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AUTHOR	Moray, Neville P., Ed.; Huey, Beverly M., Ed.
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ABSTRACT

The Panel on Human Factors Research Needs in Nuclear Regulatory Research was formed by the National Research Council in response to a request from the Nuclear Regulatory Commission (NRC). The NRC asked the research council to conduct an 18-month study of human factors research needs for the sa.e operation of nuclear power plants. This report describes the sociotechnical system implied by the panel's conception of human factors and outlines the factors tha affect the performance of that system. It then reviews the chronology of the NRC's human factors research from 1981 to 1985. Following a brief discussion of research methodology and management, this report identifies a set of broad research areas and suggested high priority topics within these areas. Descriptions of these areas and topics, together with recommendations on the management of human factors research, form the core of this report. The panel used the potential for increased plant safety as a criterion against which to evaluate the topics considered. Nine pages of references are included. An appendix includes biographical sketches of the 16 members of the panel. (CW)

Human Factors Research and Nuclear Safety

Neville P. Moray and Beverly M. Huey, *editors*

Panel on Human Factors Research Needs in Nuclear Regulatory Research

Committee on Human Factors
Commission on Behavioral and Social Sciences and Education
National Research Council

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NOTICE: The project that is the subject of this report was approved by the Governing Board of the National Research Council, whose members are drawn from the councils of the National Academy of Sciences, the National Academy of Engineering, and the Institute of Medicine. The members of the committee responsible for the report were chosen for their special competences and with regard to appropriate balance.

This report has been reviewed by a group other than the authors according to procedures approved by a Report Review Committee consisting of members of the National Academy of Sciences, the National Academy of Engineering, and the Institute of Medicine.

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PANEL ON HUMAN FACTORS RESEARCH NEEDS IN NUCLEAR REGULATORY RESEARCH

NEVILLE MORAY (Chair), Department of Industrial Engineering, University of Toronto
LINDA COHEN, Department of Economics, University of California, Irvine
RUSSELL DYNES, Department of Sociology, University of Delaware
HERBERT ESTRADA, MPR Associates, Washington, D.C.
CLAY E. GEORGE, Department of Psychology, Texas Tech University
PAUL M. HAAS, Advanced Systems Technology, International Technology Corporation, Oak Ridge, Tennessee
LARRY HIRSCHHORN, Wharton Center for Applied Research, Philadelphia, Pennsylvania
JOYCE KEEN, Clinical Psychology, Iowa Methodist Medical Center, Des Moines, Iowa
TODD R. LAPORTE, Institute of Governmental Studies, University of California, Berkeley
JENS RASMUSSEN, Cognitive Engineering, RISO National Laboratory and Technical University of Denmark, Roskilde, Denmark
RICHARD SHIKIAR, Battelle Human Affairs Research Centers, Seattle, Washington
J. ED SMITH, J. Ed's Nuclear Service Corporation, Central, South Carolina
DAVID WARD, E.I. du Pont de Nemours and Company, Savannah River Laboratory, Aiken, South Carolina
DAVID WOODS, Westinghouse Research and Development Center, Pittsburgh, Pennsylvania
THOMAS B. SHERIDAN (ex officio), Chair, Committee on Human Factors

HAROLD P. VAN COTT, Study Director
STANLEY DEUTSCH, Study Director (1985–1987)
BEVERLY M. HUEY, Research Associate/Consultant

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ROBERT C. WILLIGES, Department of Industrial Engineering and Operations Research, Virginia Polytechnic Institute and State University

HAROLD P. VAN COTT, Study Director
STANLEY DEUTSCH, Study Director (1984-1987)

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Preface

The Panel on Human Factors Research Needs in Nuclear Regulatory Research was formed by the National Research Council in response to a request from the U.S. Nuclear Regulatory Commission (NRC). The NRC asked the Research Council to conduct an independent 18-month study of human factors research needs for the safe operation of nuclear power plants. This study was conducted under the auspices of the Committee on Human Factors within the Research Council's Commission on Behavioral and Social Sciences and Education.

The members of the panel chosen to carry out this charge represent a diversity of professions and backgrounds: utility plant managers, nuclear engineers, psychologists, professionals in human factors, specialists in management research, economists, and political and social scientists.

Several members of the committee have research experience in problems of management and the sociology of large complex organizations. One member chaired a task force for the President's Commission on Three Mile Island (the Kemeny Commission). Another has extensive knowledge of the economics of energy systems. Two members have conducted research and have been consultants in human factors related to nuclear power plant operation and regulation in Europe and Canada. One is an expert on the effects of stress and stress management. Three members have worked in the nuclear power industry: one as the manager of a large commercial nuclear power plant for a major utility, one as an engineering consultant, and one as a scientist who has conducted cognitive research in the research department of a major vendor of nuclear steam supply systems. Another member is a professor of engineering in a university; he has conducted power plant control room design reviews and advised a utility owners group on human factors. Still another panelist was an engineer in one of the national laboratories conducting nuclear human factors research and is now working in the industry. We were also fortunate in having a member of the Advisory Committee on Reactor Safeguards as a panel member. This diversity of panel education and experience helped to ensure a comprehensive approach to the problem at hand (see the Appendix for biographical sketches of panel members and staff).

The panel held six meetings over the duration of this project, one of which included a site visit to Unit 1 of the General Public Utilities plant at Three Mile Island. We received information and were briefed by representatives of the NRC, the Department of Energy, the Electric Power Research Institute, the Institute for Nuclear Power Operations, and one of the national laboratories of the Department of Energy. We reviewed past human factors research conducted by the NRC and other organizations. In addition, we received information from a major vendor of nuclear steam supply systems, from members of professional societies in human factors and nuclear power, from researchers in human physiology, and from the Nuclear Utility Management and Resource Committee.

This report describes the sociotechnical system implied by the panel's conception of human factors and outlines the factors that affect the performance of that system. The panel believes that this conception is essential to an understanding of how people can affect plant safety and what research is needed. We then review the chronology of the NRC's human factors research from the year it was initiated in 1981 until it was terminated in 1985. This history provides a point of departure for the research agenda that the panel recommends. Following a brief discussion of research methodology and management, this report identifies a set of broad research areas and suggested topics within these areas that the panel judges to be of high priority. Descriptions of these areas and topics, together with recommendations on the management of human factors research, form the core of this report. In identifying research needs, the panel used the potential for increased plant safety as a criterion against which to evaluate the candidate topics we considered. Although the agenda proposed is not advanced as a detailed program plan, it is intended as an initial advisory step toward a recommended reinitiation of human factors research by the NRC and its continuation by other elements of the nuclear community.

We are appreciative of the cooperation we received from the many individuals and organizations who helped us. We are especially grateful to Drs. Thomas Ryan and Daniel Jones of the Nuclear Regulatory Commission for their continuing assistance in providing extensive information and materials requested by the panel in the pursuit of this study.

Neville Moray, Chair
Panel on Human Factors Research
Needs in Nuclear Regulatory Research

Summary and Recommendations

This report presents the panel's recommendations for an agenda of applied research on the human factors issues involved in the safety of nuclear reactors. It is addressed to all elements of the nuclear community. However, undertaking such an agenda by a diverse community requires leadership, and it is clear to the panel that responsibility for that leadership should rest with the U.S. Nuclear Regulatory Commission (NRC). Accordingly, many of the research topics presented here are ones that the panel judges to be most appropriately undertaken by the NRC.

Part I of the report presents a context for human factors research on nuclear safety. It cites the charge given to the panel and the approach the panel took to the problem of human factors in nuclear safety. As background to specific research topics, Part I includes a review and discussion of human factors research both before and after the Three Mile Island accident. An important discussion of research methodology and management is also included in Part I. In this section the panel makes a variety of recommendations about how to conduct high-quality research that will produce useful and applicable results.

Part II of the report contains an agenda of human factors research needs for the nuclear industry. Topics of higher priority within this agenda are identified. The panel has made no attempt to develop a detailed program plan, schedule, or budget; that is more properly the task of those managers responsible for implementation of the research program. We propose that nuclear reactor safety and the recommended research be viewed from a perspective that recognizes the nuclear power plant as an element of a more extensive sociotechnical system, and we suggest criteria for managing a human factors research program that are needed to address the problems existing within the context of this extended view of the system.

A word about the type of research proposed here is in order. In some cases we have suggested research in areas with gaps in knowledge, and research has been proposed to fill these gaps; this is particularly true with respect to sociotechnical systems, whose dynamics, though of critical importance to safety, are as yet not well understood. In other cases the problem is not a deficiency of knowledge but rather a failure to transfer and adapt existing knowledge from other disciplines and other related systems. Yet another type of research calls for empirical studies of innovations or modifications to existing technology and operational practices; research of this type is necessary to demonstrate that a change is workable and worthwhile.

RECOMMENDATIONS

The remainder of this section summarizes the recommendations of the panel. These recommendations are of two types: (1) recommendations to facilitate the initiation, planning, management, conduct, and use of human factors research and (2) recommendations on specific research topics to be investigated by the NRC and the rest of the nuclear community. The panel has not attempted to suggest how the research topics it recommends should be allocated within this community. Some studies, particularly those that can provide the basis for improved regulatory analysis and decision making, will be appropriate undertakings for the NRC. Others may be more appropriately undertaken as individual or collaborative efforts. Decisions regarding which elements of the nuclear community should be responsible for which topics, and whether research will be done on a collaborative basis, are tasks for the nuclear community and do not fall within the charge of the panel.

The panel recommends a general agenda of research on the human factors issues involved in the safety of nuclear reactors. The proposed agenda is divided into five major topics: human-system interface design, the personnel subsystem, human performance, management and organization, and the regulatory or environmental context. Each of these areas includes a number of research topics, some of which have been identified as having higher priority. The specific issues involved in each proposed research topic are elements that are necessary to improve design, construction, performance, operations, maintenance, and regulation to ensure public safety.

Recommendation 1: Commitment to Human Factors Research

The panel recommends that the NRC make a firm public commitment to applied behavioral and social science (human factors safety) research. This would require a decision to increase staffing and financial support. Without such a commitment, the public and the nuclear industry can reasonably assume that human factors is not regarded by the NRC to be a matter of importance, nor will the NRC be able to attract the highly competent staff it will need. In addition, the human factors program should be directed at the level of branch head, not as a subdivision of the reliability branch.

In our opinion, it is of paramount importance that the NRC and the nuclear industry recognize that research and development (R&D) in human factors safety has to be an integral part of any continued national programs in nuclear power systems, just as R&D in materials, radiation protection, severe accident phenomenology, and reactor systems are part of ongoing research programs. While there have been major advances in nuclear system human factors since the Three Mile Island accident, the problems that existed have not and will not be resolved completely by a program of a few years' duration. Furthermore, new problems will inevitably arise, especially as new or improved systems are introduced.

Recommendation 2: Adopting a Systems-Oriented Approach

In recognition of the many ways in which human behavior can affect nuclear power plant safety, the panel recommends that the NRC's research program maintain a broad perspective. The operator/maintainer-plant interface is extremely important; but other factors arising from the way in which a plant is organized, staffed, managed, and regulated and the way it interacts with other elements of the industry can also affect human performance, induce human error, and increase the level of risk of a plant.

The panel firmly believes that research that recognizes a systems approach, in which the "system" is broadly defined, has great potential for delivering results that yield useful recommendations for safety improvements. The systems approach to safety requires multidisciplinary teams and close coordination of programs dealing with different levels and facets of the system. As part of a systems approach, risk assessment results need to be used to control plant safety by providing a basis to support management decisions over the total plant life cycle of design. This also means that safety level indicators need to be developed to measure the effectiveness of the improvements to plant operations suggested by research and to support operational risk management.

Recommendation 3: Peer Review and Enhanced Access to Nuclear Power Research Facilities and Personnel

The panel recommends that the NRC involve a diverse group of knowledgeable researchers in planning, conducting, and evaluating its research program. In addition, peer review of proposals and of draft reports by behavioral science experts is needed to ensure the quality of sponsored research.

One of the barriers to effective human factors research has to do with providing behavioral science researchers access to realistic settings, to facilities such as simulators, and to people such as experienced operators. While the panel recognizes the practical difficulties involved, we strongly urge the NRC and the nuclear industry to take significant steps that enhance researchers' access to these facilities and people. One step to achieve this goal would be to create a national research facility for the study of human factors in nuclear power systems.

Recommendation 4: Continuity in the Research Program

The human-factors-related activities carried out by the NRC in the past have been of two types. Work by the Office of Nuclear Reactor Regulation (NRR), typically called "technical assistance," has been concerned with short-term solutions to specific problems or with support to regulatory analysis and decision making. Human factors work within the Office of Nuclear Reactor Research

(RES) has been concerned with longer-term research issues. While this may have been a useful and practical separation of functions that may be appropriate to retain, the panel is concerned about the effects of the short-term priorities of NRR on the longer-term research programs of RES. For the research programs to produce useful, practical results, continuity on important issues is essential. To be effective, a research program must operate coherently for an extended period rather than change in response to each new, immediate, external demand. Since effective research is cumulative, continuity is as important as level of expenditure.

Recommendation 5: Transfer of Knowledge

The panel recommends that the NRC take the greatest possible advantage of existing research in the behavioral and social sciences by increasing the transfer of knowledge to the nuclear industry. To this end, the panel recommends that the NRC publish an annual review of the human factors research relevant to the nuclear power industry.

Recommendation 6: Dissemination of Human Factors Research by the Nuclear Industry

The panel has observed that several problems exist in the usability and transfer of human factors research reports prepared by the NRC, its contractors, the national laboratories, and other elements working on human factors research related to nuclear power that should be addressed.

One impediment is the difficulty in searching for and retrieving human factors research reports. We are not aware that any central bibliographic data base or search service exists to abstract, index, and make available bibliographic or full text information, including NRC human factors publications. We recommend that mechanisms to improve the dissemination of human factors results throughout the industry be developed. One element is to use or develop a bibliographic search service. As a first step the panel recommends the development of a bibliographic system for NRC-supported human factors reports.

Recommendation 7: A Human Factors Research Agenda

Based on the panel's approach to the interaction of the human and technical systems, the research agenda has been organized into major areas. The panel followed three criteria in determining higher priority research topics within these areas. First, some research topics may have a critical impact on safety and thus must be addressed immediately. Second, in some areas research is needed as a basis for evaluation. Third, a particular research topic may be an essential building block for a long-term program. In all cases research should be aimed at management, maintenance, and other ancillary workers, as well as control room operators.

The five major areas of the panel's recommended research agenda appear below.

(1) *Human-System Interface Design.* Research on the human-system interface design seeks to improve the interface between individuals and the technical system. With the rapid advances in computer technology, automation, and software, the panel believes that research on computer-based control and display, automation, and computer-based performance aids and the human factors aspects of software are of particular importance. The highest priority research topic in this area is:

- Automation and computer-based job performance aids

(2) *Personnel Subsystem.* Research on the personnel subsystem is concerned with the design of jobs and the development of systems to ensure that personnel assigned to those jobs are sufficient in number and have the requisite training and qualifications to perform them. The panel placed higher priority on three personnel subsystem topics:

- Maintenance and enhancement of operational skill (new training approaches)
- Improvements in licensing examinations
- Shift scheduling and vigilance

(3) *Human Performance.* The ability to measure and predict human performance within the system is fundamental for the meaningful design and operation of a sociotechnical system. The panel recognizes a critical need to establish an integrated research

program, to develop the methodology and data for characterization, measurement, and prediction of human performance. The highest priority research topic is:

- Causal models of human error, especially for situations with unplanned elements

(4) *Management and Organization.* This area deals with the effects of organizational design and management decisions on safety. Areas for priority attention include:

- The impact of regulations on the practice of management
- Organizational design and a culture of reliability

(5) *The Regulatory Environment.* This area focuses on the actions of regulatory bodies and the interactions between regulators and utilities that affect safety, both directly and indirectly. The highest priority research topics are:

- The appropriate mix of government regulation and industry self-regulation
- Developing and tracking a wide array of performance indicators

More details of these research priorities are given in the body of the report.

CONCLUSION

The panel is encouraged by the initiative shown by the NRC to develop and fund a new human factors research program. If this plan is implemented in 1988, receives the strong support of the NRC and of the industry, is managed by a qualified human factors specialist, is staffed by a team of multidisciplinary scientists, and is organized as a separate branch rather than as a subdivision of the reliability branch, then the initial steps of leadership required of the NRC in this critical area will have been taken. Further steps will be taken as the NRC and the industry review and implement the recommendations made by the panel.

Part I
The Context for Human Factors Research in Nuclear Safety

1
Introduction

THE PANEL'S CHARGE

The responsibility of the Nuclear Regulatory Commission (NRC) for ensuring the safety of nuclear power plants is the basis for its human factors research program. Events, some of them near tragic, of the past decade suggest that improvements in that research program are essential to the health of the nuclear industry and the safety of nuclear plants and the public. Since the accident in 1979 at the Three Mile Island Unit 2 plant, the nuclear industry and the NRC have become acutely aware of a fact already established in many industries, that human error in some form is responsible for a large proportion of accidents and is a challenge to system safety and productivity (Meister, 1971; Miller and Swain, 1987).

The panel was charged by the NRC "[to] identify study areas in the current and recent programs that may have received inadequate attention and to provide guidance to the Office of Nuclear Regulatory Research, the Nuclear Regulatory Commission (NRC), and other research and development agencies in government, private industry, and universities regarding an appropriate research program in human factors to enhance the safe operation of nuclear power plants."

THE DEFINITION AND ORIGINS OF HUMAN FACTORS

Human factors is a multidisciplinary field that draws on the methods, data, and principles of the behavioral and social sciences, engineering, physiology, anthropometry, biomechanics, and other disciplines to design 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, that protect systems from human frailties, and that protect humans from hazards associated with operation of the system. In short, human factors has been an applied science of people in relation to machines.

Human factors in the United States had its origins in World War II, when it was discovered that new technologies were either misused, or could not be used in ways that would fully exploit their potential, because human characteristics had not been adequately considered in the design, operation, and maintenance of the technologies.

The earliest research and development in the field was concerned with how displays and controls should be designed to match the sensory, perceptual, and motor capabilities of their human users. Although limited in scope, it was a novel and successful approach that opened new dimensions and perspectives on systems engineering. As a result of the application of human factors knowledge, for example, high performance aircraft that previously could not be flown safely could be deployed effectively because cockpits had been redesigned around the capabilities of the pilots who would fly them.

This early work was greeted with sufficient acclaim to justify research in other areas of what was called "man-machine system design." As time progressed, specialists in human factors were asked to address problems of personnel selection, staffing, training, design of training equipment, protection from unusual and dangerous environments, and the many other factors that must be considered in achieving a habitable environment and a workable symbiosis between people and machines. However, even with this expanded scope questions concerned with the larger sociotechnical organization in which a system was embedded were often not addressed.

In recent years, however, it has become clear that knowledge broader than the traditional scope of human factors must also guide the design of the sociotechnical organizations in which individuals and physical systems interact and function. Just as individual errors can degrade the performance and safety of a system because of the way the hardware interface is designed or because of inadequate operator training, so too can errors in the design and management of an organization or the regulation of the overall system degrade system performance.

Because of the historical focus, it was natural that in the wake of the Three Mile Island accident the industry and the NRC would look to the operator-plant interface as a potential cause of operator error that might benefit from redesign. While it is clear that proper design of this interface is critical to safety, conditions other than the control room interface can also induce error and increase the level of risk in the operation of a plant. These conditions can arise from the way in which a system—including people, hardware, software, and facilities—is designed to be operated and maintained, the way in which it is organized, managed, and regulated, and the way it interfaces with the many other elements of the industry.

Recognizing this early in its deliberations, the panel considered the term human factors to include those conditions that affect the performance both of individuals and of organizations. We believe that to ensure safety of nuclear power plant operation it is necessary to address the issues associated with human performance within systems from a view of human factors which encompasses not only the human-machine interface but also the larger sociotechnical system in which it is embedded. The panel used this definition of human factors to assess the long-range human factors research needs of the NRC and the nuclear industry.

THE PANEL'S APPROACH: NUCLEAR REACTOR OPERATION AS A SCOIOTECHNICAL SYSTEM

Aside from being the worst commercial nuclear accident in the United States up to that time, the events of March 28, 1979, at Three Mile Island are a case of what Lanir (1986) calls a "fundamental surprise." A fundamental surprise, in contrast to a situational surprise, is the sudden recognition of the incompatibility between one's beliefs and reality—what a psychologist would call cognitive dissonance. Examples of fundamental surprise include the 1941 attack on Pearl Harbor and the 1957 launching of Sputnik for the United States, and the 1973 Yom Kippur war for Israel.

An appropriate adaptive response to a situational surprise can be derived from existing knowledge. The same is not true, however, for an adaptive response to a fundamental surprise. Existing knowledge may offer neither a full explanation of its causes nor a proposal for dealing with it in the future. A fundamental surprise calls for fundamental learning, which occurs in stages rather than by revelation. Small increments of knowledge are acquired and small steps are taken to apply the new knowledge. Ultimately, however, a new knowledge base and belief structure emerge that are capable of handling future surprises. Fundamental learning can sometimes be arrested if it is believed that partial knowledge and the solutions derived from it are complete and sufficient. Such a partial response appears to represent that taken by the NRC and the industry since the Three Mile Island accident.

One of the first lessons learned by the industry from Three Mile Island was that the errors made by operators in a control room were a significant contributing factor to the accident and its unsuccessful management. Accident investigations disclosed that these errors were due to a variety of factors: inadequate training, a control room poorly designed for people, questionable emergency operating procedures, and inadequate provisions for the monitoring of the basic parameters of plant functioning.

As a result of this early learning, a variety of remedial activities were undertaken to improve training, encourage the acquisition of plant-specific training simulators, review and improve the human engineering of control rooms, upgrade procedures, incorporate instrumentation for post-accident monitoring, and add safety parameter display systems to control rooms. In addition, steps were taken to initiate a human factors research program in the NRC, and the Department of Energy laboratories were called on to support that program.

Some utilities hired human factors specialists. The Electric Power Research Institute expanded its human factors research program. It was clear from actions such as these that the first stage in fundamental learning had taken place. The important role played in plant operation and safety by plant crews had been recognized, as had the realization that existing knowledge on this role was incomplete.

Encouraging as this was in the process of implementing the lessons learned from Three Mile Island, the actors involved appear to have come to treat the accident as a mere situational surprise and to apply purely technical solutions to human problems. This is a reaction that might be expected of a community with a strongly established engineering culture. The lesson that was not yet fully learned was that, in reality, the operation of a nuclear power system is far more complex than had previously been supposed: it is a technical system embedded within a much larger, more complex, sociotechnical system of people, organizations, and regulations that interact with one another in ways that are not yet understood.

The words "system" and "systems" are used in several senses which should be clear from the context. A "system" in the report is an interconnected set of parts making up a whole entity which has a common purpose. Thus, in one context we may speak of the "emergency core cooling system" meaning all that equipment which together is designed to cool the reactor core in emergencies. We may speak of the "human-machine system" and mean the combination of human and reactor, turbine, etc. which collectively make up a nuclear power plant. Or we may talk of the management and organizational system and mean those subgroups of humans responsible for setting policy, making rules, etc. to govern the behavior of those who operate the nuclear power plant. By a "sociotechnical system" we mean the combination of plant hardware whose behavior is governed by physical laws, humans whose individual behaviors are governed by the laws of biology and psychology of individuals, and the interaction of the social group of the humans involved in nuclear power plant operation, management, and maintenance where the interactions are governed by the hierarchies, pressures, and influences of social forces.

On the other hand, by a "systems approach" we mean a way of looking at a nuclear power plant not as composed of components whose properties can be examined in isolation, but rather as a collection of components including human components, each of whose properties affects and is affected by the others dynamically from moment to moment, so that to predict the performance of any component requires that one consider the state of, in general, many others.

Figure 1 illustrates the principal elements of this sociotechnical system. The innermost layer represents the physical system—the nuclear power plant. The interface between it and the individuals who operate and maintain it—often called the "human-machine interface"—is represented by Boundary A. This boundary has been the focus of traditional human factors engineering. The performance of the individuals on one side of this interface and plant

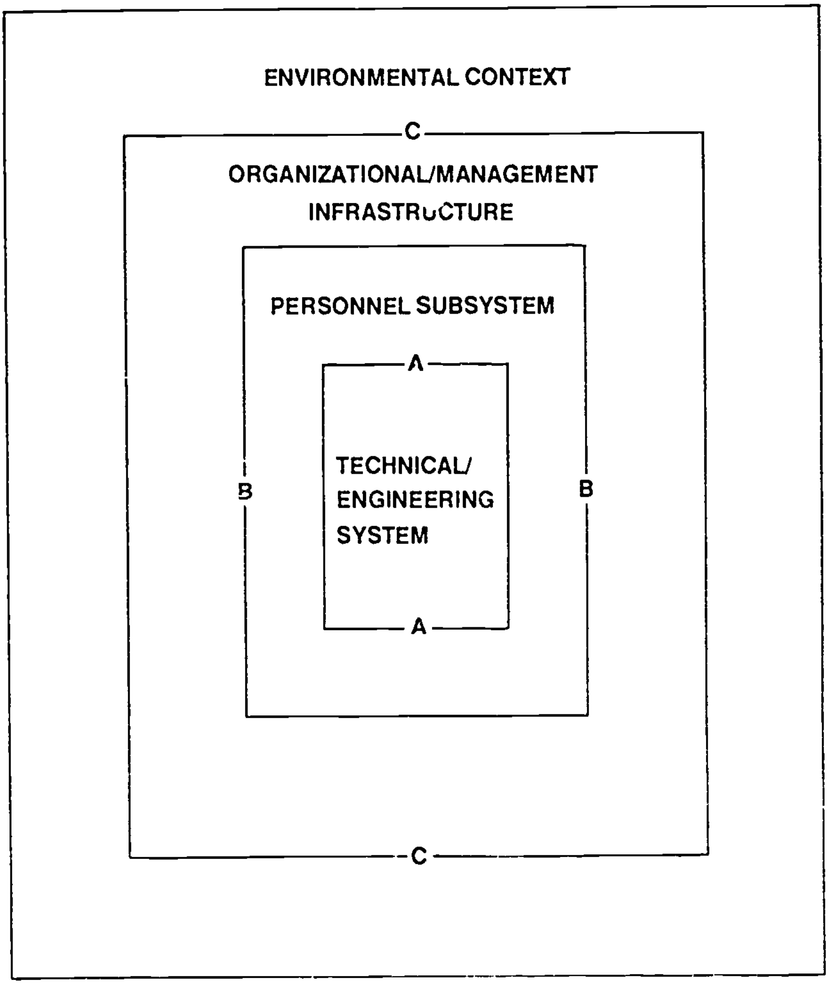

FIGURE 1 Components of an integrative system safety analysis. Adapted from Shikiar (1985).

systems on the other is influenced by its design. However, the display and control interface is but one piece of the picture because the performance of these individuals is affected by more than displays and controls. The cognitive processing of operators, personnel selection policies and methods, training and training devices, procedures, and the less tangible but potent effects of motivation, group interaction, boredom, fatigue, stress, and morale all play a role. These areas are traditionally the realm of industrial psychology.

As we move out from the center of Figure 1, we see that the people in the plant (the personnel subsystem) operate in an organizational environment that results from management decisions concerning organizational design and structure. There appears to be a great deal of recognition on the part of the NRC and the nuclear industry of the crucial role played by management leadership in safe operations. What is less frequently recognized is that at this level of analysis a number of important research questions can be posed, the answers to which may result in improvements to safety.* This level of analysis is the traditional realm of management sciences and organizational behavior research.

It is important to recognize that the nuclear power plant and its personnel and management all operate within an economic, political, and social context, as shown in the outer layer of Figure 1. This level of analysis recognizes that safety is influenced by production and profit pressures, public support or opposition to the nuclear power plant, relations between the various regulators and the utility management, as well as the specific policies and actions of the regulators. While it is easy to see how this level of analysis affects public health and safety, it is more difficult to see how this could be the subject of research. Nevertheless, we identify it as an important area to be investigated by economists, political scientists, and lawyers for research approaches that may be offered by these disciplines to improve safety.

The panel firmly believes that research that recognizes a systems approach, with the "system" broadly defined as in Figure

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* In this report to increase safety is to decrease the probability that people, property, or environment will be harmed by some event arising from the construction, existence, or operation of a nuclear power plant; to decrease safety is to increase that probability.

1, has great potential for delivering results that yield useful recommendations for safety improvements. Failure to recognize the effects of the outer layers of Figure 1 on safety may result in valid improvements to safety being unimplemented or ineffectively implemented because management or environmental constraints were ignored. At best, approaches to improving plant safety that do not recognize these constraints will be incomplete.

The systems approach points out that risk estimates by implication embody a design and operation philosophy for the plant. These probabilities, at best, can be correct only if the plant is operated in accordance with the assumptions made by those performing the risk analysis. But those assumptions are not usually made explicit, or at least they are not explicitly incorporated into training, the design of operating procedures, and other elements of plant operation. Unless the assumptions made during risk analysis are explicit as an operating philosophy, there can be no guarantee that even the best estimates are valid at any moment. Any changes in operating practices, maintenance practices, or other functions must be fed back into a further risk analysis, which in turn should feed forward into the management and operational philosophy. The aim of the research program proposed by the panel in the report is to suggest such changes in regulation, management, and operations, which would lead to a formal statement of research philosophy.

Research will suggest changes in design, procedures, and operation, but by themselves these changes will not guarantee safe operation, and by itself research cannot guarantee safety. Research must be used in a coherent philosophical framework. In engineering it is standard practice to control error by a feedback system. Controlling human error, and hence human-induced or human-exacerbated risk, should be done in the same way. Human factors research should be seen not as an answer to a question about risk, but as a control signal in a feedback system. Risk analysis suggests aspects of operation that require modification because they are prone to the effects of human error. Research suggests ways to change human behavior so as to reduce human error. The results of these changes alter the values in the risk analysis. Further risk analysis and task analysis of new methods of operation will suggest further changes in operation or new candidates for sources of human error—and the cycle will repeat.

In the past, viewing research as the answer to a specific question has led to the classic and common mistake that is seen in the operation of complex systems. The removal or change in value of a single variable leads not only to a local result but also to complex interactions that propagate through the system in often unpredictable ways. This is as true of research on the human components of a system as it is of any other component. If the results of research are to lead in a direct and practical way to the reduction of error and the reduction of risk, then research must be coupled to reliability analysis and to management, operations, maintenance, and regulation, so that an effective control signal is sent through the system. The NRC must conduct regulatory research on the problem of coupling the control signals of research to their reliability and risk analysis so as to optimize the control operations, not just to answer questions and accumulate knowledge.

A SCENARIO

To emphasize the need for a sociotechnical approach, consider a control room crew confronted suddenly by a burst of alarms indicating that an abnormal transient has occurred. What will determine whether they are able to handle the emergency?

The quality of displays is of course critical. Their layout and legibility affect the time required to locate and read them. Whether they display raw data or derived measures affects the extent to which short-term memory and complex cognitive processes will be demanded of the crew. The layout of controls and whether they conform to stimulus-response stereotypes affect the probability that an operator will press the button or activate the intended switch.

Software and hardware that have desirable properties from the point of view of engineers and computer specialists may be difficult to use. A crew member may know what information is needed but be unable to obtain it because of the characteristics of computer graphics or data bases. How long does the system take to repaint the screen? At what distance and from what direction can it be read? Does the 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? Such matters should influence computer system decisions.

The operator's ability to deal with an abnormal or emergency event, even at the level of reading displays, can be affected by regulation and management style, as much as by the design of displays. For example, the ability of operators to respond to emergencies is affected by fatigue and motivation. The structure and organization of shift work will also affect operator efficiency, due to disruptions in biological circadian rhythms. A management insensitive to comments by operators about their working conditions, or that penalizes operators for inconsequential infringements in matters such as dress codes, may obtain obedience to rules but will not encourage participation in the pursuit of excellence. Civilians do not adopt "military" styles voluntarily and may resent them if imposed by management. Management, whose experience may have been predominantly with military systems, may find it hard to tolerate "civilian" attitudes. An undeserved rebuke for failing to follow ambiguous directions can destroy morale in an instant and make it difficult to rebuild for many months.

Now consider another area: plant maintenance. How is it organized? Are maintenance personnel adequately trained? Are they encouraged to play an active role in developing good maintenance practices, or do they see their role as merely to carry out commands but show no initiative? Does management feel directly responsible for the quality of maintenance and, in return, encourage maintenance people to feel a pride in their work? Do maintenance personnel feel that they are part of a team with the operators? Do they communicate with each other? Do maintenance people understand the significance of the details of their work and its effect on operations? Do the design engineers design for maintainability? Do they choose components that force the operator to use them correctly, thus minimizing error? If maintenance is poor, operators will know they cannot trust the hardware and software, and lack of trust between human and machine can be expected to have as devastating an effect on their cooperation as can a lack of trust between people.

THE NEED FOR AN INTERDISCIPLINARY APPROACH

'Good hardware with poor management leads to low morale, inefficiency, and errors. Good management with poor hardware leads to distrustful and stressful operation. Hardware decisions change the work of operators; manning levels affect training; regulations affect the designs or design changes, the manning and training methods, and the work group organization that can in principle be considered. The effect of a change to any part of a system may necessitate changes that require inputs from a great variety of disciplines. Changes to design, operations, and maintenance research and proposals for innovation by one discipline should be planned and reviewed by several disciplines.

The very high rate of change in technology today has already created a context in which human factors and social science professionals work with engineers, computer scientists, and others to provide complementary research skills required in an age of information and cognitive science. As the roles of level of automation, degree of supervisory control, and use of artificial intelligence and robotics increase, it should become increasingly common for behavioral scientists to work with mechanical and electrical engineers, since no single discipline has the expertise to solve both technical and human systems interaction problems.

In a comparable way, there has been a growing realization that human interaction in groups and organizations is as central to safety and efficiency as is the interaction of a human with a machine. Within small groups, the dynamics of social interaction can determine whether behavior is cooperative or antagonistic. The efficiency, content, and style of communication both within groups such as control room crews and between different levels in the hierarchy from management downward can have a major impact on safety, on morale, and on the attitudes of supervisors and workers. Whether the question is how best to integrate the shift technical advisor into the crew, how to facilitate timely exchange of information between operators and maintenance crews, how to encourage personnel to report near-miss incidents in a constructive way and how to encourage management and the NRC to use such reports, or how to communicate effectively with regulators and the public, organizational factors are, in many cases, paramount.

Because of the range of topics that require research, we believe it is important to open the door to experts from a wider range of fields than traditional human factors. Consequently, we see a need to complement human factors work with research activities in the social and behavioral sciences, including organizational theory and management science. Research on safety and reliability should include human factors and organizational behavioral research and should be performed by teams of professionals from these different disciplines. In Europe the response to the changing nature of advanced technological systems has already been to include in research teams representatives from topics as far-ranging as linguistics and anthropology in an effort to understand the way in which communication and displays affect decision making and problem solving.

Today, the knowledge base that can account for the performance of the sociotechnical system we describe is at best fragmented, weak, and incomplete in many areas. In some respects its complexity appears to defy description and analysis. Yet, if the goal of improved nuclear safety is to be realized, the task of developing an understanding of nuclear power generation as a sociotechnical system must commence. And the initial step in this process must be informed by a program of research that calls on the expertise of the many disciplines that can contribute to this understanding. Before Three Mile Island, a plant was primarily perceived as a technical entity. After Three Mile Island, this view was enlarged to include the human-machine interface, primarily in the control room, and largely directed at measures to strengthen that interface. This was the first necessary, but not sufficient, step to achieving the goal of a reliable, safe system of nuclear power production. To ensure public safety, it is critical that the nuclear industry use a multidisciplinary approach to establish a research program to identify and evaluate means of improving safety.

2
The NRC's Human Factors Research Program

RESEARCH IMPETUS

Although the 1975 fire at the Browns Ferry nuclear plant and the 1979 accident at Three Mile Island were clear-cut signals that all was not well with the state of human factors in the nuclear industry, these were not the first nor the only such warnings.

In 1972 the Atomic Energy Commission—the forerunner of the Department of Energy and the Nuclear Regulatory Commission—asserted that insufficient attention was being given to control room design and staffing and operator training and procedures (U.S. Atomic Energy Commission, 1972). In 1975 a study by Sandia Laboratory identified human factors deficiencies in the design of the engineering safety panels at the Zion plant and others that were visited (Swain, 1975). In 1976, the Electric Power Research Institute—the research arm of the electric power industry—published a negative review of the design of five typical control rooms (Electric Power Research Institute, 1976). Another review of 18 control rooms conducted for the NRC by the Aerospace Corporation in 1977 was equally negative (Finlayson et al., 1977). Other investigations disclosed that human factors deficiencies were not limited to control rooms but extended to other parts of nuclear power plants, such as design for maintainability, surveillance, testing, and security.

After seven years of repeated investigations and warnings, why had so little attention been paid to the application of human factors knowledge to nuclear power plant design and operation? The principal reason appears to be that, prior to Three Mile Island, the nuclear power industry relied on conventional engineering approaches to the design and operation of nuclear power plants, as did the architectural and engineering firms and nuclear steam supply system and other vendors who supported the industry. Many of these approaches had their origins in earlier engineering practices used in the design of fossil fuel power plants and process control systems. Since these practices had been effective in the past, it was assumed they would be equally effective when applied to nuclear power plants. However, as the accident at Three Mile Island so dramatically demonstrated, this assumption proved to be invalid.

Several major investigations that followed Three Mile Island—the President's Commission (Kemeny et al., 1979), the Rogovin Report (Rogovin and Frampton, 1980), the Nuclear Safety Analysis Center of EPRI report (EPRI, 1979), an NRC report (NUREG-0585, 1979b), and others—all pointed out clearly and forcefully, as did the NRC's own investigations, that major improvements were needed in the way in which human capabilities and limitations were factored into the design, operation, and maintenance of plants, in the training of personnel, in the design of procedures, and in the process of selecting and examining qualified personnel. A theme common to all the investigations was succinctly stated in the report of the NRC's Office of Inspection and Enforcement (U.S. Nuclear Regulatory Commission, NUREG-0616, 1979a, p.3):*

> Human factors played a key role in the precursor events, in the accident scenario, in the response to the accident, and in many other related aspects. Human factors are involved in the perception of the precursor events in the man-machine interface, and in the operators' response to the event. Human factors appears to be a fertile area for consideration....This area, which is not well understood, should be better developed.

THE NRC'S RESEARCH PLANS

Although the NRC had funded research on human factors and human reliability as early as 1972, it had no formal long-

* In this report, publications of the U.S. Nuclear Regulatory Commission are referred to in the text by their technical report number and listed in the references by date under "U.S. Nuclear Regulatory Commission."

range human factors program until 1980, a year after Three Mile Island. In that year it formed the Division of Human Factors Safety in the Office of Nuclear Reactor Regulation to deal with short-term problems associated with the response to Three Mile Island, such as the development and application of guidelines and criteria for the human factors review of control rooms and procedures. Later that year it established two units to conduct human factors research. By 1981 the two units had been consolidated into a single branch in the Division of Facilities and Operations in the Office of Nuclear Regulatory Research.

In 1983 the NRC published its first long-range human factors research plan (NUREG-0961, 1983c). This program was aimed at providing the technical knowledge base for resolving seven important regulatory issues:

- Upgrading personnel qualifications and examinations;
- Upgrading operating procedures;
- The utilization of computers;
- The impact on safety of organization and management;
- Human contributions to risk and how to reduce them;
- Human-machine technology changes that should be considered; and
- Human factors requirements for severe accident management.

General guidance for the NRC human factors research plan came from several sources: the five NRC commissioners, the executive director's office, other NRC units, and recommendations of the report of the Study Group of the Human Factors Society (NUREG/CR-2833, 1982b). Guidance was also provided by the Office of Nuclear Reactor Regulation and its Division of Human Factors Safety.

In early 1983, the NRC Human Factors Program Area Review Group was formed to help the director of the Office of Nuclear Reactor Regulation determine whether the program plan was being properly implemented. This review group consisted of representatives from the major offices and divisions of NRC headquarters, its regional offices, and the Office of the Executive Director. In addition, the Advisory Committee on Reactor Safeguards, a committee reporting to the U.S. Congress, provided guidance to the NRC on the program.

During the planning and implementation of the program plan, management and technical exchanges occurred between the NRC, the Electric Power Research Institute, and the Institute of Nuclear Power Operations. This was arranged to help ensure that each organization was aware of the other's activities and to exchange research results of common interest. Exchanges also occurred with nuclear steam supply system vendor companies, with the national laboratories of the Department of Energy, with other countries engaged in human factors research, and with the Halden Project in Norway—a multinational research group established by its supporting member nations to conduct research on nuclear power plant design and safety. Some NRC research projects were even conducted in cooperation with utilities and utility owners groups; one study made use of a utility-owned training simulator and licensed personnel. In 1985 the NRC's human factors program was terminated. In light of the data (e.g., Trager, 1985) that shows the significant contribution of the human element to nuclear safety and risk, this action was not a sign of the leadership that is required of the NRC.

In June 1987, after a two-year suspension of human factors research, the NRC began the development of a new program plan, which is scheduled for implementation over a period of three years (fiscal 1987 to fiscal 1989). Copies of the new plan in draft form were provided to the panel for its examination near the end of the panel's term. The draft contains three sets of research recommendations: a Human Factors Safety Program Plan (dated June 1, 1987, 1987b) prepared by RES; a Human Reliability Research Plan (dated July 16, 1987, 1987c) also prepared by RES; and a Prioritized List of Human Factors Research Topics (dated November 9, 1987, 1987d) prepared by NRR. The NRC plans to integrate these and other elements into a final plan.

We are encouraged by the initiative shown by the NRC in 1987 to develop and fund a new human factors research program plan. If this plan is implemented in 1988; receives the strong support of NRC management; is appropriately staffed by a team of multidisciplinary specialists; establishes a link to leading behavioral and social scientists for ongoing advice on program planning, proposal evaluation, and review of research results; and is managed at the level of branch chief or higher by a person with training in human factors, the initial steps to provide the leadership required of the NRC in this critical area will have been taken.

TABLE 1 Summary of Nuclear Regulatory Commission Research

Organization and management	8
Training simulators	7
Emergency preparedness	4
Operating procedures (including emergency operating procedures)	10
Operator errors	14
Displays and SPDS	22
Selection	1
Job and task analysis	8
Allocation of function	2
Qualifications and licensing	23
Performance measurement	7
Training	8
Operator behavior, STA	9
Control room design evaluation	6
Maintenance	13
Human error probability and PRA	27

Note: This table, based on list of NUREGs and NUREG/CRs provided by the NRC, shows the number of reports that have been published since 1975 on each topic of research. In some cases, reports have been included in more than one category because of the nature of the work.

A COMMITMENT TO RESEARCH

In the ten-year period between 1977 and 1987, the NRC funded 125 human factors research projects, studies, and related efforts. Table 1 shows a breakdown by topic of the NRC's human factors projects from 1975 to the present. Until 1979, the year of the Three Mile Island accident, the funding was quite limited: $340,000 in 1977 and $345,000 in 1978. Funding was increased in 1979 to $1 million; in 1981 to $4 million; and in 1982 funding reached $5.5 million. In 1982, when human factors research funding was at its peak, it accounted for 2.2 percent of the NRC's total research budget. After September 1985, when the human factors program was terminated, human factors research was sharply curtailed, and by 1987 was limited entirely to studies of human reliability.

The reasons for this reduction in NRC support of human factors research are not clear. Overall cuts in federal spending, a lack of conviction of the value of human factors research by NRC management, possible disappointment in the usefulness of research results in regulatory decision making, and the assumption by some NRC executives that within a five-year period following

Three Mile Island the major human factors problems in nuclear plants had been resolved are some of the explanations the panel heard.

In its review and evaluation of the NRC safety research program for fiscal 1986 and 1987, the Advisory Committee on Reactor Safeguards (NUREG-1105, 1985m, p.36) took exception to the NRC's decision to fund no human factors research in 1986:

> We believe that while the industry and other public institutions can do much of the research, the NRC must take a leadership responsibility, just as it has in the past in other technical areas. Therefore, we believe that a substantial program of human factors research, of the order of $2 million to $3 million per year, should be funded in RES in FY 1986 and in ensuing years. This program should address longer range needs and should not be constrained by immediate user needs and the Human Factors Program Plan.

The panel agrees with the observations of the advisory committee and with its emphasis on long-range research needs. We also believe that short-range needs should be addressed as well.

Although the panel applauds the NRC's recent decision to reinitiate research on human factors in fiscal 1988, the collapse of the program since 1985 is one of many signs of historically uncertain support in this important area. In the past, many projects—particularly longer-term projects as opposed to technical assistance—have been curtailed or postponed in mid-course. This history establishes the view that support for the human factors program is weak. If the industry is to take the interaction of the human and technical systems seriously, then we believe that a signal must be sent to all the relevant professional communities that strong, stable, and sustained support for a human factors program, broadly defined, will be provided.

The NRC, in its organization of its research programs within the Office of Nuclear Reactor Regulation (NRR) and the Office of Nuclear Reactor Research (RES), has distinguished research that might be thought to be narrowly concerned with regulatory analysis and decision making from research on the broader problems of rendering nuclear power plants safe. The former type of research we call "technical assistance," and the latter we call applied research. It is useful to think of NRR as undertaking reactive studies and RES undertaking longer-term generic or confirmatory studies.

If the NRC is to understand the human issues related to nuclear power plant safety, it needs to institute a comprehensive program of behavioral science research. The data obtained from this research will be applicable to both current and future problems and may be used to evaluate potential improvements to safety and to guide future direction. We believe that by drawing on other disciplines and adopting new methods and by focusing not only on the human-machine interface but on the larger sociotechnical system in which it is embedded, the demands of the nuclear industry to enhance safety can be met.

3
Research Methodology and Management

APPLIED RESEARCH

Applied research usually is thought of in terms of the direct transfer of knowledge to application in a particular industry. When there is a clear objective to be met as well as a framework of knowledge that can be brought to bear on the problem, then it seems reasonable to sponsor specific studies that will produce tangible results ready for application to nuclear power plants. However, if this is the only kind of applied research sponsored by the nuclear industry, then the industry is hostage to the maturity of basic research developments in a particular scientific field.

Partial knowledge and approximate models (by the standards of basic research) can have important implications for incremental improvements on significant problems in the applied world. This means that one kind of applied research is the collection and synthesis of existing research results applicable to the nuclear power plant context. This requires people or teams of people that have expertise or experience that spans disciplines. Although at the time of Three Mile Island few behavioral scientists were familiar with the world of nuclear power, this is no longer a critical bottleneck. However, one should note that actually doing this type of review and synthesis is difficult. Too often the result is a dilution of the results of basic research for the noninitiated when what is desired is a distillation of what is really essential and relevant to the basic behavioral science questions that ultimately motivated the research.

The nuclear industry should also seek to influence research conducted in other institutions so that the research base available to solve the industry's problems will expand. This means that the NRC and the nuclear industry should attempt to influence the research agendas of organizations that perform research (e.g., universities, institutes, laboratories, research companies, and research organizations within industrial firms) in the direction of NRC and industry goals and needs. One way to do this is to provide access to experienced nuclear personnel and facilities for such researchers.

The types of applied research that should be sponsored or conducted by nuclear industry organizations fall into two categories: (1) the utilization of available research and (2) nuclear-specific research activities. Activities in the utilization of available research category begins with the decision of what behavioral science issues are relevant to nuclear power plants. Research can then be sponsored to identify, collect, and synthesize knowledge. Since the research base changes over time, this category includes tracking research over time. In some cases the existing knowledge base is impoverished; as a result, there is little information to synthesize and apply. In that case what is needed is to encourage and stimulate growth on the behavioral science issues relevant to nuclear power plants. This does not necessarily mean sponsoring nuclear-specific research, but fostering through various means research on the sociobehavioral issues that are seen to have relevance to nuclear power plants. For example, the research base on measuring the quality of computer-based displays is thin. While some interim results are available, the industry needs to encourage more work to identify the elements of an effective display so that results can be transferred to the nuclear industry.

The focus of nuclear-specific research activities is the application of behavioral science and research methods knowledge to the nuclear power plant. There are two parts to this activity. First, there is the need to sponsor, encourage, and stimulate informed innovation in developments intended directly for the nuclear industry. The words *encourage* and *stimulate* are used in addition to sponsor because NRC policies can have strong effects on the willingness of industrial organizations to develop new systems, techniques, and on-line or off-line human performance aids.

Informed innovation is an open-ended creative process to convert the research base into systems and techniques that have an impact. In today's era of computer technology, many developments are possible, and it is difficult to decide a priori which will be most effective. For example, behavioral science research can reveal the potential benefits of exploratory training systems. There may be many different specific systems which could be developed to realize that potential. The NRC and the nuclear industry together need to create an environment that supports and stimulates this process of informed innovation.

Second, feedback is needed on the effects of changes to help filter and focus innovation. Feedback and evaluation complement innovation. In many areas, changes have been introduced into the nuclear power plant as a sociotechnical system, but the effects of those changes have not been assessed and are not yet understood.

RECOMMENDED RESEARCH APPROACHES

There are many important considerations in managing research: how to set the research agenda, how to achieve higher quality, how to achieve more useful research results, and how to achieve maximum leverage from available funds. Peer review of proposals and of draft reports by behavioral scientists with expertise in the broad range of disciplines required for an integrated approach of the human-technical system is needed to ensure the quality of sponsored research.*

To be effective, a research program must operate coherently for an extended period rather than change in response to each new, immediate external demand. Since effective research is cumulative, continuity is as important as level of expenditure. Timely research is always assisted by improvement in the quality of research archives. At our request the panel was supplied with a complete list of NRC human factors reports. The amount of work and time required to obtain this list was substantial and reflected a poor cataloging system. If the NRC cannot rapidly and effectively retrieve its own research, how can it be used either for regulation or by industry? Attention should be given to compiling an annual review of relevant research. This review would include not only

* We are aware of at least one case where this has occurred successfully: the NRC-sponsored research on cognitive modeling (NUREG/CR-4862, 1987a), for which a technical review by a distinguished group of scientists was held.

NRC work but also work related to regulatory human factors in general. The current NRC report on the status of its programs is primarily for internal administrative use and does not summarize achievements in a way that facilitates successful transfer of results to industry.

The task of managing, directing, and conducting behavioral and social science research in the context of the nuclear industry is a challenging one, and our picture of the intricacies of a systems approach supports this claim. Human factors and organizational research requires formal training and sustained experience. It must be conducted by qualified people and overseen by qualified monitors. If human factors research is to be maintained at a level of endeavor and with the quality necessary to cope with the problems encountered, leadership at the branch head level or above must be provided by someone with the necessary experience and qualifications. In this connection, we believe that human factors and social science research is not to be managed as a part of human reliability research; rather, human reliability research is one important portion of a broader human factors and social science research program.

To date much activity and research related to human factors in the nuclear industry has for the most part been one-shot attempts to generate a final answer to the particular human-related issue in question. The attitude appears to have been one of getting these human issues resolved once and for all. While this research has sensitized many to the importance of human-related issues, it is now time for a serious and continuing commitment to research on the nuclear power plant as a total sociotechnical system.

Barriers to sociotechnical research applicable to the nuclear power plant world have as much to do with getting good researchers to address behavioral science problems with relevance to nuclear power plants as with having adequate funds for research. Part of taking the interaction between the human and technical systems seriously in nuclear power plant safety means that this access to realistic settings, to facilities such as simulators, and to people such as experienced operators must be greatly enhanced. Research money alone will not provide the needed knowledge base without good access to the nuclear power plant world for behavioral science experts. For example, actual incidents are an important source of data to calibrate analytic models of human performance, yet to our knowledge no one with expertise in human performance and error is part of either the NRC's or INPO's incident investigation teams.

Although difficult, it is important to collect data on human performance with new interfaces and decision aids. While research activities should not conflict with the operational needs of running plants or meeting training requirements, one can bring together for study experienced personnel and examples of new interfaces or decision aids. Ways are needed to allow research and operational needs to coexist and to assist one another. If mechanisms to enhance researchers' access to facilities and people are put in place, the nuclear power plant will become an application world that offers exciting research possibilities from a scientific perspective that can at the same time produce results that will contribute to enhanced safety.

Several important general problems arise when conducting research on complex human-machine systems. One is generalizability. In order for the results of a particular research project to be generalizable to an industry population (of nuclear operators, maintenance personnel, or managers), certain statistical criteria must be set. A second problem is a sufficiently large number of trials, people, and treatment conditions are needed to make the statistical power of the results adequate and meaningful. Because of the small population of experienced nuclear power plant personnel and their demanding schedules, it is frequently difficult to find a sufficient number of participants for experimental studies. In the human factors area by far the greater number of research reports published by the NRC are not experimental studies but rather reports on methods (such as task analysis), models (such as simulations or conceptual models of task allocation), or surveys. Very few are true experiments or well designed observational studies.

How can facilities be provided for the use of researchers to investigate important issues? Access for researchers to sites, simulators, and personnel in cooperation with the utilities and industry is critical. Pilot studies can often be conducted using part-task simulators or in laboratories, but research that is adequate to convince the utilities and the public and to bear the weight of regulation must have industrial validation.

A case could also be made for a national research facility for the study of the human factors of complex systems. A generic or

PANEL ON HUMAN FACTORS RESEARCH NEEDS IN NUCLEAR REGULATORY RESEARCH

NEVILLE MORAY (Chair), Department of Industrial Engineering, University of Toronto
LINDA COHEN, Department of Economics, University of California, Irvine
RUSSELL DYNES, Department of Sociology, University of Delaware
HERBERT ESTRADA, MPR Associates, Washington, D.C.
CLAY E. GEORGE, Department of Psychology, Texas Tech University
PAUL M. HAAS, Advanced Systems Technology, International Technology Corporation, Oak Ridge, Tennessee
LARRY HIRSCHHORN, Wharton Center for Applied Research, Philadelphia, Pennsylvania
JOYCE KEEN, Clinical Psychology, Iowa Methodist Medical Center, Des Moines, Iowa
TODD R. LAPORTE, Institute of Governmental Studies, University of California, Berkeley
JENS RASMUSSEN, Cognitive Engineering, RISO National Laboratory and Technical University of Denmark, Roskilde, Denmark
RICHARD SHIKIAR, Battelle Human Affairs Research Centers, Seattle, Washington
J. ED SMITH, J. Ed's Nuclear Service Corporation, Central, South Carolina
DAVID WARD, E.I. du Pont de Nemours and Company, Savannah River Laboratory, Aiken, South Carolina
DAVID WOODS, Westinghouse Research and Development Center, Pittsburgh, Pennsylvania
THOMAS B. SHERIDAN (ex officio), Chair, Committee on Human Factors

HAROLD P. VAN COTT, Study Director
STANLEY DEUTSCH, Study Director (1985–1987)
BEVERLY M. HUEY, Research Associate/Consultant

COMMITTEE ON HUMAN FACTORS

THOMAS B. SHERIDAN (Chair), Department of Mechanical Engineering, Massachusetts Institute of Technology

CLYDE H. COOMBS, Department of Psychology, University of Michigan, Ann Arbor, Michigan

JEROME I. ELKIND, Information Systems, Xerox Corporation, Palo Alto, California

OSCAR GRUSKY, Department of Sociology, University of California, Los Angeles

DOUGLAS H. HARRIS, Anacapa Sciences, Santa Barbara, California

JULIAN HOCHBERG, Department of Psychology, Columbia University, New York

THOMAS K. LANDAUER, Information Sciences Division, Bell Communication Research, Morristown, New Jersey

JUDITH REITMAN OLSON, Graduate School of Business Administration, University of Michigan

CHRISTOPHER I. WICKENS, Aviation Research Institute, University of Illinois

ROBERT C. WILLIGES, Department of Industrial Engineering and Operations Research, Virginia Polytechnic Institute and State University

HAROLD P. VAN COTT, Study Director

STANLEY DEUTSCH, Study Director (1984-1987) reconfigurable simulator could be installed at a laboratory dedicated to high-technology human factors, in a national research laboratory or university. We understand that steps have been taken by the NRC to acquire such a facility in the form of three simulators. In the meantime, efforts should be made to arrange for utilities and vendors to provide facilities. Efforts should also continue to be made to foster international cooperation as a form of cost-effective research.

To summarize these points: the NRC and the nuclear industry should try to stimulate research activity in relevant areas of behavioral science, to use outside experts to track and synthesize this research with an eye to opportunities to apply the results to nuclear power plants, to use outside experts to maintain a coherent strategy for research needs on human-related issues, to improve the technical review of programs, to provide researchers access to nuclear power plant personnel and facilities, to sponsor the best people in the relevant behavioral areas, and to emphasize continuity and long-term progress in important areas.

SOURCES AND USE OF EXISTING KNOWLEDGE

Two major sources of knowledge contain information that is applicable to the problems of improving the human side of nuclear safety. The first source is the published and unpublished research literature from the areas of human factors, behavioral science, organizational theory, management science and computer science and engineering. The second source of knowledge is derivable from the ongoing programs and expertise of those institutions who sponsor or conduct research and information gathering programs related to human performance and nuclear safety. This section reviews these two important knowledge sources, examines current barriers to their use, and suggests actions that, if taken, would reduce these barriers.

The Existing Literature

Within the past fifty years a large literature has accumulated in the fields of human factors and related behavioral and social science areas. Some of this literature is in the form of published journal articles, theoretical monographs, texts, handbooks, design guides, and state of the art summaries. Even though much of this work has been done on other types of systems and organizations than nuclear, it nevertheless constitutes a valuable knowledge base that should be exploited by those concerned with the administration, planning, and conduct of nuclear safety research. For example, recent state of the art summaries in the human factors area by Boff, Kaufman, and Thomas (1986), Boff and Lincoln (1987), and Salvendy (1987) contain fundamental data and principles related to human performance in systems contexts that are applicable to nuclear concerns. While it might be assumed that the published literature would be easy to identify and access, it comes from many fields and speciality areas and therefore is covered by many different indexing, abstracting, and bibliographic services and housed in many different libraries. Unless a potential user is well-versed in information and library science, obtaining information from these diverse sources can be a major problem.

Another important source of information exists in the form of technical reports which are often not available from private or federal bibliographic search services and libraries. For example, many relevant reports published by military laboratories and their contractors; by the NRC, the national laboratories and their contractors; by other organizations such as the Electric Power Research Institute (EPRI); and by the Institute for Electric and Electronic Engineers (IEEE) on human factors standards are not systematically covered by current abstracting and indexing services or readily available from most libraries. Even less available is work on performance indicators developed by the Institute for Nuclear Power Operations (INPO) which is seldom made public to researchers.

The inability of a typical user to quickly and easily locate, evaluate, acquire, and apply information from these published and technical report sources represents a barrier to the use of knowledge that already exists and wastes resources unnecessarily when it is duplicated.

Those responsible for the administration and conduct of the human factors research of the type presented in the panel's agenda should be able to access a single bibliographic data base that contains abstracts of all of the published and technical report literature applicable to their needs and interests. Such an information search and retrieval system does not now exist and should be developed.

Those who administer and conduct research and those who use research results for regulatory analysis and decision making also need access to a periodically updated review of research that is applicable to the problems of improving the human side of nuclear safety. Such a state of the science and art review would distill, summarize, and synthesize research findings in a variety of applicable fields; identify where gaps in knowledge exist; and point to promising application areas. It would provide an objective rather than an intuitive basis for informing regulation. While the development of such a review would be a significant undertaking, involving expertise from a variety of disciplines, its benefits would outweigh its costs.

The development of the knowledge access and review mechanisms suggested here, if jointly undertaken by the NRC, DOE, EPRI, and INPO, represents an ideal opportunity for these institutions to cooperate with one another in an undertaking which does not threaten the integrity of any participant.

Ongoing Programs

Another major source of applicable information can be derived from a knowledge of the ongoing research programs and expertise of the institutions concerned with the human side of nuclear power safety. We briefly describe these programs below and suggest actions that could be taken to enhance mutual cooperation and information exchange among them.

Electric Power Research Institute (EPRI)

The long-standing human factors research program of EPRI has produced a series of high quality research reports and research products that are used widely throughout the industry. One reason for the success of this program has been EPRI's emphasis on developing mechanisms that ensure that the results of its research are transferrable to the industry that EPRI supports. An example of a widely used EPRI report is the *Guide to Technical Reports Published 1972 through 1981* (EPRI, 1986a) and the *Guide to Technical Reports Published January 1982-September 1, 1986* (EPRI, 1986b).

Because the scope and direction of its research is largely defined by the industry, its program will not necessarily cover all topics that require research from a safety perspective and is likely to emphasize research with a relatively short-term payoff. It is more likely to be concerned with the human factors aspects of control room design, hardware, and software than with research on management and organizational issues. However, several EPRI studies have been concerned with the way in which work and communications within plants is structured.

EPRI is also active in developing systems based on techniques from the field of artificial intelligence and expert systems. The NRC should undertake research on methods to evaluate such systems before they are incorporated into nuclear power plant operations, maintenance, and training.

Institute of Nuclear Power Operation (INPO)

INPO is an important broker for the successful transfer of technology from research to the industry. Since it is not the intent of INPO to undertake research, it cannot be expected to provide significant effort in that area. However, together with the Nuclear Utility Management and Resource Committee (NUMARC), INPO could be the key to the application of research and, through the monitoring of performance indicators, assess the long-term effects of research applications on plant safety.

The conduct of several human factors projects recommended by the panel requires access to industry facilities, such as simulators, as well as to industry personnel and industry data. INPO and NUMARC should be encouraged to develop mechanisms where this necessary access could occur.

The Institute of Electrical and Electronic Engineers (IEEE)

The Institute of Electrical and Electronic Engineers has, through its Nuclear Power Engineering Committee (NPEC), worked for several years on guidelines and standards activities. Although it does not conduct research, NPEC could make use of a well-organized data base. Moreover, the work of this kind of group could be a source of ideas for research, which would help the NRC to target its efforts. It is most important that guidelines and standards agree with the NRC regulations to avoid sending conflicting signals to industry. When they differ research results and not regulatory fiat should resolve the conflict. NRC should have sufficient liaison with groups such as NPEC to ensure good communication.

Department of Energy (DOE)

Another potentially useful source of knowledge applicable to the commercial nuclear power industry are DOE programs concerned with such topics as artificial intelligence and expert systems. We encourage the NRC to maintain an awareness of this research and of its commercial applicability and to develop methods to evaluate these products as they emerge from DOE, EPRI, and other programs.

Given the work of DOE on inherently safe reactor designs and its role in identifying candidate systems for the next generation of nuclear power plants, there should be close and continuing cooperation between DOE and the NRC during the development of this program. For example, the panel learned at one of its briefings of a proposal for a small, inherently safe reactor that might allow one operator to control several units at a single site. As interesting as such a proposal may be, it raises questions about the workload on the operator of such a system, maintenance, and other human factors issues.

National Laboratories

The charter of the national laboratories is to provide support to the NRC and DOE. Since the NRC has lacked the human factors staff to manage and direct all of its research, it has relied on the national laboratories to provide it with the needed expertise. Because of this need some national laboratories built up human factors capabilities, which constitute a valuable resource in some areas of human factors for the industry. If support, directive, and commitment are provided by the NRC and DOE, it can be presumed that the laboratories, as in the past, will respond appropriately by rebuilding their programs.

Part II
Human Factors and Nuclear Safety: An Agenda for Research

Human Factors and Nuclear Safety: An Agenda for Research

The panel recommends a general agenda of research on the human factors issues involved in the safety of nuclear reactors. Topics in major areas of needed research are described in sufficient detail to illustrate approaches that may be taken in each of them. The panel has made no attempt to develop a detailed program plan, schedule, or budget. That responsibility more properly rests with the manager of the NRC human factors research program and the nuclear industry. We do, however, attempt to place the topics in an overall sociotechnical context of nuclear reactor safety and to provide guidance for the management of a human factors research program needed to address the problems that exist within this context.

In setting out to develop a research agenda, the panel considered whether to concentrate on existing or future plants. There was a great temptation to concentrate on future plants because the application of human factors technology is most cost-effective if it begins in the earliest stages of the design of a plant. However, because the likelihood of new plant construction within the U.S. in the next decade is low, the panel decided to concentrate on research applicable to existing plants and their potential life extension. As recent incidents continue to point out (e.g., Davis Besse [NUREG-1154, 1985h], Rancho Seco [NUREG-1195, 1985g], San Onofre [NUREG-1190, 1985i]), the human interaction with the technical system is an important factor in the safety of today's plants. In addition, there are potent factors that can and will produce change in human-related aspects of the nuclear power plant. These factors include changes in technology due to systems obsolescence and replacement, changes in the technology baseline (the capabilities of affordable computer-based systems has dramatically increased in the last five years), regulatory forces, and cost or insurance benefit justification.

The panel also recognized that, to be manageable, the scope of its study would have to be limited. Therefore, we decided to restrict our attention to human factors research on commercial nuclear power reactor systems without considering other related human factors issues concerned with radioactive waste transportation or disposal, waste site management, fuel inventory management, quality control in plant construction, and the safeguarding of nuclear power plants from insider threats, sabotage, or terrorist attacks.

In the judgment of the panel, human factors research is required in five general areas: human-system interface design, the personnel subsystem, human performance, management and organization, and the regulatory or environmental context. Each of these five areas includes a number of research topics, some of which have been identified as being of higher priority. The specific research issues involved in each proposed research topic are elements that are judged to be necessary to improve design, performance, operations, maintenance, and regulation of plants. To provide answers to important questions, the proposed research program must operate coherently for an extended period rather than jump about in response to each new immediate external demand. Continuity of research is deemed essential to a productive program.

The panel followed three criteria in determining the higher priority research topics. First, some research topics may have a critical impact on safety and thus should be addressed immediately. Second, in some areas research is needed as a basis for evaluation of innovation expected in the near term. For example, in the very near term it is likely that the NRC will be asked to rule on the acceptability of employing computer-based decision systems in nuclear power plants; research on some topics is essential to provide a sound basis for making these decisions. Third, a particular research topic may be an essential building block for longer-term progress and to resolve future issues. An example of this is research on the development of causal models of human error that will increase the ability to make more accurate predictions of the conditions under which it could occur. Progress in this area will require several years' effort but will have a broad impact on all aspects of nuclear power plant safety—regulation, design, operation, and maintenance.

During the period in which the initial research studies are conducted, the NRC, together with the advisory assistance described in Chapter Two (A Commitment to Research section), should review the broader scope of research suggested by the topics described in this report and should develop an ongoing program plan to include those additional topics the panel has identified as program elements, which are not already being investigated. Funding should be allocated for research that becomes urgent due to unforeseen circumstances in such a way that the systematic research program continues without significant interruption. It is most important to note that in all cases we believe that research should be directed at management, maintenance, and other support activities in addition to operation in the control room.

4
Human-System Interface Design

Human-system interface design addresses the boundaries between the technical systems and the people who interact directly with those systems (see Boundary A in Figure 1). At present, the central issues in this area are the introduction and effect of rapidly advancing computing technology and, at least implicitly, the allocation of functions between people and software-hardware combinations.

We have grouped research needs in this area under three topics: (1) computer-based control and display, (2) automation and computer-based performance aids, and (3) human factors in software development. Each of these topics is described in the following sections. Specific topics identified by the panel as higher priority contain more detail.

A successful research program on human-system interaction should help reduce the probability of human error due to poor design of human-computer interfaces, decision aids, and automation. It should also support the further upgrading of control room design begun with the control room design reviews. Maintenance activities should also be improved because, increasingly, maintenance personnel will be supported by portable computers, robots, and intelligent decision aids. The need for research on this topic will increase with increasing levels of automation.

COMPUTER-BASED INFORMATION AND DISPLAY SYSTEMS

Rationale and Background

In nuclear power plants, large quantities of data are made available through some medium (e.g., hard-wired instruments, sets of displays) to people who are responsible for controlling, troubleshooting, maintaining, and supervising operations. Research in a variety of disciplines has addressed the issue of how to build effective systems to deliver data to people; this is part of the body of research on human-computer interaction. One part of this research addresses domain-independent issues such as the legibility of displays and the potential accessibility of data bases. Although this research is generally applicable to nuclear power plants, it is not a higher-priority need because factors affecting legibility and accessibility are generally well-known and practical guidance is available (e.g., NUREG/CR-4617, 1987e; NUREG/CR-4227, 1985e). The problems involved are concerned with deploying this knowledge when building or evaluating interfaces.

The Safety Parameter Display System (SPDS) requirement has become, for all practical purposes, an effort to establish the use of computer-based information handling and display systems in the control room. There is now or soon will be a computerized data base and a computer-based display medium in a majority of control rooms. This provides an opportunity to expand the use of computer-based information and display systems, if meaningful innovations can be defined.

What is missing from current design and evaluation of computer-based information and display systems is a focus on how to influence human performance positively. 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 (Lenat and Brown, 1984; Rasmussen, 1986). Thus, questions about the display of data 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.

This viewpoint goes beyond questions of the media of display, legibility, the potential availability of the data presented, and other questions that are independent of the tasks involved and focuses attention on ways in which information displays can assist human performance. It is research on this aspect of human-computer interaction that should be pursued (see also the section on automation and computer-based human performance aids.)

The default design position has been simply to make accessible to the problem-solver all of the available data and evidence from which judgments can be constructed. If there is only one kind of representation available, then the common belief is that it must be the most detailed representation of the state of the world that would ever be needed under any circumstances (Rasmussen, 1986). This is often referred to as separable display of data or as a one-measurement-one-display-unit philosophy of data display (Goodstein, 1981). Given this view, it is the role of research on human-computer interaction to provide guidance to ensure that elemental data are legible and potentially accessible.

However, simply making data legible and accessible does not guarantee that the user will access the correct data at the correct time (NUREG/CR-4532, 1986b). In many cases in the history of human-machine systems (especially nuclear power) technological choices contained serendipitous relations between the form and content of a representation that were used to advantage by the problem solver. For example, the position of a device usually controlled by an automatic system was indicated via digital hard-wired counters. These mechanical step counters happened to make clearly audible clicks when the device position changed. Operators were able to make use of the clicking sounds to monitor this system because the clicks and click rate contained information about the behavior of the automatic controller. However, in many other cases, changes in technology hindered user performance because these serendipitous relations disappeared and no functional alternative was provided. One example is tile-annunciator-based alarm systems and initial attempts to shift to computer-based chronological lists of alarms. Recent studies have shown that the spatially distributed tile system supports operator extraction of many useful forms of information (Kragt and Bonten, 1983). The shift from a spatial to a temporal organization that occurred when the tile technology was replaced with chronological listing of the same data on abnormal conditions removed the serendipitous benefits provided by the spatial organization inherent in the tile medium. For this reason, in at least one case the new technology was abandoned, forcing a return to the tile system (Pope, 1978).

Research Recommendations

Given today's computer technology and the evolution from analog systems to distributed digital systems, new human-computer interfaces and decision aids will be introduced into nuclear power plants, and new problems may arise with the improper use of the new capabilities. Regulatory positions about these kinds of developments may retard the introduction of systems that could enhance safety. On the other hand, an inability to regulate the introduction of new technology may create new safety problems, such as new opportunities for human error. Thus, a method to specify and evaluate the adequacy of new interfaces and decision aids is important. Computerized versions of paper procedures may be the first of these items to challenge NRC and the industry.

Research on what constitutes effective computer-based information and display systems is not yet complete. It is important that the nuclear industry foster and track progress in this area; otherwise this research may be driven by other applications that are not generalizable to the nuclear power plant context. Most design guidelines for display are oriented toward dialog applications, such as text editing or data base retrieval, and not to real-time graphic display of data. There is an opportunity for informed innovation to create more effective control room information and display systems; this opportunity exists because most control rooms now contain a computer-based display medium. Additional opportunities exist in other areas of the nuclear power plant such as maintenance, tests, calibration, and monitoring of technical specifications.

There have been a number of applications of computer-based displays already in the nuclear industry, both prototypes and systems in use (e.g., SPDS). However, no useful interpretation of experiences with the introduction of computer-based interfaces has emerged. This gap is unfortunate and eliminating it is important to future innovations and development.

AUTOMATION AND COMPUTER-BASED HUMAN PERFORMANCE AIDS

Rationale and Background

In the past, allocation of function has been based on catalogs of "things computers do better" and "things people do better." With the current rate of technological development, however, existing catalogs are obsolete, and this distinction may soon cease to be relevant in most situations. As artificial intelligence technology develops, the idea of fixed allocation is no longer appropriate. NUREG/CR-3331 (1983d) outlined an approach to functional allocation that correctly emphasizes an iterative approach to the solution for conventional systems, but the panel believes a different conceptual framework is required.

For a given allocation of functions and design of controls and displays, appropriate performance aids may be identified. The question of new automation and new human support systems will arise because of changes in technology. First, changes in current technology will naturally occur with system upgrades and system obsolescence and perhaps with plant life extension. A notable example is the changeover in many plant systems to newer distributed digital technologies. Second, new opportunities will exist for aiding and automation afforded by new technologies, such as the opportunities for decision aiding and automation afforded by artificial intelligence techniques and expert systems.

Research Recommendations

Innovations are currently under development in several areas that will challenge the NRC's and the industry's ability to deal with issues surrounding new computer-based support systems. Research is therefore needed to deal with them. Questions concerning utilization of available research include: What is effective computer-based support? How can brittle problem-solving systems be avoided (Brown, Moran, and Williams, 1982; Roth, Bennett, and Woods, in press)? How should human and machine intelligence be combined into an effective overall system (Hollnagel, Mancini, and Woods, 1986; Mancini, Woods, and Hollnagel, in press)? What are effective human plus machine decision maker systems (Sorkin and Woods, 1985)? What are effective supervisory control architectures (Sheridan and Hennessey, 1984; Moray, 1987)? What factors affect decision making in multiperson, multifacility systems (Fischhoff, 1986)? How can one measure the effect and quality of different kinds of computerized aids? Research on questions such as these should be undertaken or tracked and used when applicable. For example, a research program is under way to track the effects of recent changes in commercial flight deck automation (Curry, 1985; Wiener, 1985b). The results of this research should be tracked and transferred to the nuclear industry.

The near future will be a time of widespread innovation and learning from the results of trial innovations. The industry needs to establish mechanisms to enhance access and to support this innovation process. Important areas in which innovation should be encouraged include the management of maintenance, test, and calibration activities; alarm systems; maintenance activities; and aids for supervisory activities, especially in the first two areas. Disturbance analysis has waned as a topic of interest to the industry because of the realization that it is a difficult problem; however, it is re-emerging under the label of artificial intelligence. While artificial intelligence techniques offer many advantages, the important problem of providing useful diagnostic and emergency management information to human problem solvers remains unsolved.

There are other areas in which innovations are currently under way that will challenge the NRC's and the industry's ability to deal with issues surrounding computer-based support systems. New computer-based system aids for measuring compliance with technical specifications and for emergency operating procedures are now available.* Several new kinds of computer-based alarm systems or alarm system supplements have been designed, and several utilities have expressed interest in alarm system upgrades. Several projects are ongoing to develop support systems based on artificial intelligence for nuclear power plant personnel. For example, a prototype expert system has been developed to support emergency notification decisions during accidents. These developments mean that there is an immediate need for effective tools

* Some utilities have contracted for such systems and some have already applied them, with mixed results.

to evaluate and measure the impact of new aids and automation on the human-technical system. Developing these measuring techniques is the highest immediate priority in this area.

The challenge of new technologies such as artificial intelligence or other forms of automation goes beyond the simple bottom-up construction of what the technology allows to be built. A nuclear power plant is already a highly automated system. When performance deficiencies are noted, they are usually attributed to the human element alone; and, from a purely technological point of view, the obvious solution is more automation. However, there are dangers in accepting a purely technological view to automation. Cases of new automation leading to new kinds of poor human performance are not unknown. Thus, it is important to conceive of new automation decisions as sociotechnical opportunities. These opportunities will arise because of changes in current technology and because of new capabilities for building decision automation.

While research is needed to evaluate emerging support systems requiring regulatory review, the same questions will arise continuously with future systems. The problem for the nuclear industry and its regulators is to learn how to achieve the benefits from new technological developments, to avoid retarding technological change, and to find and mitigate deficiencies in the use of the new technologies. Careful examination of the history of automation reveals that shifts have sometimes created new types of errors or accidents because they have changed the entire human-machine system in unforeseen ways (e.g., Nobel, 1984; Hirschhorn, 1984). Some examples of the unintended and unforeseen negative consequences that have followed from purely technologically driven deployment of new automation capabilities are summarized below:

- Shifts from manual to supervisory control in process control in which productivity actually fell from previous levels when there was a failure to support the new supervisory control demands (British Steel Corporation, 1976);
- Automation-related disasters in aviation (e.g., Wiener, 1985a);
- The shift in power plant control rooms from tile annunciator alarm systems to computer-based alarm systems that eventually failed and forced a return to the older technology, because strategies to meet the cognitive demands of fault management that were implicitly supported by

the old representation were undermined in the new (Pope, 1978);

- Shifts from paper-based procedures to computerized procedures that have also failed due to disorientation problems, because of the failure to anticipate the cognitive implications of technological changes for human problem-solving (Elm and Woods, 1985).

Automation may make significant improvement possible, but it is not always beneficial. The point is not that new technology should be avoided—because the automation does make possible significant improvements. Similarly, the point is not that new technology is always beneficial—because there are post-conditions associated with its introduction that must be satisfied in order for the potential to be achieved and for undesirable consequences to be avoided or mitigated.

Furthermore, these post-conditions can influence the way the technology is employed. Examples of ignored post-conditions undermining the benefits of technological change are numerous. Automation decisions then become a trade-off between the degree to which potential benefits are achieved and their magnitude against the costs of implementing the new technology plus either the costs of identifying and meeting post-conditions or the costs associated with accepting the new failures that may occur.

The relation of operators and maintenance workers to their equipment should be a symbiotic one. Research should not be conducted on allocation by simple assignment of tasks to either the human or to the machine. Formulating the allocation issue in this way assumes that human-related problems can be solved by just a little more engineering. Human-related problems, however, are symptoms, not causes, of underlying problems in the sociotechnical system. One should therefore question how to design the system so that each can support the other, request and give help as needed, and produce the most effective joint outcome.

There is little understanding, at present, of what makes a person trust or distrust a machine, 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 complex systems and center on the nature of the operators' mental models, through which they interpret the demands of the task, be it operation or maintenance. Researchers should investigate the merits and methods of dynamic allocation, consider whether the human role should be exclusively in a high-level supervisory capacity, and determine the difference in allocation for routine and emergency operations to ensure good performance under both.

One critical behavioral science issue related to questions of automation is the man-in-the-loop or man-out-of-the-loop architectures. This issue involves the relation between the human and the machine roles in controlling and managing a complex machine process; it is not an issue of the level of automation. In the past, the result of increased automation was to move the human role farther away from direct contact with the controlled process. In this new role, the human becomes a supervisor and manager of partially autonomous machine resources (e.g., Sheridan and Hennessy, 1984). This means that, with increases in the level of automation, the human is moved "out-of-the-loop." Research on the effects of automation are beginning to suggest (e.g., Wiener, 1985a) that this architecture may be poor for person-machine control of complex processes. As an alternative, this research suggests the need for new architectures in which the level of machine involvement is high (a highly automated system) but in which the human plays a more continuously active role in the control and management of the process—is more "in-the-loop" than in past, partially automated systems. Such a concept has profound implications for the course of future automation and decision support in nuclear power plants.

Numerous attempts have been made in recent years to improve plant operating procedures, particularly emergency operating procedures (EOPs). For example, symptom-based or function-based procedures seem to be an improvement. However, frequent complaints are still heard from operators about the size and complexity of EOPs. It has been suggested that computer-based EOPs may improve performance, but this will be critically dependent on their design. When EOPs are computerized, the resulting system is one form of a computer-based human performance aid. This means that all of the research issues discussed in this section become relevant to improve procedure design and presentation.

Research on the mechanisms that produce human error is also critical to the development of improved procedures. For example, 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 EOPs, as with any computer-based human performance aid, should be a systems process in which the layout of the control room, manning levels, and training are taken into account. EOPs must be validated in the control room or in a full-scale simulator to determine whether it is possible for crews to carry them out in a timely manner and to observe what will happen if a reduced-size crew has to use them. At present, there is no coherent theory for the design of EOPs, and research is required to develop such a theory (Fehrer et al., 1986a, 1986b).

The current literature on the evaluation of expert systems and artificial intelligence simulation of cognition should be reviewed. The nature of validation as applied to such systems should also be examined, since the common criterion, a system's ability to simulate human performance, is inadequate for a system designed to enhance human performance. Attention should also be given to the problem of verifying that software has been fully debugged. Experimental studies should be conducted in simulators with operators who have had many hours of practice with the proposed systems: probably a minimum of 50-100 hours is required. Attempts should be made to find situations in which the system is tested against unknown faults or faults beyond the design basis, and cascading faults whereby many small failures combine to place intense cognitive demands on the operator. The whole concept of validating or assessing such systems is itself a major research problem whose solution is at present unknown. Research should concentrate on the validation and assessment of such systems, leaving their developments to industry. Meeting this research challenge is one example in which access for researchers to nuclear power plant facilities and personnel is critical.

The benefits of research in this area include improved safety through new human performance aids and improved evaluation of new systems. This research will also be needed to address such questions as the impact of high technology, expert system applications, severe accident management, enhanced technical support centers, and measurement of human reliability with new forms of support systems.

HUMAN FACTORS IN SOFTWARE DEVELOPMENT

Rationale and Background

One result of the general trend toward increasing levels of automation in nuclear power plants is that system performance (safety, reliability, availability, etc.) will increasingly become a function of the quality of software performance and there are many human factors issues in the development of high quality software (Soloway and Iyengar, 1986; Shneiderman, 1980).

A typical current estimate of the best human performance in computer programming is 3 programming errors per 1,000 lines of code; this is comparable to error rates in many other human tasks. While many of the errors in software development may not be critical, this error estimate suggests that for the software-intensive systems of the future, which can be expected to contain hundreds of thousands of lines of code, software errors will be a major problem unless the rate of programming errors is reduced. Other types of errors, such as conceptual modeling errors and errors due to mismatches between the mental models of programmers, engineers, and users or operators, may be less numerous but of greater importance. As additional decision making is allocated to "intelligent" software, the potential for more severe consequences from a single error is increased, and testing and validation of this software is likely to become a critical bottleneck to its acceptance.

Research Recommendations

A program should be initiated to review and assess the literature on software psychology to identify problems of importance to nuclear plant safety, to determine what, if any, nuclear-plant-specific research is required, and to carry out research as appropriate. The panel expects that the results of an initial study will disclose that continued tracking, assessment, and adaptation of general research in the field will be sufficient. However, since many of the problems may involve industry-specific issues and technology, development for the nuclear industry will be needed, especially in the long term. The nuclear industry should encourage research in the area, since it will benefit from the results.

Some requirements and guidelines for incorporating human factors concerns into software development can be developed quickly. However, other requirements and guidelines cannot be developed without further advances being made in software psychology.

5
The Personnel Subsystem

It is essential to ensure that suitably trained people are available at all levels of plant maintenance, control, and management. Without adequate training, people cannot perform effectively and efficiently. Research on the personnel subsystem is concerned with the design of jobs and the development of systems to ensure that the people assigned to those jobs are sufficient in number and have the requisite knowledge, skills, abilities, aptitudes, and attitudes to perform them effectively. We discuss these research issues under the topics of training, qualifications, and staffing.

Although there has been considerable regulatory activity on nuclear plant staffing and on the training and qualification of personnel, there has been almost no research to measure the effectiveness of these activities and little to give direction to such activities in the future. Research on personnel selection, training, and qualifications of personnel does exist in other industries, most notably in commercial and military aviation. Accordingly, an active program to follow such research and, in some instances, to support it is recommended. Research topics that the NRC should follow and foster include: (1) the general use of part-task simulators; (2) the effectiveness of various training regimens in skill and knowledge development; (3) the identification of techniques to manage stress in operating personnel; (4) the use of psychophysiological profiles in screening power plant personnel; (5) factors that affect team performance; and (6) the selection of personnel for problem-solving skills.

There are also a number of areas related to personnel selection, training, and plant staffing that are specific to the nuclear industry. Such topics include: (1) the effectiveness of part-task simulators as training tools for tasks unique to the nuclear industry; (2) the use of replicate simulators as an operator training tool and the role of fidelity, task selection, and performance measurement in establishing the effectiveness of full-scope simulator training; (3) the relative importance of skill-based training versus knowledge-based training in the development of nuclear plant operators; (4) further development of selection tests for nuclear plant operators and the correlation of the selection criteria for operator trainees with operator performance; (5) determination of the practicality and benefits of licensing nuclear operators as teams, rather than as individuals; (6) the effectiveness of periodic retraining for skill maintenance, especially for rarely performed activities; and (7) qualifications of the regulatory staff and their subcontract personnel engaged in measuring the qualifications of nuclear plant operators.

TRAINING

Measuring Training Effectiveness

Rationale and Background

The most fundamental change in nuclear power plant training resulting from the Three Mile Island accident has been the adoption of a systems approach to training. The industry, led by the Institute of Nuclear Power Operation (INPO) and encouraged by the NRC, has adapted the Instructional Systems Development (ISD) process developed by the U.S. military and is implementing it through INPO's accreditation program. While the research effort required has been small because of the existing data base available from the military, there is now a need for industry-specific research to develop the technology base for further improvements in existing systems and the development of future training systems. For example, one recurring issue in technical training is the effectiveness of part-task simulators.

There is general agreement that there can be effective training on part-task simulators, and a general conclusion has been that a mix of part-task and whole-task simulators, in addition to other training media, are required for training on complex systems. But questions remain: What is the proper mix, i.e., what tasks are best trained by one medium versus another? What is the best way to integrate part-task and whole-task training to facilitate positive transfer and minimize cost? Are part-task simulators adequate for licensing, or does competence on individual tasks have to be demonstrated within the context of a complete realistic environment on a full-scale simulator? These are examples of issues that are task- and environment-dependent and require industry-specific research.

Additional areas, such as the measurement of training effectiveness, the measurement of trainee performance, feedback to trainees, skill retention and decay with respect to retraining requirements, require research in the short term for existing systems. Embedded training is currently receiving considerable attention in the training literature and should be explored in the nuclear power plant context. Basic issues of principle versus procedural training and academic versus skill training also require industry-specific research.

Nuclear plants are among the most complex man-made systems, and training is a critical element contributing to system safety and availability. If the industry is intent on excellence, it should begin now to move to the forefront of training research and development.

Research Recommendations

Research on the measurement of training effectiveness should be one of the first areas of attention. Training research in the nuclear industry is very sparse. At the least, a modest program should be initiated for near-term developments for existing plants. In the long term, training should become a significant aspect of the nuclear in try's human factors program, whether the research is conducted by the NRC or the industry.

Some training issues can be addressed by small research teams in an academic environment; others may require training simu tors or in-plant studies. Field research usually cannot progr s beyond a limited point without longitudinal studies. For this reason alone, cooperation with operating utilities is essential. In addition, the economic incentives for training research are probably as great as, and perhaps more readily demonstrated than, the safety incentives. Figures given in DOE EP-0096-1983 show very large economic gains from well-designed training schemes.

Independent NRC research in the closely related area of operator licensing examinations (testing) appears to be warranted and appropriate; there should be strong interactions between the two programs.

New Training Approaches

Rationale and Background

Training currently focuses on whole-scope tasks with high face validity—an entire emergency incident or an entire plant startup in an environment with high physical fidelity using a full-scale plant-referenced simulator. Training on component tasks, especially the most difficult or critical ones, is given less emphasis.

Although the industry, led by INPO, has adopted an aggressive systems approach to training, the work to date has focused entirely on the application of training technology and not on more fundamental questions of the nature of skill acquisition, maintenance, and decay. Research in these areas has the potential to improve the performance of nuclear power plant staff dramatically.

New developments in training technology are increasing the potential for alternative approaches that emphasize concept training (Hollan, Hutchins, and Weitzmann, 1984), exploration training for procedural and controls skills (Woolf et al., 1986), and decision-making training for cognitive skills (e.g., Chipman, Segal, and Glaser, 1985). Developing and applying this knowledge to the nuclear power plant context provides the opportunity to achieve substantial performance improvements, especially for rarely performed or difficult tasks and maneuvers. These new approaches to training may radically affect the methods employed to test operators for certification or recertification, because training and assessment are intimately connected.

Research Recommendations

Research is required on at least the following topics:

- The potential of exploration training, which can provide the basis for more performance-oriented testing of personnel;

- Special training for rare events, including those beyond the design basis;
- Skill and theoretical training on difficult but infrequent maneuvers;
- Problem-solving training, especially in the context of managing problems involving many people and facilities. This research should be coordinated with current EPRI programs.

There is already a considerable research base in each of these areas, which, if properly used, would provide a cost-effective start to develop new innovations.

Significant improvements in operator skills might be obtained by more frequent simulator exercises, but it is not clear that the exercises normally chosen for simulator training are effective in developing operator skills to cope with the unusual. Finally, it is not clear what impact the physical fidelity of a simulator has on training effectiveness. Some plants train operators on simulators built for other plants. These simulators may have different dynamics and control board arrangements than the plant at which the operators work.

In addition to acquiring and maintaining skills for specific emergency scenarios, plant personnel must master the skills required for dealing with novel, complex, and ambiguous events. Research is required to understand how best to obtain these skills. Similarly, the social context in which performance takes place must be understood. For example, team training (e.g., NUREG/CR-4258, 1985b) is an issue that has great potential for safety improvements in nuclear power plant operations (see Foushee, 1984, for a description of the effect of team factors on safety in commercial aviation). The key is to develop a research program that deals with the types of skills required in the nuclear power plant context and that feeds into the systems approach to training that has been widely adopted by industry.

Classes of independent variables of importance include training equipment (e.g., full-scale simulators versus part-task simulators), training contexts (e.g., individual versus team), training techniques, and personal characteristics of the trainees (e.g., education, experience, stress tolerance). Tests should include both familiar and novel situations. The question of verisimilitude of the test bed with actual plant events is itself a question worthy of research; training on unlikely sequences of events might prove to be superior preparation for emergencies than training on known accident scenarios. A variety of dependent measures must be explored (e.g., "objective" performance, performance ratings) and measured over various time intervals to explore skill decay.

This research will have direct implications and provide a base for a variety of issues that face the NRC. For example, questions of academic education versus skill training, the frequency and content of requalification exams, the role of team training and qualifications in the licensing process, and the role of plant personnel in severe accident mitigation would all benefit from the proposed program of research. A training research program should be a central and ongoing element in human factors research.

QUALIFICATIONS

Degree Requirements

Rationale and Background

This section is concerned only with whether control room staff should have engineering degrees because of the immediate relevance of this topic to the NRC. Many other important research issues related to personnel qualifications are not discussed. One example involves the proficiency and qualifications of maintenance personnel; each plant has relatively large numbers of mechanics, electricians, and instrument-and-control technicians that perform thousands of different maintenance tasks of various levels of difficulty at widely differing intervals of time under stressful environmental conditions.

One question for which there is currently no answer has been the subject of intense discussion and disagreement following the events at Three Mile Island: Should all control room staff, or at least senior control room operators, have engineering degrees?

Intuitively it seems obvious that more knowledge must help an operator, particularly when dealing with a situation for which the operating procedures are inadequate or for which there has been no training. There will always be more ways for a system to fail than skills for which there is time to train. In some cases it may be necessary for an operator to draw on general engineering knowledge and knowledge of nuclear physics, in addition to plant systems knowledge, to diagnose the state of the plant and decide on appropriate actions. It has been suggested by some within the NRC that degree qualifications in the relevant disciplines improve an operator's ability, and this position has led, on several occasions, to the statement that degree qualifications should be mandatory.

It is, in fact, difficult to determine the appropriate degree qualifications for a job in a high-technology system. Several countries require higher academic qualifications than does the United States (OCED-NEA, 1985), but other characteristics, such as national character, organizational structure, physical plant differences, and training make it impossible to conclude that this requirement is a valid one for the United States. In France, for example, the safety engineer (equivalent to the shift technical advisor) not only has degree qualifications, but also has responsibility for safety decisions during emergencies. In Canada, training to be fully qualified takes seven years and requires higher qualifications than in the United States, but reactor designs are quite different and are more automated than U.S. plants. Thus, international comparisons alone cannot be used to decide the question.

A few laboratory studies exist on the effectiveness of theoretical knowledge on fault diagnosis (e.g., Duncan, 1981; Shepherd et al., 1977; Surgenor, 1981). None has found such knowledge to be beneficial. However, this finding is inconclusive because it has not been made clear what is meant by theoretical knowledge. The theoretical knowledge needed by operators is not the same as that needed for engineering analysis (Brown, Moran, and Williams, 1982; Roth, Bennett, and Woods, in press). Traditional engineering curricula do not provide instruction on fault diagnosis. However, it does not necessarily follow that education at the engineering level is of no value or merit for plant operations.

There is widespread opposition to the idea of degree requirements among operators in the United States (see, e.g., Professional Reactor Operator Society, 1987). It would be easy to dismiss this opposition as the natural objection of qualified, experienced operators to being required to go back to school and being faced with a threat to their careers, but that would be less than fair to the operators. Some have taken degrees after being qualified, and a number of them have paid for the degree themselves and were not given paid time off to earn them. In short, many operators with degrees were penalized rather than rewarded for their efforts.

Furthermore, several have reported that the courses they took were largely irrelevant to their needs (Professional Reactor Operator Society, 1987), a position supported by NUREG/CR-4051 (1985c).

Research Recommendations

There are two levels to the degree question. First, from the perspective of the human-system interface, what is skill and expertise? Second, from the organizational perspective, where do people come from—what are their career paths? If the organizational climate changes, it will affect the organizational perspective of what degrees are required.

Current degree programs do not couple theoretical knowledge to plant-specific practice and as such are not likely to enhance operational skills (Moray, 1986). But it still seems plausible to assume that better understanding of a plant, even at a theoretical level, would provide better diagnostic and control skills.

Before the decision is made to make a degree mandatory, research is required to establish the necessary course content to ensure that such courses are available and to ensure that people are rewarded, or at least not penalized, for taking them. Such research is methodologically difficult, and the design of appropriate courses may be costly. There is also the problem of locating institutions able and willing to provide such courses. This research is urgent and should have higher priority. An injudicious regulation could lead to problems with both morale and recruiting without necessarily improving safety.

Testing and Licensing

Rationale and Background

The NRC licensing and requalification examinations administered to reactor operators and senior operators represent an important method for ensuring that these personnel can operate the plant in a manner consistent with public health and safety. Although the NRC has taken several steps to ensure that questions on the examination are related to the knowledge an operator must master (e.g., NUREG-1021, 1983e; NUREG-1122, 1985f; NUREG-1123, 1986a), research is still required to improve the examination and the process of its administration. Specifically, questions have been raised by people close to the examination process as to the qualifications of the examiner, the interval between requalification examinations, the feasibility of licensing crews of operators, and the validation of and general improvement in the job-relatedness of examinations. Research that delineates the questions germane to the examination process and gives them priorities will help the NRC make better decisions as to whom to entrust with the operational safety of nuclear power plants.

There is a legal requirement that control room and senior control room operators must be licensed by the NRC before they are allowed to handle the controls in a nuclear power plant control room. The NRC administers a licensing examination comprised of written questions and simulator exercises (if a replicate simulator exists) to ensure that candidates have the requisite knowledge and ability. This procedure is based on the assumption that satisfactory measures of performance are being used. At present, however, there is no basis on which to effectively determine satisfactory measures. Research is therefore needed in this area and is discussed in the section on human performance.

Fundamental to any examination are issues of its validity, reliability, and utility. Although the NRC has moved to a program in which the examination content includes items judged to be important to safety, this should be viewed as only a first step. A research program that evaluates the strengths and weaknesses of the current examination and results in recommended improvements is required. There exists extensive examination technology (e.g., Anastasi, 1985) demonstrating that improved tests in terms of validity and utility result in improved performance by operators. This technology should be addressed as a first step in research planning.

Shikiar, Saari, and Wood (1984), NUREG-1122 (1985f), and NUREG-1123 (1986a) form the basis for a content sampling approach to licensing examinations. In particular, Shikiar, Saari, and Wood (1984), which forms the basis for NUREG-1021 (1983e), delineates an approach to be used in constructing written, simulator, and oral questions, as well as guidelines for grading responses to the questions. However, many of these research issues have yet to be addressed in a systematic way.

Research Recommendations

Improvements in the validity, reliability, and utility of licensing examinations depend on better understanding of the issues discussed above in the sections on training effectiveness, new training approaches, and human performance. Developments in these areas should be applied to develop and test improvements in licensing examinations. The result should be an improved examination process and an increase in the confidence of the industry and the public in the licensing process.

STAFFING

Shift Technical Advisor

A relatively new plant position is that of the shift technical advisor (STA). It is clear both from informal and formal reports (NUREG/CR-4280, 1985d) that research is needed on how to improve the effectiveness of this position. The contrast between U.S. practice, in which the STA is a purveyor of expertise if and when it is requested, and the French practice, in which a person with those skills is seen as the one responsible for making and implementing decisions when an emergency occurs, is striking. The relation between the control room operator hierarchy and its responsibilities and emergency management has recently been examined by the Atomic Energy Control Board of Canada (Feher et al., 1987a, 1987b). This work should be reviewed as a way of enhancing an understanding of issues in this area.

If the knowledge and skills of the STA are essential to safety, then research is needed on how to improve that role and its relation to other members of the control room crew.

Screening and Selection

A classic topic in this area is the set of dimensions on which to base the selection of personnel. If one is thinking in terms of fault diagnosis and fault management, then selection for problem-solving skills would be the pertinent dimension. If one thinks in terms of the ability to remain alert during prolonged periods of normal operation when little intervention by the operator is required, then different personality characteristics may be relevant. Research is also needed on the selection of personnel other than operators, including both maintenance personnel and managers. Whatever the result, it is essential to realize that selection alone cannot guarantee effectiveness; it must be related to training, to workplace management and morale, to recruiting and retention, to job descriptions, and to other personnel issues and seen as part of a systems approach.

A well-established technology is available for selecting people who can perform jobs well or who can be efficiently trained to do so on the basis of their abilities and aptitudes (Dunnette, 1976). The NRC's plan (NUREG-0985, Rev. 1, 1984g) emphasized the need for selection research; however, for reasons of economy, this emphasis was later abandoned (NUREG-0985, Rev. 2, 1986f). According to SECY-85-129 (1985k), the Edison Electric Institute is currently researching selection with nuclear power plant personnel.

Another aspect of selection is to identify people with an aptitude for problem solving under risk and time stress. Some research on this topic has been done in aircraft pilot selection (e.g., Gopher, 1982). It is highly desirable to have screening instruments and procedures that identify psychologically high-risk individuals for industries like nuclear power. However, the practicality of selection or screening on the basis of personality variables remains highly controversial. Gough (1976) concluded that research tending to support the construct validity of personality measures would be adequate to justify their use in industrial selection. McCormick and Ilgen (1985, Chapter 10), suggested that a rather rigorous set of requirements should be met before personality measures are used for this purpose. "Standards for Educational and Psychological Testing" (American Psychological Association, 1985) also supports a cautious approach to such use.

Shift Scheduling and Vigilance

Rationale and Background

The recent cases of operators found sleeping in a control room illustrate the relevance of the issues of shift scheduling and vigilance (or sustained attention) to nuclear power plants. Poor work schedules can lead to stress, fatigue, and other undesirable side effects (Hockey, 1983; Eastman Kodak, 1986). Boring tasks and inappropriate shift structure can produce loss of alertness, which can lead to serious industrial accidents (Commission of Inquiry: Hinton Train Collision, 1986).

Large bodies of research exist on each of these topics (e.g., Davies and Parasuraman, 1982; Parasuraman, 1984; Colquohoun and Rutenfranz, 1980). Industrial accident data indicate large changes in efficiency as a function of time of day. Poor work schedules can increase the probability of human error. The shift duration, the total amount of work per week, and the pattern of work rotation are all critical factors in determining the amount and quality of human performance under different work schedules. A variety of shift schedules are used in the nuclear industry (NUREG/CR-4248, 1985l), including some that are known to cause high fatigue and poor performance. For example, two factors that, in general, degrade performance are day-night-afternoon shift rotations and weekly rotation schedules (Eastman Kodak, 1986).

Ever since research was conducted on the behavior of radar and sonar operators in World War II, it has been known that people are often unable to maintain a vigilant attitude when monitoring systems for long periods during which few significant events occur. While the phenomenon is generally well understood (Hockey, 1984; Warm and Parasuraman, 1987), methods to prevent it are often not easy to devise. The central problem is how to keep operators and other personnel alert. There is a tendency to look for hardware solutions to this problem such as auditory alarms and acknowledgment systems. For example, on Japanese long-distance trains, the engineer must respond to an alerting signal every few minutes or the train is automatically halted. However, experimental evidence suggests responses to signals can become automatic and do not always ensure vigilance (Oswald, 1962). There are many factors that contribute to a loss of vigilance, including fatigue, inappropriate shift schedules, and the effects of circadian biological rhythms. Treating causes of losses of vigilance may prove to be more effective than treating the symptoms.

There are also other factors that condition how effective an alerting device is or how disruptive fatigue is. If morale is high and a strong desire to excel exists, the operator is likely to carefully monitor the state of the plant even under difficult circumstances. If morale is low, he is likely to do the minimum needed to acknowledge an alerting signal without actually checking for changes in plant state. Such an attitude is as likely to be due to poor management style and practice as it is to any inherent lack of motivation in plant personnel. This is an example of why research is needed at all levels shown in Figure 1.

Research Recommendations

Because large amounts of research on both shift scheduling and vigilance exist, applied research in the nuclear industry should consist of synthesizing this knowledge base for application to power plants and developing and testing possible treatments (informed innovation). A model for this process can be found in EPRI's project on heat stress management (EPRI, 1986c, in press).

6
Human Performance

It has long been established that human error plays a major role in the malfunctioning of complex, technological systems and in accidents associated with their operation (Meister, 1971). In the nuclear industry, estimates of the incidence of human error as a percentage of all system failures range from 20 when Licensee Event Reports (reports to the NRC from utilities that describe events that were a threat to plant safety) are analyzed (Potash, 1981) to 65 when Loss of System Safety Function Events (reported events in which there was a total or partial loss of a function related to the maintenance of plant safety) are examined (Trager, 1985). Whatever estimates are used—and there have been many—even the lowest one of 20 suggests careful attention and some form of remedial action.

Research on human reliability has always occupied a central position in NRC research because it is widely accepted that human actions account for a large proportion of the initial causes of plant faults and accidents. In fact, it was the only human factors research topic that continued to receive support from 1986 to 1987. A principal goal of this research has been to provide estimates of the probability of human error for use in probabilistic risk assessment. The research done to date has been concerned with improving methods of eliciting expert judgments of the probability of various kinds of human errors (e.g., NUREG/CR-1278, 1983b; NUREG/CR-2743, 1983g; NUREG/CR-4016, 1985a) and developing a human error data bank.

While the intent to predict the probability of human error is commendable, current methods do not do this adequately. Most research has relied on subjective estimates by experts and has aimed at improving what are, in effect, sophisticated guesses. Further development of this methodology will result only in additional guesses. The panel believes that research to further improve subjective estimates of human error should not receive a major emphasis in the future. A more fundamental understanding of the nature and causes of human error is needed if the nuclear industry is to make further progress in measuring, predicting, and reducing human error and the human contribution to risk.

Implicit throughout much of this report is the need for knowledge about four aspects of human performance in nuclear power plant systems: (1) to be able to measure human performance in existing systems, (2) to understand and predict the effects of changes in human performance on performance of the overall human-technical system and the effects of changes in human performance that would result from proposed modifications to the technical system, (3) to predict human performance in situations that are by design expected rarely, if ever, to occur and cannot be tested in the operating system, and (4) eventually, to predict human performance in new systems especially before they are operational, indeed very early in the conceptual design stages.

At present, only limited data and capabilities exist to measure human performance in nuclear power plant systems. The collection of data on human error since Three Mile Island has resulted in increased emphasis on obtaining and employing feedback from operational experience; however, the extent of data collection is still quite limited and, more important, the data are typically not related to any underlying theoretical framework or model of human performance and behavior. Without such a framework, the ability to interpret data and advance beyond simply counting and categorizing human error is severely restricted.

The methodology that has been chosen for examining human performance in systems is human reliability analysis within the framework of quantitative probabilistic risk assessment. Current methods for human reliability analysis are inherently limited in their ability to model human performance, to model the effects of human performance on the overall system, and to model the dynamic interrelations of the human and technical elements of the system. They are particularly limited in what is felt to be the most critically important area of problem solving (cognitive) behavior: human decision making.

A comprehensive, systematic research program is necessary to characterize human performance in nuclear power plants; to develop adequate measures of performance along with techniques, tools, and processes for measuring performance; and to develop iteratively the models and data base to be able to predict performance within a reasonable band of uncertainty. Human performance denotes not only the performance of individuals, but also that of teams and organizations. This program needs to be an industry-wide effort and does not have to be centralized under the direction of one organization, as long as a single organization or team exists whose job is to integrate the theoretical, analytical, and empirical results from the various sources in the nuclear industry and other applicable fields. The latter would be an appropriate role for the NRC.

Characterizing performance means systematically describing, categorizing, and discriminating between aspects of performance and the behaviorally important aspects of the context of the performance. It also means discriminating levels of quality of performance identifying good versus better versus best performance. This characterization needs to be made within a theoretically based framework of sufficient rigor and specificity to permit communication with, and possibly mapping to, alternative ways of describing the same performance. The characterization would also permit systematic investigation of variables affecting performance. In other words, one would like to be able to recognize good performance (or better or worse performance) when it occurs, be able to describe it at least well enough for it to be recognizable when it occurs again, and be able to compare measurements of performance taken by different people in different places at different times. It is insufficient for an experienced supervisor to "know a good operator when he sees one."

To make progress in identifying the underlying causes of good and poor performance in nuclear power plants, one needs to be able to characterize performance in terms of the parameters of an underlying theoretical model in such a way that other investigators, with data on other performance in other contexts, will at least be able to say that this performance and context is similar to or different from that one and compare measurements made in different contexts. Some sort of characterization is typically derived as part of the development of a task analytic data base. A performance or behavioral taxonomy is developed, either explicitly or implicitly, and usually subjectively, as part of the process of a task analysis. The taxonomy or basis for characterization depends on the purposes of the analysis.

Considerable effort has been expended, primarily by INPO and the NRC, to develop extensive data banks of task analyses for different purposes. There is no need to continue to develop task analytic data banks of this nature.

Those taxonomies and task analyses may or may not be consistent with a theoretically based model that is useful for advancing knowledge about human behavior in nuclear power plants. Thus, the INPO task analysis base, generated for development of training systems, may define the correct performance of an operator in taking specific actions, within a specific scenario, at a particular type of plant. And, because the knowledge, skills, and abilities thought to be necessary are cataloged for each task, it is possible to make some decisions about what should be included in a training program. However, such an analysis may indicate little about the likelihood that an operator so trained will perform the task correctly under less than ideal conditions. It may not indicate what should be modified (except for the training program) to improve the likelihood of correct performance. It does not indicate what is "better" or "outstanding" performance, only what is minimally acceptable in order to meet the specified success criterion for the task. Such questions require that the characterization of performance match the key parameters and concepts of a model of human performance that can be manipulated in a systematic way to drive an empirical program. It is this theory-driven, empirically based research program that the panel recommends.

To improve our understanding and ability to predict performance, the development and application of more formalized models are necessary. There exists a considerable base of human performance modeling technology on which to draw, in particular for supervisory control tasks typical of nuclear power plants. Most of it has been developed for military and aerospace application, but certainly the general approaches, and in many cases specific models, are applicable to the nuclear power plant control room context. Some of the first models to go beyond the analytical approach of the Technique for Human Error Rate Prediction (THERP) (NUREG/CR-1278, 1983b) were the network simulation models of Siegel and Wolf (1969). The NRC supported development of such a simulation model, Maintenance Personnel Performance Simulation (MAPPS) (NUREG/CR-4104, 1985j), to describe the performance of nuclear power plant maintenance personnel. The power and potential of such simulation models, however, extends far beyond the narrow use apparently intended by the NRC for MAPPS (i.e., generating human error probability estimates for probabilistic risk assessment). Further development and application of such models to design, design testing, trade-off studies, etc., should be encouraged. Reviews of such modeling approaches appear in NUREG/CR-4532 (1986b) for the nuclear context and in a broader context in two Committee on Human Factors reports currently in pregration (reports of the Working Group on Human Performance Modeling and the Panel on Pilot Performance Modeling in a Computer-Aided Design Facility).

Another framework for supervisory control modeling is the control-theoretic approach (NUREG/CR-2988, 1982a). Problem solving models and the rapidly developing array of models coming from cognitive science (artificial intelligence, expert systems, parallel distributed processing models) need to be brought to bear when applicable. An example specific to the nuclear industry is given in NUREG/CR-4862 (1987a).

Empirical data from available sources, operational experience, laboratory-scale experiments, part-task simulation and mockups, and full-scale experiments in high-fidelity training simulators need to be integrated with the modeling development, thereby iteratively validating models and suggesting modeling needs.

In the longer-term future, models could be employed in advanced computerized design methodologies that would include both technical system models and human models (e.g., Pew et al., 1986).

Research issues in this area include human performance measures and measurement tools, human performance modeling, human reliability analysis and its incorporation into PRA, data collection, and analysis. We recommend a research program that involves progression from descriptive to predictive models based on an iterative design-test-design approach between modeling and data collection. Data collection should include feedback directly from operating experience as well as from a broad program of empirical studies ranging from laboratory experiments to controlled studies on high-fidelity simulators or actual plants.

CAUSAL MODELS OF HUMAN ERROR, ESPECIALLY FOR SITUATIONS WITH UNPLANNED ELEMENTS

Rationale and Background

Research on human error has always occupied a central position in NRC human factors research. Its principal goals have been to provide estimates of the probability of human error for different tasks that can be used in conducting probabilistic risk assessments of plants in identifying the factors that contribute to human error.

These are appropriate goals that the panel endorses. However, the panel recommends new directions for future research.

A number of NRC-sponsored projects (e.g., NUREG/CR-1278, 1983b; NUREG/CR-2743, 1983g; and NUREG-4016, 1985a) have been concerned with improving the methods for eliciting the subjectively based estimates of experts on the probability of various types of human error. To be usable, these subjective judgments, even when made by experts using the best available methods of estimation, must be validated by comparison with objective data on the actual probabilities of error. Without such objective data, one cannot know how accurate the judgments of experts are. But if objective data on human error are available, why are subjective estimates needed? The only justification, in the panel's opinion, for the use of expert judgments of human error and for research on methods for improving the judgmental process, is to provide estimates on an interim basis on tasks for which objective error probabilities do not yet exist. We believe that rather than expend limited resources on further studies to improve expert judgment, a high priority should be given to methods to obtain objective estimates.

There is no doubt that a comprehensive bank of objectively based human error rates is desirable. However, one of the drawbacks inherent to an embedded performance measurement system is the fact that the errors it identifies are limited to errors made in the overt behavioral responses of a control room crew. At present, performance measurement methods are unable to detect cognitive errors. The design of these and similar error-capturing systems would benefit substantially if some means of obtaining information on cognitive errors were to be developed.

Research Recommendations

Research on human reliability has traditionally concentrated on statistical estimates of human error rates. Such work cannot identify when an error is likely to occur, nor propose changes in systems design or operation that will prevent errors on a particular occasion. What is required is research on causal models of human error that can have a direct impact on design and operation of plants.

The important behavioral science questions in this area include the following:

- We need to understand the sources of error (especially important is sources of cognitive failure forms such as fixation and missing side effects and group problem solving);
- We need to generate causal models of human performance that include models of error mechanisms;
- We need to understand how to avoid the causes of error in order to reduce the likelihood of these failure forms and improve human performance;
- We need to understand how changes in the person-machine system (e.g., new support systems and aids) affect error types.

Our estimates of the probability of human error have not, in general, been validated; and human error rates are well known to vary over very large ranges (NUREG-1278, 1983b) in response to "performance shaping factors." It is far more desirable to understand at what particular moment an error is likely to occur, or in what circumstances and at what time the probability of error increases. If an error is even stochastically predictable in being more likely to occur at some time or in some situation, steps can be taken to monitor an operator's behavior or to provide the operator with extra assistance at that time. Such knowledge will also often suggest preventive redesigns of equipment, procedures, management, selection, or training. To do this it is necessary to understand why errors occur. Human error is a failure of some kind in human information processing. We have a good understanding of certain aspects of human information processing, particularly of many aspects of signal detection, perception, attention, and motor responses (Boff et al., 1986). We can describe properties of the environment that predispose people to make errors. Several models for error causation have been proposed for limited aspects of human behavior, and from them it is possible to make a number of predictions as to circumstances in which errors are likely to occur, and also suggest a means of dramatically reducing the likelihood of errors (Reason and Embry, 1985; Reason and Mycielska, 1982; Norman, 1981, 1983; Senders et al., 1985; Rasmussen, Duncan, and Leplat, 1987). But there remains a number of issues that are not well understood. These include errors of planning, the tendency to become fixated on part of a problem, the relation of the operator's mental model to errors, and the extent to which errors are really "chance" events. It should be especially noted that many incidents in nuclear power plants have their origin in errors of maintenance. Valves are left in an incorrect position; maintenance personnel work on the "wrong unit, wrong train," procedures are not followed, etc. The cause of such errors, if understood, can be dealt with. This is of far greater importance than having a probabilistic estimate of how often human errors may occur.

In addition, research on human performance in unplanned-for situations is absolutely essential in a world that has proven time and again that not all factors can be anticipated in advance. For example, in a recent analysis performed on about 30,000 events that occurred in nuclear power plants and collected in the Abnormal Occurrence Reporting System, half of them were represented by unique combinations of systems, components, and human failures (Mancini, in press).

Improving the ability of nuclear power plant personnel to handle unplanned-for situations depends on behavioral science research in a number of areas: multiperson and multifacility decision making (distributed problem solving); knowing how to prepare personnel for rare or unanticipated situations; using new computational technology to assist operational personnel, especially in plan monitoring, adaptation, and repair; and knowing how to avoid the problem of "brittle" problem solving (that is, behavior that is efficient providing rules can be followed, but collapses when standard practices do not work).

A better understanding of the nature of human error, where the error-prone points occur, how likely these errors are to occur, and how to eliminate the error-prone points are the most critical research needs for improved nuclear power plant safety. Progress here drives or interacts with virtually all other behavioral science research issues. After all, it is the performance of the operational personnel that is the front line of safety from the human perspective, and understanding how to measure and improve human performance is the essential guide for how to find and use the possibilities resident in technology.

Laboratory, simulator and field studies should all be supported and integrated. In addition, the NRC should make better use of the large amount of knowledge available for reducing human error. (One significant source would be a collection of information from the many detailed control room design reviews now available.) Experimental and quasi-experimental studies should concentrate on investigation of cognitive errors—errors of thought, planning, diagnosis, reasoning, and decision making. The military and NASA have recognized that to have effective man-machine systems in a complex world requires sophisticated human-machine performance modeling capabilities. They have active programs to develop sophisticated analytical models of human performance (e.g., Hartzell, 1986; Pew et al., 1986).

Theoretical and empirical work in several directions should begin immediately, one on control room activity and one on maintenance activities. A third should consider the role of social interaction among the members of a team, the effect of hierarchical and other organizational features, communication, etc. Particular attention should be focused on errors that occur as a result of a large number of small incidents that cascade, rather than one major "single cause" incident.

A major reduction in the r[illegible] of human error in nuclear power plant operations is the intended goal. It may be valuable to target the research at some of the errors with more important consequences, but the overall plan must be to support our generic understanding of the causes of human error. This research will also be needed to address enhanced technical support centers, computer-based supervisory centers in the control room, team performance, the structure and organization of emergency procedures, training to handle accident conditions (decision training), severe accident management, and measurement of human reliability.

This work should begin immediately and become a permanent central element of human factors research.

7
Organizational Aspects of the Nuclear Industry

The research suggested about the human-system interface, the personnel subsystem, and human performance will not, by themselves solve all the problems. Problems of training, skill maintenance and enhancement, and motivation and morale still remain. Dispirited personnel will be likely to use good equipment carelessly, and poorly trained personnel to use it inefficiently. This implies a need for research at the outer layers of Figure 1 to complement the program we have described in the previous sections for the two innermost levels.

The panel recognizes that the focus of human factors in the nuclear industry has been on people who directly interact with the machine—operators and maintenance personnel. A complete treatment of human factors also includes broader questions about the organization and atmosphere in which these people function. While recommendations that follow are addressed to the nuclear industry, much of the needed research is not nuclear specific. In part this is because research on organizational factors is not as advanced as, for example, on human-system interface design. Because most people in the nuclear industry are not familiar with the social and behavioral science fields that address this level, the discussion of research background and needs is kept at a general level for the nonspecialist.

The panel's primary concern in the area of organization and management is the extent to which the organization is able, quickly and efficiently, to prevent, detect, and react to any threats to overall system safety. Within the constraints imposed by regulatory bodies and standards, management decisions affect many aspects of plant safety, both directly and indirectly. Managers determine or are ultimately responsible for the type of equipment employed and the extent to which that equipment incorporates human behavioral knowledge in its design. They determine recruitment, selection, training, promotion, and compensation policies, thereby determining membership and placement within the organization. Management practices are responsible, directly or indirectly, for establishing and maintaining an organizational culture that reinforces safety and the quality of performance. Managers decide how they will interact with other organizations outside the plant, including utility groups (e.g., INPO), unions, and state and federal regulators. And finally, managers are largely responsible for determining the type of people who are admitted into their own ranks, which clearly affects the continuity of a given organizational culture. Management's role is central to the safe functioning of plants.

Deep understanding of the factors affecting management decisions and the consequences for safety and the quality of performance is essential for effective regulation and operation. Recent examples of the crucial importance of management and organization include management failures in the Challenger tragedy (Rogers, et al. 1986) and the well-documented failures in the Three Mile Island incident and at Chernobyl (NUREG-1250, 1988). It is important to note that the ways in which management and organization affect safety in the context of nuclear power plant operations are researchable questions (e.g., NUREG/CR-1656, 1980b; NUREG/CR-3215 volumes 1 and 2, 1983f; NUREG/CR-3601, 1984e; NUREG/CR-3645, 1984c; NUREG/CR-3737, 1984d). Answers may result in the reduction of risk and the acquisition of useful tools (e.g., NUREG/CR-3215, volumes 1 and 2 1983f). We believe that management and organizational factors have a significant effect on plant safety as well as productivity and must be subjected to systematic research.

The topics discussed in this section are not a comprehensive list of researchable topics in the area of management and organization. They reflect the panel's judgment as to important areas of inquiry that are likely to bear fruit in terms of improved safety. The panel views two topics—organizational design and culture and the effects of regulatory measures on operating and maintenance crews—as most important for immediate attention. Other topics for subsequent, longer-term research are also suggested.

THE IMPACT OF REGULATIONS ON THE PRACTICE OF MANAGEMENT

Rationale and Background

Organizations and entities beyond a utility's boundaries have a significant effect on its policies and practices. This is particularly true with respect to various regulatory agencies, especially the NRC, but also state PUCs, and the environmental, health, and safety agencies of the states and the federal government. Management serves as the lens through which the external environment is focused on the utility. If management is adroit and skilled, variations in local practices and corporate situations can be taken into account in applying regulations. If it is not, regulations may result in inflexibilities in the workplace that hamper control room operations and maintenance crew performance.

In addition to their relations with regulatory agencies, utilities also deal with INPO, EPRI, EEI, and other organizations supported by utilities themselves, as well as union organizations. How utilities respond to the opportunities and challenges presented by these organizations bears on their openness to new ideas and innovative human factors technology, their ability to independently evaluate the products of research or consulting, and their commitment to continual self-improvement. Since utilities are placing greater dependence on INPO for establishing practices that result in excellence for individual utilities, it is important to understand the relation between individual utilities and INPO.

Utilities must also deal on a regular basis with unions. The unionization of power plant operators and maintenance personnel may have a positive, negative, or neutral effect on attaining high degrees of safety.

Research Recommendations

Some regulations must be applied directly and specifically without modification to local conditions. To what degree does specificity have the desired effect? Are there organizational conditions that produce a sense of regulatory overload among operators or maintenance crews, or evoke informal norms that reduce their intended effect (Bardach and Kagan, 1982)? Research examining the responses of management to pressures from the regulatory environment would shed light on how safety at a facility is enhanced or impaired by regulatory actions intended to have positive consequences.

What conditions are associated with the contribution of unions to safety, on one hand, and to high production capacities, on the other? Are these conditions mutually exclusive? One might expect unions to stress investment in safety equipment and procedures; however, as pressures for economizing arise, such investments could be seen as potential threats to the number of jobs in the plant. What union policies and practices reinforce or erode emphasis on plant operating safety and quality maintenance? How can unions and management be encouraged to work cooperatively to encourage safety?

ORGANIZATIONAL DESIGN AND A CULTURE OF RELIABILITY

Rationale and Background

The formal structure, procedures, and practices of an organization bind the behavior of its members and strongly affect the norms and perspectives they have regarding critical activities. Utilities vary in scale, diversity, and their legal relation with state PUCs. Most employ multiple sources of electrical power generation; nuclear power reactors are not usually the predominant source of supply. Therefore, corporate policies must take into account the operating demands of varying mixes of power-generating technologies. The operating demands of nuclear reactors are more stringent than other generating technologies. Relations between corporate and plant management may vary from highly supportive, with considerable plant management autonomy, to distant and distracted, with punitive reactions to problems that may arise due to unexpected technical developments. The management and operation of nuclear power reactors present operators with very demanding circumstances. Failures have serious consequences. Operator and maintenance crews are effective only if they have full knowledge of the appropriate processes and high motivation to carry them out. A great many of these processes are formalized in standard operating procedures (SOPs). But SOPs, or informal operating rules, rarely provide sufficient guides for behavior to account for all the technical and cooperative skills or motivations necessary for effective, safe performance. The gaps are filled by an organization's culture, and motivations sustained by its managerial climate.

The culture of management in [illegible]lear power plants is likely to be colored by an engineering [illegible] ar navy ethos. Managers socialized in an engineering cultu[illegible] devalue operational knowledge and knowledge from the field, [illegible]e managers socialized in the military often underemphasize t[illegible]rizontal coordination of units and overemphasize the vertical chain of command. There is reason to believe that in some circumstances a strong vertical chain of command inhibits the flow of information from operating levels reporting hazards and troubles (NUREG/CR-3737, 1984d).

Research Recommendations

Given this background, a higher-priority research topic is the relation of formal structure and practice to the development of norms and expectations that reinforce safe, reliable behavior by operators and maintenance crews. To what degree do the stringent operating demands result in tensions within the corporation? Are differential rewards and punishments necessary as a function of the type of generating technology? How do various utilities manage these differential requirements? Is this a source of tension for the nuclear operations? If tensions exist, do they increase the difficulty of establishing a safe operating environment?

What are the variations in corporate-plant management practice and style across the several types of utilities? Is there systematic variation in the level of safety and days of high-capacity production? What supports are provided by the corporation for training, quality assurance, and other aspects of operation that are seen as necessary by plant management?

What group norms are evident within a nuclear power plant concerning relations among and obligations to group members and to the organization as a whole? What organizational conditions, practices, and incentives reinforce commitments to production as well as to very high levels of safety? How does the adversarial culture of regulation effect the development of cooperative norms? It should be emphasized that research on adversarial relations is extremely difficult and may have to be directed by a third party rather than those in the adversarial relationship.

To what degree does the employment of operators, supervisors, and managers trained in the military reinforce patterns of vertical authority and centralized administration? Does this lead managers to emphasize mechanisms of vertical integration and downplay mechanisms of horizontal integration? Under what conditions does such training result in a limited flow of error-identifying information? How can managers orient changes to improve their effectiveness if such changes are alien to the culture from which they come?

In sum, how might managers manipulate organizational design to meet the challenges of information flow in knowledge-intensive settings? How do such variables as span of control, vertical height, horizontal breadth, functional specialization, interunit coordination, and the linkages between staff and line ultimately affect safety?

OPERATIONAL DECISION MAKING

Rationale and Background

Decision making in organizations' operating technologies based on sophisticated knowledge presents both managers and operators with a continuous challenge of reconciling the formal authority of hierarchical position and the responsibility to make decisions under circumstances in which non-decision-making operators may have better information on conditions and consequences than managers. Managers can attempt somehow to command the knowledge necessary to understand operating conditions quickly enough to set directions, indicate a course of action, etc. Or, if it becomes impossible to stay on top of a current technical situation (a more likely case), managers can, by establishing formal relations with subordinates, make it possible to delegate decisions to lower-level participants, trusting that they will inform decision makers of untoward conditions—even if such conditions result from the operators' own actions.

Research Recommendations

Relations between plant management and operators vary widely among utilities. Some are quite satisfactory; others are distant and strained. Are there systematic differences in the structure and dynamics of managerial and operator relations? Do they affect the speed and quality of decision making between operators, supervisors, and plant management? Are there particular communication, training, or promotion factors associated with top performance and nearly "failure-free" operations? What are the communication patterns between the corporate offices and power plant management that ensure the information necessary for timely emergency decision making? Do the conditions that foster effective communication between supervisors and work teams in different types of situations vary by type of worker?

TIMELY RECOGNITION OF EMERGENCIES

Rationale and Background

Most recent research on emergency response has examined the increasing sophistication of monitoring devices. While these technical improvements may prove to be valuable aids to operators, they may also compound the problem of recognizing the patterns of information necessary to identify an emergency. Recognizing the onset of emergencies is a process that makes use of complex and changing channels of information, some of which may be suspected as unreliable. Hence, identifying an emergency in plant operations is inevitably a group process.

Research Recommendations

Understanding the ways in which groups evaluate evidence and reach conclusions under stress is crucial for the design of emergency operating procedures and the development of better training methods.

Research is needed on models of organizational design to deal with emergencies (NUREG/CR-3524, 1984f; NUREG/CR-1745, 1980a), for it is reasonable to assume that an organizational design well suited to normal operations may not necessarily be equally effective in responding to emergencies.

CHARACTERISTICS OF MANAGERS

Rationale and Background

Who are the managers whom we entrust with safe and productive operations? What type of qualifications, experience, and training do they receive for these crucial positions? The NRC-sponsored research on the STA highlights the links between problems of career management and knowledge management (NUREG/CR-2952, 1983a; NUREG/CR-3396; 1981b; NUREG/CR-3785, 1984a; NUREG/CR-4280, 1985d). Many operators and utilities were disappointed with the role of the STA and some had difficulty in filling this position. Engineers who became STAs disliked the shift work, often lacked operating experience, could not gain the respect of the operating crews, and often had no meaningful work to do when the plant was operating smoothly. NRC researchers note that utilities experimented with or at least considered various alternative roles to meet the purposes of this function, such as a shift engineer's getting a license or a shift supervisor's earning an engineering degree. Such proposed alternatives must resolve two difficult labor market and career issues: (1) people with engineering degrees want a career nd may tolerate shift work only for the short run, and (2) the labor market cannot supply many people who combine both operations and engineering competence.

Upgrading and professionalization of the work force are reshaping the balance between internal and external labor markets. This poses a substantial challenge to nuclear utilities. Employees in field or low-level jobs who receive more responsibility and training yet lack advanced degrees and further technical or general training at school cannot advance into management ranks. Traditional "bridge" jobs that linked the bottom of the job ladder with the middle are disappearing, in part because of automation, while credential requirements mean that those without degree cannot advance, even if they are competent.

Knowledge-intensive industries may be developing a new system of integrating training, jobs, and careers. Evidence thus far suggests that people without degrees will be more intensively trained, while occupying paraprofessional jobs. Such people are likely to return to school, often taking a new job with another company. They move in and out of enterprises and colleges more frequently to shape an upwardly mobile career.

Research Recommendations

Analysis of the training, education, and experience of U.S. nuclear power plant managers is a necessary baseline for tracking changes over time, as demograp!· nd economic forces change the profile of this work force. In addition, comparison of these qualifications to judgments concerning acceptable qualifications would point the way toward improvements, should any be needed. Better knowledge of managerial qualities could result in increased public confidence in nuclear power generation as a safe energy source for the United States.

There is also a question of whether utilities have an adequate conception of operators. Are they merely workers, or are they professionals? If the latter, how can a utility overcome the constraints of a tight labor market? Would it be too costly to create a professional corps of operators who have degrees, operating licenses, and well-defined career paths? Could experience in fields employing paraprofessionals, such as paralegal, paramedical, and police personnel, be applied to nuclear power plants? What is the consequence of this method of competing in today's rigorous labor market?

The implications for the nuclear industry's personnel and training programs are likely to be significant and warrant sustained study. What relations with local educational institutions could be developed? What changes in career structure could be encouraged by changes in utilities' hiring and promotion practices?

8
The Regulatory Environment

The nuclear industry is one of the most heavily regulated industries in the United States. The activities of nuclear utilities are constrained by a large set of external organizations and legal institutions that includes federal regulatory agencies, state public utility commissions, siting agencies, and environmental agencies. In addition, nuclear utilities are subject to constraints imposed by self-regulating agencies such as INPO and NUMARC, interested third parties such as independent standard-setting agencies and accreditation boards, and legal systems that define financial liability (e.g., the Price-Anderson Provisions of the Atomic Energy Act of 1954 (P.L.83-703) and establish administrative procedures and public rights.

Although the regulatory environment is seldom considered as a topic for human factors research, the panel believes it is integral to decisions made within the nuclear utilities and to human factors in nuclear safety. At a general level, the regulatory organizations and institutions affect the incentives and the legal considerations of operation. Regulatory requirements constrain the choices of utilities in hardware, management, and personnel areas; and they impose costs on utilities, which may be either effective or counterproductive from a safety standpoint. These costs influence the resources available to the utilities for safety. Regulation, in addition, constrains the profit-making opportunities in ways that may interact with their safety activities (Joskow and Noll, 1981;

Burness, Montgomery, and Quirk, 1980; Breyer, 1981; Joskow, 1974).

At the very least a regulatory body should ensure that its own regulations meet accepted human factors standards with respect to lack of ambiguity, comprehensibility, and conformance to human performance requirements. All regulations should be reviewed with this in mind.

The panel identified three research areas that are of particular importance to current policies for nuclear regulation, each of which includes a set of research topics. The first concerns the possibility of assigning regulatory activities to different organizations and devolving some regulatory functions from the regulatory bodies to the utilities themselves. This topic is motivated by current proposals for reform, particularly those advocating more self-regulation by the industry and consequent greater financial liability.

The second research area of importance is a closer examination of the effects of regulation. Specific topics of importance include assessing costs imposed by regulation on utilities and incentives created for (or against) innovation by utilities. Diverse regulation by state public utility commissions has raised concerns that regulations tying profits to certain performance measures may detract from safety. Related research topics include examining the extent to which this is true and the possibility of formulating contracts that provide incentives for safety as well as short-term cost minimization.

The third set of topics concerns human factors within the NRC itself such as staffing requirements and management issues. Because the NRC's activities are so pervasive, its own internal operations define the types of regulations it is able to engender and enforce.

MODELS OF REGULATION

Rationale and Background

A critical factor in nuclear safety is the incentives facing nuclear utilities to ensure the safety of their operations. Traditionally, the government has relied on a combination of financial responsibility and direct regulation; however, federal regulation of the organization and management of utilities is limited. Many of the human factors aspects of nuclear safety, including specifically organization and management, has been left to individual utilities.

Since the Three Mile Island accident, attention has focused on the role of institutions and organizational factors in nuclear safety. The NRC conducted and commissioned research in this area in the early 1980s and considered more stringent regulation. At the same time, the nuclear industry organized industry groups (most notably, INPO and NUMARC) that have undertaken a self-regulatory effort in operator training and other organization and management assessment activities. Many human factors areas have been proposed as appropriate for self-regulation, and utilities have taken the initiative in regulating training programs and related activities. Third parties have not received as much attention, but their roles have been proposed in certain areas (e.g., nuclear experts to run utility-owned power plants). Finally, attention has focused on reforming the Price-Anderson Provisions of the Atomic Energy Act of 1954 (P.L.83-703), with its implicit financial incentives, and the potential safety impacts of other financial constraints facing nuclear utilities (Wood, 1983).

The nuclear industry is a special case with regard to nongovernmental regulation. Catastrophic accidents, which are of special concern, are associated with small probabilities of occurrence (Slovic, Fischhoff, and Lichtenstein, 1985). They are associated with consequences that are necessarily beyond the financial liability of the utility. Furthermore, beliefs about nuclear safety vary substantially among the public, the industry, and third parties, and divergence of opinion about nuclear safety has been viewed as a major constraint on industry expansion (Wood, 1983). It should be emphasized that, although different parties may have different beliefs regarding accident risks, it does not follow necessarily that industry incentives for safety are less than those of the public (Starr, 1980). Nevertheless, utilities cannot (because of limited financial exposure) and may not (because of different assessments-of-accident probabilities) view the risks of operations in the same way as do other interested parties, such as the government or the public, and their attitudes to regulation will vary accordingly.

The NRC has the statutory responsibility for regulating nuclear power plants so as to ensure public health and safety. In theory, there is ample room for variation in how the NRC actually exerts its responsibility. At one extreme, the NRC could give extremely detailed specification for all aspects of nuclear power plant construction, operation, maintenance, and management—for example, imposing educational and experience qualifications for managers, delineating specific training curricula, decreeing control room design retrofits, specifying surveillance and maintenance schedules for equipment, and so forth. In a sense, this represents regulation of inputs to safety, i.e., those aspects of plant operation that are believed to lead to safe production of electricity. At the other extreme, the NRC could fulfill its obligations by giving utilities wide latitude in how they operate their plants, i.e., self-regulation. The role of the NRC in this instance would be to monitor plants to ensure that they are being operated safely, without regard to the specific measures the individual utilities adopt to achieve safety.

In reality, the model of regulation adopted by the NRC varies over time and with respect to domain of interest. For example, in the area of operator training, the NRC responded to congressional mandates about training contained in the Nuclear Waste Policy Act of 1982 (P.L.97-425) by allowing INPO to take the lead in developing training criteria and accrediting the training programs of individual utilities. The NRC's role in this case has been to review INPO's accreditation program. This example might be contrasted to more specific NRC requirements with respect to the minimum numbers and qualifications of control room and senior control room operators on each shift.

Research Recommendations

The wide latitude that exists in how the NRC carries out its statutory responsibilities begs the question of whether one approach results in greater safety than another. Arguments can be developed to defend almost any regulatory approach, from detailed specifications to self-regulation. Over the last several years there has been increased reliance on industry initiatives in the human factors area—including such areas as training, management, and performance indicators. And there has been a concomitant decrease in NRC initiatives in these areas. Is this wise? Will it lead to improved safety in the short or long run? What types of NRC sanctions and incentives are most effective in a self-regulatory model? How is public input and participation protected in self-regulation? These are all questions amenable to an avenue of research known as policy analysis, incorporating such methods as case studies and comparative studies of organizations.

While much has been written about regulatory reform in general (Joskow and Noll, 1981; Noll, 1985; Noll and Owen, 1983; Friedlaender, 1978; Abolafia, 1985), to our knowledge research specific to the NRC has not been carried out. Given the unique aspects of nuclear power production and the potential for endangering public health and safety, this represents a serious omission.

Several types of analysis can be used to address the issue of preferred regulatory models. Case studies and historical analyses of other regulatory agencies and of nuclear regulatory bodies in other countries may yield data on the expected effects of different regulatory models. Similarly, within the specific NRC context, case studies of specific instances of newly implemented regulations and instances of specific regulations being deferred to industry initiatives could yield important information as to the effectiveness of the different approaches. In addition, the effectiveness of new initiatives could be treated empirically using performance indicators.

Ideally, an empirical basis for selecting models of regulation that will yield greatest safety would be the outcome of such research. In reality, we recognize that the empirical basis would represent only one of several bases for selecting modes of regulation. Other bases would include political and economic pressures, hortatory argument, and the personal biases of key decision makers. Studies of several years' duration would be required to allow sufficient time to fully assess the impacts of different regulatory approaches.

How can the public and its representative, the NRC, be assured that regulations and regulatory actions result in the net enhancements to safety that are intended? Regulations and regulatory requirements have increased over the years, as have the concomitant demands on regulatory and utility resources. Is there a point at which these demands on resources reduce safety? In addition, given the number of different regulatory bodies affecting utility behavior, is it possible that the actions of one regulatory body have results that run counter to the goals of another? The answers to these questions bear directly on the issues of overall enhancement of safety at nuclear power plants and have implications for regulatory strategies.

NRC regulations and requirements place substantial costs on utilities. Obviously, such regulations are intended to ensure safety; nevertheless, some are confusing, repetitive, internally inconsistent, and require an onerous quantity of paperwork to comply with accounting and reporting requirements (see Advisory Committee on Reactor Safety, 1980; Cohen, 1980; Wood, 1983; Committee on Nuclear Safety Research, 1986). The issue arises as to whether some regulations are detrimental to safety, because utilities divert excessive resources—in particular, staff time and energy—toward formal compliance with regulations. To the extent that utility staff believes that safety regulations are counterproductive, the regulations degrade utility-NRC relations and hence may be detrimental to nuclear safety overall.

This problem is hardly new. Recommendations to rationalize and simplify NRC regulations have cropped up frequently (e.g., SECY-85-129, 1985k). That a recommendation is not novel does not detract from its importance. Research on effective organization and behavior must consider the time and efforts of staff in complying with regulations. If the regulations can be improved, benefits accrue both in improving utility staff efforts and in improving relations between utilities and the regulators.

PLANT PERFORMANCE INDICATORS

Rationale and Background

To know whether regulations and utility actions are increasing safety at nuclear power plants, one must first be able to measure plant safety. The fundamental purpose of performance indicators is to be able to readily monitor and assess individual plant performance and take action when appropriate. The major driving goal is to be able to track plant performance and to understand how changes in plant operation and maintenance, whether utility- or NRC-initiated, affect that performance. Ideally, we should have valid indicators that temporally are as far removed from actual threats to safety as possible. Knowing that a plant is heading for trouble 10 months in advance is certainly more valuable information than having that knowledge 10 minutes in advance. Of course, there is typically a trade-off in terms of the accuracy versus timeliness of such information.

Both INPO and the NRC have embarked on well-publicized programs of performance indicators (see SECY 86-317, 1986d;

NUREG/CR-4378, 1986c; NUREG/CR-4611, 1986e). However, the current set of performance indicators is limited to information that is publicly available. The data that utilities currently must report to the NRC (e.g., licensee event reports) do not cover all the valid indicators, especially those having early diagnostic value.

Research Recommendations

We believe that an ongoing research program is required to support these efforts and should include several types of analysis. A research program that examines a wide variety of measures, not limited to those currently publicly available, should be initiated. These measures should include a search for "inputs" (e.g., mean time between maintenance of critical equipment, thoroughness of training progam), "throughputs" (e.g., unplanned down time due to equipment failure, retention rate of personnel throughout the training program), and "outputs" (e.g., radiation exposure due to equipment failure, events due to human error). In addition, the search for indicators should include those at different levels of the nuclear power plant system, including individual, team, and plant performance. Finally, the research should involve the continuous update and validation of these indicators. This is essential because, as technology changes, plants age, and new regulatory requirements are implemented or rescinded over time; all of which may affect the validity of an indicator.

The result of this research will be both a regulatory tool with the ability to differentiate plants in terms of their likely safety performance and an important research tool against which all other changes can be assessed.

The search for candidate indicators beyond those already collected by the NRC and their initial validation will require a two-to-three-year effort—depending on the difficulty of obtaining the measures from utilities. Beyond that, a modest level of effort will be required to continually update and validate the measures.

Increasing discontent with traditional rate-of-return regulation has led a number of states to institute or experiment with alternate incentive financial regulation for utilities (Seagraves, 1984; Block et al., 1985). Details of these contracts differ, but the general point is to create incentives for utilities to operate their systems in a cost effective manner, generally by sharing extra profits or imposing penalties should costs exceed some predetermined amount.

Although this trend in regulation raises concerns, it simultaneously presents opportunities to enhance nuclear safety.

The concerns raised are that, in attempting to minimize short-run operating costs, utilities may incur increased nuclear safety risks by cutting maintenance and other safety-related expenses. Descriptive, but not statistically significant, evidence suggests that in fact long-run electricity generation is greater and costs are lower at plants that are well-managed, well-staffed, and have lower incidences of events that are associated with safety problems (e.g., *Wall Street Journal*, July 28, 1987, p.2). Nevertheless, presented with some of the financial incentives proposed by state public utility commissions, it is possible that utilities may have incentives to cut some short-term costs in ways that are detrimental to safety.

The opportunity presented by these changes in state regulation is that the concept of incentives regulation can include incentives for long-run maintenance, investment, innovation, and, in general, safety. While only some of these issues have been considered, current research in economics has focused on such mechanisms, using both experimental and theoretical analyses (Smith, 1974; Loeb and Magat, 1979; Cox and Isaac, 1987). A natural extension of this work is to consider mechanisms that incorporate long-run safety incentives. Because of the potential relevance of the results, and because the situation is currently in flux, this is a particularly important and timely research issue.

There have been several instances of public utility companies' instituting incentive programs for utilities whereby the given utility's rate is dependent on meeting certain financial or performance standards. The effects of these programs on safety, not to mention performance, have not been fully analyzed. Regulatory actions such as these, which have clear implications for productivity and therefore have safety implications as well, should be subjected to analysis and research.

To begin, those incentive programs that are already in place could form a body of case studies, whereby characteristics of the specific incentive plan, utility and plant management responses to this plan, and actual plant performance would be carefully delineated and analyzed in terms of both safety and production. The interactions among these three sets of variables— incentive plan characteristics, utility responses, and plant performance— would serve as the basis for structuring regulatory mechanisms to improve both safety and performance.

CONCLUSION

Having reviewed the course and nature of human factors research at the NRC over the last ten years, the panel is encouraged by the recent initiative shown at the NRC to develop and fund a new human factors research program. If this plan is implemented in 1988, receives the strong support of the NRC and of the industry, is managed by a qualified human factors specialist, is staffed by a team of multidisciplinary scientists, and is organized as a branch rather than as a subdivision of the reliability branch, then the initial steps of leadership required of the NRC in this critical area will have been taken.

In this report, the panel has emphasized higher priority items as a point of departure. The panel envisions, however, that in the next few years, the NRC would develop a full program covering all topics listed in the report, and that, over time, the full program would be implemented. It is anticipated that additional research will be required as the NRC and the industry review and implement the recommendations set forth by the panel in this report.

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Appendix
Biographical Sketches

NEVILLE MORAY (Chair) is professor of industrial engineering at the University of Toronto with responsibility for the human factors program. He has held academic positions at Stirling University, the University of Toronto, the University of Sheffield, the University of Hull, and the Massachusetts Institute of Technology. He is currently also a Miller visiting professor in the departments of Mechanical and Industrial Engineering and Psychology at the University of Illinois at Urbana-Champaign. For five years he represented the United Kingdom on the NATO Science Committee Special Panel on Human Factors. His basic research is concerned with the role of the human in complex automated systems and the estimation of operator mental workload. His consulting work has included work for nuclear regulatory bodies in the United Kingdom and Canada on human factors issues for the Sizewall "B" public inquiry, task analysis, the design of emergency operating procedures, models of operator error, and the use of simulators in training. He has been responsible for organizing NATO workshops on mental workload on human error, has served on a committee of the IEEE on guidelines for nuclear industry human factors, and is vice president of Human Factors North, Inc. He received B.A. and Ph.D. degrees from Oxford University.

LINDA R. COHEN is a visiting assistant professor in the Department of Economics at the University of California, Irvine. She conducts research on the political economy of nuclear power, energy policy, and electricity. She has also studied federal programs to develop new technology including nuclear research and development programs. She was a member of the Advisory Panel in Support of the Office of Technology Assessment of the U.S. Congress, assessing magnetic fusion research and development in 1986-1987, and a member of the Department of Energy's Program Review Committee on Airborne Nuclear Waste Management in 1980–1982. She was an assistant editor of *Public Policy* from 1978 to 1980. She received an A.B. in mathematics from the University of California, Berkeley, and a Ph.D. in economics from the California Institute of Technology.

RUSSELL R. DYNES is chair and professor of the Department of Sociology at the University of Delaware. He is also President of the Research Committee on Disasters, International Sociological Association. He has held academic positions at various universities including University College, Cardiff, the University of Delaware, the University of Delhi, Aims Shams University, the Arab States Center for Education in Community Development, Ohio State University, Capital University, and the University of Tennessee. His research experience has included work on educational changes in a transitional community, laboratory simulation studies of organizational behavior under stress, community reaction to water resource problems in relation to planning cross cultural studies of disasters, organizational response to major community crises, organizational communication and decision making in disaster, and delivery of emergency medical services and mental health services in disaster. He has been a participant in numerous conferences and workshops on disasters and was a member of the Task Force on Emergency Planning and Response to the Accident at Three Mile Island. He has consulted for the Federal Disaster Assistance Administration, the Federal Emergency Management Agency, the Community Services Administration, the President's Reorganization Project, the Secretario de Gobernacion, the Stanford Research Institute, and a number of private law firms. Dynes received A.B. and M.A. degrees from the University of Tennessee and a Ph.D. from Ohio State University.

HERBERT ESTRADA, JR., is president of MPR Associates, Inc. He has had firsthand experience in engineering of fluid and control systems, 12 years of which were devoted to the design, analysis, field installation, test and evaluation of naval nuclear propulsion plant systems. Since 1964 he has been responsible for the technical coordination and direction of projects including design, analysis, testing, and operation of nuclear fossil-fueled power and marine propulsion systems, hydraulic, pneumatic, and electronic control systems, electrical systems, and fluid systems. From 1951 through 1963 he worked at the Bettis Atomic Power Laboratory of Westinghouse Electric Corporation; his responsibilities there included: supervisor of advanced surface ship control engineering, chief test engineer for acceptance testing of Bettis-designed reactors for nuclear submarines at Portsmouth Naval Shipyard, lead engineer for nuclear plant analysis of Skate Class Nuclear Submarines, and designer of power range instrumentation and reactor protection systems and hardware for the U.S.S. Nautilus. Estrada received a B.S. in electrical engineering from the University of Pennsylvania. He has taken graduate courses in physics and mathematics at the University of Pittsburgh.

CLAY E. GEORGE is professor of psychology at Texas Tech University. He has conducted research on adaptive behavior, team effectiveness, team performance, intragroup coordination, interference and fatigue in multitask training situations, and team member coordination. He has held positions at George Washington University, Arizona State University, the University of Houston, and Texas A & M University. He has been a consultant for numerous institutions, including Goodyear Aircraft, the U.S. Army Infantry School, the U.S. Army Human Engineering Laboratory, the Houston Chapter of Industrial Engineers, Lubbock Mental Health Association, Matheson, Bieneman, Veale, & Parr, Attorneys at Law, and Applied Science Associates, Inc. He is a member of the American Psychological Association. George received a B.S. in psychology and sociology from Arizona State University, M.A. degrees in psychology and anthropology from the University of Arizona, and a Ph.D. in psychology from the University of Houston.

PAUL M. HAAS is a manager of Advanced Systems Technology, International Technology Corporation, and is responsible for technical management of a national program related to severe accidents in advanced nuclear reactors and for development of programs in systems engineering and science. From 1976 to 1987 he was head of the Reliability and Human Factors Group, Engineering Physics and Mathematics Division, Oak Ridge National

Laboratory, where he had technical, management, and administrative responsibility for an interdisciplinary group conducting research in human-system engineering and science. He has 13 years of professional experience in systems safety, reliability, and human factors. His research experience has included analysis of severe accidents in advanced reactors, reliability data systems and data anlaysis, human factors, training systems and human performance modeling. His management experience includes technical, personnel, and financial management of tasks, projects, and multiproject programs. His professional affiliations include the American Nuclear Society, the Human Factors Society, and the Risk Society of America. Haas received a B.S. in engineering science and M.S. and Ph.D. degrees in nuclear engineering from the University of Virginia. He has taken a postdoctoral course in cognitive psychology at the University of Tennessee.

LARRY HIRSCHHORN is a senior researcher at the Management and Behavioral Science Center of the Wharton School. He conducts research in the areas of manufacturing and office technology, the problems and opportunities posed by group and team work, and the impacts of computerized production processes on job and organization design. In addition, he does consulting work on such issues as organization design, job design, organization process, and problems of role and authority. His clients have included the Sun Company, Exxon Enterprises, the Nuclear Regulatory Commission, the Legal Services Corporation, and Wallace, Roberts and Todd. Hirschhorn received a B.A. in economics from Brandeis University and a Ph.D. in economics from the Massachusetts Institute of Technology.

BEVERLY M. HUEY served as a research associate to the panel. As a staff member of the Committee on Human Factors, the projects she is involved in include one on pilot performance modeling in CAD/CAE facilities and a workshop report on multicolored displays. While completing course requirements for a doctoral degree, she has had practica placements as an engineering psychologist in the Close Combat (Light and Heavy) Directorate of the U.S. Army Human Engineering Laboratory and as a data analyst and consultant for a counseling center. In addition, she has taught courses in statistics and the use of computer statistical packages. She is currently a member of the Human Factors Society, the American Statistical Association, Psi Chi, and Alpha Kappa

Delta. Huey received B.S. degrees in psychology and sociology from Virginia Polytechnic Institute and State University and an M.A. in psychology from George Mason University. A graduate student in the Psychology Department of George Mason University in the Human Factors Engineering Program, she expects to receive a Psy.D. degree in 1989.

JOYCE KEEN is the director of the Department of Clinical Psychology at Iowa Methodist Medical Center, the largest health system in Iowa. In addition to administrative duties, she is an active clinician specializing in psychophysiology and behavioral medicine. Her previous research has included human isolation studies, longitudinal child development studies, the psychology of morbid obesity patients electing gastric stapling, and indexing studies in behavior therapy for the Ford Foundation. She was formerly a registered nurse, with experience in spinal cord injury, neurosurgery, urology, medicine, surgery, psychiatry, as well as chemical dependency and eating disorders. She received a B.A. in psychology from the University of Alabama, a Ph.D. in clinical psychology from Nova University, and completed a postdoctoral internship in clinical psychology at the Ohio State University Hospital.

TODD. R. LAPORTE is professor of political science and associate director of the Institute of Governmental Studies at the University of California, Berkeley. He conducts research on the structure and decision-making dynamics of complex, technologically intensive organizations, and the effects of advanced technologies on organizational and regulatory development. His recent work includes studies of public policy and organizational dilemmas of radioactive waste management, as well as institutional effects of alternative energy technologies on utilities and regulators in the operating technologies demanding a very high level of operational reliability, especially, air traffic control, regional electrical power systems, the nuclear power fuel cycle, and naval aircraft carrier operations. He has served on the National Research Council's Board on Radioactive Waste Management and on the External Advisory Committee, Energy Division, Oak Ridge National Laboratories. He is a member of the National Academy of Public Administration, has been a fellow at the Woodrow Wilson International Center for Scholars, Smithsonian Institution, and has been a research fellow at the Sciences Center in Berlin. He received a B.A.

from the University of Dubuque and M.A. and Ph.D. degrees from Stanford University.

JENS RASMUSSEN is a professor of cognitive engineering at the Riso National Laboratory, Roskilde, and the Technical University of Copenhagen, Denmark. Previously he was head of the Electronics Department at Riso. He has been working on control and instrumentation for research reactors and reactor experiments and has been chairman of the Riso reactor safety committee. Since 1960 he has been active in research in probabilistic risk analysis and, in particular, in human reliability and analysis of human performance in complex systems. He has served on several panels and committees on these issues; he was the chair of a group of experts on human error analysis and quantification under the OECD Committee on the Safety of Nuclear Installations and a member of the NATO Special Program Panel on Human Factors. He is an member of the Danish Academy of Technical Sciences. He received an M.Sc. degree in electronic engineering from the Technical University of Copenhagen.

RICHARD SHIKIAR is director of the Human Affairs Research Centers (HARC) of Battelle Memorial Institute. Previous positions at HARC include director of the Social Change Study Center and coordinator of its organizational effectiveness program. Over the past eight years, he has directed and worked on a number of research and consulting projects involving human behavior in potentially hazardous facilities. His substantive contributions include safety assessments at a chemical facility, determination of generic human factors improvements to safety at liquified natural gas facilities, and a variety of applications at nuclear power plants. The latter include development of a content sampling approach to the operator licensing exam administered by the Nuclear Regulatory Commission, determination of appropriate educational qualifications for operators, assessment and improvements in emergency operating procedures, and development of methods for assessing utility management. As manager of the safety technology program, he was involved in analysis of the human side of safety from man-machine interface issues to management and organizational analyses. Prior to his positions at Battelle, he was associate professor of industrial/organizational psychology at Colorado State

University. He received a B.S. degree at the City College of the City University of New York and M.S. and Ph.D. degrees in psychology from the University of Illinois.

J. ED. SMITH is president of Ed's Nuclear Service Corporation. He retired from Duke Power Company in 1986 after a career there beginning in 1949. He has extensive power plant experience in both fossil and nuclear plants, the last 27 years in the nuclear field. After completing the Oak Ridge School of Reactor Technology in 1961, he participated in the checkout, startup, operation, and decommissioning of the Carolinas-Virginia Tube Reactor. In 1967 he was named station manager for the three-unit Oconee Nuclear Station and served in this position until 1984, when he became an assistant to the vice president, nuclear, and served as such until his retirement. He has broad industry experience including work with the Institute of Nuclear Power Operations, the Nuclear Utility Management and Resource Committee, and the American Nuclear Society. Currently, he provides nuclear consulting services to three utilities, primarily as a member of their independent safety review boards. He holds a B.M.E. degree from North Carolina State University and an M.S. in nuclear engineering from the University of South Carolina.

HAROLD P. VAN COTT is senior staff officer and study director of the Committee on Human Factors. He has served as vice president of the Essex Corporation; chief scientist at Biotechnology Inc.; chief of consumer sciences research at the National Bureau of Standards; and director of the Institute for Human Perfomance Research at the American Institutes for Research. His nuclear human factors experience includes work on the development of NUREG-0700 and NUREG-0801; management of 10 control room design reviews; human factors studies for Toledo Edison, the Electric Power Research Institute, the Oak Ridge and Lawrence Livermore National Laboratories, the Atomic Energy Control Board of Canada; and the development and presentation of human factors workshops for power plants and Department of Energy laboratories. He is a fellow of the Human Factors Society and a member of the American Psychological Association, the American Association for the Advancement of Science, and the Washington Academy of Science. Van Cott obtained M.A. and Ph.D. degrees from the University of North Carolina.

DAVID A. WARD is a research manager on special assignment at the Savannah River Laboratory of E.I. duPont de Nemours and Co. He is also currently a member and past chairman of the Advisory Committee on Reactor Safeguards to the Nuclear Regulatory Commission. Prior to his present assignment, Ward was manager of the Reactor Safety Research Division and, earlier, of the Nuclear Engineering Division at the Savannah River Laboratory. From 1975 to 1980, he was superintendent of the Reactor Technology Department at the Savannah River Plant. He joined the DuPont Company after receiving a B.S. degree in mechanical engineering from the University of Illinois in 1953 and has held a variety of other engineering and supervisory assignments involving research and development activities in thermal hydraulics, safety analysis, and operations of nuclear reactors. He has been a member of the Advisory Committee on Reactor Safeguards since 1980 and has been extensively involved with the committee's work in human factors. He was a member of the National Research Council's Committee on Advanced Nuclear Systems in 1982 and is a fellow of the American Nuclear Society.

DAVID D. WOODS is a senior research psychologist at Westinghouse Research and Development Center. He conducts research on human perception, attention, and decision making. He created and managed a research program in cognitive engineering that investigates human problem solving in complex-driven worlds. This work explores what is effective support for human problem solvers through (1) studies of problem solving in dynamic situations, (2) models of cognitive processes in person-machine environments, and (3) the development of new kinds of support systems. He has conducted some of the initial work on operational decision making in simulated and actual nuclear power plant situations. He was also the codirector of two international meetings on cognitive engineering and artificial intelligence in complex worlds. Woods received a B.A. in psychology from Canisius College and M.S. and Ph.D. degrees in cognitive psychology from Purdue University.