difficult to use because they require operators to store and retrieve the connections between controls in their memory, thereby increasing the cognitive demands associated with the job. Operators can reduce this load by referring to the CRT status displays instead of the panels.

In summary, being a modern design, the Darlington control room represents an improvement over the control rooms at Pickering B and Bruce B. But nevertheless, the Darlington design has basic design deficiencies which make monitoring more difficult than it needs to be. A few examples were given but many more were found during the observations, including poorly worded alarm messages, and computer-based displays freezing in place if both DCCs fail at the same time.

Automation design. Another remaining problem is the feedback offered by the automation (i.e., the control systems). With the replacement of many analog controllers by digital controllers, the information available to monitor the state of the automation is increasingly provided in the form of computer-based displays, such as the one shown in Figure 5. Aside from the rudimentary problem 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., 1996 for a more detailed discussion). From what we were told, all of this information is not provided on all of the control systems status displays. For example, some control systems displays show the demand signal but not the current state (e.g., Liquid Zone System), 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 a problem.

Furthermore, as shown in Figure 5, 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 to 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.

Insufficient training/experience with mundane but frequently-encountered tasks. As at Pickering B and Bruce B, all of the operators we observed at Darlington noted that the training and co-piloting periods do not provide them with sufficient experience to comfortably deal with mundane but frequently-encountered events. The training program justifiably focuses on rare, emergency events but this has the unintended side-effect that operators get essentially no experience in dealing with the less severe but much more frequent job demands. Of particular importance are the demands associated with work requests, such as the scheduling and approval of testing, maintenance, and repair jobs. The co-piloting period provides an opportunity to get experience with these more mundane situations, but all operators reported that this period is too

brief for them to be able to deal with these demands in a comfortable manner. In particular, operators reported that it is initially very difficult to set priorities between monitoring the unit and dealing with work requests. There is a tendency to try to do everything which can put operators in a position where they are bound to miss a significant indication. Thus, it takes anywhere from 12 to 24 months from the point where they first get their license before operators develop the skills and experience base sufficient to feel comfortable with monitoring a particular unit. Interestingly, however, moving to a new unit or being away for one's regular unit for an extended period of time (e.g., because of holiday) disrupts this feeling of comfort and makes monitoring more difficult.

In terms of our preliminary model of operator monitoring (Mumaw et al., 1996, Figure 5), it seems that it takes some time before operators can effectively develop an accurate mental model of the current plant (as opposed to the idealized plant they get trained on in the simulator) and substantial episodic knowledge, both of which are required to build accurate situation models. Furthermore, changing units or being away from a unit usually means that one's mental model of the current plant is no longer accurate and needs to be updated. This process of resynchronizing a mental model of the current plant seems effortful and makes monitoring difficult.

Increased demands associated with a shut down unit. Although we did not observe any shutdown units, we were told that the demands associated with monitoring are significantly increased under such conditions because the displays and the alarm system are not context-sensitive. Therefore, many alarms are generated and many displays provide what seem to be abnormal values. This makes monitoring challenging because it is more difficult to discriminate a real abnormality amongst the numerous false alarms which are actually normal, given the shut down state. These observations are very similar to those made at Pickering B and Bruce B.

Control room layout. As already mentioned, the Darlington control room layout is different from those at Pickering B and Bruce B (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 an upset and needs 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 an operator has to come over to help another operator in an upset, 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 control room layout seem to lead to a trade-off between noise level (see above) and awareness of other units.

Conclusions

As one would expect, the control room at Darlington is better designed in several respects than the previous generation designs at Pickering B and Bruce B, thereby facilitating monitoring slightly. Nevertheless, there are still design deficiencies, especially in the analog and computer-based displays. This is somewhat surprising given the rudimentary nature of the deficiencies and the importance placed on human factors in control room design after the Three Mile Island accident. 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 a poorly design interface.

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 Darlington plant and instrumentation seem to be more reliable and trustworthy than either Pickering B or Bruce B. This means that there are fewer factors that operators have to take into account in transforming their mental model of the ideal plant into their mental model of the current plant. Also, the mental model of the current plant needs to be updated less often because 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 operators are still not given extensive training on mundane but frequently encountered tasks. 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 control room technology which 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.

Finally, we also uncovered a new factor that makes monitoring difficult but that seems to be independent of control room technology. This insight was revealed in a situation where an operator did not have the information he needed to monitor effectively. The goal in this situation was to transfer oil from one place to another via an underground line. The operator wanted to calculate how much oil was being moved from the source and how much was being received at the sink, to make sure that the two amounts matched. A mismatch would indicate that there was a leak in the underground line, a potentially serious event. Thus, the operator wanted to confirm that the operation was going as planned. However, he did not have indicators for, nor was he able to calculate, the amount of oil in either the source or the sink. Thus, monitoring can be difficult because operators do not have the information they need.

In summary, most of the factors that made monitoring difficult at Bruce B and Pickering B can also be found at Darlington. 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 control room technology improve or inhibit operators' abilities to deal with these challenging demands?

STRATEGIES THAT OPERATORS USE FOR MONITORING

In previous reports, we outlined a number of clever strategies that operators have adopted in order to monitor effectively (Mumaw et al., 1995, 1996; Vicente & Burns, 1996), including: building and maintaining a situation model; relying on knowledge-driven monitoring; and especially, using facilitating activities. Do operators at Darlington use the same, or a different, set of strategies to facilitate monitoring?

Building and Maintaining a Situation Model

At Pickering B and Bruce B, 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

Darlington NGS. 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 one 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. Thus, it seems that the effort that operators devote to updating their situation model of a unit 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 control room technology. At Pickering B and Bruce B, 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 Darlington 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 interesting because it shows that the task goals can be the same in control rooms with different technology, but that the behavioral manifestations of these goals are shaped by the control room technology. This is a theme that appeared several times in our observations.

Knowledge-driven Monitoring

Just as at Pickering B and Bruce B, we found that operators at Darlington 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 context. Several examples of this type of activity were observed.

a) During refueling, nuisance 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.

b) After refueling, we saw one operator compare the new thermal power value to the old one on a printout to confirm that the refueling operation was successful.

c) 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 of knowledge-driven monitoring were observed.

Again, we observed the shaping effect of the control room technology. For instance, if there is a reason to monitor a certain variable particularly closely, operators at Pickering B or Bruce B might open a strip chart recorder door or make an external reminder to monitor the variable. At Darlington, 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 refueling. 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 refueling. Note, however, that by temporarily dedicating a CRT to knowledge-driven monitoring, operators have to remove a display from that CRT. Thus, they will not have access to this information (see the keyhole effect described earlier).

This contrast in the activities required to achieve the same objective with different control room 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 informal methods (e.g., opening the door on strip chart recorders, creating external reminders). In contrast, computer-based displays offer a wealth of 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 refueling). Although these methods of tailoring were not anticipated by designers, they do rely on the interface flexibility that was explicitly built into the computer system by designers. Whereas in hard-wired control room designs, operators have to go outside of the means explicitly provided by designers, in computer-based control room 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.

Facilitating Activities

So far, we have established that the strategies used by operators at Darlington are similar to those used by operators at Pickering B and Bruce B in that effort is devoted to building and maintaining an accurate situation model and knowledge-driven monitoring is used a great deal. The next issue to be addressed is the use of facilitating strategies. In previous phases of this research, we observed that operators at Pickering B and Bruce B have developed an ingenious set of strategies that reduce the cognitive demands imposed by monitoring tasks (Mumaw et al., 1996), including: enhancing existing signals; reducing noise; documenting a baseline or trend; acting on the plant to determine the validity of an indication; creating a new indication or alarm; creating an external reminder for monitoring; creating external cues for action or inaction; and employing additional operators. As this subsection will show, the same categories of strategies can be used to capture the facilitating activities of Darlington's operators, although the manifestations of these strategies are again shaped by the control room technology in many cases.

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 its range on a 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.

Reduce noise. Operators at Darlington also exhibited many different strategies whose common goal is to facilitate monitoring by reducing the noise created by the control room interface. For example, in one case an operator pulled out a DCC Y light that was blinking on the control panels. The flashing light was distracting him from monitoring the panels, so he quickly removed this unwanted source of noise.

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

The shaping influence of the control room technology can also be seen in these strategies. At Pickering B and Bruce B, 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 analog meters (a feature that was not explicitly designed for this purpose). At Darlington, there is only one analog 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 informal facilitating activities, whereas flexible computer-based displays can provide built-in means that operators can rely on to facilitate monitoring.

Document baseline or trend. As in our previous studies, we found that operators at Darlington 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 refueling.

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.

Act on interface to determine validity. We did not observe any operators rely on this facilitating activity, although there is no reason why it cannot be used in a computer-based control room design. Perhaps, it is not necessary to determine the validity of an indication as much at Darlington because the instruments are more reliable than those at Pickering B and Bruce B (see above).

Create new indication 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 of all was the way in which the 4 CRTs embedded in the unit panels (see Figure 3) were used by all operators. These 4 CRTs are flexible in that they can be used to display any computer-based display available to 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 is clearly far from arbitrary. One the contrary, there is a clear pattern which 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 Darlington operators have chosen to display on these four CRTs correspond quite closely to the variables that operators at Pickering B monitor periodically in order to get an overview of the unit (Vicente & Burns, 1996). The difference of course is that at Pickering B, operators quickly consult this information on a regular basis simply by moving their eyes. At Darlington, 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 Darlington can actually be interpreted as a direct response to the keyhole effect mentioned earlier. Because 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 Darlington can be categorized as creating a new indication (an overview display). All of the operators we spoke to have adopted this practice, thereby showing its importance and value.

We also found examples of activities that create a new indication or alarm that were more similar to those observed at Pickering B and Bruce B.

a) 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.

b) 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 degrees. Thus, the alarm system will notify him if there are further increases, thereby relieving him from having to remember to watch that variable periodically.

c) Another example occurs when operators are draining the pressurizer, an operation that takes 10 to 12 hours. 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 completed rather than having to devote his scarce attention resources to periodically monitoring pressurizer level.

d) 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 to observe its previous activity. However, 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 indirectly infer the number and timing of the valve openings.

These examples are quite interesting because they are analogous to strategies that we had observed at both Pickering B and Bruce B. The primary difference is that, in those older control rooms, the strategies were frequently implemented using the adjustable setpoints on the analog 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 setpoints on the analog 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 also observed several other examples of creating a new indication or alarm at Darlington that were implemented, not on the computer system, but with other media.

e) During refueling, there is a manual valve that 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. An example Panel Information Notice we observed read: "Throttled _ turn open to provide proper flow to FIM's".

f) When working on the shutdown cooling system, operators may need to throttle the shutdown coolant motorized valves. However, the panel indications only indicate whether these valves are fully opened, fully closed, or somewhere in between. There is no indication of exactly how far open the valve is when it is in an intermediate position (there is supposed to be a valve position indicator on a CRT display but it has not been commissioned yet, so it reads irrational.). As a result, when the operator throttles the motorized valves, he is blind to the actual intermediate position of the valves. To compensate, the operator counts how many seconds he holds the handswitch down, and then writes this value on a post-it, which serves as a surrogate indication of valve position.

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 Darlington, just like at Pickering B and Bruce B.

a) The simplest example is that operators frequently use a scratch pad as an external reminder to monitor one or more variables.

b) 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" x 5" rectangle) to place near the CRT to help remind them of the variables that need to be monitored.

c) Another example is interesting because it is related to the control room technology. Because 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 for a recurring problem with the ECI system.

Create external cues for action or inaction. Like the operators we observed at Pickering B and Bruce B, operators at Darlington 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.

a) A red printed plaque used to warn operators that an approved work practice (AWP) was in effect, and that therefore certain activities should not be performed.

b) Tags that are green (caution), yellow (work permit), or blue (op memo) are used as reminders for inaction.

c) 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 labeled "AWP 39-8" put up on the reactor panel. This was a cue to indicate that fuel handling activity (duct work) was going on in containment, and that certain activities such as changing power should not be performed.

d) 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 to fix the problem, to monitor the variable more closely, or to periodically bring up a trend).

e) 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 minutes. Just as the Pickering B and Bruce B operators 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.

Employ additional operators. Operators at Darlington NGS also rely on additional operators to facilitate monitoring, just like operators at Pickering B and Bruce B. For example, it is not

uncommon for an operator to direct a SCPO to monitor a display or an instrument when the operator's workload is high.

New Facilitating Category: Create External Descriptor

All of the facilitating activities we have discussed so far had already been previously identified in previous phases of this research. Our observations at Darlington also 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 for monitoring, thereby relieving the load on operators' memory. Several examples of this activity were noted.

a) 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.

b) 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.

c) The dummy graphical trends display the AI 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 corresponds to the AIs being trended. This offloads the operator from having to look up, or memorize, the AI 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 AI number and header

number. For example, for ROH, this correspondence is as follows: 1 is 1445, 3 is 1465, 5 is 1046, and 7 is 1066.

d) Also, a white 'Panel Information Notice' sticker is used to provide a reminder of information about a reading that is also documented in a deficiency report. For example, in one case we saw a sticker with "test valve is closed, reading above normal pressure" written on it, along with the corresponding deficiency report number.

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

New Strategy: Workload Regulation

One of the most important insights we uncovered during our field study at Darlington was the fact that operators explicitly regulate their workload to facilitate monitoring. This is accomplished by approving and scheduling work requests in such a way that monitoring is not ignored or degraded. To achieve this goal, operators must have a well-calibrated sense of their capabilities, which they can use to set priorities to make sure that they do not overextend themselves. Several examples can be offered to illustrate this strategy.

a) In one case, an operator was in the middle of refueling when a worker came to get approval to perform a job in the field. If approved, this job would bring in nuisance alarms, which would be added to the nuisance alarms normally triggered during refueling. This would greatly increase the demands associated with monitoring because the operator would be frequently interrupted by alarms. Furthermore, the operator would have to determine if any alarm that came up was merely due to the job being performed in the field, by the refueling, or by some other (perhaps critical) event. Under these conditions, it would be very easy to miss an important alarm amongst the constant stream of nuisance alarms. For this reason, the operator decided to defer the job until later in the day, after refueling was completed. Thus, this operator made a conscious decision to regulate his workload by spreading out task demands more uniformly during his shift rather than creating a demand peak that would increase the likelihood of monitoring errors.

b) It was also not at all uncommon to see maintenance/engineering staff wait patiently until the operator was ready to attend to them. This resulted in a highly unusual style of interpersonal interaction, where the operator would not even acknowledge the presence of the individual(s) queued up, until he was ready to attend to them. To the uninitiated, this felt socially uncomfortable (as if it signaled an extreme difference in status.) However, the operators were on excellent terms with the maintenance and engineering staff. The unusual interaction style simply reflected an adaptation to the operator's high attentional demands and was understood that way by the engineering and maintenance staff, who respected the need of the operator to regulate when he could attend to them.

c) There are a number of generic methods that operators use to regulate their workload when prioritizing jobs. Among the factors they consider are the following:

- what else is going on at the same time?
- which meters will be unreliable or unavailable?
- what is the worst case scenario with respect to potential impact on operation?
- how much attention and dedicated effort will the job require of the operator?
- how much operator field support is it going to need?
- does the job have to be done now (i.e., is it urgent)?
- is there a time later in the day when the demands will be lower?

In summary, one of the ways in which operators can deal with the challenging demands associated with monitoring (see previous section) is by explicitly regulating their workload to make sure that it does not reach their resource limits.

We did not explicitly identify this strategy in previous phases of this research. However, looking back at the comments we obtained, we have strong reasons to believe that this phenomenon is not at all unique to Darlington. On the contrary, we believe it is an integral, albeit high-level, part of monitoring strategies in any type of control room design.

<u>Conclusions</u>

The strategies that operators use at Darlington to make monitoring easier are largely the same as those previously captured in our model. However, in many cases, the same activities are performed using different behaviours, thereby showing the shaping effect of the control room technology. The various ways in which operators manipulate alarm setpoints to their advantage provides a good example of this shaping effect. We also found that some of the facilitating activities observed at Darlington seemed to be a direct response to the keyhole effect associated with computer-based displays. The creation of an overview display through the dedicated use of the four panel CRTs provides a good example of this response to task demands. Thus, it is clear that the control room technology has an impact on the specific behaviors required to implement facilitating activities, although at a higher level, the goal of those activities seems to be relatively invariant across differences in control room technology.

One of the most important findings uncovered in this field study was that operators use workload regulation activities to deal with the challenging demands imposed by monitoring. Well-calibrated workload regulation can make the difference between reliable monitoring and error-prone monitoring. This insight has important implications for our model of operator cognitive monitoring under normal operations.

REVISED MODEL OF OPERATOR MONITORING

Given these findings, we can now revisit the preliminary model of operator monitoring proposed in the previous phase of this research program (Mumaw et al., 1996). In general terms, we found surprisingly few differences between the monitoring behaviours and strategies we observed at Pickering B and Bruce B and those we observed at Darlington. As a result, the preliminary model was able to account for the vast majority of our findings. Nevertheless, a few changes to the model are warranted.

Figures 6 to 8 provide a detailed graphical representation of the revised model of operator monitoring. Since the details of the model remain largely unchanged, we will only provide a brief description of its basic structure (see Mumaw et al., 1996 for a detailed discussion). Items that represent changes from the preliminary model are described in more detail.

Beginning with Figure 6, the heart of monitoring is the operator's situation model. This model originates with a mental model of an ideal plant which is then modified to better reflect the current status of the plant. This mental model, when combined with the contextual details of a particular situation and the operator's episodic knowledge, allow the operator to derive a situation model which can be used to support situation assessment or response planning. With respect to monitoring per se, five different reasons that would motivate monitoring to support situation assessment had already been identified in previous work (SA 1 to SA 5). Also, four different reasons that would motivate monitoring to support response planning had been identified (RP 1 to RP 4). But as shown in Figure 6, a fifth reason for monitoring in support of response planning (RP 5) was uncovered during our field study at Darlington - assess preconditions for actions.

This category is an addition to our model, so we will provide a few examples to explain it in more detail.

a) An operator needed to shut down DCC X so that maintenance could be performed on it. The first step the operator took was to switch control of the unit from DCC X to DCC Y, while still leaving DCC X up and running. Then, he monitored the unit for a while to see if there were any problems now that DCC Y was in control. He also checked the alarm summary generated by DCC Y to see if it matched that generated by DCC X. Only after determining that there were no problems with DCC Y did the operator then turn off DCC X. Thus, rather than turning off DCC X right away, the operator carefully assessed whether the preconditions for doing so were satisfied (i.e., that DCC Y was functioning properly). Only after performing this evaluation did the operator carry out his primary actions.

b) Engineering wanted to perform a liquid zone conductivity test which can have the unintended and undesirable effect of raising system conductivity. Before giving permission to do the test, the operator first checked the current system conductivity level on the Liquid Zone Control Display. He discovered that it was unusually high (the normal is around 20, it was at 70 and the alarm setpoint is at 100). He then took action to bring the level down, and put the test on hold until system conductivity was back down to around 20. Again, rather than preceding right away with a

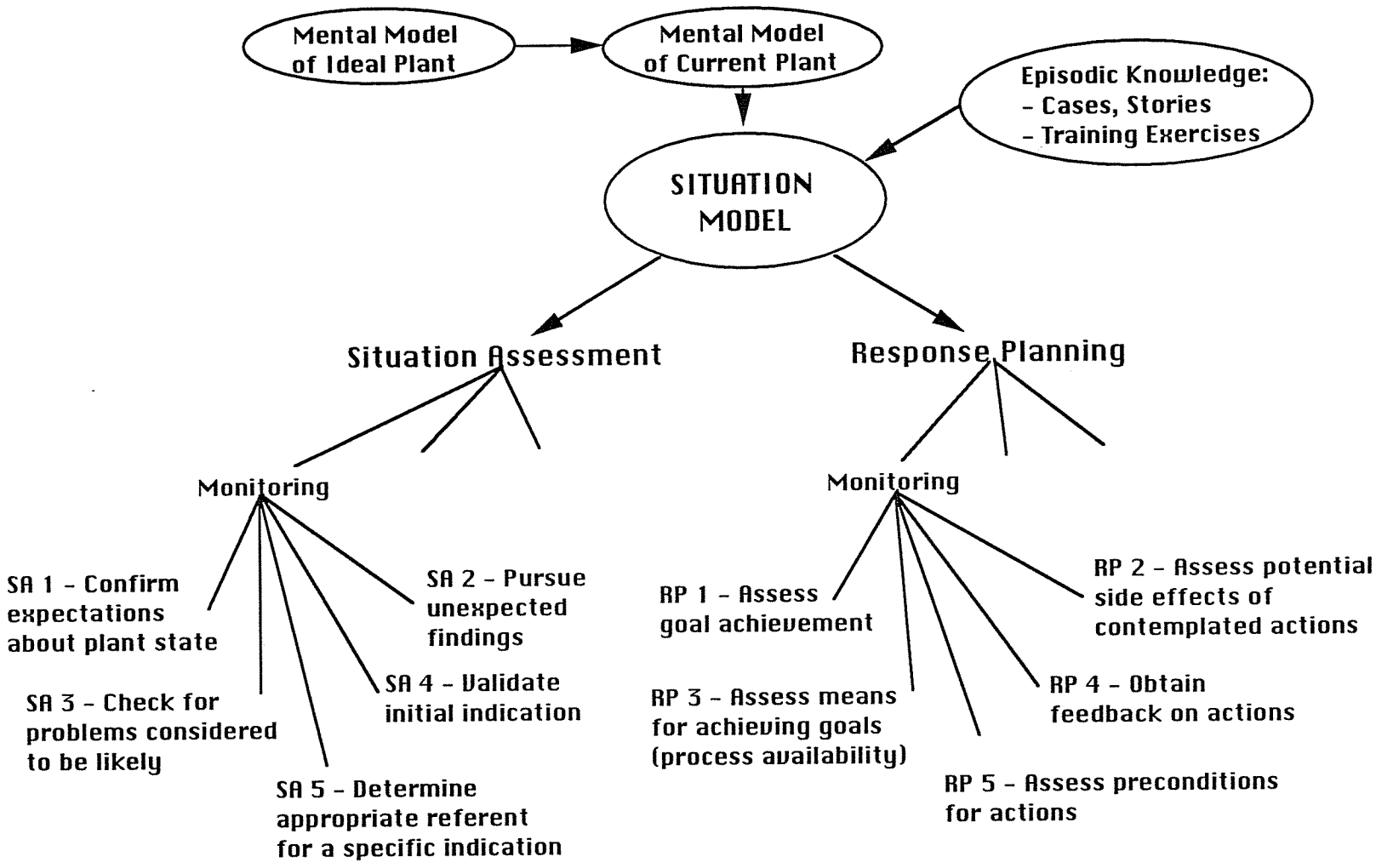

Figure 6. The Role of the Situation Model.

task at hand, the operator first made sure that the preconditions for that task were satisfied. In this case, they were not and the task was deferred until later.

In summary, the RP 5 category provides greater insight into operator monitoring, complementing the categories that had already been identified in the preliminary model.

Moving on to Figure 7, we can see the role that the situation model and the SA and RP categories play. Beginning on the far left of the figure, an episode of monitoring can be initiated by three types of events: scheduled task or activity; practices, policy, or procedures; or a data-driven indication. The operator's situation model serves as his referent to evaluate the input. This model allows operators to quickly evaluate whether an indication is expected, valid, or normal. Once the input is evaluated, additional monitoring may be required to support either situation assessment or response planning. There a number of different types of reasons why an operator may want to continue monitoring (represented by the categories SA 1 to SA5 and RP1 to RP5). Based on the pertinent justification, operators then need to identify the relevant data, establish a monitoring priority, and establish a monitoring frequency. Using their knowledge of the interface and strategies for creating or extracting information, operators then find the data and develop a monitoring plan.

The remainder of the model, illustrated in Figure 8, which lists the monitoring activities and the facilitating activities. The latter are activities which allow the operator to obtain information, whereas the former are activities which make it easier for the operator to obtain information. As described earlier, two new categories have been added to the list of monitoring activities: monitor indications on another unit, and print out a CRT display on a laser printer. Also, one new category has been added to the list of facilitating activities: create external descriptor.

Workload Regulation

Perhaps the most interesting revision to our model is the identification of workload regulation as a key ingredient in making monitoring more manageable. Figure 9 illustrates the nested relationship between this factor and the other we had already identified. The lowest level loop comprises the monitoring activities themselves. These are influenced by the facilitating activities

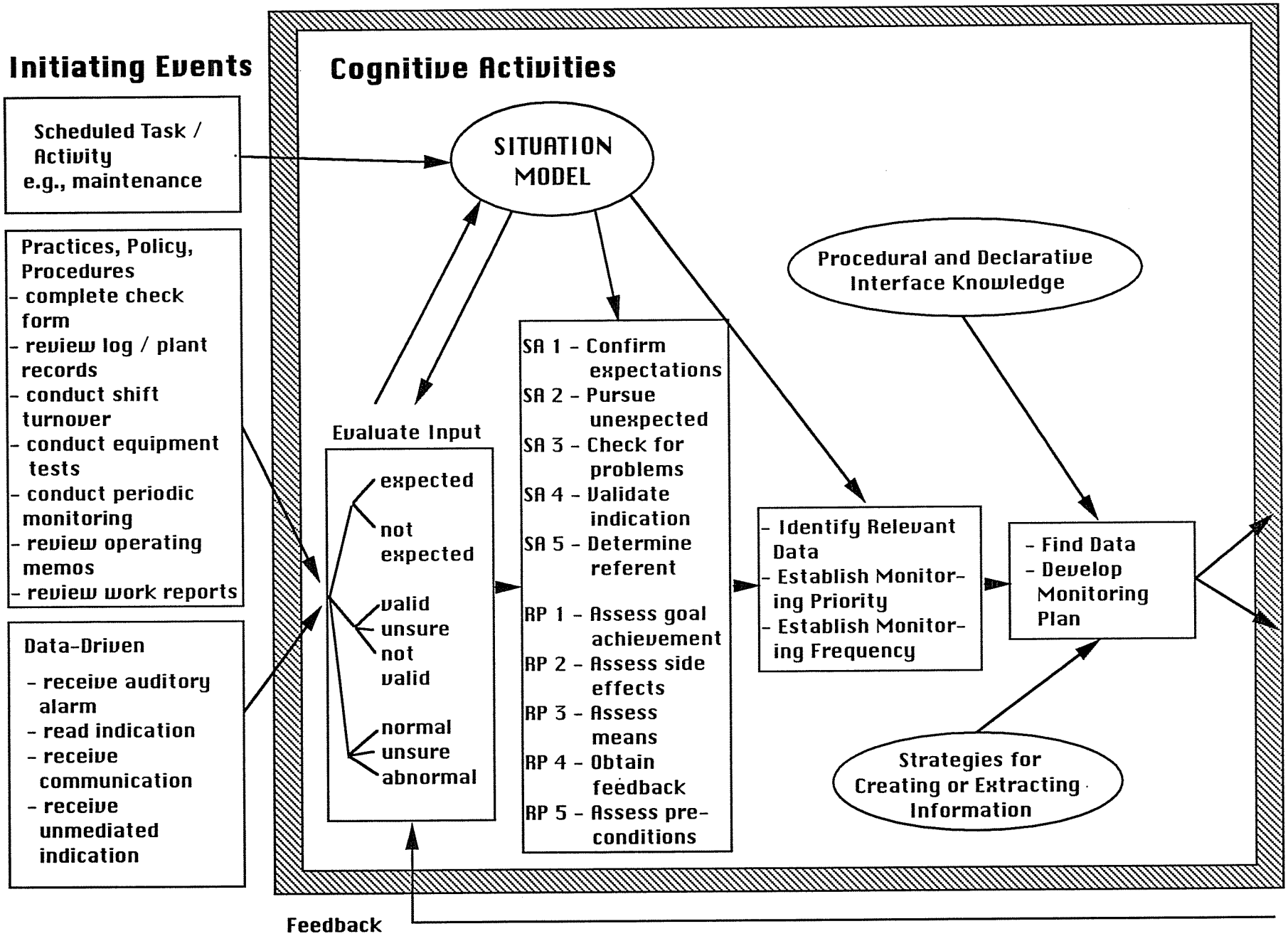

Figure 7. The Left Half of the Operator Monitoring Model.

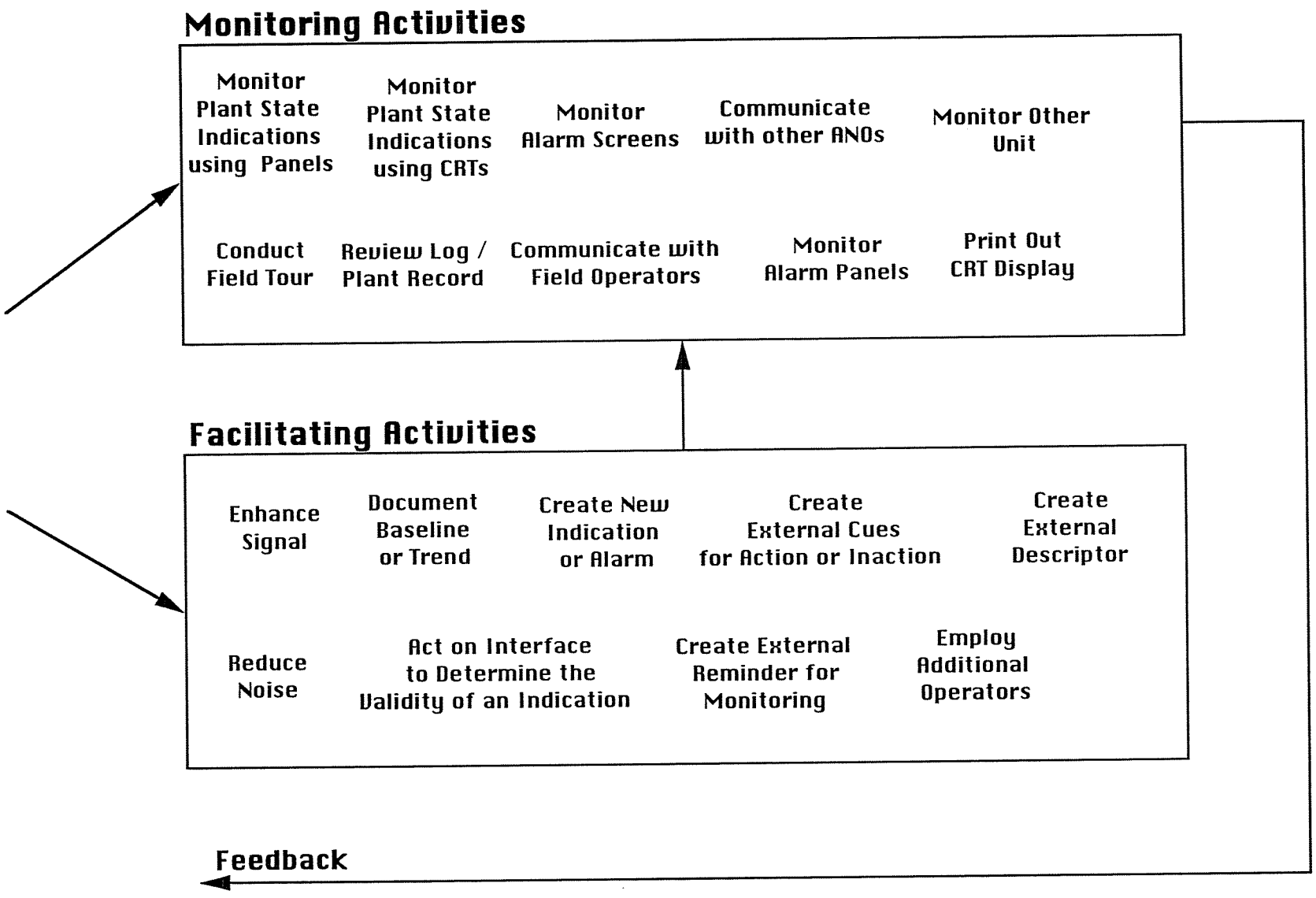

Figure 8. The Right Half of the Operator Monitoring Model.

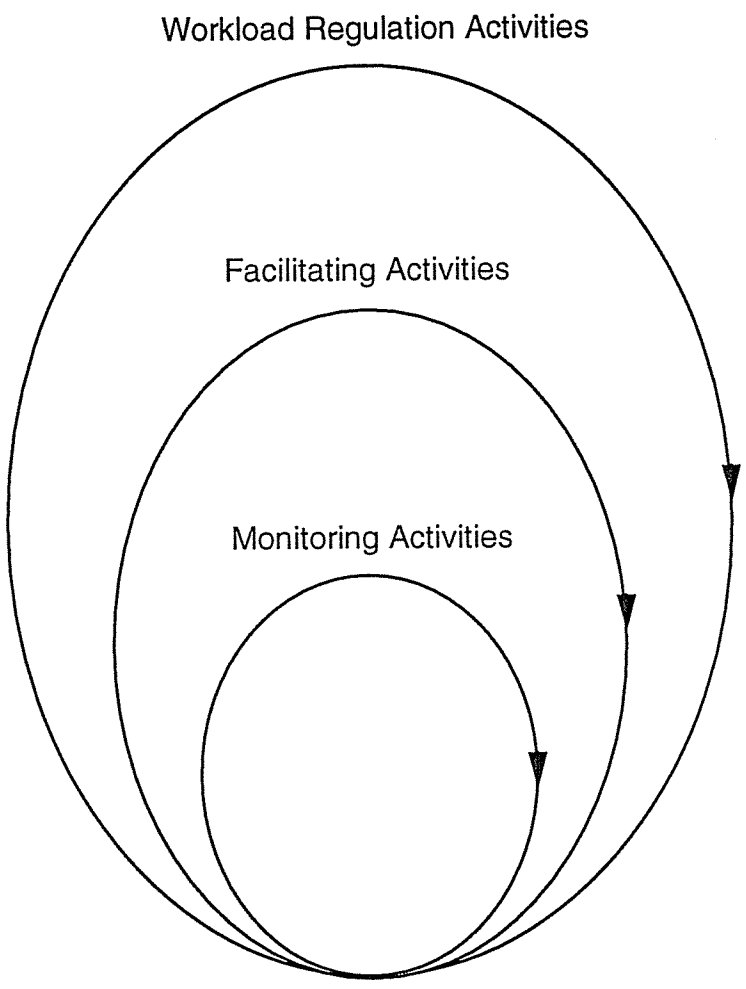

Figure 9. The nested relationship between monitoring activities, facilitating activities, and workload regulation activities.

that operators have cleverly adopted to make monitoring a more manageable task. Facilitating activities set the context for performing monitoring activities. Similarly, workload regulation activities represent an outer third loop that constrains both facilitating and monitoring activities. This higher level of control deals with issues such as setting priorities, scheduling jobs, and allocating personnel. The success of monitoring depends, to a great extent, on the decisions made at this outer level. If operators can effectively regulate their workload, then they will rarely put themselves in a position where errors will occur. On the other hand, if operators do not effectively regulate their workload, then errors are almost sure to occur, even if facilitating activities are adopted.

Newer operators find it very difficult to regulate their workload effectively because they receive no formal training and very little practice (just the 3 month co-piloting period) at more "mundane" non-emergency activities, particularly dealing with work order requests. As a result, they have not yet calibrated themselves to the level of activity that they can reliably handle without significantly increasing the potential for error. Yet the effective regulation of activity (i.e., ensuring that current demands do not exceed existing resources) is critical to effective monitoring.

While the topic of workload regulation has not been very well addressed in the human factors literature in North America, it is a well-known phenomenon in the Francophone ergonomics literature in Europe (e.g., Sperandio, 1978). Given its importance to operator monitoring, the topic seems worthy of additional study.

Conclusions

The preliminary model of operator monitoring we had proposed was able to account for the vast majority of the observations we made at Darlington. A few minor changes to the model had to be made. In addition, one substantial change was made, namely the addition of workload regulation activities as a crucial way of coping with the complexities of monitoring.

Although our observations at Darlington led to revisions in the model we had proposed earlier, we believe that the new categories are just as applicable to monitoring at Pickering B, Bruce B, or any other NGS. These issues seem to be independent of control room technology. This is

not to say that there are no differences in monitoring as a function of the control room technology. There are, but the revised model subsumes those differences. This will become more apparent in the following section.

THE INFLUENCES OF CONTROL ROOM TECHNOLOGY ON OPERATOR MONITORING

We are now in a position to offer some thoughts on the influences that control room technology can have on operator monitoring in NGSs. In particular, we are interested in the differences between analog, hard-wired control panels and digital computer-based interfaces.

Literature Review Revisited

Recall that the literature review presented earlier identified the following issues as being pertinent to the introduction of advanced control room technology:

1. Computer-based HMIs can make it more cumbersome for operators to find information and act on the system in an efficient manner compared with traditional control rooms.
2. Computer-based HMIs can make it much more difficult for operators to get an overview of the plant compared with traditional control rooms.
3. It is important that operators be provided with rich information that they can use to become familiar with the status of automation at all times.
4. It seems that it is possible to overcome these limitations by designing computer-based HMIs according to sound human factors practices and principles.

How do our findings compare with these issues?

With regard to the first point, we found that operators at Darlington did not seem to have any problems finding information with the computer-based displays. There could be at least two reasons for this difference in findings. First, it could be that the Darlington design is better in the sense that it is based on a greater understanding of human factors principles. For example, the navigation scheme and the dialogue format may be better designed than other computer-based control rooms. This would support the fourth point, above. Second, it is also possible that operators at Darlington have received more training, or have extensive experience, with the computer-based interaction format. We do not know which of these factors is most important.

As for the second point, the keyhole effect was indeed identified as a potential problem with computer-based displays. However, operators developed facilitating practices that were directed at overcoming this problem. In effect, they have created their own overview of the unit. Nevertheless, parts of this overview may have to be given up when other displays need to be brought up on one of the four panel CRTs. Although operators told us that they were not concerned about this problem, the possibility for losing track of the big picture in computer-based control rooms is certainly greater than in traditional control rooms, unless designers make explicit attempts to provide a systematically designed overview display.

The third point is an equivocal one. On the one hand, the control systems status displays are not very well designed from the viewpoint of making the functioning of the automation transparent to operators. They leave out relevant information, and present information in a form that makes it effortful for operators to extract relationships between individual values. On the other hand, the automation seems to be very reliable, and in the rare case that a controller does fail, an alarm will eventually be generated. Consequently, operators do not regularly monitor the control system status displays but instead rely on the alarm system to tell them that there is a problem. From our observations, we were not able to determine whether monitoring would be improved appreciably if better displays for the automation were provided to operators. This remains as a topic for future research.

As for the fourth and final point, we did not study two different control rooms with equivalent levels of computerization in the control room. As a result, we do not have any substantial evidence to determine if the aforementioned problems with computer-based designs can be completely overcome with good human factors design practice. The research to test this possibility has yet to be conducted.

The literature review raised some relevant points that were also brought up during our field study observations. However, if we compare the four points listed above with the findings presented in this report, it becomes apparent that the field study decribed here provides a much richer set of findings. These insights provide a basis for making some unique and novel insights

into the impact of control room technology on operator monitoring during normal operations. The remainder of this report summarizes what we learned about the differential impact of hard-wired instruments and computer-based displays on monitoring.

Hard-wired Instruments vs. Computer-based Displays

As mentioned earlier, the model summarized graphically in Figure 6 to 8 can account for the monitoring behaviours we observed at all three control rooms we studied during this research program. Thus, the categories of the model seem to be relevant, independent of the control room technology. At the same time, however, the model can also be used to discuss some of the more substantial impacts of control room technology on operator monitoring. Referring to Figures 7 and 8, the most important differences between traditional and computer-based control rooms seem to be localized to two points in the model: a) procedural and declarative interface knowledge, and b) strategies for creating or extracting information. These differences then propagate through the model to affect the processes associated with: finding data, developing a monitoring plan, facilitating activities, and eventually the monitoring activities themselves.

Interface knowledge. The impact of control room technology on operators' procedural and declarative interface knowledge is relatively straightforward. In a hard-wired control room, information is presented in a static, parallel form so the main requirement on operators is to know where all of the different indicators are located. In a computer-based control room, 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 unit) to resolve the degrees of freedom offered by the flexible design of the system. In summary, changes

in control room 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 control room, much of the work is done with the eyes (i.e., visual scanning). In contrast, with a computer-based control room, 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. One 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 that operators engage in traditional control rooms 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 (see Figure 7) in hard-wired vs. computer-based control rooms. As we will see, differences in strategies turn out to be more subtle and more interesting than the differences in knowledge.

Strategies for creating/extracting information. Figure 10 tries to capture the implications of control room technology for monitoring strategies by comparing the degrees of freedom in hard-wired instruments vs. computer-based displays. The figure on the left represents the intended degrees of freedom that a designer builds into a control room based on hard-wired instruments. With this technology, the designer is required to make numerous decisions which 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, what form the variables should be presented in, 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 in the left side of Figure 10 by the funneling down of degrees of freedom to a single point where no choices remain.

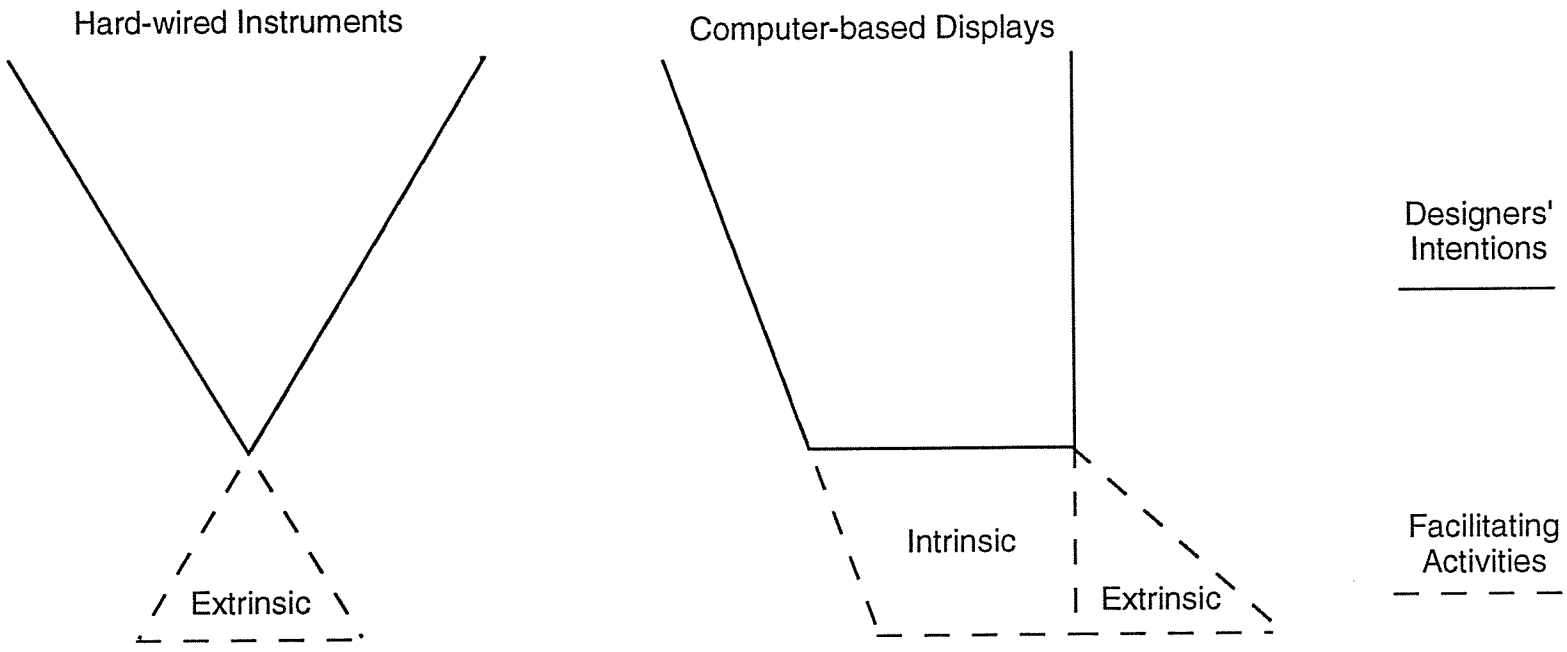

Figure 10. Comparison of degrees of freedom in hard-wired instruments versus computer-based displays (see text for detailed description).

One way to think of this is that the control room 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. Because the control room 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 which essentially contextualize the control room to make it fit their needs at the time. These facilitating activities, illustrated in Figure 10 by a dotted triangle, have two important characteristics. First, they are accomplished by using means that are outside of those that are intentionally provided by the designer. At Pickering B for instance, we frequently saw operators using post-its, creating external reminders, opening up strip chart recorder doors, and manipulating alarm setpoints on analog meters. None of these means were anticipated or intentionally provided by the control room 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 control room. Different facilitating activities are adopted at different times, so the control room 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 more clear by examining the degrees of freedom associated with computer-based displays.

The graphic on the right of Figure 10 shows a very different pattern. Because of their flexibility, computer-based displays intentionally leave a considerable number of degrees of freedom to the operator. For example, at Darlington, operators can: decide where to put a given display, what the time scale on a trend graph should be, what the range on a trend graph should be, what form to present a variable in (e.g., trend, bar, bar-trend, digital), what variables should be graphed together, and so on. Not only can the operator 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 in the right side of Figure 10 by the funneling 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 control room 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. Second, in a computer-based control room, intrinsic facilitating activities have the result of reducing, not expanding, the degrees of freedom. Operators do not use all of the flexibility offered by the system. In the Darlington control room, for instance, there are at least thousands of different "looks" that the control room can have depending on what displays are brought up on what CRTs, and how those displays are configured. Intrinsic facilitating activities pick out one useful display configuration from the myriad of 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 control room 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 have cited earlier in this report show, this is not always the case. As shown in Figure 10, 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 Pickering B and Bruce B. Even in computer-based control rooms, 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.

Open Issues

Our efforts in this section have been focused on reformulating the question of how control room technology impacts monitoring in a conceptually more precise way. The result, summarized in Figure 10, allows us to pose the following questions:

1. How much effort does it take for operators to resolve the degrees of freedom in a computer-based control room (i.e., to manage the interface), and how can this effort be reduced?
2. How much effort does it take for operators to expand the degrees of freedom in a hard-wired control room (i.e., to "finish the design"), and how can this effort be reduced?
3. Does reliance on extrinsic facilitating activities in a hard-wired control room lead to better or worse monitoring performance (i.e., reliability, workload, accuracy) than reliance on intrinsic facilitating activities in a computer-based control room?
4. What steps can be taken to ensure that the flexibility provided by designers in computer-based control rooms is of the type that operators require to facilitate monitoring?
5. Is there a significant difference between extrinsic facilitating activities in a computer-based control room compared to those in a hard-wired control room?

We are not able to answer these questions with the limited descriptive evidence we collected in this research. However, we offer the following speculative comment with regard to the final point. We suspect that extrinsic facilitating activities are more difficult to implement in a computer-based control room than in a traditional control room. Because the former is dealing with software rather than hardware, certain actions are more difficult or impossible to take. For example, in one of the cases we described earlier, an operator pulled a flashing light out of the panel because it was distracting him. If an analogous situation occurred with a computer-based display (e.g., one value among the several on the screen flashing), the same action could not be taken. The operator could of course remove the display from the CRT but then he might lose valuable information provided by the other non-flashing variables. Thus, it seems that computer technology can bring some benefits but some hidden costs as well.

Conclusions

To conclude, we offer the following recommendations:

1. More attention should be paid to basic human factors issues in the design of control rooms, whether they be based on hard-wired instruments or computer-based displays. There is considerable room for improvement.

2. Examples of the type we have collected in this, and previous, reports could be compiled and used as a training device for new operators. This would be particularly valuable at Darlington since a number of operators will be retiring in the next 10 years.

3. Designers 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. The system designed by Guerlain and Bullemer (1996) provides a good model for this type of design approach.

4. 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.

5. 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.

6. The issue of workload regulation, despite being very important to effective monitoring, is not very well understood and could benefit from further investigation.

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REFERENCES

Chou, Q. B., Acchione, P. N., & Hohendorf, R. J. (1993). Digital technology in nuclear power plants: White knight or black hole? In Proceedings of the Topical Meeting on Nuclear Plant Instrumentation, Control, and Man-Machine Interface Technologies (pp. 366-373). La Grange, Park, IL: ANS.

Colin, M. D. (1996). Instrumentation and control upgrade project final decisions. In Proceedings of NPIC & HMIT '96: The 1996 American Nuclear Society International Topical Meeting on Nuclear Plant Instrumentation, Control, and Human-Machine Interface Technologies (pp. 389-394). La Grange, Park, IL: ANS.

Gaddy, C. D., Taylor, J. C., Beare, A. N., Humphrey, M. D., Christiansen, E. C., & Blanco, M. A. (1993). Transfer of human factors lessons learned from fossil power plant advanced control room displays to nuclear power plant applications. In Proceedings of the Topical Meeting on Nuclear Plant Instrumentation, Control, and Man-Machine Interface Technologies (pp. 209-214). La Grange, Park, IL: ANS.

Gaver, W. W. (1996). Situating action II: Affordances for interaction: The social is material for design. Ecological Psychology, 8, 111-129.

Guerlain, S., & Bullemer, P. (1996). User-initiated notification: A concept for aiding the monitoring activities of process control operators. In Proceedings of the Human Factors and Ergonomics Society 40th Annual Meeting. Santa Monica, CA: HFES.

Heslinga, G., & Herbert, M. (1995). Experiences with advanced systems for human-machine interaction. In Proceedings of the 6th IFAC/IFIP/IFORS/IEA Symposium on Analysis, Design and Evaluation of Man-Machine Systems (pp. 253-258). Cambridge, MA: MIT.

Kawano, R., Fujiie, M., & Ohtsuka, T. (1996). Evaluation of human-machine interface of the ABWR type control room panel based on operators' behaviors and subjective data. In Proceedings of CSEPC 96: Cognitive Systems Engineering in Process Control (pp. 200-207). Kyoto, Japan: Kyoto University.

Makino, M., Nishiyama, H., & Asano, H. (1993). Toshiba advanced instrumentation and control system for nuclear power plants. In Proceedings of the Topical Meeting on Nuclear Plant Instrumentation, Control, and Man-Machine Interface Technologies (pp. 291-296). La Grange, Park, IL: ANS.

Makino, M., Ikeda, J., Saito, K., & Kobayashi, M. (1996). Advanced man-machine system A-PODIA for nuclear power plants. In Proceedings of CSEPC 96: Cognitive Systems Engineering in Process Control (pp. 192-199). Kyoto, Japan: Kyoto University.

Mumaw, R. J., Roth, E. M., Vicente, K. J., & Burns, C. M. (1995). Cognitive contributions to operator monitoring during normal operations (AECB Final Contract Report). Pittsburgh, PA: Westinghouse Science & Technology Center.

Mumaw, R. J., Roth, E. M., Vicente, K. J., & Burns, C. M. (1996). A model of operator cognition and performance during monitoring in normal operations (AECB Contract Final Report). Pittsburgh, PA: Westinghouse Science & Technology Center.

Sperandio, J. C. (1978). The regulation of working methods as a function of workload among air traffic controllers. Ergonomics, 21, 193-202.

Vicente, K. J. (1992a). Multilevel interfaces for power plant control rooms I: An integrative review. Nuclear Safety, 33, 381-397.

Vicente, K. J. (1992b). Multilevel interfaces for power plant control rooms II: A preliminary design space. Nuclear Safety, 33, 543-548.

Vicente, K. J., & Burns, C. M. (1996). Cognitive functioning of control room operators during normal plant operating conditions (AECB Final Contract Report). Toronto: University of Toronto, Cognitive Engineering Laboratory.

Vicente, K. J., Burns, C. M., Mumaw, R. J., & Roth, E. M. (1996). How do operators monitor a nuclear power plant? A field study. In Proceedings of NPIC & HMIT '96: The 1996 American Nuclear Society International Topical Meeting on Nuclear Plant Instrumentation, Control, and Human-Machine Interface Technologies (pp. 1127-1134). La Grange, Park, IL: ANS.

Vicente, K. J., Mumaw, R. J., Roth, E. M., & Burns, C. M. (1996). A field study of operator monitoring: Strategies for adapting control room technology. In Proceedings of CSEPC 96: Cognitive Systems Engineering in Process Control (pp. 222-229). Kyoto, Japan: Kyoto University.

Woods, D. D. (1984). Visual momentum: A concept to improve the cognitive coupling of person and computer. International Journal of Man-Machine Studies, 21, 229-244.

Yoder, C., Brown, E., Wilkinson, D., & Bliss, M. (1993). Instrumentation and control upgrade planning at Calvert Cliffs nuclear power plant. In Proceedings of the Topical Meeting on Nuclear Plant Instrumentation, Control, and Man-Machine Interface Technologies (pp. 3-9). La Grange, Park, IL: ANS.