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HUMAN FACTORS SURVEY OF ADVANCED INSTRUMENTATION & CONTROLS*

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HUMAN FACTORS SURVEY OF ADVANCED INSTRUMENTATION AND CONTROLS

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ABSTRACT

A survey oriented towards identifying the human factors issues in regard to the use of advanced instrumentation and controls (I&C) in the nuclear industry was conducted. A number of United States (U.S.) and Canadian nuclear vendors and utilities were participants in the survey. Human factors items, subsumed under the categories of computer-generated displays (CGD), controls, organizational support, training, and related topics, were discussed. The survey found the industry to be concerned about the human factors issues related to the implementation of advanced I&C. Fifteen potential human factors problems were identified. They include: the need for an advanced I&C guideline equivalent to NUREG-0700; a role change in the control room from operator to supervisor; information overload; adequacy of existing training technology for advanced I&C; and operator acceptance and trust.

INTRODUCTION

The nuclear power industry has used analog I&C in their control rooms and technical support centers since the first nuclear power plant went on-line in the late 1950s. Even today the industry, as a whole, has been slow to implement advanced/digital I&C. The utilization of digital I&C appears, however, to be the wave of the future because analog components and systems are becoming obsolete and no longer available. These advanced systems will probably be utilized in the life extension of nuclear plants. It has been demonstrated in other industries, e.g., petroleum refineries, chemical manufacturing plants, and aircraft systems, that digital I&C provides almost error-free performance that is three-to-four orders of magnitude better than analog components performing the same function. With the increase in sophistication in the operation of modern nuclear power plants that is needed to handle the multiple (and sometimes conflicting) goals of efficiency, reliability, economic operation, and safety, the nuclear industry will be compelled to make use of advanced I&C.

Oak Ridge National Laboratory (ORNL) is performing a research project for the U.S. Nuclear Regulatory Commission's (NRC) Office of Nuclear Regulatory Research. The purpose of the project is to provide the technical basis for the development of regulatory criteria to evaluate the safety implications of human factors associated with advanced I&C systems in nuclear power plants. During the first part of this project, a survey of the U.S. and Canadian utilities and vendors was conducted. The survey was oriented towards determining the human factors issues related to the current, planned, and potential future uses of digital systems in the control room and technical support center. Two reports describing the survey were prepared earlier (Carter & Uhrig, 1989; Uhrig & Carter, 1989).

SURVEY METHOD

Survey Participants

The survey was conducted at five U.S. nuclear utilities who have begun to use advanced I&C. It was additionally administered at two advanced reactor and three light water reactor vendors. The Canadian nuclear power plant vendor and the principal Canadian utility also participated in the survey. Groups of persons interviewed at each nuclear facility included human factors personnel, control room operators, software developers/computer programers, I&C engineers, and trainers/instructors.

Survey Instrument

A survey instrument consisting of open-ended questions was generated through an iterative process; its construction was based on guidance provided by Jones (1985) and LoSciuto (1981). The survey instrument was subsequently bench-tested at the reactor facilities of four national laboratories. Changes were made to the instrument based upon the results from the test. The derived survey instrument was divided into five main areas: (a) description of the digital I&C, (b) software validation and verification (V&V), (c) artificial intelligence and expert systems, (d) usefulness and operability, and (e) human factors issues. The human factors portion was further subdivided into five sections: (a) CGDs, (b) controls, (c) organizational support, (d) training, and (e) related topics.

Survey Process

The survey took place over a nine-month period from July, 1988 through March, 1989. The twelve nuclear facilities were surveyed by a team of three scientists: a human factors psychologist, a nuclear engineer with expertise in I&C and expert systems, and a certified senior reactor operator/ instructor. The U.S. sites were visited for one day each; the Canadian for a day-and-a-half. Personnel at each utility/vendor were interviewed either individually or in groups of two-to-five. The amount of time spent with particular individuals varied between one-half and three hours.

Before each group of individuals was interviewed, they were informed of the purpose and background of the survey and the benefits for the industry through their participation. They were also told that their specific comments would be kept confidential and that no published material would identify remarks or views expressed by a specific utility/vendor or individual. The survey instrument was used to guide the course of the interviews, but the discussions themselves were semi-structured and took form as they proceeded. Only those items which were applicable to either a specific facility or particular group of people were discussed. Comments by the participants were recorded manually by the survey team.

RESULTS

Information gathered during the survey was reviewed and analyzed. The results from the human factors portion of the survey are summarized below. They are discussed under the headings of U.S. utilities, U.S. advanced reactor vendors, U.S. light water reactor vendors, and Canadian facilities.

U.S. Nuclear Utilities

Control Rooms

All five of the U.S. nuclear power plants surveyed have incorporated advanced instrumentation into their control rooms, some to a higher degree than others. One utility utilizes a nuclear net console in its control room that contains thirteen cathode-ray tubes (CRT); nine are used with the display control system, three with the plant monitoring system, and one is dedicated to the display of alarms.

The nuclear net CGDs include piping and instrumentation diagrams (P&ID), parameter values, and alarms. The P&ID screens use symbols which are similar to those found on hard-copy drawings. Motor status is indicated by alphanumeric text superimposed over the component. Valve status is indicated by shading. The nuclear net CGDs are arranged so that the displays are situated above the meters, dials, and knobs.

Computer-Generated Displays

Operators at four of the five plants said that they have a high level of confidence in the output from the plant computer system and the CGDs. The displays at all five plants appear to be simple, clear, understandable, and comprehensible. Personnel at one of the utilities commented that the CGDs should present information only when the operators need it and that the displayed information must be kept simple. All of the utilities utilize alphanumerics, graphics, and color in their CGDs. The CGDs at three of the utilities support multiple users; every CGD can be called up on all of the CRTs.

The operators are about evenly split on the issue of whether they routinely use the parameter readings from the CGDs to confirm readings on the conventional instrumentation, or vice versa. Personnel at one utility remarked that operators routinely use both the parameter readings from the CGDs and analog instrumentation to monitor systems in the control room. They said that the operators do not rely totally on either of the presentation modes. The operators are taught to check everything. The operators stated that they use CGDs more during normal operations, and control board indications more during off-normal operations. At another utility, the control boards are the operator's primary source of information. However, each operator has his own way of gathering and using the information. Some operators rely on the CGDs (unless the information is unreliable) and use the parameter readings to verify readings on the conventional instrumentation. Others rely mostly on the conventional instrumentation, using the computer as a redundant source of parameter values. The operators noted that the CGDs are treated as if they were operator aids and that they could operate without the CGDs and the computer.

The features of the CGDs at the five plants that operators find most useful include: having a large quantity of data in a compact area, trends of key plant parameters, P&IDs, and presentation of reactor core limits. The plants were about evenly split on the issue of whether the CGDs have made diagnosis of off-normal conditions more efficient and reliable. Personnel at four utilities did say however, that since the CGDs were introduced into the control room, the operators rely upon them for information. The fifth utility indicated that the use of CGDs is an individual practice. Some operators use the displays as their primary source of information and rely upon them; others use the CGDs as a secondary source and do not strictly rely upon them. A training instructor at one utility remarked that it is hard to teach the operators not to have a "blind" reliance on advanced instrumentation.

Controls/Expert Systems

None of the utilities has as yet implemented either advanced controls or expert systems within their control rooms. One utility is, however, contemplating the possibility of putting a digital feedwater control system and a digital steam generator level controller into their plant. (Such systems have already been installed in plants not included in this survey). They believe that digital control is less expensive and more reliable than existing controls. Another utility indicated that they would go to advanced controls only for improved plant performance, safety, reliability, and/or life extension. The same utility said that their management is very supportive of expert systems technology but that expert systems will most probably be introduced in non-operating situations before they are utilized in control room operations.

Organizational Support

Personnel at four of the utilities remarked that management supports the use of advanced instrumentation within the control room. However, each said that their managers are very concerned with cost vs. benefits and that advanced I&C will be considered only if management determines that improvements in the operation of the plant justifies the cost. One utility indicated that regulatory requirements are a driving factor in most upgrade decisions. All of the utilities indicated that management made the decision to install the advanced I&C within the control room. Three said that their operations department participated in the decision to purchase or design the systems. They also noted that an operator needs assessment was conducted, to define the requirements and constraints, prior to the purchase and/or design of the systems.

Personnel at three of the utilities stated that an implementation plan (i.e., how the advanced instrumentation fits in with the existing I&C in the control room) was developed. Four noted that the instrumentation was introduced into the control room in a way which supported operator acceptance. One utility indicated that operators were allowed to design their own computer displays using a list of computer data points. They also stated that, in order to gain operator acceptance of the advanced I&C, it must work correctly from day one. Three utilities indicated that engineers, operators, and trainers worked together during the design process. They also commented that human factors personnel were involved. One utility noted that the operator must be brought "into the loop" early in the design process, because they resist changes and want to know what is going on.

Training

Training was discussed with personnel at four of the plants. Three indicated that operators are involved in the writing of control room procedures. One plant indicated that operators are also consulted during procedure changes. They remarked that when a problem is identified, the operators make recommendations on how the procedure should be modified. All of the utilities indicated that very little is taught on signal sources, transmission, shaping, and computer-display generation. The plants were evenly spilt on the issue of whether students normally enter the training program with some computer knowledge. All of the utilities, however, indicated that the training personnel are generally more knowledgeable about computer fundamentals than most students and that some formalized training is given on the advanced instrumentation before it is introduced into the control room. Three also noted that features of the advanced instrumentation are discussed during other systems training in order to show system interrelationships. The plants were evenly divided on the issue of whether instructors encourage the use of the advanced instrumentation during normal and/or off-normal operations. One utility person stated that operators are encouraged to use the computer to its fullest capacity/extent, but not to blindly rely on it. They are taught to use as much computer information as possible, but the final decision remains with the individual operator. Another utility indicated that instructors do not try to influence operations philosophy. They stated that the operations department is responsible for operating procedures. All of the utilities have found that training for advanced instrumentation is no more difficult than training for other plant systems.

Related Topics

Personnel at all five of the utilities commented that the use of advanced instrumentation in the control room has lightened the operator's workload. They also said that it has made the operator's job more efficient. One utility also indicated that going to advanced I&C in the control room should make the maintenance technician's job easier and probably reduce workload. Four of the utilities noted that the operator's role with regard to authority and responsibilities has not changed as a result of the introduction of advanced instrumentation into the control room. They, however, believe that this situation will eventually change with the introduction of more and more advanced I&C. They felt that the role of the operator will become more supervisory oriented. Three utilities said that the introduction of advanced instrumentation has not as yet had an impact on the selection and qualification requirements for control room operators. Four utilities were asked whether operators were involved in the software V&V process; half responded yes and half no. The plants were also about evenly divided on the issue of whether an intelligent display of plant operating procedures would be beneficial. One utility said that such a system would be good if it worked and "stayed ahead of the operator". They also remarked that it would be a "great candidate" for an expert system.

U.S. Advanced Reactor Vendors

Control Rooms

One advanced reactor vendor's control room will consist mainly of CRTs. It will have one supervisory panel, four reactor panels, one turbine panel, and one assistant operator panel. The other vendor's control room will have three control consoles, each having four CRTs. There will be one large screen overview display behind each console. The CRTs on the operator's console will provide detailed information on each reactor in the power block, key parameter values, alarms, and process flow diagrams of plant systems. The large screen display will provide a plant overview showing all reactors in the power block, the steam generator, major pumps, main turbine-generator, balance of plant, and key parameters. The large display will permit operators to determine quickly the status of the other power blocks.

Computer-Generated Displays

A person at one of the advanced reactor vendors said that their CGDs will present the operator with high-level information; he is quite concerned that the presentation fits in with the operator's "mental model" of the plant. The other vendor indicated that graphics will be used to mimic systems, and parameters will be displayed using alphanumerics. One of the reactor vendors remarked that all of their CGDs will be color-coded and be redundant, (i.e., all displays will be able to be presented on any of the CRTs). They noted that blind reliance on advanced I&C could be a major issue and that training may be the only way to instill operator trust in a display system.

Organizational Support

Both vendor designers remarked that thus far during the design process, engineers, trainers, and human factors personnel have worked together. They both said that these people will continue to interface. One of the vendors commented that only about 50% of NUREG-0700 (U.S. NRC, 1981) is applicable to its design. They would like some guidance and/or set of guidelines with regard to the role of the operator for automated systems and the degree of task analysis required for non-class 1E systems.

Related Topics

Both advanced reactor vendors indicated that their designs will significantly change the role of the operator when compared to current plant designs. The operator will be more of a supervisor; he will have a "verification" role. Both vendors stated that the operator will become a plant mission manager. The locus of control will be with the operator; he will tell the control system what he wants it to do and the system will take the necessary actions. One of the vendors noted that the operators will assume a "pilot" and "co-pilot" type of role among themselves.

Both vendor designers said that their reactor designs should decrease physical workload, but they disagreed on cognitive workload. One of the vendors stated that one of the goals of its system is to take operator error out of the system. Both remarked that fewer people will be needed to "man" the control room. They disagreed on whether the introduction of advanced I&C will have an impact on the selection and qualification requirements for control room operators. Both vendors said that an intelligent display of operating procedures would be beneficial in future plants.

U.S. Light Water Reactor Vendors

Control Rooms

All three of the light water reactor vendors are engaged in the development of advanced control room designs. One vendor's control room will have three types of workstations. The first is the supervisory console which will be designed to support the systems manager role. There will be no plant controls on this workstation, but all information resources about plant design and real-time process data will be available. The remaining two stations will be designed to support two or more operators responsible for the tasks associated with the operator and/or maintainer role. These workstations will be configured in a circular fashion around the supervisory console. The circular board will be organized by the plant functions resulting from a "goal-means structure". In general, the organization will follow energy production and flow from left to right through the plant; primary system controls just to the left of center, secondary system and turbine-generator controls just to the right of center. The remainder of the board will contain peripheral functions concerned with such things as containment and waste heat management, and vital and nonvital electrical power. Situated in the center section of the circular board will be a sit-down station for the operator or maintainer to monitor detailed plant performance during normal operation.

This vendor's advanced control room will utilize both integrated and dedicated graphics. (Dedicated graphics are those associated with a particular part of the control panel.) The integrated graphics will be presented on the central sit-down console. The control room will be able to be run from the integrated graphics alone. The computer screens will present two very tightly coupled networks of displays. The first will depict the plant process from a functional perspective. The second will show the physical system layout corresponding to the functional display being viewed.

The control room of another light water reactor vendor will rely heavily on CGDs. There will, however, be a sufficient number of conventional displays to support the operation of the plant should a CGD system fail. High-level information on plant status and the primary systems is to be presented by a large CGD called the "integrated process status overview". It is to be a fixed-format display that will only "flag failures in the plant systems". Plant computer displays will consist of a high-level display and a large number of lower-level displays. The high-level display of the plant computer will provide an overview of the plant. The low-level displays will provide the operator with information on individual systems, parameter trends, and alarms. Icons are to be used to depict the operator's choices on each screen. A "live" icon on each screen will inform the operator of an alarm on one of the other displays. Each screen will contain a limited amount of information to keep the displays uncluttered.

The control room of the third light water reactor vendor will consist of a large, flat, horizontal display panel and a control console consisting of five CRTs. The display panel will present a plant overview, critical plant parameters, and alarm processing. The control console will display operator prompts and be the consolidated control area. The CGDs will display process and instrumentation diagrams, alarms, and parameters that reflect the plant operating mode.

Computer-Generated Displays

All three of the light water reactor vendors indicated that confidence/trust in the output from the computer systems and advanced I&C is important. One vendor remarked that operators feel uncomfortable with a large change from what already exists. They want only minor modifications to what they currently have in the control room. All three vendors commented that their CGDs will use color and color coding. They also said that their displays will support multiple users. One of the vendors noted that a benefit of CRTs is that they can present massive amounts of data in a small space. Another stated that blind reliance on the CGDs could be a problem. They noted that the operator must be encouraged/motivated to interrogate the CGD information. Reference experience is important in the issue of blind reliance; that is, if operators have used older equipment, they have a reference by which to compare the new equipment.

Controls

Two of the light water reactor vendors are designing advanced controls. Both are developing an advanced feedwater control system. One is also creating a recirculation flow control system and a steam bypass and pressure control system. They said that one of the design objectives of their advanced control systems is to reduce the need for "manual" data processing, thereby keeping the need for operator input to a minimum. One vendor will use touch screens for manual inputs to the control system. The other is going to use the same type of hard keys that are used in existing plants. The vendor has been told that this is what the utilities want.

Expert Systems

Two of the light water reactor vendors are developing expert systems. One is designing an emergency operating procedure tracking system (EOPTS). Its purpose will be to reduce the potential for human error during off-normal situations by determining which plant functions need to be restored and then displaying the appropriate operator actions for the existing plant conditions. The data base of the EOPTS expert system will contain plant specific, symptom-based emergency operating procedures. The vendor commented that the expert system will mesh well with the operator's mental model. The other vendor who is developing expert systems stated that it has not found many places where a deterministic approach is not adequate, and that none of the expert systems which it is designing are to be utilized directly in the control room. They noted that if they were to develop an expert system for the control room it would be for specific pieces of the control room; they would not attempt to design an all encompassing expert system for the entire control room. The third light water reactor vendor noted that utility management in the United States is not currently in the "correct frame-of-mind" for expert systems for control room retrofits. They predicted that expert systems will be selectively used in plants in the mid-1990s.

Organizational Support

Two of the light water reactor vendors described where they think the initiative for the development of advanced I&C is coming from. One noted that the design of new systems is being driven by requests from the U.S. utilities. They said that economics is the main reason for moving to digital instrumentation. The other vendor remarked that it is involved with the initiation of advanced I&C development. They stated that they use a rapid prototyping approach to systems development. The vendor commented, however, that the design of its advanced control room is being driven primarily by the wants and needs of the utilities and reactor owner groups.

All three light water reactor vendors have design teams which consist of engineers, operators, and human factors personnel. One vendor remarked that the user population must be involved during the entire life-cycle in order to ensure operator acceptance.

Related Topics

All three of the light water reactor vendors were asked how the use of advanced I&C in the control room will effect operator workload. Two vendors said that it will decrease physical workload, but increase cognitive workload. One remarked that the reduction in physical workload will be accomplished by the small console design and less required manual data processing. The other vendor questioned felt that it will decrease both. They provided a number of reasons for their opinion: the number of physical display devices will be reduced; the quantity of data will be simplified; and redundancy and diversity will be provided in the display systems. Two vendors commented that the performance of the operator should improve and the job should become easier as a result of the use of advanced I&C in the control room. Two also stated that advanced I&C should make the operator more efficient in responding to off-normal situations. One vendor said that the utilities are concerned with the impact/effect of advanced I&C on the operator and his performance.

Personnel at two of the light water reactor vendors remarked that the role of the operator in the control room will change significantly. One stated that the operator will become more of a supervisor of the automatic system than a manipulator of controls; the other that the operator will be an "observer of automation." One noted, however, that the roles of the human and automation are being driven by the desires of the utilities. It said that there are a couple of questions which are determining factors for the development of all advanced I&C systems. They include: How much knowledge-based behavior do you want the operator to have and what is the operator going to be responsible for? The third light water reactor vendor commented that the role of the operator will remain essentially the same in an advanced I&C control room; a few minor changes will, however, take place. The operator will intercede only when he needs to maintain plant safety. He also will not need to rely as much on mental processing and sorting of data during stressful situations because much of this will be performed by the computer.

One of the light water reactor vendors remarked that ease/accessibility for maintenance is considered in the design of its advanced I&C. All of the vendors commented that an intelligent display of plant operating procedures would be beneficial for the operator. Each is developing computerized off-normal event procedure display systems.

Canadian Nuclear Facilities

Control Rooms

The Canadian utility's control room has a control panel which is approximately 34 feet long. Mounted across the top of this panel are a number of annunciation CRTs which are grouped by function. There are also three other CRTs arranged across the middle of the panel; they are used to display system parameters and system drawings. Situated in front of the panel is a small console, consisting of four CRTs, where the first operator sits during the monitoring mode.

The Canadian vendor's most modern control room was developed for an oil-fired power plant. This control room consists of four CRTs and a single interactive keyboard. The CGDs are fully redundant and have been designed such that the plant can be controlled during any phase of operation through only two of the CRTs. Except for the start-up phase, adequate control is possible from only one CRT.

The vendor is designing an advanced nuclear control room. It will consist of a control panel and two consoles, a main control console and a safety system testing console. The panel will have three physical levels. At the top will be the annunciation system windows. In the middle will be the CRTs and monitoring instruments. The lower level will contain switches, controls, and keyboards. The main control console will allow access to all of the computer setpoints and displays which are available at the CRTs mounted in the control panel.

The vendor is also developing the "nuclear control room of the future" (ten-to-fifteen years from now). It will be a compact module and contain a few sit-down computer consoles that will provide information to the operator that has been processed to reflect the context of his specific objectives and tasks in each particular situation. Current plant status at the most detailed level will be available in the form of computerized flowcharts on CGD screens. The control room will also have large, dynamic color mural mimics depicting the major equipment and system status of the entire plant.

Computer-Generated Displays

The Canadian utility's CGDs are arranged in a hierarchial structure. They have been programmed so that they can be modified easily and quickly in order to present information in another manner or to add or delete specific parameters, if the operators so desire. Alphanumerics are used in the system parameter CGDs. The plant system drawing CGDs utilize graphical symbology. The CGD screens present many types of data displays. The CGD screens also present: symbols for valves, pumps, fans, dampers, etc.; flow diagrams; bar graphs; and alarm messages. The vendor's oil-fired power plant control room has three layers of CRT screens. Alphanumerics and graphics are also used with these CGDs. The most recent alarm is displayed at the bottom of every screen. Screen functions are selected via a hierarchial system of menus. The screens can be adjusted and configured and the schematics can be edited on-line.

High resolution color is presented on the CRTs in the two control rooms. However, because redundant information is presented by the symbology and colors on the CGDs, the CRTs can be run in monochrome if there should be problems with the color generators. Color coding is also used in the control rooms to depict the status of components and to help identify the severity of the plant status.

The main CRTs in the Canadian utility's control room support multiple users. They are totally redundant in that every CGD can be presented on all CRTs. Also the operator can monitor any CGD on the four CRTs on his control console. The vendor's control room can be operated by only one operator.

Controls
Utility operators provide information to the control system through their control panel. Input includes start-up rate and power levels to be maintained. Operators, functioning within the control room designed by the vendor, are able to monitor the state of the plant and take control actions through the CGD console facilities. All control and data acquisition is accomplished via the interactive graphics. The operators adjust automatic controller parameters and setpoints, acknowledge alarms, and perform data-logging activities via the CRTs.

Expert Systems
The Canadian utility is developing two expert systems for its control room. The first will be for use with the coolant injection system, and the other is called the "feedback" expert system. The feedback system will process information and knowledge and be interposed between the operator and the plant in the feedback loop. The vendor has not as yet implemented an expert system at any Canadian utility. They are, however, planning to implement a real-time expert system within the next year. Both the utility and vendor are developing a number of automated operator aids.

Organizational Support
Digital equipment appears to have been introduced into the utility's control room in a manner which supports operator acceptance. Management at the Canadian utility wholeheartedly supports the use of advanced I&C in its nuclear generating station control room. Also, the operators were involved in the design process and thoroughly trained on the digital I&C before it was implemented within the nuclear station. Training instructors at the utility commented that training on the digital I&C in the simulator has had a lot to do with operator acceptance of advanced technology.

The changes in the control room developed by the Canadian vendor have been well accepted by the operating personnel, and the operators are enthusiastic about the modifications. The vendor stated that it is very important to have operating personnel, if available, involved during control-room design from early in the development cycle. The vendor engineers noted that the ability to realistically demonstrate the operator interface as it is being developed allows prompt feedback from the plant operating personnel and prompts an early understanding of the nature of what they will have to deal with.

Related Topics

Vendor personnel said that the use of advanced I&C technology has simplified the required operator actions. They stated that through the use of the technology, they have tried to unload the human of mundane and tedious tasks. The Canadian utility believes that the technological changes which have been made in its control room will reduce operator workload.

Canadian vendor personnel commented that the operator is perceived as a "weak link" in nuclear plant safety. They stated that, through the use of advanced I&C technology, they have minimized operator involvement in routine tasks and tasks where required response is well defined. The vendor believes that by doing this it has reduced the frequency of potential control room operator errors well below the levels typical in conventionally instrumented pressurized-water reactors. The human factors group at the utility has conducted a number of time-line studies of the operator in the control room. Their results suggest that the performance of the first operator has indeed changed; he now makes fewer errors and does his tasks more quickly than before.

In Canada the operator is considered to be the monitor of actions and has responsibility for the control actions performed. He can intervene and take over control of the situation whenever required. The level of automation allows for no required operator actions within fifteen minutes of an unexpected or abnormal event.

Personnel at both the Canadian utility and vendor believe that intelligent display of normal and off-normal operating procedures would be beneficial to control room operators. The utility stated that a display of critical parameters to monitor during off-normal events would also be helpful.

IDENTIFICATION AND RANKING OF THE ISSUES

All of the information generated during the survey was evaluated and further analyzed by the survey team. A number of potential human factors issues were identified and ranked in order of importance by five individuals: two members of the survey team, two independent ORNL scientists (one having a background in I&C and the other in human factors), and the NRC project manager. Each person rated each of the items either high, medium, or low. Values were assigned based upon each issue's perceived potential impact on safety and regulatory policy. Fifteen human factors issues were identified of which five were given an importance rating of "high," six as "medium," and four as "low." These issues are presented in Table 1. The order within a given rating is arbitrary and has no significance. Each of the issues is discussed below.

Table 1. Potential Human Factors Issues

HIGH RATING

Operator Acceptance and Trust of Advanced I&C/Blind Reliance on the Computer Output

Role Change in the Control Room from Operator to Supervisor/ Demographical, Selection, and Qualification Requirements for Operators in the Control Room of the Future

Need for an Advanced I&C Guideline Equivalent to NUREG-0700 (i.e., Interface of the Human, Displays, and Controls)/Lack of Consistency between Human-Advanced I&C Controls Interfaces

Information Overload - What Is the Threshold where Intelligent Operator Aids Are Needed?

Adequacy of Existing Training Programs, Techniques, Methods, and Tools for Training on Advanced I&C

MEDIUM RATING

Impact of CGDs on the Operator's Mental Model

Need for a Dynamic Allocation of Functions and Tasks between the Human and Advanced I&C/What Tasks Are Appropriate for the Human in an Advanced I&C Control Room?/Locus of Control between the Human and the Advanced I&C

Operations Staff Must Be Involved during the Entire Life-Cycle of the Instrumentation/Control System

User Friendliness of CGDs and Human-Computer Interfaces

Effect of Advanced I&C on Operator Performance/Job Efficiency

Systems Integration/How Does One Manage Human Factors Information?

LOW RATING

CGDs for Multiple Users

Organizational Climate of the Nuclear Utility

Knowledge Acquisition for Expert Systems

Display of Maintenance Information in the Control Room (the Operator Needs to Know the Status of Plant Equipment)

High Rated Issues

Operator Acceptance and Trust of Advanced I&C/Blind Reliance on the Computer Output

This issue deals with the operator's reaction to the output from the computer system. There appears to be two extremes. First, will the operators like the computer presentation and accept it, will they be comfortable with the CGD and use it when needed, and will they believe that the system will work and that it is useful? Above all, will the operators trust and have confidence in the information presented on the CGD?

At present there is little understanding of what makes a person trust or distrust a computer, the advice it gives, or the action it takes, and there is only the beginning of an understanding of the nature of the human cognitive processes that underlie the acquisition and assessment of evidence and the genesis of decisions on which trust is based. Yet these processes lie at the core of human control of advanced I&C.

At the other extreme of the paradigm, one must be concerned that the operator does not become too dependent on the information exhibited on the CGD, especially during abnormal or emergency events. An undue or "blind" reliance could possibly occur. The computer-generated information should only be one of many inputs upon which the operator bases decisions; it should not dictate the course of action.

Role Change in the Control Room from Operator to Supervisor/Demographical, Selection, and Qualification Requirements for Operators in the Control Room of the Future

It is not known how the selection and qualification requirements for operators will be impacted as a result of advanced I&C. However, the operator most probably will need different kinds of knowledge and skills. The role of the control room operator will most certainly change as a result of the introduction of advanced I&C. In analog-instrumented control rooms, the operator is primarily responsible for "metering up", reviewing the analog displays, and operating the controls on the control-room panels. In digital I&C control rooms, the operator probably will be more of a supervisor. His role will be primarily that of a monitor. Plant functions will be performed more automatically than at present, and the operator will intervene and take over control of the situation only when he perceives a requirement to do so. The operator will function more as a manager and planner than at present.

Need for an Advanced I&C Guideline Equivalent to NUREG-0700 (i.e., Interface of Human, Displays, and Controls)/Lack of Consistency between Human-Advanced I&C Controls Interfaces

A number of different kinds of controls can be used with digital I&C and CGDs including traditional controls such as pushbuttons, rotary switches, and conventional typewriter/computer keyboards. They also consist of state-of-the-art controls, namely, touch screens, light pens, mice, trackballs, joysticks, and special computer keyboards. Whatever controls are used, their layout and motion/movement should resemble the traditional controls in respect to their modes of presentation and operation. Also all of the input stations should be identical and operate the same way. This guidance is driven primarily by the principles of stimulus-response stereotypes and positive transfer. Stereotypes affect the probability that an operator will press the button or activate the intended switch in the correct manner. Positive transfer occurs when either a stimulus similar to the original requires the same response or a different stimulus is followed by a new type of response.

All control and data acquisition should be accomplished through the interactive graphics of the CGDs. Controls should be the operator's prime means of communicating with the computer. They should be able to adjust parameters and setpoints, acknowledge alarms, and perform data-logging activities via the CGDs. If the advanced I&C require any operator input, the information should be readily available and not take very long to put into the system via the controls. Smith and Mosier (1984) offered five other high-level objectives for data entry: consistency of data entry transactions, minimal input actions by the operator, minimal memory load on the operator, compatibility of data entry with the CGD, and flexibility for operator control of the data entry.

Human factors guidelines for the design, test, and evaluation of human-advanced I&C interface, computer-based displays, and controls should be consulted during each system's life-cycle. There is some doubt, however, as to whether the existing human factors guidelines (e.g., NUREG-0700) are applicable to advanced I&C. NUREG-0700 is a set of guidelines for control room design which was derived from many different sources. Since NUREG-0700 was, however, designed to evaluate existing control room features, it is limited to designs that exist in today's control rooms. As a result, very little guidance is provided on human-computer interface or new control and display technology.

<u>Information Overload - What Is the Threshold where Intelligent Operator Aids Are Needed?</u>

The digital I&C should not "overload" the operator; rather, it should simplify the required operator tasks and unload the operator of mundane, routine, and tedious tasks. This will allow the operator to attend to more critical tasks. If at all possible, the I&C should reduce/relieve some of the existing workload, both physical and cognitive, on the operator. Two questions which need to be asked any time a new item of digital I&C is introduced into the control room are: does the system lighten or increase the operator's physical workload; and does it lighten or increase his cognitive workload? If it is found that workload is somehow increased, then the task should be considered as a candidate for the application of an intelligent operator aid.

<u>Adequacy of Existing Training Programs, Techniques, Methods, and Tools for Training on Advanced I&C</u>

Nuclear utilities develop and design their operator training programs based upon a systems approach to training (SAT). The SAT is a five-step process involving: analysis of training needs, design or modification of the curriculum, development of additional training materials, implementation of the new program, and establishment of a means to assess how effective the training process is. There is a question as to whether the SAT process and its associated tools, techniques, and methods are applicable to the development and preparation of training programs and courseware for advanced I&C.

Medium Rated Issues

Impact of CGDs on the Operator's Mental Model

A question that must be asked about CGDs is: Does the interface support the way in which the operator processes information, solves problems, and makes decisions, or was it merely determined by the way the nuclear engineer describes the physics of the system? The CGD information must mesh well with the perspectives and control strategies used by the operator, and the way in which the information is displayed should correspond to his mental model of the plant. People's view of the world, of themselves, of their capabilities, and of the tasks that they are asked to perform, or topics they are asked to learn, depend heavily on the conceptualizations that they bring to the task. In interacting with the environment, with others, and with the artifacts of technology, individuals form internal mental models of themselves and of things with which they are interacting (Norman, 1983).

Need for a Dynamic Allocation of Functions and Tasks between the Human and Advanced I&C/What Tasks Are Appropriate for the Human in an Advanced I&C Control Room/Locus of Control between the Human and the Advanced I&C

The needs of the operators must be specified early in the design cycle of the advanced I&C. During the needs assessment, the needs and desires of the operators should be identified, and areas that need improvement in the control room should be determined. The needs assessment should consist of three types of analyses: organizational, task, and person.

A function allocation and a division of labor between the advanced I&C and the operator should be conducted after the needs assessment, but before the system is designed. The operator should be consulted during this process. The human should only be assigned those functions which he is most capable of performing and which best utilize his skills, knowledge, and abilities. In the past, allocation of functions was based on catalogs of "things computers do better" and "things people do better." With the current rate of technological development, existing catalogs are becoming obsolete, and this distinction may soon cease to be relevant in most situations. As advanced I&C develops, the idea of fixed allocation is no longer appropriate. Pulliam, Price, Bongarra, Sawyer, and Kisner (1983) outlined an approach to function allocation that correctly emphasizes an iterative approach to the solution for conventional I&C systems, but a different conceptual approach may soon be required. The relation of the operator to the digital I&C should be a symbiotic one. Human-related problems are symptoms, not causes, of underlying problems in the sociotechnical system. Research needs to be conducted to look at better methods and criteria for allocating functions between the operator and the advanced I&C. Research should also be conducted on how to better design the digital I&C so that each can support the other and produce the most effective joint outcome.

Operations Staff Must Be Involved during the Entire Life-Cycle of the Instrumentation/Control System

Operators should be consulted during the entire life-cycle of the advanced I&C so that they feel/believe that they are part of the design process. They should be especially involved during the needs assessment, development, evaluation, and integration phases. Besides the operators, engineers, management, trainers/instructors, software developers/computer programers, and human factors personnel should also interface and work together during the design process so that there is cohesiveness between these types of personnel.

User Friendliness of CGDs and Human-Computer Interfaces

"User friendliness" needs to be considered in the design of CGDs. This is a "motherhood and apple pie" statement and a rather vague notion to implement. Shneiderman (1987) has, however, provided some help. He has defined five criteria with which to base and measure user friendliness. They are: time for the operator to learn, the speed of his performance with the displays, rate of operator errors, subjective satisfaction of the displays, and operator retention over time.

Effect of Advanced I&C on Operator Performance/Job Efficiency

Advanced I&C and CGDs should make the operator's jobs more effective and efficient. The I&C and interactive computer displays are effective only to the extent that they support an operator (or crew) in a manner that leads to improved performance, results in a difficult task being less difficult, or enables accomplishment of a task that could not otherwise be accomplished. An evaluation of the effects of the advanced I&C upon operator performance (e.g., errors and time) should be conducted before it is implemented in the work environment.

Also, research needs to be performed on ways in which the advanced I&C and CGDs can assist human performance. People use data displayed about an environment in order to solve problems in that environment. To do this, problem solvers must collect and integrate available data in order to characterize the state of the environment, to identify disturbances and faults, and to plan responses. A premise from cognitive science is that the representation of the world provided to problem solvers can affect their problem-solving performance (Rasmussen, 1986). Thus, questions about advanced I&C and CGDs can be reinterpreted to be questions about how different types of representations vary in their effect on the problem solver's information-processing activities and problem-solving performance.

Systems Integration/How Does One Manage Human Factors Information?

This issue deals with how the advanced I&C systems are incorporated/implemented within the control room. When it is introduced, the I&C should be thoroughly integrated with the other hardware, software, and tools in the operators' work environment. Digital I&C should be introduced in a way which supports operator acceptance. The impact of advanced I&C upon the other functions and tasks that the human performs should be evaluated and investigated. This issue also has to do with how human factors information is utilized during the design cycle of the I&C. One solution would be to assure that human factors is an integral part of the development process; a human factors engineer should be a member of the design team.

The systems integration issue deals with more than just human factors concerns. It has to do with the design process for human-machine interfaces in advanced control rooms. It is a multidisciplinary process necessitated by the use of digital computers. Networks and distributed processors introduce new elements for the control room operator to monitor, operate, and manage. These elements will impact the operating organization. Also, the interfaces among the elements must be coordinated during the design process if one hopes to develop a reasonably error free interface for the operator's use. It is expected that the design of an advanced control room will involve an order of magnitude more detail than does the design of an analog-hard wired control room.

Low Rated Issues

CGDs for Multiple Users

CGDs should support multiple users. Multiple users can be defined as operator-operator, operator-maintainer, and operator-supervisor. The CGDs should be totally redundant in that every screen should be able to be presented on all of the CRTs in the control room.

Organizational Climate of the Nuclear Utility

The operator's ability to deal with an abnormal or emergency event, even at the level of reading CGDs, can be affected by the management style and the organizational support for the use of advanced I&C in the control room, as much as by the design of the displays themselves. The ability of operators to respond to off-normal events is also affected by both fatigue and motivation. The structure and organization of shift work will affect operator efficiency due to disruptions in his biological, circadian rhythms. Utility management that is insensitive to comments by operators about their working conditions and to suggestions in regards to digital I&C and interactive computer graphics, may obtain obedience to rules, but will not encourage participation in the pursuit of excellence. Civilians do not adopt dictatorial styles voluntarily and may resent them if imposed by management. Management practices are responsible, directly or indirectly, for establishing and maintaining an organizational culture that reinforces safety and the quality of performance. The formal structure, procedures, and practices of an organization bind the behavior of its operators and strongly affect the norms and perspectives they have regarding critical activities (National Research Council, 1988).

Knowledge Acquisition for Expert Systems

Acquisition of knowledge is critical for successful implementation and operation of expert systems because an expert system is only as good as its knowledge base. For a number of reasons, knowledge acquisition is perhaps the biggest bottleneck in expert system development. First, the knowledge engineer must be familiar with the problem domain and specific task before he starts the knowledge acquisition sessions with the expert. A second major problem is the ability of the knowledge engineer to probe the expert's mind to obtain the pertinent facts and rules of thumb. Third, biases of both the expert and the knowledge engineer are unintentionally imparted during the knowledge acquisition process. These biases inhibit the transfer of knowledge between the two individuals. Improved ways of performing the knowledge acquisition are therefore needed.

Display of Maintenance Information in the Control Room (the Operator Needs to Know the Status of Plant Equipment)
Maintenance information is typically not displayed in the control room of today's nuclear plants. It appears, however, that the operator will need to know more about the status of advanced I&C than he does about analog equipment. A number of questions arise concerning this issue including: how much information does the operator really need to know; should the NRC develop guidelines for the amount of maintenance information presented in the control room; and is the information needed during off-normal events or just during normal operations?

CONCLUSIONS/RECOMMENDATIONS

The U.S. nuclear industry, as represented by the utilities and vendors visited, appears to have addressed a number of the human factors concerns and potential problems which were discussed during the utility and vendor survey. They seem to have considered seriously the human factors implications of the utilization of advanced I&C within the control room.

Computer-Generated Displays
Operators at a majority of the utilities have a high level of confidence in the output from their plant computer and the CGDs. The displays at all of the utilities seem to be simple, clear, understandable, and comprehensible; they utilize alphanumerics, graphics, and color. The CGDs at about half of the utilities support multiple users, and the operators rely upon them for information.

A majority of the vendors indicated that confidence/trust in the output from the computer systems and advanced I&C is important. All vendor CGDs will use color and color coding, and half will support multiple users. The design teams at all six of the vendors consist of engineers, trainers, and human factors personnel.

Organizational Support
Management at a majority of the utilities supports the use of advanced instrumentation within the control room, and about half of the operations departments participate in the decision to purchase and/or design the advanced systems. About half also have implementation plans for incorporation of the advanced I&C within the control room, and it appears as though the advanced I&C has been introduced in a way which supports operator acceptance. The design teams at about half of the utilities consist of engineers, operators, trainers, and human factors engineers. Training is a major activity at all of the utilities.

Related Topics

All of the utilities believe that the use of advanced I&C will lighten the operator's workload and make his job more efficient. About half of the utilities interviewed indicated that the introduction of advanced instrumentation has not had a large impact on the selection and qualification requirements for control room operators. A majority feel that the operator's role in the control room will change with the introduction of more and more advanced I&C.

Almost all of the vendors believe that: advanced I&C will decrease physical workload, and their advanced control rooms will significantly change the role of the operator when compared to current plant designs. All indicated that an intelligent display of operating procedures will be beneficial for operators in future plants.

General Comments

A number of high priority human factors issues which need to be investigated and/or further addressed were identified during the survey. They include: (a) the need for an advanced I&C guideline equivalent to NUREG-0700 (i.e., interface of the human, displays, and controls)/lack of consistency between human-advanced I&C interfaces; (b) role change in the control room from operator to supervisor/demographical, selection, and qualification requirements for operators in the control room of the future; (c) information overload - what is the threshold where intelligent operator aids are needed?; (d) adequacy of existing training programs, techniques, methods, and tools for training on advanced I&C; and (e) operator acceptance and trust of advanced I&C/blind reliance on the computer output. The first three appear to be most important in regards to their potential impact on safety and regulatory policy.

It is recommended that the NRC study and evaluate the derived list of prioritized human factors issues. They should subsequently construct a research program oriented towards resolving the human factors concerns and should allocate resources to address the most pressing issues. There may be some important human factors issues that the NRC determines are not within their purview or mission. Those issues should be addressed by the Electric Power Research Institute, the Institute for Nuclear Power Operations, and/or the nuclear industry itself.

NOTES

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REFERENCES

Carter, R. J. & Uhrig, R. E. (1989). Human factors issues associated with advanced instrumentation and controls technologies in nuclear plants (NUREG/CR-5439). Washington, DC: U.S. NRC.

Jones, R. A. (1985). Research methods in the social and behavioral sciences. Sunderland, MA: Sinauer Associates, Incorporated.

LoSciuto, L. (1981). Questionnaires and interviews. In L. H. Kidder (Ed.), Sellitz, Wrightsman, and Cook's research methods in social relations (4th Ed., pp 144-197). Chicago, IL: Holt, Rinehart, and Winston, Incorporated.

National Research Council (1988). Human factors research and nuclear safety. Washington, DC: National Academy Press.

Norman, D. A. (1983). Some observations on mental models. In D. Gentner and A. L. Stevens (Eds.), Mental models (pp 7-14). Hillsdale, NJ: Lawrence Erlbaum Associates, Publishers.

Pulliam, R., Price, H. E., Bongarra, J., Sawyer, C. R., & Kisner, R. A. (1983). A methodology for allocating nuclear power plant control functions to human or automatic control (NUREG/CR-3331). Washington, DC: U.S. NRC.

Rasmussen, J. (1986). Information processing and human-machine interaction: An approach to cognitive engineering. New York, NY: North-Holland.

Shneiderman, B. (1987). Designing the user interface: Strategies for effective human-computer interface. Reading, MA: Addison-Wesley Publishing Company.

Smith, S. L. & Mosier, J. N. (1984). Design guidelines for the user interface for computer-based information systems. Bedford, MA: The Mitre Corporation.

Uhrig, R. E. & Carter, R. J. Survey of Canadian uses of digital computers in control, safety systems, and human-machine interfaces in nuclear power plants (ORNL/NRC/LTR-89/6). Oak Ridge, TN: ORNL.

U.S. NRC (1981). Guidelines for control room design reviews (NUREG-0700). Washington, DC.