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Evaluation of a Rankine Cycle Display for Nuclear Power Plant Monitoring and Diagnosis

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Traditionally, nuclear power plant control rooms have been designed according to a single-sensor single-indicator (SSSI) philosophy. Various researchers have proposed new display design principles, such as the mapping principle, which tries to overcome the limitations associated with the traditional approach by displaying higher-order functional information directly to operators. The mapping principle is exemplified by the Rankine cycle display, which is an overview display for monitoring and diagnosing the state of nuclear power plants. In this paper we present the results of the first formal evaluation of the Rankine display, comparing it with an SSSI display and a variation of the SSSI that also contains a pressure-temperature graph. The performance of undergraduate and graduate students in mechanical and nuclear engineering is compared with that of licensed nuclear power plant operators. Participants in each of these three groups were required to detect and diagnose abnormalities in dynamic scenarios using one of the three displays. The results indicate that the nuclear power plant operators outperformed the other two groups and that the Rankine cycle display led to more accurate detection and diagnosis performance than did either of the other two displays. Finally, we discuss some additional issues that must be addressed before one can recommend that the Rankine cycle display be implemented in commercial nuclear power plant control rooms.

INTRODUCTION

Traditionally, nuclear power plant (NPP) control rooms have been designed according to a single-sensor single-indicator (SSSI) philosophy (Goodstein, 1981). Each sensor datum is displayed in an independent location on hard-wired panels consisting of a large number of analog meters. The limitations of this type of control room design are well known (Goodstein, 1981; Vicente & Rasmussen, 1990; Woods, 1991). To control the plant, operators usually require answers to higher-order questions (e.g., Is the plant in a safe state?). To answer these questions with an SSSI display, operators must (a) determine which data are relevant for the current task, (b) gather the relevant data from individual instruments (e.g., pressure,

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temperature, level), which are often located on different control boards, and (c) integrate these data mentally to derive the higher-order properties of interest (e.g., mass inventory, heat transfer).

These demands can impose a great cognitive burden on operators under the best of circumstances. However, during abnormal situations, one or more of the constraints that usually allow operators to derive higher-order properties from individual instruments are violated (Vicente & Rasmussen, 1992). Under these circumstances, it may not be possible to derive higher-order properties from lower-level elements, making it difficult and sometimes impossible to consistently diagnose the nature of the abnormality. Note that this problem is not automatically solved by the current move toward advanced computer-based displays. Advanced control rooms can also exhibit these problems (Woods, 1991) if they create the need to integrate alphanumerical data across several display pages.

In recognition of these deficiencies, several cognitive engineering researchers have proposed alternatives to the SSSI approach. For instance, Vicente and Rasmussen (1990, 1992) proposed an *ecological interface design* as a framework for overcoming these limitations. Similarly, Woods (1991) has advocated an approach based on what he calls *representation aiding*. Bennett and Flach (1992) pointed out the benefits of *configural displays*. Although there are notable differences in the details of these respective views, a common underlying theme unites them. The theme, which Woods (1991) referred to as the *mapping principle*, is that higher-order functional information necessary for effective control and diagnosis should be directly displayed in a manner that allows operators to effortlessly extract that information using their powerful perceptual capabilities. This is accomplished by mapping the goal-relevant constraints in the work domain onto salient perceptual properties of the display. As we will demonstrate, displays based on the mapping principle go well beyond traditional mimic diagram representations, which portray merely the status of physical components, not higher-order domain functions.

In this paper we describe an evaluation of the Rankine cycle display, which is an overview display for NPPs developed by Beltracchi (1987, 1989, 1991; see also Lindsay & Staffon, 1988). Although it was designed before the mapping principle was developed, the Rankine cycle display is consistent with this design principle. In the following subsection, we discuss the rationale behind the display.

Background

To understand the link between interface design and human performance, it is important to distinguish between the demands imposed by the work domain and the psychological processes used to deal with those demands. For a given application domain, the former are usually given. However, the latter can vary as a function of several factors, one of which is the interface used to perform the task. The important conclusion is that no inherent coupling exists between work domain demands and psychological processing, because the domain demands are fixed whereas psychological processing depends on the interface, the context, and the competencies of the operator.

An example of a fixed work domain demand is the safety-critical requirement to maintain reactor core integrity in pressurized water reactors. To do this, operators must not let pressure reach the point that would allow the water in the primary loop to boil. The work domain constraints (i.e., the thermodynamic properties of water relating temperature, pressure, and boiling point) must be taken into account if operators are to maintain the plant in a safe state. These relationships cannot be ignored. However, the psychological resources required to cope with this set of demands will vary depending on the aids available. What are some different ways in which these constraints can be taken into account?

One way would be for operators to perform this task unaided based on the elemental data provided by an SSSI interface. For example, operators could find the appropriate meters and determine that pressure is 7 MPa and temperature is 269°C. Does this mean that the water is in a liquid, gaseous, or two-phase state? Clearly, this is an extremely difficult task to perform unaided because it requires operators to internalize the thermodynamic properties of water across a very wide operating range.

A second method of carrying out this task would be to observe the elemental data and then consult thermodynamics steam tables to determine whether the primary coolant is subcooled or saturated. This is an improvement because the task constraints no longer have to be represented mentally (they are embedded in the steam tables). However, several steps requiring controlled processing are still necessary to do the task. One has to correctly read (and remember) the current temperature and pressure from the available analog displays. Then, one has to look up the saturation temperature (or pressure) for the current pressure (or temperature) value. Finally, one has to compare the saturation value with the observed value to see whether saturation conditions have been achieved. Because of the symbolic (i.e., alphanumeric) representation provided by the steam tables, this can be a time-consuming, effortful, and error-prone procedure.

A third method is to embed the domain constraints into an external representation (such as steam tables) but to represent those constraints graphically (rather than alphanumerically) so that operators can determine quickly, easily, and reliably "at a glance" whether the primary loop is saturated. This is precisely the approach adopted in the Rankine cycle display developed by Beltracchi (1987). This display represents not only the degree of subcooling but also other thermodynamic plant functions in a form intended to enhance information extraction. To help the reader understand this display, in the following paragraphs we provide a simplified overview of the thermodynamic properties of water (for a more detailed, technical account, see Wood, 1991).

Water can be found in three different states: ice, liquid, and steam. In NPPs, the latter two are the most important because one does not usually encounter frozen water. Whether water is in a liquid or steam state depends on the temperature, entropy, and pressure of that water. In fact, these three variables are partially redundant, so knowing the values of two of them is sufficient to determine whether water is in a liquid or steam state. These relationships are graphically summarized in Figure 1, which shows the saturation curve for water in a two-dimensional graph defined by temperature (T) and entropy (s) axes (*s* is the standard symbol for entropy in thermodynamics). Different lines or areas of the T-s diagram represent qualitatively different classes of thermodynamic states. For instance, the area of the graph to the left of the curve represents the subcooled state, in which water is in a liquid phase. The line representing the left edge of the saturation curve represents the saturated liquid state. Along this line the water is in a liquid state, but adding any additional energy will cause the water to start to boil. The area under the curve represents a mixed state in which there is a combination of liquid and steam. The farther one moves to the right, the greater the proportion of steam and the lesser the proportion of liquid. The line representing the right edge of the saturation curve represents the saturated steam state. Along this line, the liquid water has all been converted to steam.

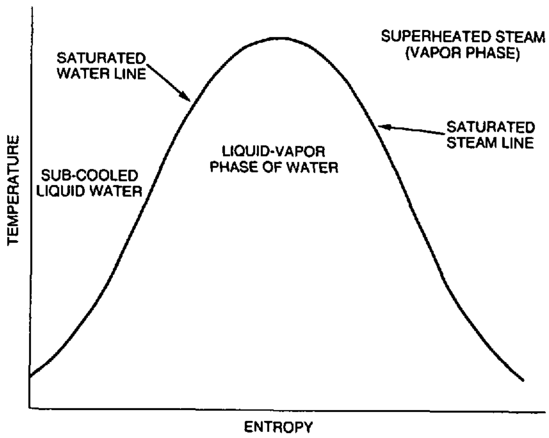

Figure 1. The saturation curve for water represented on a temperature versus entropy diagram.

Adding any additional energy will cause the process to move into the area to the right of the saturation curve, which represents a superheated steam phase.

The T-s diagram, illustrated in Figure 1, has been consistently used in thermodynamics textbooks for decades to explain the thermodynamic properties of water. It contains information similar to that found in steam tables, the main difference being that it is a graphical representation rather than an alphanumeric one. In fact, the T-s diagram can be considered an instantiation of the mapping principle because it maps functional properties of the domain (qualitatively different thermodynamic states) onto salient perceptual features of the display (easily distinguishable regions and lines in the T-s diagram).

What does this have to do with the Rankine cycle? The Rankine cycle is a heat engine cycle that describes the thermodynamic transformations that occur in a water-based NPP. The cycle consists of different phases, each consisting of a certain type of transformation. Interestingly, these different phases of the Rankine cycle have been graphically represented for decades in thermodynamics textbooks using the T-s diagram shown in Figure 2. This figure is similar to Figure 1, except that several additional lines have been superimposed on the saturation curve. Each of these lines represents a major phase of the Rankine cycle, which is implemented by specific plant subsystems. Starting on the left, the purpose of the feedwater system is to take subcooled water and heat it until it reaches saturation temperature (i.e., until it reaches the left edge of the saturation curve in Figure 2). This water then enters the steam generator, where more heat is added. Because the water was already saturated, the additional heat makes the liquid water boil, thereby turning it into steam. This line in the diagram is horizontal in Figure 2 because the transformation from liquid to steam occurs at a constant temperature. Under the saturation curve, temperature and pressure are linked, so constant temperature also means a constant pressure. Eventually, all of the liquid is converted to steam, and saturated steam is produced (indicated by the point at which the horizontal line reaches the right edge of the saturation curve in Figure 2). At this point, the steam is driven through a high-pressure turbine. This is indicated in Figure 2 as a vertical line because the transformation occurs at constant entropy. Then the steam is reheated, thereby increasing its temperature until it is superheated, as indicated by the reheat line that ends to the right of the saturated steam line.

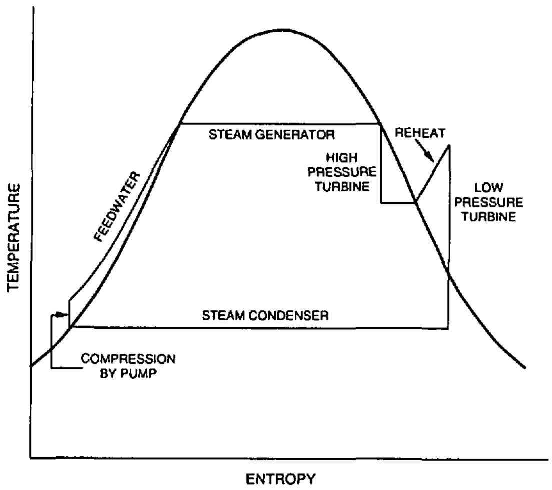

Figure 2. The various phases of the Rankine cycle heat engine (with reheat) represented on a temperature-versus-entropy diagram.

At this point, the steam passes through a low-pressure turbine. This transformation also occurs at constant entropy and is therefore indicated as a vertical line in Figure 2. Next, the steam is passed through a condenser, which cools the steam, bringing it back to a saturated liquid state (indicated by the point at which the horizontal line meets the left edge of the saturation curve in Figure 2). This state transformation occurs at a constant temperature (and pressure) and is therefore shown as a horizontal line in the T-s diagram. Finally, a pump compresses the liquid, thereby increasing its temperature. This transformation occurs at constant entropy and is therefore shown as a small vertical line in the T-s diagram in Figure 2. In summary, Figure 2 is an idealized graphic representation of the various functions of the Rankine heat engine cycle with reheat. These are the functions that a water-based power plant must fulfill for it to function as designed.

This diagram, like Figure 1, can also be considered as an example of the mapping principle. Functional properties of the plant (the various phases of the Rankine heat engine cycle) have been mapped onto salient perceptual properties of the display (the various lines superimposed on the saturation curve). From a human factors point of view, the T-s diagram provides an especially good mapping because it makes it easy to see the invariant properties of the Rankine cycle. For example, the conversion of liquid to steam in the steam generator occurs at a constant temperature, which is represented as an easy-to-detect horizontal line in the T-s diagram. The same is true for the cooling process achieved by the condenser. Another example is provided by the expansion of steam through both the high- and low-pressure turbines. Ideally, each of these transformations occurs at constant entropy and so can be easily spotted as vertical lines in the T-s diagram.

The cycle illustrated in Figure 2 is an ideal one and cannot be achieved in practice. However, the fact that the ideal is mapped onto salient features such as horizontal and vertical lines makes it easy to spot abnormalities or inefficiencies. For example, an actual turbine is not perfectly efficient, as indicated in the T-s diagram by a deviation from vertical in the line representing the turbine phases of the cycle. The farther the bottom of those lines deviate to the right, the more inefficient the turbine is. Similar examples of how perceptual features of the display can reveal abnormalities can be provided not only by lines deviating from vertical or horizontal but also by where points or lines are located in space. For instance, if the point representing the end of the reheat line in Figure 2 were to be lowered and moved to the left until it reached the saturated steam line, then one could conclude that the reheating system was in fact not providing enough heat because the steam entering the low-pressure turbine was merely saturated, not superheated. Graphically, one could observe this because the point would be on the saturated steam line, not to the right of that line where it should be, as shown in Figure 2. In summary, the representation of the Rankine cycle in a T-s diagram is an example of the mapping principle and, therefore, has many of the qualities of a good display. It should not be surprising, then, that Beltracchi (1987) used this particular diagram as a basis for designing a display for NPPs.

The Rankine cycle display evaluated in the experiment described in this paper is illustrated in Figure 3. (The additional elements in Figure 3 will be explained later.) The basic idea is to graphically display dynamic data describing the state of the different phases of the heat engine cycle so that a knowledgeable observer can easily determine the thermodynamic state of the process. The display is driven primarily by pressure and temperature readings taken at key points in the plant (e.g., feedwater system, steam generator, high-pressure turbine, low-pressure turbine, condenser) that provide information about the status of different phases of the Rankine cycle. The pressure and temperature at each of these points can then be graphed as data points on the T-s diagram. Recall that temperature, pressure, and entropy are partially redundant, so knowing the temperature and pressure is sufficient to identify a point in the T-s diagram. The reason temperature and pressure are measured to drive the display is because entropy cannot be measured by sensors. Conversely, the reason entropy is used instead of pressure for the display itself is that, as mentioned earlier, it makes it easier to see the invariant properties of the heat engine cycle. These dynamic data points are then connected to one another, thereby creating an animated polygon, the shape of which changes over time as the plant status evolves. Ideally, the shape of the polygon should be as shown in Figure 2; deviations from this shape are indicative of meaningful changes in the underlying status of the plant.

Thus the Rankine cycle display presents the

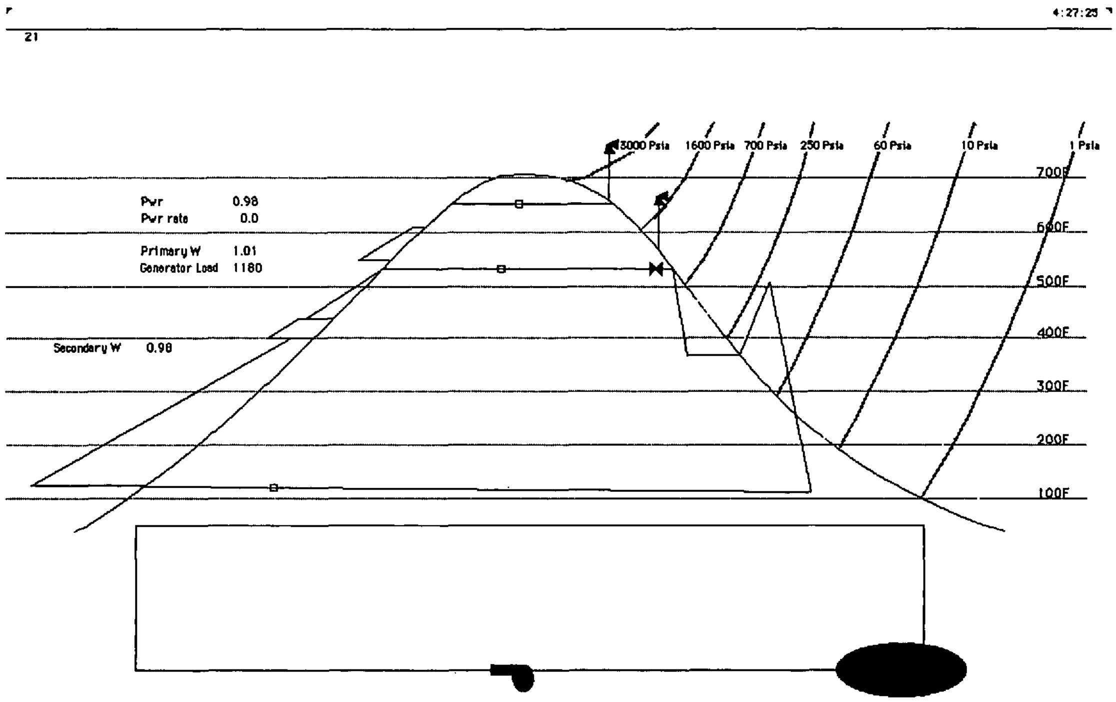

Figure 3. The Rankine cycle display. (The details in small type are presented in order to faithfully represent the displays and are not meant to be readable.)

same raw data that one might find in an SSSI display, but it does so in an integrated manner. Instead of presenting a large number of independent data points, the Rankine display exploits the features of the T-s diagram described earlier. As a result, instead of having to derive higher-order system properties, operators should be able to perceive these at a glance. It would seem, therefore, that the Rankine display, being based on the mapping principle, would have an advantage over an SSSI display consisting of analog meters displaying the same data. However, although it has been around for well over a decade (see Abbott, 1982), the Rankine cycle display has never been empirically evaluated.

In an effort to fill this gap in the literature, we conducted an experiment comparing the Rankine display in Figure 3 with two other display types. One of these, illustrated in Figure 4, is similar to existing control room designs in that it is based on an SSSI philosophy. This display contains the same data points as found in the Rankine display, the only difference being that these data are presented on individual analog meters. The task of integrating these data to determine the status of higher-order plant functions is left to the operator. The final display, illustrated in Figure 5, is a hybrid of these two. Like the SSSI display, it consists primarily of individual analog meters. However, some of the meters in the SSSI display have been removed and replaced by a pressure-temperature (PT) plot. The PT plot, like the Rankine display, is intended to serve as a graphical representation that allows operators to perceive the status of higher-order plant functions directly (Broughton & Walsh, 1981). It has been used in some plants in the United States (e.g., U.S. Nuclear Regulatory Commission, 1988). However, it differs from the Rankine cycle display in that it does not show the status of all of the phases of the heat engine cycle in an integrated, graphical

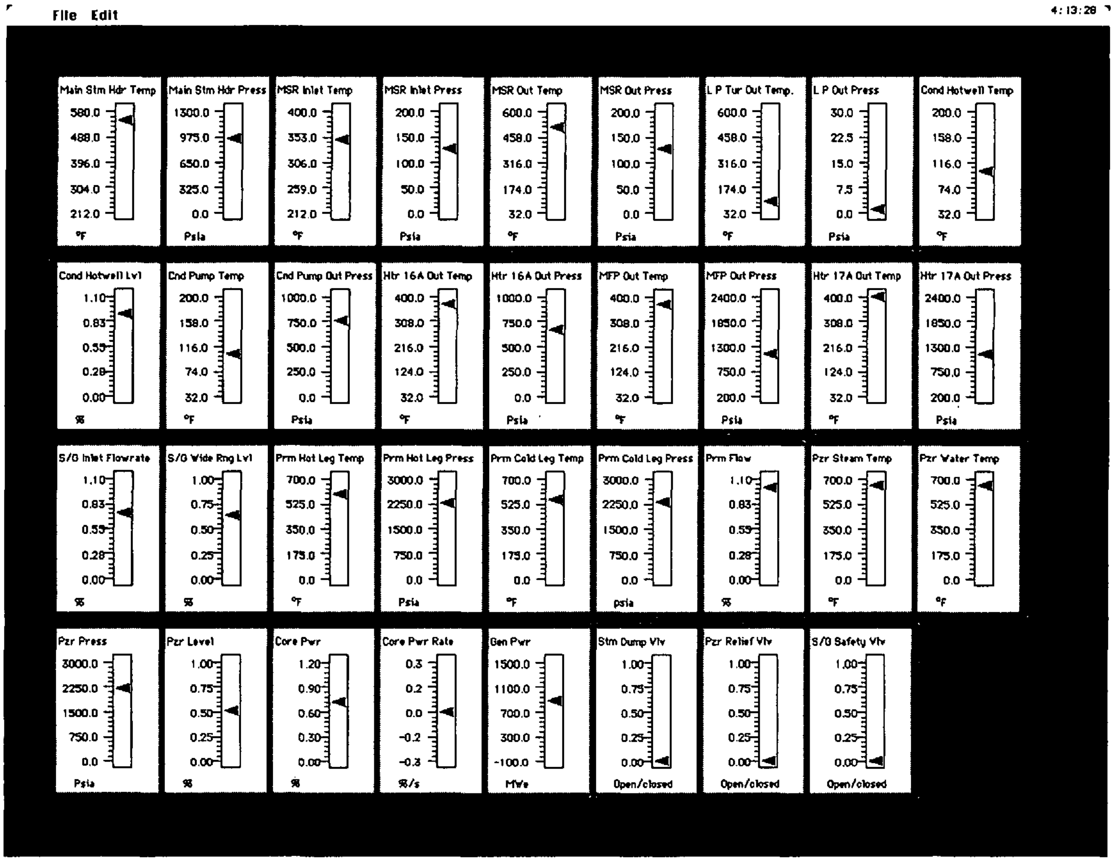

Figure 4. The single-sensor single-indicator display. (The details in small type are presented in order to faithfully represent the displays and are not meant to be readable.)

fashion. Therefore, this display contains some of the features of the SSSI display (represented in the analog meters) and some of the features of the Rankine display (represented in the PT plot). The three displays differ only in their visual form and structure. Despite the enormous difference in appearance, each display represents the same set of variables.

Hypotheses

The mapping principle predicts that the effectiveness of the displays for identifying system state should be proportional to the degree to which higher-order functional information is presented in a form that facilitates information extraction. Therefore, the Rankine cycle was expected to lead to the best performance, followed by the PT, and finally the SSSI. An interaction with expertise was also expected. It seems that to take advantage of the benefits of the Rankine display, one would have to have a fair amount of domain knowledge. Without such knowledge, study participants might have difficulty understanding the concepts presented in the Rankine display and in interpreting that information properly to achieve an accurate diagnosis of system state.

METHOD

These hypotheses were tested in the following experiment. The intention was to determine how well each of the three displays supports

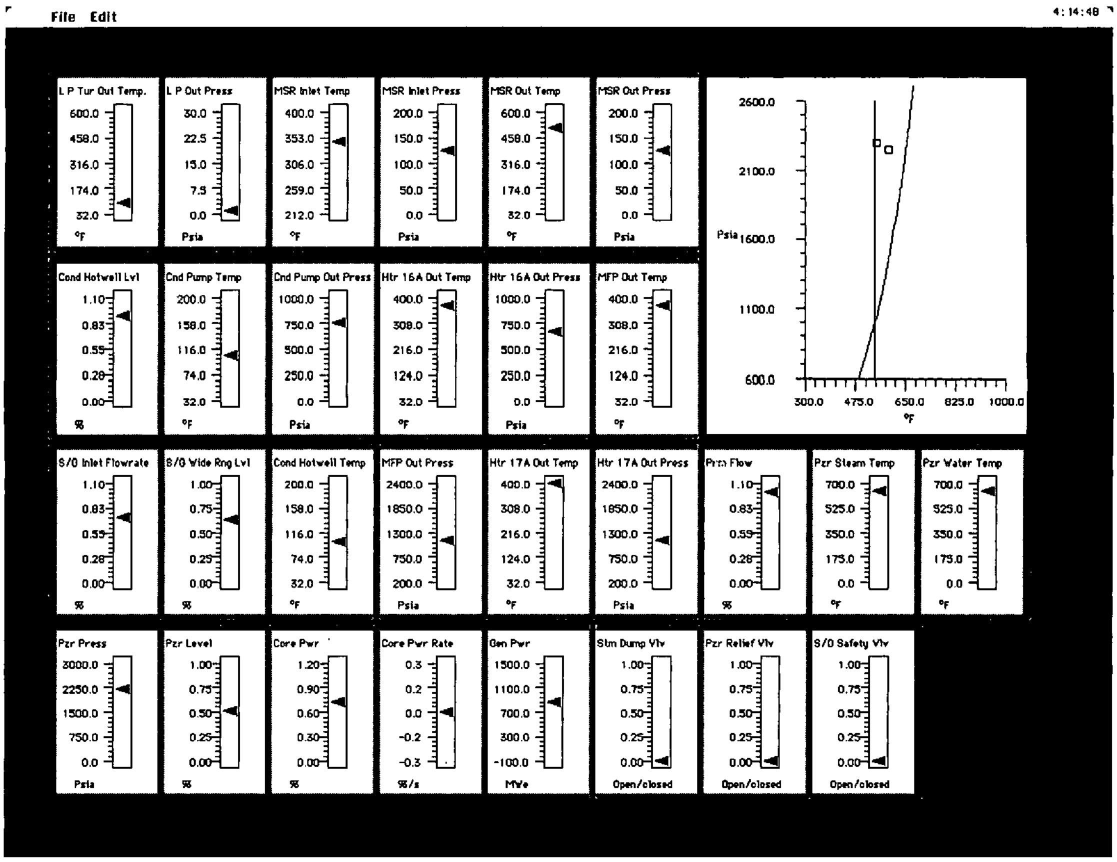

Figure 5. The pressure-versus-temperature display. (The details in small type are presented in order to faithfully represent the displays and are not meant to be readable.)

problem-solving or knowledge-based behavior (Rasmussen, 1983). Thus participants were required to perform an open-ended diagnosis task and one of two memory recall tasks.

Experimental Design

The experimental design was modeled after that of Vicente (1992). The effects of two between-subjects factors were investigated: display (Rankine, PT, SSSI) and expertise (novice, graduate, expert). Thus the full design was a 3 × 3 factorial with seven participants per cell.

Displays

All three displays presented the same subset of 35 variables chosen from the full set available in typical control room displays. The subset was chosen after discussions with the contract monitor, members of the nuclear engineering department at the University of Illinois, and members of staff at the utility that supplied the data. The data set was selected to represent the most important variables for diagnosing plant state.

The Rankine cycle display is illustrated in Figure 3. Although this display is based on the T-s diagram representation in Figure 2, several embellishments and changes to the traditional, static textbook format have been made to make the representation more informative for use in real-time monitoring of an NPP. For example, constant pressure has been represented as upward-curving lines through the superheat region and as horizontal lines through the saturation region to serve as reference points for interpreting the displayed data. Constant pressure lines are not shown in the subcooled region because water is nearly incompressible and the lines would all lie very close to the edge of the subcooled region. Instead of representing pressure of the water in the subcooled region, this diagram codes the degree of subcooling as the distance from the saturation curve: the farther to the left, the greater the subcooling. For example, the degree of subcooling for the hot and cold leg temperatures are indicated by the two lines emanating from the left side of the saturation curve near the horizontal line representing the status of the steam generator. These lines allow one to determine whether the primary loop is subcooled (by the horizontal length of each line into the subcooled region) and whether heat is being transferred to the secondary loop (by the vertical separation between the hot and cold leg temperatures). These are display features that have been added to the traditional T-s diagram.

The display has also been adapted to include information about the liquid levels in the pressurizer (the horizontal line near the top of the saturation curve), steam generator (the middle horizontal line under the saturation curve), and condenser (the horizontal line near the bottom of the saturation curve). These levels are coded by the position of a small box on each of these horizontal lines. The horizontal distance between each box and the right edge of the saturation curve represents the level. Thus maximum level is achieved if the box is located on the left edge of the saturation curve (representing all liquid and no steam), whereas zero liquid level is achieved if the box is on the right edge of the saturation curve (representing all steam and no liquid). Beneath the saturation curve, the heat transfer loop that cools the steam in the condenser has also been shown; the oval represents the source of cooling water for this loop, usually a lake or a river. Several valve symbols (similar to bow ties) representing relief valves of different types are also displayed. The colors of these valves change when the valves open and close (usually they are all closed). In addition to the graphical information, this diagram also contains some numerical information describing the flow rates and power production rates. For a more detailed discussion of the design rationale behind this display, see Beltracchi (1987).

The actual display is in color. The background of the screen is black, and the isobars and temperature lines in the superheat region appear in white. The area under the saturation curve is white, and the lines indicating the cycle and the pressurizer appear in cyan. The preheat and valve icons are green in normal and red in abnormal conditions. The alphanumeric text is yellow or red. Curves indicating blowdown (i.e., release of steam through a relief valve that is usually closed) appear during some transients as a white curved line in the superheat region. Abnormal values of the Rankine cycle line in the superheat region are coded red.

Figure 4 shows the SSSI display based on analog meters, with each of the 35 plant variables corresponding to one of the 35 meters. The location of the meters on the screen corresponds to a crude functional grouping. For example, the meters associated with the steam passing through the turbines lie in the upper row of the display, and the meters associated with the preheating of the water lie in the second row. The scale limits and names match those used in an actual NPP. The display includes colored backgrounds that reinforce the functional grouping of the instruments. For example, all the indicators of the steam passing through the turbines have a pale-blue background. The form of the meters, the functional grouping, and the color coding represent not an ideal design or the layout of any particular control room but simply a design representative of the current SSSI interface style used in many NPP control rooms.

Figure 5 shows the PT display. This display contains 29 analog meters plus a pressure-temperature plot. The meters match those in the SSSI display. Similarly, the area behind the meters is color coded to reinforce the functional grouping created by the layout of the meters. The PT plot replaces the six analog meters used to represent the pressure and temperature of the hot and cold leg of the primary loop and the pressure and temperature at the output of the steam generator. The small square blocks in the graph representing the hot- and cold-leg temperatures and pressures are color coded red and blue, respectively. The vertical line represents the saturation temperature of the water in the secondary side of the steam generator, and the curved line represents the saturation curve for water. When the temperatures or pressures of the hot and cold legs of the primary system change, the small square blocks on the PT plot move accordingly.

The PT display portrays several important characteristics of the plant by placing important variables in a meaningful context. First, it shows the relationship between the state of the water (liquid or steam) and temperature and pressure. The water to the right of the curved line in Figure 5 is steam, and the water to the left is liquid. This is particularly important information for monitoring the primary coolant. If the primary coolant passes from liquid to steam, the cooling of the core can be severely hampered. For safe operation, the boxes representing the hot and cold legs must remain to the left of the saturation curve. Second, the PT plot also groups related information. It places the temperature and pressure of the hot and cold legs near each other and shows their relationship to the temperature in the steam generator. The lower temperature of the cold leg indicates energy transfer to the secondary coolant. The line showing the temperature of the steam generator shows the amount of cooling that can occur. The cold leg of the primary system cannot drop below the temperature of the steam generator of the secondary system to which it transfers energy.

Participants

Three groups participated in the study. The first group, the novices, were third- and fourth-year undergraduate students studying mechanical or nuclear engineering at the University of Illinois at Urbana-Champaign who had completed at least one thermodynamics course. The demographic data show that the novices had completed an average of three or four physics courses, one or two thermodynamics courses, and 3.48 years of postsecondary education. It was important for the novices to have this minimal level of thermodynamics knowledge so that they could at least have a chance of understanding the Rankine cycle display. None of these students had any experience with NPPs, either as operators or in any other capacity.

The second group, the experts, were graduate students studying mechanical or nuclear engineering at the University of Illinois at Urbana-Champaign. They had no experience operating NPPs, but they had completed an average of four physics courses, five thermodynamics courses, and 6.12 years of postsecondary education. Therefore, the undergraduate and graduate student groups differed primarily in their theoretical knowledge of thermodynamics.

The third group, the operators, were professional operators who had significant experience in operating NPPs but had fewer years of university education and theoretical courses than did the students. The operators averaged only one or two courses in physics and one or two courses in thermodynamics, compared with the four or five courses in both physics and thermodynamics taken by the graduate students, but they had an average of nearly eight years' experience in NPP operation.

All participants were volunteers. The students were each paid $10 for their participation. All participants signed consent forms that made it clear that they could withdraw without penalty at any time.

Experimental Simulation

A full-scope, commercial NPP training simulator was used to generate the data for this experiment, so the scenarios represent actual NPP behavior, with the following exceptions. For a number of reasons, only 35 variables were selected (see Moray et al., 1993). First, the simplified plant contains only one of the usual four secondary loops. Second, many of the feedwater heaters have been eliminated, together with their heat sources. Third, the information displayed to the participants contains only wide-range values. In an actual plant, both wide- and narrow-range values would be available, but for the purposes of this experiment displaying only wide-range values was sufficient. In addition to eliminating many instruments, the model of the plant used in the experiment lacked the emergency safety systems that would have otherwise compensated for the faults. The simulator was used to generate the scenarios described in the following section.

Scenarios

The scenarios presented a dynamic trajectory of plant behavior that was driven by "canned" data that had been generated off-line. The nine transients were chosen after discussions with the contract monitor and the training staff at the utility that provided the data. The aim was to cover a reasonable range of "typical" transients, including examples of hydraulic incidents, power loss transients, and instrumentation failures. Every participant saw all nine scenarios during the experiment. Each scenario began with 3 to 15 s of steady-state behavior followed by a transient. The length of the transients ranged from 2 to 4 min. Because the screen updated every 3 s, the length of the trials ranged from 45 to 82 updates. The scenarios were presented in an order that was different for each participant and random without repetition, under the constraint that the scenarios with instrument failures did not occur in the first trial. This precaution was taken to ensure that participants had a positive initial impression of the fidelity of the data presented to them. Otherwise, they (especially the operators) might not take the experiment seriously. For a detailed description of the nine scenarios, see Moray et al. (1993).

Apparatus

All the studies were carried out using Macintosh IIci computers with 19-inch Rasterops color monitors. The displays were programmed in Microsoft® BASIC. The data driving the displays were generated off-line by a full-scope simulator in the training facility of a nuclear power utility.

Procedure

The experiment consisted of three phases: instructions, data collection, and debriefing. Each participant received three sets of instructions. The first set provided a general description of the simplified version of the NPP that they would observe. The second described the specific characteristics of the display that they would be using (SSSI, PT, or Rankine). The third described the memory recall and diagnosis questions that participants were to complete at the end of every trial.

After reading the instructions, the participants began the first trial. They were told that this trial was intended to familiarize them with the experiment but that they should try to complete the recall and diagnosis as accurately as possible. During this trial, they could ask questions to clarify their understanding of what was required. Following the demonstration trial the participants completed eight more trials.

Each trial consisted of viewing a 2- to 4-min transient followed by completing the recall test and a written diagnosis of the nature of the transient. The recall test required participants to remember the final state of the displayed variables (for more details, see Moray et al., 1993). Following the recall, participants identified the system state by writing their diagnosis of the transient on a form provided by the experimenter. This diagnosis consisted of answers to a structured questionnaire that led them to describe the scenario at two levels of detail (see also Vicente, 1992). First, the volunteers were asked to state whether a disturbance occurred during the trial. Although all scenarios had faults or sensor failures, the participants were not aware of this, so detection accuracy is a meaningful measure of performance. Second, the participants were asked to describe the nature of the fault or disturbance (if one occurred) or provide a functional description of the plant's behavior if a fault did not occur. Thus this questionnaire provided measures of a participant's ability to detect a disturbance and diagnose the cause of the disturbance.

Although the participants could view the scenario only for a period determined by the experimenter, recall and diagnosis were self-paced, and participants were encouraged to take as much time as needed to complete them. After completing the recall and diagnosis tasks, the participants began another trial by clicking on a window on the computer screen. The complete set of nine transients, combined with the recall and diagnosis, lasted approximately 60 to 90 min. Almost all participants completed the entire experiment within 2 h, and very few completed it in less than 1½ h.

At the end of the experiment, the participants received a written debriefing and answered questions about the purpose of the experiment.

Performance Measures

We will discuss the results of two performance measures: detection accuracy and diagnosis accuracy. Participants received one point for each trial in which they correctly detected that some type of disturbance had occurred. They also received one point if they correctly diagnosed the nature of the disturbance. To obtain a correct diagnosis, the participant had to describe the transient using terms unequivocally identifiable to the experimenters as the name given to the scenario when it was designed, even though the exact phrasing might be slightly different. Both detection and diagnosis were evaluated after the scenario presentation, and no response time limit was imposed. Several measures of memory recall performance were also obtained, but the results obtained from these measures were inconclusive and therefore are not discussed here (see Moray et al., 1993).

RESULTS

The discussion of the results is presented in three sections: detection accuracy, diagnosis accuracy, and informal comments. Post hoc pairwise comparisons of means were conducted using a Newman-Keuls test at $\alpha = .05$.

Detection Accuracy

Detection data were averaged across all nine scenarios for each participant, resulting in a single percentage-correct score for each participant, summarizing his or her detection accuracy. These data were then submitted to a two-way analysis of variance (ANOVA) with expertise and display as the main factors. The results, illustrated in Figure 6, revealed a significant effect for expertise, $F(2, 108) = 17.4$, $p < .0001$. Post hoc tests indicated no significant difference between novices and experts (57.3% vs. 61.1%, respectively) but did demonstrate that operators (77.8%) were reliably more accurate than were either novices or experts. The main effect for display, illustrated in Figure 7, was also statistically significant, $F(2, 108) = 5.77$, $p < .004$. Post hoc comparisons indicated no reliable difference between the SSSI and PT displays (63.2% vs. 60.6%, respectively), but the Rankine display (72.5%) led to reliably more accurate detection than did either the SSSI or PT displays. It was not possible to determine whether these differences in detection accuracy resulted from sensitivity or response bias, because not enough data points per participant were generated to conduct a meaningful signal-detection theory analysis. The Display × Expertise interaction was not significant.

Diagnosis Accuracy

The diagnosis data were also averaged across all nine scenarios for each participant, resulting in a single percentage-correct score for each person. These data were then submitted to a two-way ANOVA with expertise and display as the

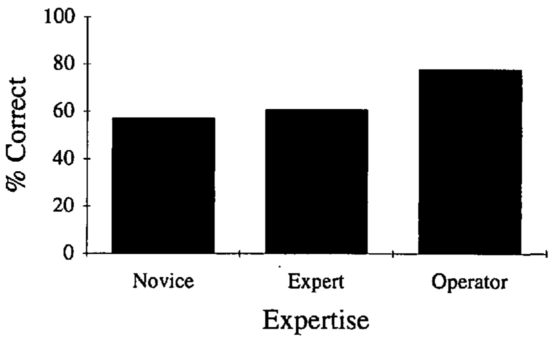

Figure 6. Means for effects of expertise on detection accuracy.

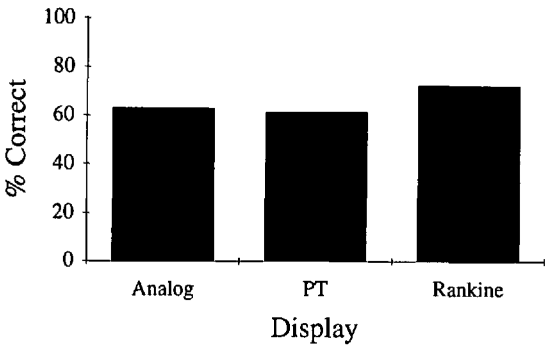

Figure 7. Means for effects of display on detection accuracy. PT = pressure-temperature display.

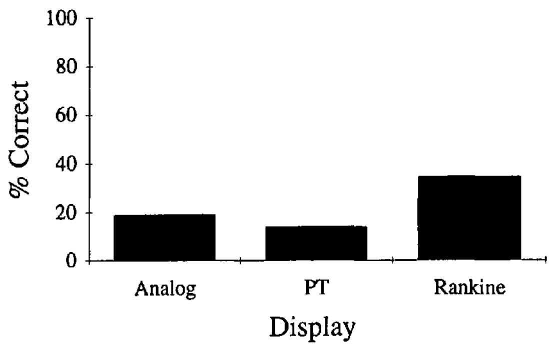

Figure 9. Means for effects of display on diagnosis accuracy. PT = pressure-temperature display.

main factors. The results revealed a significant effect for expertise, $F(2, 108) = 71.2, p < .0001$, as illustrated in Figure 8. Post hoc comparisons indicated that all groups were reliably different from one other, with operators being the most accurate, followed by experts and then novices (45.0% vs. 15.2% vs. 7.9%, respectively). The main effect for display, illustrated in Figure 9, was also statistically significant, $F(2, 108) = 20.9, p < .0001$. Post hoc tests indicated that there was no reliable difference between the SSSI and the PT displays (19.3% vs. 14.3%, respectively) but that the Rankine display (34.7%) led to reliably more accurate performance than did the SSSI or PT. Again, the Display × Expertise interaction was not significant.

Informal Comments

Further insight into these results can be obtained by examining the informal comments obtained from participants during debriefing. Some of the novices complained of not knowing the ways in which such a plant could go wrong. Although they were familiar with the Rankine cycle, they were not familiar with NPPs. This explains why they were unable to detect abnormalities and perform diagnoses. Nevertheless, it is noteworthy that the few successful novice diagnoses all occurred with participants who were observing the Rankine display.

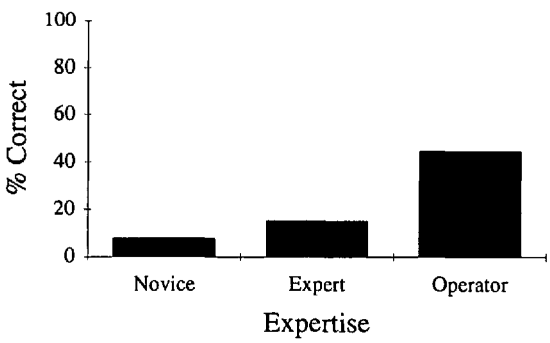

Figure 8. Means for effects of expertise on diagnosis accuracy.

For the most part, the operators commented that they did not like the Rankine display because they were not at all familiar with it. They also complained about the absence of traditional annunciators (i.e., alarms) and said that they would normally perform diagnoses by recognizing familiar patterns of illuminated annunciators. However, some operators suggested that although the Rankine display may be too unfamiliar to introduce into today's control rooms, it may be worthwhile to introduce it into current training programs.

DISCUSSION

The Rankine display led to more-accurate detection and diagnosis of transients than did either of the other two displays. No significant difference occurred between the PT and SSSI displays for either detection or diagnosis. As one would expect (and hope), a steady improvement in diagnostic performance was observed from the novices to the experts to the operators. Perhaps surprisingly, the experts performed only slightly better than the novices. This difference was significant for diagnosis but not for detection. This finding shows that one must be very careful in the criteria one adopts for defining expertise (see also Vicente, Christoffersen, & Pereklita, 1995). However, the operators were significantly better at detection and diagnosis than were either of the other groups and by a very large margin. Contrary to expectations, the interaction between display and expertise was not significant.

These findings are important for three reasons. First, they are generally consistent with the predictions made by the mapping principle and therefore show that there is merit to this design principle. Second, this is the first rigorous evaluation of the Rankine cycle display and thus the first time that experimental evidence demonstrating its advantages has been obtained. Third, the superiority of the Rankine display for detection and diagnosis takes on a different light when one considers the negative comments obtained from the experienced operators. Aside from confirming that preferences and performance can sometimes be dissociated, this finding suggests that the most significant problem with the Rankine display may be that it is very different from current control room designs. However, the findings of this study show that it is possible to overcome this "inertia" arising from traditional practices and demonstrate superior detection and diagnosis performance in licensed operators.

The fact that the overall level of operator performance was low is not surprising and does not reflect a poor level of training or knowledge. As many operators pointed out, they were working with an impoverished set of data compared with that found in a normal control room. Furthermore, they did not have alarms and procedures available to them as they usually do. In any case, the low absolute level of performance is not important, because the primary purpose of this study was to compare the relative performance achieved with the different displays.

CONCLUSIONS

This study has shown that the Rankine cycle display can lead to improved performance compared with more traditional displays, thereby showing the value of the mapping principle. These results should be of interest to the NPP industry. The Rankine cycle display has already been implemented in advanced control room simulators at the Halden Reactor Project Laboratory in Norway (Haugset, Berg, Førdestrømmen, Kvalem, & Nelson, 1991) and at the Toshiba Nuclear Energy Laboratory in Japan (Itoh, Monta, Sakuma, & Makino, 1993) and in operational form at the Experimental Breeder Reactor II (EBR-II) in Idaho Falls, Idaho (Lindsay, 1990). However, the Halden and Toshiba implementations have yet to be evaluated, and only informal comments are available from the EBR-II implementation. The anecdotal evidence from EBR-II is consistent with the empirical evidence presented here. The display has been in regular use there for several years, and informal comments from the operators have been extremely favorable. The experimental findings presented here therefore complement the informal insights gained from these industrial prototyping efforts.

Although these initial results are encouraging, many issues remain to be addressed before one can defensibly recommend that the Rankine display be implemented into commercial NPP control rooms. First, there is the issue of integration. For the Rankine display to demonstrate its advantages in practice, it is essential that it be integrated with the rest of the control room, including the annunciators, procedures, training, controls, and lower-level displays. Previous experience in the nuclear industry has clearly shown that introducing a new design concept without integrating it into existing operations in a coordinated manner will result in lack of acceptance and lack of use on the part of operators (Woods, Wise, & Hanes, 1982). Second, the Rankine display needs to be more thoroughly tested under a wider and more representative set of conditions. For example, in this experiment, participants could not rely on annunciators or procedures. Will the advantages of the Rankine cycle display still manifest themselves when these aids are also present? Furthermore, the fact that a display can effectively support detection and diagnosis does not necessarily mean that it will lead to effective control. The ability of the Rankine cycle to support operators in tasks requiring compensatory actions needs to be empirically determined.

Finally, there is a need to assess the behavior of the Rankine display under a wider range of sensor failures and component faults. It is essential to evaluate any display under a variety of failure modes to ensure that the display does not provide misleading information under unusual circumstances. The Rankine display presents only raw sensor data, so there is no danger of propagating failed values through calculations. However, the effect of a failed sensor on operators' understanding and control of the plant is unknown. This experiment suggests that the Rankine cycle display makes a sensor failure very salient and therefore much easier to detect. However, when one data point fails, the lines showing the relations between that point and other points connected to it are distorted (note that this is a general property of emergent feature displays). For example, in our experiment, a failed sensor resulted in a display in which the distortion was extremely salient. This facilitates detection, but it is not known what effect this might have on operators' abilities to interpret the remaining information on the display. Likewise, it is unclear how this might affect operators' abilities to compensate for other disturbances. Perhaps this potential problem can be overcome through sensor verification and validation techniques. These issues should be investigated in future research.

In the meantime, it may be useful to follow up on the suggestions made by some operators in this study to introduce the Rankine display into training. Operators in the United States already receive instruction on the Rankine cycle, so the display could perhaps serve as an effective instructional tool. Gradually, operators may become accustomed to it, and introducing it into the control room may later seem like a natural step to take.

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