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HUMAN FACTORS ASPECTS OF ADVANCED INSTRUMENTATION IN THE NUCLEAR INDUSTRY *

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HUMAN FACTORS ASPECTS OF ADVANCED INSTRUMENTATION IN THE NUCLEAR INDUSTRY

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SUMMARY

An important consideration in regards to the use of advanced instrumentation in the nuclear industry is the interface between the instrumentation system and the human. A survey, oriented towards identifying the human factors aspects of digital instrumentation, was conducted at a number of United States (U.S.) and Canadian nuclear vendors and utilities. Human factors issues, subsumed under the categories of computer-generated displays, controls, organizational support, training, and related topics, were identified.

BACKGROUND

The nuclear industry has used analog instrumentation in their control rooms and technical support centers since the first nuclear power plant went on-line in the late 1950's. Even today the industry, as a whole, has been slow to implement advanced/digital instrumentation. The utilization of digital instrumentation 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 refining plants and aircraft systems, that digital instrumentation 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 driven to the use of advanced instrumentation.

The point has been reached where the issues in using advanced instrumentation systems in nuclear power plants are not hardware and software reliability or performance, but rather the interface between the human and the machine system, and other human factors aspects. A human-machine system is defined as a combination of one or more human beings and one or more physical components interacting to bring about, from given inputs, some desired output (McCormick and Sanders, 1982). Human factors is a multi-disciplinary field oriented towards designing systems that are compatible with the capabilities and limitations of the people who will use them. Its goal has been to design systems that: use human capabilities in appropriate ways, protect systems from human frailties, and protect humans from hazards associated with the operation of the system.

RESEARCH PROGRAM

Oak Ridge National Laboratory is currently 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 instrumentation 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.

Research Method

Survey Participants

All five of the U.S. nuclear vendors and five utilities who have begun to use advanced instrumentation participated in the survey. The survey was also administered at one Canadian vendor and utility. Table 1 exhibits the vendors and utilities/power plants who participated in the survey. Groups of persons interviewed at each nuclear facility included human factors personnel, control room operators, software developers/computer programers, instrumentation and controls engineers, and trainers/instructors.

Table 1. Survey Participants

Vendors	
Atomic Energy of Canada, Limited	
Babcock and Wilcox	
Combustion Engineering	
General Atomics	
General Electric	
Westinghouse	
Utilities	**Power Plant**
Arkansas Power and Light	Arkansas Nuclear One
Northeast Nuclear Energy	Millstone Nuclear Power Station
Ontario Hydro	Darlington Nuclear Station
Pacific Gas and Electric	Diablo Canyon Nuclear Power Plant
Pennsylvania Power and Light	Susquehanna Steam Electric Station
Southern California Edison	San Onofre Nuclear Generating Station

Survey Instrument

A survey instrument consisting of over eighty 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 pilot-tested at a number of Government nuclear facilities (i.e., Savannah River Plant, Idaho National Engineering Laboratory, Advanced Test Reactor, and Fast Flux Test Facility). Changes were made to the instrument based upon the results from the pilot test. The derived survey instrument was divided into five main areas: (1) description of the digital instrumentation, (2) software verification and validation, (3) artificial intelligence and expert systems, (4) usefulness and operability, and (5) human factors issues. The human factors portion was further subdivided into five sections: (1) computer-generated displays, (2) controls, (3) organizational support, (4) training, and (5) related topics.

Survey Process

The twelve nuclear facilities were surveyed by a team of three scientists, the first a human factors psychologist, the second a nuclear engineer with expertise in instrumentation, controls, and expert systems, and the third 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 people 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 comments would be kept confidential and that no published material would identify remarks made 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.

HUMAN FACTORS ASPECTS

Results from the survey were first reviewed and scrutinized; they were then evaluated. Table 2 exhibits the issues identified during the human factors portion of the survey. A more elaborate presentation of the results and a discussion of the findings are described below.

Computer-Generated Displays

Computer-generated displays should be simple, clear, and understandable/comprehensible. By understandability/comprehensibility, it is meant that the structure, format, and content of the display dialogue must result in meaningful communication. In other words, the "messages" presented by the computer-generated display must be interpretable by the operator, and the messages which he/she wants to transmit back to the computer must be expressible. During the design process, the terminology, abbreviations, formats, and so on should all be standardized. The format should be familiar

Table 2. Human Factors Issues

Topics	Issues
Computer-Generated Displays	o Simplicity, clarity, and understandability
	o Screen layout
	o Type of information
	o Use of color
	o Support of multiple users
	o Operator's reaction
	o User friendliness
Controls	o Required operator input
	o Identical input stations
	o Method of operation
Organizational Support	o Management style/support
	o Needs assessment
	o Function allocation/division of labor
	o Operator involvement during the life-cycle
	o Manner of implementation
	o Use of guidelines
Training	o Begin early in life-cycle
	o Vendor support
	o Computer knowledge of students
	o Integration with existing training program
	o Methods of training
Related Items	o Impact on workload
	o Effects of stress
	o Effect on operator performance/job efficiency
	o Impact on mental model
	o Selection and qualification requirements
	o Software validation and verification

to the operator and be related to the tasks he/she is required to perform with the information. The operators should also be able to get the information in the form most convenient for the specific task they are working on. The display screens should be arranged in a hierarchical structure and be arranged so that the operators are not required to remember information from one screen for use on another (Smith and Mosier, 1984).

The physical presentations to the operator should consist of concise, high level information to support his/her cognitive functions. The computer-generated displays and the response expected from the operator must be compatible with the human input-output abilities and limitations (i.e., sensory, perceptual, and cognitive capabilities, human physical characteristics, and human physiological characteristics and capabilites.) Succinctly, regardless of the overall advanced instrumentation objectives, operators have to be able to read the computer-generated displays. Otherwise there is a risk that the displays will be inherently useless (National Research Council, 1988). The quality of the computer-generated displays is critical. Their layout and legibility affect the time required to locate and read them. It also affects the distance and angle at which they can be read. Whether computer-generated displays present raw data or derived measures affects the extent to which short-term memory and complex cognitive processes will be demanded of the crew. The factors of legibility and accessibility are generally well-known and practical guidance is available (e.g., NRC, 1985).

The display information can be presented via a number of modes: graphics, alphanumerics, textual information, and mimics. It can be displayed in either monochrome or color. For many applications, monochrome displays are adequate and even preferred, especially if the monochrome display has a higher resolution (Shneiderman, 1987). Color can, however, make computer-generated displays more attractive and effective for the operators. Color images are attractive to the eye, and color coding of screen objects can lead to rapid recognition and identification (Robertson, 1980). Of course, excessive or inappropriate use of color can inhibit performance and confuse users (Durrett and Trezona, 1982). If color is used in the display, the display should also be presentable in monochrome. One must be concerned with the number and type of colors. The recommended number of colors is three (Grether and Baker, 1972). Two other related questions are: is color coding used and, if it is, how is it utilized? The color coding should be used to depict the status of the components and to help identify the severity of the plant status. The coding should also be understandable and be consistent with that of conventional displays and indicators.

Computer-generated displays should support multiple users. They should be totally redundant in that every screen should be able to be presented on all of the cathode-ray tubes (CRT). The displays should be programmed so that they can be modified very easily and quickly (i.e., within about fifteen minutes) in order to present information in another manner or to add or delete specific parameters, if the operators so desire.

The operators who were interviewed during the survey indicated that the use of computer-generated displays has made diagnosis of off-normal conditions more efficient and reliable than before. They said that the most

important displays are: reactor regulating status, data logging display, and alarm/annunciation filtering displays.

The operator's reaction to the output from the computer system needs to be considered. There seem to be two extremes. The first is: will the operators like the presentation and accept it; will they be comfortable with the computer-generated display 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 CRT? At the other extreme, one must be concerned that the operator does not become too dependent on the information exhibited on the CRT, 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 makes his/her decisions; it should not dictate his/her course of action.

"User friendliness" should also be considered in the design of computer-generated displays. 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/her performance with the displays, rate of operator errors, subjective satisfaction of the displays, and operator retention over time.

Controls

There are a number of different kinds of controls that can be used with the digital instrumentation. They include 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 accomplished through the interactive graphics of the computer-generated displays. The controls should be the operator's prime means of communicating with the computer. They should be able to adjust parameters/setpoints, acknowledge alarms, and perform data logging activities via the CRTs.

If the advanced instrumentation requires 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. They include: consistency of data entry transactions, minimal input actions by the operator, minimal memory load on the operator, compatibility of data entry with the computer-generated data display, and flexibility for operator control of the data entry.

Organizational Support

The operator's ability to deal with an abnormal or emergency event, even at the level of reading computer-generated displays, can be affected by the management style and the organizational support for the use of advanced instrumentation 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/her biological circadian rhythms. An utility management, insensitive to comments by operators about their working conditions and to suggestions in regards to digital instrumentation 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).

Design of much digital instrumentation is doomed to failure because managers/engineers are more interested in designing the advanced instrumentation than in first assessing the needs of the operators. There is always a danger in beginning any design program without a complete assessment of the control room/technical support center needs. Machinists do not chose their tools before they examine their jobs; builders do not order their materials or plan their schedules until they have their blueprints. Why then should engineers design advanced instrumentation and computer-generated displays without first specifying what the needs of the operators are? A needs assessment of the operators should be conducted prior to the design of any digital instrumentation so that the utility does not spend its money unwisely. During the needs assessment, wishes and desires of the operators should be identified and areas that need improvement in the control room and technical support center should be determined. The needs assessment should consist of three analyses, organizational, task, and person (Goldstein, 1986).

A function allocation and a division of labor between the advanced instrumentation 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/she is most capable of performing and which best utilize his/her skills, knowledges, 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 instrumentation 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 instrumentation systems, but a different conceptual approach may soon be required. The relation of the operator to the digital instrumentation 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 instrumentation. Research should also be conducted on how to better design the digital instrumentation so that each can support the other and produce the most effective joint outcome.

Operators should be consulted during the entire life-cycle of the advanced instrumentation 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, and human factors personnel should also interface and work together during the design process so that there is cohesiveness between these types of personnel. When the digital instrumentation is introduced/implemented within the control room and/or technical support center, it should be thoroughly integrated with the other hardware, software, and tools in the operators' work environment. The instrumentation needs to be introduced in a way which supports operator acceptance. The impact of the advanced instrumentation upon the other functions and tasks that the human performs should be evaluated and investigated.

Guidelines for the design, test, and evaluation of human-advanced instrumentation interface and computer-based displays should be consulted during each system's life-cycle. A number of existing guidelines are those by Carlow Associates (1987), Smith and Mosier (1984), and Frey and Sides (1984). Human factors guidelines should also be utilized during the development of the digital instrumentation. There is some doubt, however, as to whether the existing human factors guidelines (e.g., NRC, 1981 and U.S. Army, 1981) are applicable to advanced instrumentation.

Training

Training program development for advanced instrumentation should begin early in the system's life cycle. Development should flow in unison with the design of the hardware and software if at all possible. Support should be received from the digital instrumentation vendor to the maximum extent; operations staff personnel should also be involved during the preparation of the training courseware. Students for the advanced instrumentation training should have some computer knowledge; however, it is not known to what degree.

Information on signal sources, transmission, shaping, and computer-display generation should be included in the training courseware. Materials developed for a specific piece of advanced instrumentation should be integrated with the existing control room training program. Features of digital instrumentation should be discussed routinely during other systems training in order to show system interrelationships. The use of advanced instrumentation during normal/off-normal operations should be encouraged during training. Implementation of the training should take place via both classroom, part-task training devices, and a full-scope simulator.

Training instructors who were interviewed commented that they have not seen any significant differences in the training requirements for digital instrumentation versus other plant systems. As a matter of fact, they said

that it might even be easier to teach candidates on advanced instrumentation than on conventional systems.

Related Topics

The digital instrumentation should not "overload" the operator more than he/she already is; rather, it should simplify the required operator tasks and unload the operator of his/her mundane, routine, and tedious tasks. If at all possible, the instrumentation should reduce/relieve some of the existing mental workload, both physical and cognitive, on the operator. Physical workload is defined as energy actually expended by the operator; cognitive workload is defined as information processing which the operator performs (Sheridan and Stassen, 1977). Two questions which need to be asked any time a new item of digital instrumentation is introduced into the control room or technical support center are: does the system lighten or increase the operator's physical workload; and does it lighten or increase his/her cognitive workload?

What the operator will do under stress must be considered. Will he/she cease to consider himself/herself responsible for safety? Will he/she be able to detect when the computer system begins to provide incorrect information and to effectively resume control of the plant?

One of the nuclear vendors commented that the operator is perceived as the "weakest link" in nuclear plant safety; the majority of the errors in control rooms are human related! As a result, the advanced instrumentation and computer-generated displays should make the operator's jobs more efficient. An evaluation of the effects of the advanced instrumentation upon operator performance (e.g., errors and time) should be conducted before it is implemented within the work environment. The digital instrumentation 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.

Research should be performed on ways in which the computer-generated display can assist human performance. People use data displayed about the world in order to solve problems in that world. To do this, problem solvers must collect and integrate available data in order to characterize the state of the world, to identify disturbances and faults, and to plan responses. A basic fact in cognitive science is that the representation of the world provided to problem solvers can affect their problem-solving performance (Rasmussen, 1986). Thus, questions about computer displays can be reinterpreted to be questions about how types of representations vary in their effect on the problem solver's information-processing activities and problem-solving performance.

Does the computer-generated display symbology support the way in which the operator processes information, or is it merely determined by the way the nuclear engineer describes the physics of the system? The CRT information must mesh well with the perspectives used by the operator, and the way in which the information is displayed should correspond to his/her 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, people form internal mental models of themselves and of things with which they are interacting (Norman, 1983).

There is little understanding, at present, 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 the human control of advanced instrumentation and center on the nature of the operator's mental models, through which they interpret the demands of the task.

It is not known how the selection and qualification requirements for operators will be impacted as a result of advanced instrumentation. However, he/she will need different kinds of knowledges and skills. The role of the control room operator will change as a result of the introduction of advanced instrumentation. In analog control rooms the operator is primarily responsible for "metering up" and reviewing the analog displays/operating the controls on the control-room panels. In digital instrumentation control rooms, the operator will be more of a supervisor. His/her 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/she so desires. The operator will act more as a thinker and planner than he currently does.

Operators should be involved in the software validation and verification process. Verification is a determination that the software has been developed in a formally correct manner and in accordance with a specified software engineering methodology. Validation means demonstrating that the completed program performs the functions in the requirements specification and is usable for the intended purposes. The validation and verification should be carried out by a group that is independent of the group which developed the software. The operators should be represented in this validation and verification group. The independence of the group should be assured by quality assurance procedures and organizational policy.

The opinions of the survey participants were about evenly split on the issue of computer-based emergency operating procedures. Some felt that an intelligent display of procedures (i.e., edited/updated frequently based on the computer's knowledge of the state of the plant) would be beneficial for both normal and off-normal events. Others believed the opposite and stated that the display would be too difficult to use and too slow for the operator's needs. It has been suggested that computer-based emergency operating procedures may improve performance, but this will be critically dependent on their design. There is evidence that people lose their place in hierarchically organized computer data bases, and questions arise about legibility, accessibility by more than one operator, and place-keeping. The design of emergency operating procedures should be a systems process in which the layout of the control room, manning levels, and training are taken into account. At present there is no coherent theory for the design of emergency operating procedures (Feher, Moray, Senders, and Rash, 1987).

FUTURE RESEARCH

The human factors issues identified during the survey are currently being prioritized by Oak Ridge National Laboratory in regards to their importance. This list of issues will then be studied and evaluated by the NRC. They will subsequently derive and fund a number of research programs which will be oriented towards solving some of the human factors concerns. The number of issues to be addressed will depend upon the amount of resources available. There may be some important human factors issues that the NRC believes are not within their purview or mission. These issues will need to 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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