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Advanced Information Systems Design: Technical Basis and Human Factors Review Guidance

Brookhaven National Laboratory

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Advanced Information Systems Design: Technical Basis and Human Factors Review Guidance

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ABSTRACT

Plant information systems provide operators with information supporting situation assessment, monitoring and detection of disturbances, response planning, and response implementation. The importance of the design of information systems for human performance and reliability has long been recognized. Recent advances in design go beyond the 'one sensor – one indicator' display systems of conventional plants. Computer-based systems provide a variety of ways to process and present data. These characteristics of design represent a trend toward making displays more immediately meaningful to personnel by mapping display representations to important aspects of plant processes and to underlying cognitive mechanisms, such as perceptual processes and mental models. The objective of this study was to develop guidance for human factors review of advanced information systems based on a technically valid methodology for developing guidance. To support this objective, we developed a characterization framework for describing key design characteristics of information systems. The characterization includes the following major components: information requirements, representation systems, interface management functions, and display devices. Representation systems were further hierarchically divided into display elements (basic building blocks of displays, such as axes, alphanumeric elements, and icons), display formats (such as mimic displays, configural displays, and novel graphics), display pages (a defined set of information that is intended to be displayed as a single unit), and display networks (the organization of display pages). Then, we examined research in the following areas: (1) generic cognitive tasks that an information system must support, (2) information requirements analysis, (3) information representation, and (4) information organization. This research was used to provide the technical basis on which guidelines for review of design were developed. These guidelines address both the design process and the implementation of advanced information systems. However, there were aspects of information systems for which the technical basis was insufficient to support the development of guidance. These were identified as issues to be addressed in future research.

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EXECUTIVE SUMMARY

The Human-System Interface Design Review Guideline, NUREG-0700, Rev. 1 (O'Hara, et al., 1996), was developed to provide guidance on human factors engineering (HFE) for the U.S. Nuclear Regulatory Commission (NRC). The NRC staff uses NUREG-0700 for (1) reviewing submittals of human-system interface (HSI) designs prepared by licensees or applicants for a license or design certification of a commercial nuclear power plant (NPP), and (2) undertaking HSI reviews that could be included in an inspection or other types of regulatory review of HSI designs, or incidents involving human performance. It describes those aspects of the HSI design review process that are important to identifying and resolving human engineering discrepancies that could adversely affect plant safety. NUREG-0700 also has detailed HFE guidelines for assessing the implementation of HSI designs.

In generating NUREG-0700, Rev 1, several topics were identified as "gaps" because there was an insufficient technical basis upon which to formulate guidance. One such topic is the integration of advanced HSI technology into conventional NPPs. The NRC is currently sponsoring research at Brookhaven National Laboratory (BNL) to (1) better define the effects of changes in HSIs brought about by incorporating digital technology on personnel performance and plant safety, and (2) develop HFE guidance to support safety reviews, should a review of plant modifications or HSIs be necessary.

Based upon the literature, interviews, and site visits, O'Hara et al., (1996) identified changes in HSI technology and their potential effects on personnel performance. The topics were then evaluated for their potential safety significance (Stubler et al., 1996); information systems was one HSI technology that was found to be potentially safety significant.

The importance of information system design for the performance and reliability of operators has long been recognized (Patrick, 1987). In conventional control rooms (CRs), the large spatially fixed arrangement of controls, displays, and alarms supports rapid scanning and pattern-recognition approaches to plant diagnosis. Information is primarily presented by detailed parameter indicators on a variety of analog devices, such as gauges and linear scales.

Computer-based systems provide a variety of ways to process and present data. Information may be presented as individual parameter displays (as in conventional systems) or in processed form; e.g., raw data parameters are integrated to provide higher levels of information. These design trends are toward making displays more immediately meaningful to personnel by mapping the presentation of information to underlying cognitive mechanisms, such as perceptual processes and mental models. However, this places a significant burden on the designer both to anticipate the information needs and map them onto appropriate display formats that correspond to the operator's mental models. This is because designs that appeal to engineers are not necessarily well suited to plant operations and maintenance personnel. If mistakes are made in the design, then their use may impair rather than support performance. This may lead to the initiation of an event or complicate operators' responses to an event by causing them to take improper actions or omit necessary actions.

In general, poor implementation of information systems can lead to human performance problems. Some human performance issues associated with display design include the following: Information overload; limited display area; lack of overview of plant status, appropriateness of display formats and page arrangements to operator tasks; and improper integration and presentation of numerical data.

We focused our efforts on those aspects of information system design that are most relevant to the nuclear industry, where the research is most active, and where the results are reflected in actual NPP design efforts: information requirements, representation, and organization. Information requirements refer to what information operators need to safely and efficiently operate the plant. This is a vital step in design of information systems and recent approaches to its analysis, such as ecological interface design approaches that largely stem from the nuclear and

process control industries, promise to enhance the analysis of information needs (e.g., Vicente and Rasmussen, 1992).

Information representation refers to how the needed information is displayed in the control room. The development of novel graphical means to represent information in a format that supports immediate and accurate understanding of plant conditions has a long history in the nuclear industry stemming from the use of simple polargraphic displays for safety information (e.g., Woods, Wise, and Hanes, 1981) to more recent efforts to represent the thermodynamic state of the plant using graphic displays based on the Rankine cycle (Beltracchi, 1995).

Finally, structure is imposed on the information representations by organizing them into display pages and the pages into an entire display network. This is a significant issue in process control facilities, because the networks may contain hundreds or even thousands of display pages (O'Hara, Stubler, and Higgins, 1996). While this aspect of information system design has been generally neglected, recent research suggests that organization is significant to operator performance, and some common organizational schemes can make it difficult for operators to perform their tasks (Heslinga and Herbert, 1995).

The objective of this study was to develop HFE review guidance for information systems based on a technically valid methodology. To support this objective, the following tasks were undertaken:

- Development of a framework for characterizing key design features of information systems
- Development of a technical basis using research and analyses on human performance relevant to information systems
- Development of HFE review guidelines for information systems in a format that is consistent with NUREG-0700, Rev. 1, and NUREG-0711
- Identification of remaining information systems issues for which research was insufficient to support our development of NRC review guidance

The status of each will be briefly addressed below.

Characterization Framework for Information Systems

Existing information systems were reviewed to identify the dimensions and characteristics along which information systems can be defined. Characterization was important because it provided a structure within which the reviewer could request information about a system, and with which to structure the guidance.

The characterization of information systems included the following major components: information requirements, representation systems, management functions, and display devices. Representation systems were further hierarchically broken down into display elements (basic building blocks of displays, such as axes, alphanumeric elements, and icons), display format (such as piping and instrumentation diagram (P&ID) displays and trend graphs), display pages (a defined set of information that is intended to be displayed as a single unit), and display networks (the organization of display pages).

Technical Basis Development

The development of detailed review guidelines began by collecting technical information on which to base the guidance. Research in the following areas was examined: (1) operators' generic cognitive tasks that an information system must support, (2) analyses of information requirements, (3) representation of information, and (4) organization of information.

The plant's information systems are the basis for operators to perform their role. The general tasks that the information system must support include situation assessment, monitoring and detection, response planning, and response implementation. Considerations of the information processing basis needed for the operators' cognitive tasks have to be reflected in design review guidance for the information system. The way in which these needs are reflected in designing information systems is in analyses of information requirements, the representation of information, and the organization of information.

In NPP design, a systems-engineering approach was recommended for identifying information requirements. Plant functions are broken down based on performance requirements and allocated to humans and machines. Human functional requirements are further analyzed to better define the information requirements of task performance. EID was identified as a potential additional approach that addressed following:

- Specification of information requirements
- Organization of information among the levels of an abstraction-hierarchy
- Development of innovative displays to show functionality
- Addition of analytical redundancy

Each of these aspects of EID may have some performance-enhancing features. However, the associated research had methodological weaknesses that limited the conclusions that could be drawn.

Once information requirements are identified, they must be represented in the information system; that is, display formats are developed to communicate the information to the operators. The success of representational aids was discussed as being a function of the characteristics of the plant, the operators, and the representation through which the operators view and act on the plant. All three are essential parts of the overall system. Approaches to representation include separable displays (individual parameters displayed in unrelated form), integral displays (individual parameters integrated into object display where the individual ones are not visible), and configural displays (individual parameters are displayed, but emergent perceptual features are created by the arrangement and organization of parameters).

In general, some research support was found for the representation principles; however, most of the studies could not be generalized due to the use of simple systems, tasks, and inexperienced participants. Thus, extending the research findings to complex systems, such as NPPs must be done with caution.

While the organization of the display page and network are important, there were few data on organizing large, complex information systems. Such studies are complicated due to the interactions between informational organization and other design considerations, such as the display area available and interface management functions. Further, some research seemed to contradict current HFE guidance and current nuclear practice; that is, very dense displays were found to lead to better performance, were preferred by operators, and the industry's common practice of function-system network organization was found to be difficult for operators to use when performing certain tasks.

HFE Review Guidelines

Once the technical information was assembled, a draft set of guidelines was developed. The guidelines were organized and specified in a standard format. In general, guidelines were only developed for those aspects of display design that, in our interpretation, are supported by the literature. Many research studies were either weak in experimental methodology or limited in generalizability to complex systems. This situation constrains the development of new HFE guidelines.

While there was a sufficient technical basis to develop a detailed design-implementation guidance, as is typical in NUREG-0700, several limitations in the technical basis were identified, and so, many issues remain for which typical NUREG-0700 guidance could not be developed (the specific issues are listed in the next section). Until sufficient information is available to support guidance development in these areas, they can be addressed for specific information systems case-by-case using design *process* review guidance. Thus two types of guidance was developed: design process review guidance and HFE design review guidance.

The HFE design process guidelines were designed in the standard format adopted in NUREG-0711(O'Hara, et al., 1994). The guidelines were organized into the following sections:

- Operating Experience Review
- Function and Task Analysis
- Human-System Interface Design
- Training Program Development

The HFE design guidelines were developed in the standard format adopted in NUREG-0700, Rev. 1. The guidelines were organized into the following sections:

- Guidelines for General Display
- Display Format
  - Integral Formats
  - Configural Display Formats

The guidance was peer reviewed and revised. The new guidance will be integrated into the existing guidance on information systems in NUREG-0700, Rev. 1.

Information Systems Issues

Where there was insufficient information for the technical basis upon which to develop valid design review guidance, an issue was defined. There were several human performance issues associated with information systems. The issues were organized into three topic areas:

- Technical Basis Issues
  - Lack of a Well-Defined EID Process
  - Lack of Specific Representation Guidance
  - Evaluation of Operating Experience
  - Critical Testing and Evaluation of EID Concepts
  - Evaluation of Displays
- Design Review Issues
  - Task and Temporal Considerations
  - Volume of Information
  - Density of Display Information
  - Operator Use of a Large Span and Variety of Displays
  - System Complexity and Emergent Features
  - Perceptual Resolution
  - Elements of Configural Display
  - Effect of Instrumentation Failures
  - Organization of Information
  - Integration of EID Displays into Remainder of HSI

- Operator-Related Issues
  - Training and Qualification Implications
  - Operators' Acceptance
  - Internal vs. External Mental Models

PREFACE

This report was prepared by Brookhaven National Laboratory for the Division of Systems Technology of the U.S. Nuclear Regulatory Commission's (NRC's) Office of Nuclear Regulatory Research. It is submitted as part of the requirements of the project *Human Factors Topics Associated with Hybrid Human-System Interfaces* (NRC JCN J-6012), specifically, as part of Task 3, "Develop Review Guidance." The NRC Project Manager is Joel Kramer and the BNL Principal Investigator is John O'Hara.

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ACRONYMS

AA	Abstraction - aggregation
ABWR	Advanced boiling water reactor
AECB	Atomic Energy Control Board (Canadian)
ALWR	Advanced Light Water Reactor
BNL	Brookhaven National Laboratory
BWR	Boiling water reactor
CBP	Computer-based procedure
CR	Control room
DOE	U.S. Department of Energy
DPI	Direct perception interface
DURESS	DUal REservoir System Simulation
EBR	Experimental Breeder Reactor
EID	Ecological interface design
EOP	Emergency operating procedure
EPRI	Electric Power Research Institute
HFE	Human factors engineering
HRA	Human reliability analysis
HSI	Human-system interface
I&C	Instrumentation and control
IAC	Information access cost
IEC	International Electrotechnical Commission
IEEE	Institute of Electrical and Electronics Engineers
ISLOCA	Interfacing systems loss of coolant accident
LOCA	Loss of coolant accident
NAS	National Academy of Science
NPP	Nuclear power plant
NRC	U.S. Nuclear Regulatory Commission
OER	Operating experience review
PCP	Proximity-compatibility principle
P&ID	Piping and instrumentation diagram
PRZR	Pressurizer
PWR	Pressurized water reactor
RCS	Reactor coolant system
RHR	Residual heat removal
RV	Reactor vessel
SA	Situation assessment
SDT	Signal detection theory
SME	Subject matter expert
SPDS	Safety parameter display system
SRK	Skill-based, rule-based and knowledge-based
TMI	Three Mile Island nuclear power station
URD	Utility Requirement Document
V&V	Verification and validation
VDU	Video display unit

PART 1

Guidance Development and Technical Basis

These design characteristics represent a trend toward making displays more immediately meaningful to personnel by mapping the presentation of information to underlying cognitive mechanisms, such as perceptual processes and mental models. However, this places a significant burden on the designer both to anticipate the information needs and map them onto appropriate display formats that correspond to the operator's mental models. This is because designs that appeal to engineers are not necessarily well suited to plant operations and maintenance personnel. If mistakes are made in the design, then their use may impair rather than support performance. This may lead to the initiation of an event or complicate operators' responses to an event by causing them to take improper actions or omit necessary actions.

In general, poor implementation of information systems can create human performance problems, as shown by the NRC's experience with safety parameter display systems (SPDSs) (Eckenrode, 1991; Liner and DeBor, 1987). Modern computer-based information systems are considerably more complex than the SPDSs of the 1980s. Some human performance issues associated with display design include the following:

Information Overload – The vast quantity of information that is available through the display system may impose high levels of mental workload. For example, demands on the operator's attention may be high (e.g., the operator may need to view multiple sets of information at the same time or in rapid succession). Also, the need to consider the relevance of a vast set of information to current task requirements may impose high demands on the operator's ability to analyze information.

Appropriateness of Display Formats and Page Arrangements to Operator Tasks – Modern information systems typically access and present a very large quantity of data and present information in a variety of formats from digital to advanced graphic formats. Graphic display formats can represent information related to plant functions, processes, and systems in ways that are different from conventional CR instrumentation and earlier computer-based display systems. For example, graphic displays contain many more elements (e.g., abbreviations, labels, icons, symbols, coding, and highlighting) than conventional ones. As displays convey more information at multiple levels of abstraction, the complexity of the elements becomes greater. The cognitive principles that support the effectiveness of these formats, and their relationship to operators' tasks, are becoming better understood. A greater understanding is emerging about the effectiveness of designs of display pages, including how display formats are combined to produce effective pages, how different formats might interact within a display page, and how complex information should be divided to form individual pages. Thus, guidelines on human factors that were developed for simple displays may not be appropriate for the complex ones that are being developed for computer-based display systems. If properly implemented, graphical displays can enhance detection, recognition, and comprehension of important information. However, improper implementation may impair an operator's performance. For example, visual clutter may be increased, which may inhibit an operator from detecting important information. New display formats may increase mental workload associated with recognizing and comprehending information. Inefficient distribution of information among display pages may result in high demands on an operator's short-term memory (e.g., remembering values from previous displays) or a loss of understanding of plant status.

Limited Display Area – A limited display area in visual display unit (VDU)-based systems has been found to be a problem. Further, compact control consoles and computer-based display devices, which contain multiple levels of information, may not be consistent with the scanning and recognition strategies of operators (NAS, 1995). When the information needed by an operator is contained on more than one display screen and only one screen can be displayed at one time, the operator may be required to make rapid transitions between screens, try to remember values, or write them on paper. Compared to the sweeping wall-to-wall panels of older conventional CRs, CRs that use these computer-based displays provide a more restricted view, even when multiple display devices are

provided. Further, since operators can only monitor what they can see, they may concentrate excessively on selected areas while ignoring others.

Lack of Overview – A vast amount of information may be available at different levels of abstraction (e.g., functional versus physical characteristics of the plant) and level of detail. This information may be distributed among separate display pages. As a result of the quality, type, and distribution of information in the display system, operators may experience difficulty in obtaining a rapid, overall assessment of the plant's status. The lack of an adequate overall assessment may impair the operator's situation awareness and ability to respond to transients and accidents.

Improper Integration and Presentation of Numerical Data – Digital displays can summarize and combine numerical data from a wide range of sources and present them in new ways, such as calculating simple, weighted, and running time-interval averages; summed values; and differences between values. If properly implemented, these displays can support an operator's understanding of the plant. However, the improper presentation of integrated data from the plant may confuse or mislead operators. Operators may not fully understand the nature of the data that are contained in the display, the data used in calculations, or the calculations. These factors may also interfere with the operator's ability to verify displayed values against other data from the plant. For example, a digital SPDS display may present the average of a set of redundant wide-range measurement instruments, rather than presenting the individual values. If the average is carried out to one or more decimal places, it may appear to have the accuracy of a narrow-range measurement instrument and, thus, may mislead the operator. As another example, a polar-graphic display (e.g., octagon) may plot the current value of a variable against a reference value. However, the basis for determining the reference value may not be apparent to the operator.

Once the trends in HSI design and the potential human performance issues associated with them were identified, each trend (O'Hara, Stubler, and Higgins, 1996), was evaluated for its potential safety significance. The evaluation indicated that display design and organization was potentially safety significant and that further research was needed (Stubler, Higgins, and O'Hara, 1996). That research is the subject of this report.

1.2 Scope of the Research

The literature addressing the design of information systems is extensive. Reviewing all of it was well beyond the scope of the project. Therefore, we focused our efforts on those aspects of information system design that are most relevant to the nuclear industry, where the research is most active, and where the results are reflected in actual NPP design efforts: information requirements, representation, and organization. Information requirements refer to what information operators need to safely and efficiently operate the plant. This is a vital step in design of information systems and recent approaches to its analysis, such as ecological interface design approaches that largely stem from the nuclear and process control industries, promise to enhance the analysis of information needs (e.g., Vicente and Rasmussen, 1992).

Information representation refers to how the needed information is displayed in the control room. The development of novel graphical means to represent information in a format that supports immediate and accurate understanding of plant conditions has a long history in the nuclear industry stemming from the use of simple polargraphic displays for safety information (e.g., Woods, Wise, and Hanes, 1981) to more recent efforts to represent the thermodynamic state of the plant using graphic displays based on the Rankine cycle (Beltracchi, 1995).

Finally, structure is imposed on the information representations by organizing them into display pages and the pages into an entire display network. This is a significant issue in process control facilities, because the networks

may contain hundreds or even thousands of display pages (O'Hara, Stubler, and Higgins, 1996). While this aspect of information system design has been generally neglected, recent research suggests that organization is significant to operator performance, and some common organizational schemes can make it difficult for operators to perform their tasks (Heslinga and Herbert, 1995).

The specific information determined to be needed by operators, its representations, and its organization into an entire information network can significantly impact operator performance and nuclear safety.

1.3 Organization of the Report

The report is divided into two parts. Part 1 describes the guidance development methodology and basis. The objectives of the study are described in Section 2, and the guidance development methodology is described in Section 3. Section 4 presents a characterization of information systems. Section 5 discusses the literature and information that served as the technical basis upon which the review guidance was developed. The actual use of the technical information to develop guidance is discussed in Section 6. Section 7 summarizes the guidance development. References are in Section 8.

Part 2 contains the results of the process for formulating the guidance, and is presented in two sections. Section 9 discusses the design process considerations for reviewing information systems, and Section 10 contains the HFE design guidelines for the review of an implemented information system design.

2 OBJECTIVE

The objective of this study was to develop HFE review guidance for information systems – specifically with respect to information requirements analysis, information representation, and information organization – based on a technically valid guidance development methodology. To support this objective, the following tasks were undertaken:

- Development of a characterization framework for describing key design characteristics of information systems
- Development of a technical basis using research and analyses of human performance that are relevant to information systems
- Development of HFE review guidelines for information systems in a format that is consistent with NUREG-0700, Rev. 1, and other NRC review guidance
- Identification of remaining information system issues for which research results were insufficient to support developing NRC review guidance

3 METHODOLOGY

3.1 Overview

Figure 3.1 shows the methodology for the overall guidance development for NUREG-0700. The process for this development is discussed in detail elsewhere (O'Hara, Brown and Nasta, 1996). The methodology that applies to this report and project is boxed in the figure. This section describes the rationale for general guidance development.

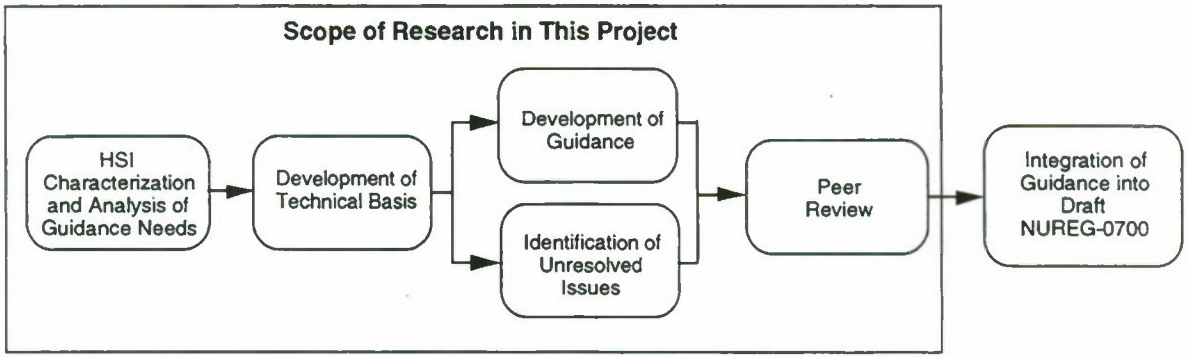


Figure 3.1 Major Steps in Developing NUREG-0700 Guidance

The methodology was guided by the following objectives:

- Establish a process that will result in valid, technically defensible, review criteria.
- Establish a generalizable process that can be applied to any aspect of HSI technology for which review guidance is needed.
- Establish a process that optimally uses available resources, i.e., develop a cost-effective methodology.

The methodology places a high priority on establishing the validity of the guidelines. Validity is defined along two dimensions: internal and external validity. Internal validity is the degree to which the individual guidelines are based on an auditable technical basis. The technical basis is the information upon which the guideline is established and justified. The technical bases vary for individual guidelines. Some guidelines may be based on technical conclusions from a study of empirical research, some on a consensus of existing standards, while others are based on judgement that a guideline represents good practices based on the information reviewed. Maintaining an audit trail from each guideline to its technical basis serves several purposes by enabling the following:

- Technical merit of the guideline to be evaluated by others
- A more informed application of the guideline since its basis is available to users
- Deviations or exceptions to the guideline to be evaluated

External validity is the degree to which the guidelines are independently peer reviewed. Peer review is a good method of screening guidelines for conformance to accepted HFE practices and for comparing guidelines to the practical operational experience of HSIs in real systems.

For individual guidelines, these forms of validity can be inherited from the source documents that form their technical basis. Some HFE standards and guidance documents, for example, already have good internal and external validity. If validity is not inherited, however, it should be established as part of the process for guidance development. Methodology was established to provide validity both inherited from its technical basis and through developing and evaluating guidance.

Figure 3.2 shows the process used to develop the technical basis and guidance. The process emphasizes information sources that have the highest degree of internal and external validity for developing the technical basis. Thus, primary and secondary source documents were sought as sources of guidance first, followed by tertiary source documents, basic literature, industry experience, and other sources. From these, we identified design principles and lessons from industry experience. Using this technical basis as a foundation, the guidance was developed. For specific aspects of the topic, in which the technical basis was inadequate for developing guidance, we defined unresolved research issues. Thus, the technical basis led to the development of both guidance and issues. The resulting guidance documentation includes HFE guidelines, technical basis, the development methodology, and unresolved research issues.

Each of the steps of this research – topic characterization, development of technical basis, guidance development and documentation, identification of issues, and peer review – is discussed in greater detail in the sections that follow.

3.2 Characterization of the Information System

The first step in developing guidance was to identify the areas for which it was needed. We reviewed existing information systems to identify the dimensions and characteristics along which information systems can be defined. The characterization was important because it provided a structure within which the reviewer could request information about a system and with which to structure the guidance for design review. The characterization of information systems is presented in Section 4 .

3.3 Development of the Technical Basis

We began to formulate detailed review guidelines by collecting technical information on which guidance would be based (Figure 3.2). The process was designed to formulate valid guidance cost effectively. First, primary source documents, HFE standards and guidance documents possessing internal and external validity, were sought. That is, the primary source documents generally provided their own research bases, and the document developers considered the available research and operational experience. Using their knowledge and expertise, they developed HFE guidelines. These primary source documents were often extensively peer reviewed. The documents added tremendous value to individual research reports. They were developed by experts who consider research in terms of its applicability and generalizability to real systems, include knowledge and expertise gained through operational experience and guidance application, and modify the guidance based on extensive peer review.

However, we found little information that addressed advanced display design. While several documents address display design in nuclear plants, their applicability and guidance for advanced display systems is limited. These documents are

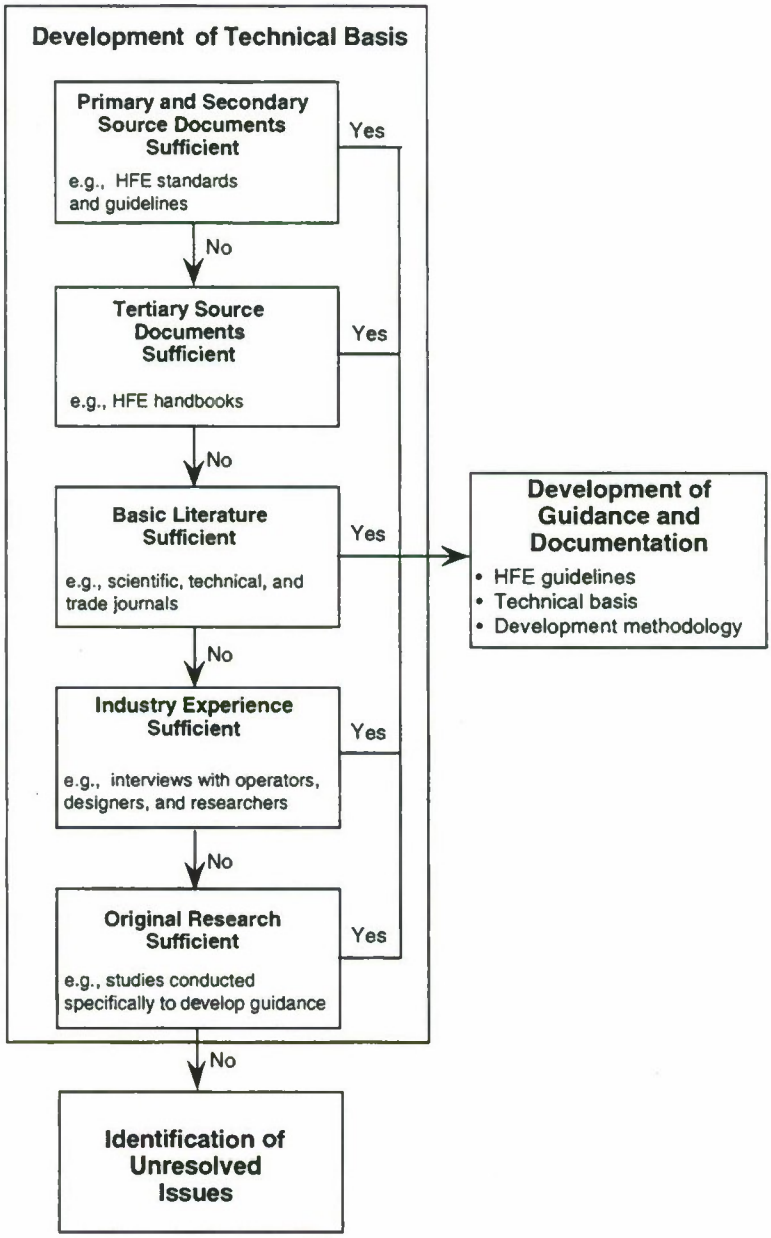


Figure 3.2 Process for Developing Technical Basis and Guidance

- Electric Power Research Institute's Advanced Light Water Reactor Utility Requirements Document (URD) (EPRI, 1993)
- International Electrotechnical Commission's (IEC) Design for Control Rooms of Nuclear Power Plants (IEC-964) (IEC, 1989)

- Institute of Electrical and Electronics Engineers' (IEEE) Guide for the Application of Human Factors Engineering in the Design of Computer-Based Monitoring and Control Displays for Nuclear Generating Stations (Standard P1289) (IEEE, 1996)

Section 10.4.4, Displays, of the EPRI URD addresses display requirements in advanced NPPs. Requirements are identified for trend displays, integrating displays and mimics (similar to group view displays discussed in Stubler and O'Hara, 1996), and electronic displays at workstations. However, the URD does not address specific formats or how displays should be organized. It states that the detailed design of displays should be tested using simulation.

Section 4.6, Information Systems, of IEC-964 discusses displays in general and refers to Appendix A Section A.4.6, Information Systems, for more details. However, neither section gives more than high-level principles, such as the need for consistency, and they do not address specific requirements for individual display formats, or the organization of information within the network.

IEC-964 also contains a supplement on "Visual Display Unit Application to Main Control Room in Nuclear Power Plants." The supplement gives applications, advantages, and disadvantages of alphanumerical displays, bar graphs, trend curves, system status displays, and logic displays. However, there is no detailed guidance for any formats, and more advanced displays and organization are not addressed. IEC-964, like the URD, requires simulator testing as part of the verification and validation (V&V) for advanced VDU-based systems.

Section 6, Typical Display Format Types, of IEEE-P1289 addresses graphs, mimics, logic displays, faceplate displays, alphanumeric displays, and integrated displays and discusses the application, advantages and disadvantages of each. The integrated display refers to a display that integrates several types of displays within a single one and should not be confused with an integral display.

Thus, the scope of these documents is addressed in NUREG-0700, Rev. 1 (Section 5.1 addresses the scope of NUREG-0700 guidance), and therefore, guidance for more advanced information systems, the focus of our current research, is not addressed. Consequently, while developing a technical basis for information systems we considered the other sources shown in Figure 3.2. Secondary sources were documents for which either internal or external validity was established. Documents for which neither type of validity was established were considered tertiary sources. The preference was to use documents for which validity had been established.

This information includes the results from basic literature that we analyzed. While the information pertaining to advanced information systems was limited in current standards and guidance documents, the situation is completely reversed in the basic literature. The literature is extensive; therefore, we focused on using published literature reviews where available, and supplementing them with more recent published accounts of individual studies.

When guidance was based on basic literature, engineering judgement was required to generalize from the unique aspects of individual experiments and studies to actual applications in the workplace. This is because individual experiments have unique constraints that limit their generalizability (such as their unique participants, types of tasks performed, and types of equipment used). For example, laboratory experiments often do not involve tasks of the complexity of NPP operations, and most experiments do not examine tasks under the same performance shaping factors (such as rotating shifts, stress, and fatigue) that exist in a work environment. While information from research is a valuable part of developing guidance, it usually cannot be blindly adopted. Thus, the results must be interpreted in the context of real-world tasks and systems, which involves judgement based on professional and operational experience.

Industry experience also was used, such as published case studies and surveys and interviews with knowledgeable domain experts. Site visits and interviews with operators, trainers, and designers were conducted as part of an earlier phase of this project, and pertinent information from that effort was used. Although such information may lack a rigorous experimental basis (and thus, a measure of validity), it is highly relevant.

Finally, some information was identified in original research. A full account of the research is published elsewhere (Roth and O'Hara, 1998). Original research has the advantage of enabling a study to be focused on the specific issues that need to be addressed in guidance development. However, because of the time and resources required to conduct original research, it is only used when important information is needed that cannot be obtained through other means.

Empirical evaluations of information systems and characteristics provided a substantial portion of the technical basis upon which to develop design review guidance. The general criteria by which such studies were evaluated will be briefly described. One of the most important considerations is that the information system studies provided a basis from which conclusions can be generalized beyond the specific individual study. To make this evaluation, the studies were considered within the context of validation studies where generalization (external validity) is a primary consideration.

O'Hara et al. (1997) discussed the detailed methodological considerations for validation of complex human-machine systems. A conceptual approach to validation was developed that identified important validation principles and their relationships. The general concepts are concerned with (1) establishing the requirements for making a logical and defensible inference from validation tests to predicted integrated system performance under actual operating conditions, and (2) identifying the aspects of validation methodology that are important to the inference process. The technical basis for inference in validation is based upon four general forms of validity: system representation, performance representation, test design, and statistical conclusion.

System representation validity refers to the degree to which the tests include those aspects of the system that are important to real-world conditions. Specifically, this validity is based on the representativeness of the system model, human-system interface, personnel, and operational events. The inference process is supported to the extent that important aspects of the integrated system are represented with high fidelity, and to the extent to which important contributors to potential variability in system performance have been adequately sampled.

Performance representation validity refers to the completeness and representativeness of the performance measures. A comprehensive, hierarchal approach to evaluation guided by supervisory control theory may be used to specify important aspects of performance ranging from operator cognitive processes to system functions. In general, the effects can be related to (1) *personnel role* – a change in functions and responsibilities of plant personnel; (2) *primary tasks* – a change in the way that personnel perform their primary tasks, such as process monitoring, situation assessment, response planning, and response implementation and control; (3) *secondary tasks* – a change in the tasks the operator must perform when interacting with the information system, such as navigating through displays and searching for data; (4) *cognitive factors* – such as a change in cognitive workload; and (5) *personnel factors* – a change in the required qualifications or training of plant personnel. Performance measures must be used that can address these effects. Failure to include measures of all important performance variables, poor measurement properties, and poorly specified criteria weaken this validity and the ability to generalize the results.

Test design validity addresses the experimental design and test procedures. Experimental design considerations address the suitability of the definitions of independent variables. Inappropriate test procedures can bias the relationship between the observations of performance and the integrated system, and thus undermine their causal

linkage. When factors introduced by the test methodology weaken the ability to interpret the system-performance correlation, validity is compromised.

Finally, statistical conclusion validity addresses the relationship between the observed data and established criteria of performance.

While the studies reviewed in Section 5 were evaluated for these types of validity and their associated methodological considerations, such an analysis is limited by the extent to which the studies are documented.

3.4 Development of Guidelines and Documentation

Once the technical information was assembled, a draft set of guidelines, which are in Part 2, was developed from the information in the technical basis. The guidelines were organized and specified in a standard format (which is discussed in Section 6).

3.5 Identification of Issues

Where there was insufficient information to provide a technical basis upon which to develop valid design review guidance, an issue was defined. Section 7 describes these issues.

From a research standpoint, issues reflect aspects of the design and use of information systems that will require additional investigation to resolve. From a design review standpoint, issues reflect aspects of design and use that will have to be addressed on a case-by-case basis. For example, an issue can be addressed as part of design-specific tests and evaluations.

3.6 Peer Review

The resulting technical basis and guidance was submitted for review by individuals with knowledge and expertise related to the review topic. Included were reviews by personnel from the U.S. NRC with expertise in HFE and engineering fields directly related to the topic. Human factors specialists who are external to the NRC and have expertise in human performance in complex systems, such as NPPs and aviation, conducted additional reviews. These external reviews include evaluations of the topic characterization along the criteria of clarity, accuracy, and completeness, and the technical basis along the criteria of organization, necessity, sufficiency, resolution, and basis. Comments from the peer reviews were incorporated into the current version of this document.

4 CHARACTERIZATION OF INFORMATION SYSTEMS

The plant information system refers to those aspects of the HSI that give information to the operator about the plant state. NUREG-0700, Rev. 1 provided a preliminary characterization of information system components. In this section, that characterization is made more definitive and expanded to accommodate the results of this research.

An information system has the following major components: information requirements, representation system, management functions, and display devices. Each is briefly described below. This section gives a general characterization of information systems, whether they are advanced or not. The term advanced, as used in this report, refers to information systems that use novel graphic forms, such as a Rankine Cycle display, and go beyond conventional forms, such as bar charts and trend graphs. This general characterization is consistent with other approaches to define the hierarchical organization of information and display systems (e.g., Woods et al., 1991).

This report addresses the first two aspects of the characterization: information requirements and representation systems. The topic of management functions is being addressed in another NRC research project because of its general applicability to human-computer interfaces, such as soft controls and computer-based procedures, in addition to information systems. The topic of display devices is hardware related and is being considered separately.

4.1 Information Requirements

Information requirements refer to the information operators need to monitor and control the plant. Information is at the center of human functions in any complex system. The operators' information needs are the requirements that must be addressed in the design of the information system. The determination of what information is needed is referred to as information requirements analysis. New approaches to information analyses conducted to define the information requirements of display systems have emerged and will be discussed in Section 5.3.

4.2 Representation System

While the information requirements identify what information operators' need, the way in which that information is presented to operators is called the representation system. Information is given to the operators via some sensory channel. In a nuclear plant, it is predominantly the operator's visual and auditory channels that are used to convey information about the plant. The representation system is the means by which information is communicated to operators; it contains the following components: elements, formats, pages, and networks. Each is discussed below. Figure 4.1 shows the representation system (along with management functions and display devices).

Display Elements

Display elements refer to the basic building blocks that are used to make up display formats, such as abbreviations, labels, icons, symbols, coding, and highlighting.

Display Format

Display formats refer to the general class of information presentation. Examples of general classes are continuous text (such as a procedure display), mimics and piping and instrumentation diagram (P&ID) displays, trend graphs, and flowcharts. This aspect of representation systems has been most affected by recent trends in design of information systems. The ability of computer graphics to portray an essentially limitless set of novel graphic forms has offered great possibilities to provide operators with enhanced representations of the plant. Woods et al. (1991)

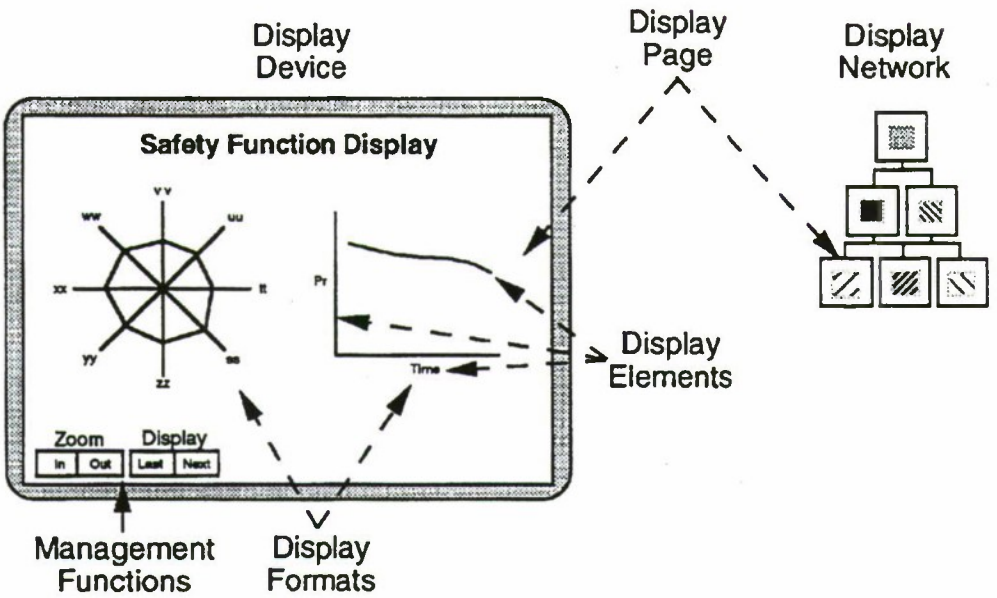


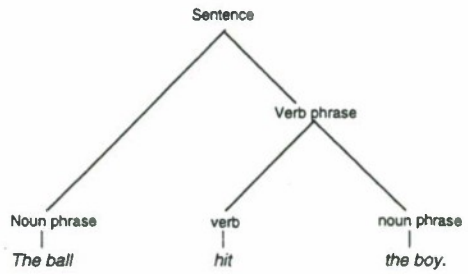
Figure 4.1 Display System Characterization
(Information requirements not shown.)

refer to this level as "Graphic Forms" and consider it the "fundamental hinge in the series of levels." The same can be said of display formats in the current characterization. Below this level, the characterization seeks to define the building blocks of display formats. Above this level, formats are successively organized into pages and then into networks. Thus, display formats, which are discussed in Section 5.4, are the most significant "unit of analysis" of the information system.

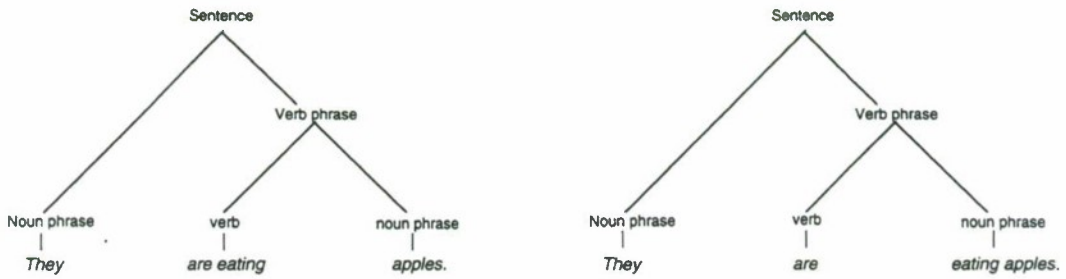
There is a grammatical aspect of display formats similar to human language. In both cases the grammar describes the relationship between the physical form (e.g., sentence or visual aspects of a graphic display) and its meaning. The link between physical form and meaning is made using transformation rules. To illustrate this point, an example from linguistics is described, followed by an example from graphic displays. Figure 4.2 shows the link between a sentence and its meaning through transformational rules. Panel (a) in Figure 4.2 shows the case where the physical form (sentence) is unambiguously linked to meaning (i.e., the sentence form has only one grammatical meaning). However, some sentence structures are ambiguous; i.e., the same physical form (sentence) can lead to more than one meaning (see panel (b) Figure 4.2). The left sentence is about apple eaters, while the right describes a type of apple that is suitable for eating.

Just as the same sentence can have two distinct meanings, two very different sentence structures can have the same meaning. Thus, there is not always a one-to-one mapping between the physical form and semantics.

Similar relationships can exist between a graphic display and its meaning(s). "Display semantics" pertains to the meaning of the display form for the plant (see Figure 4.3). The semantics must consider the instrumentation and the data processing that are used to drive its format. Thus, the display's grammar describes the correspondence between the display and the aspects of the system it represents by relating its physical form and functions to its meaning to the plant's functions and states. There are syntactical rules that relate the display form and its semantics.

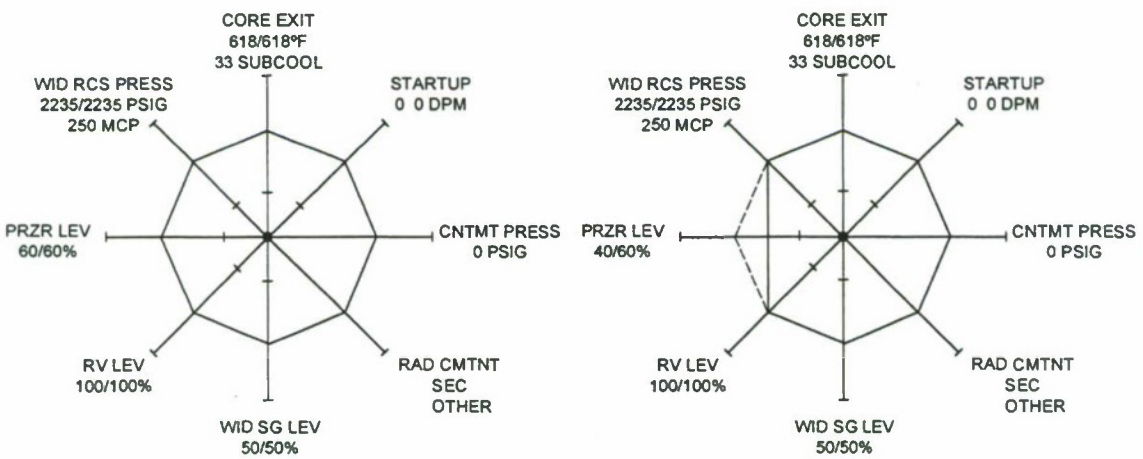


(a) Unambiguous Sentence



(b) Ambiguous Sentence

Figure 4.2 The Relationship Between Surface Structure and Sentence Meaning
(Adapted from Reynolds and Flagg, 1977)



(a) (b)

Figure 4.3 The Relationship Between Surface Structure and Semantics in Display from a Loss of Coolant Accident (LOCA) in a Pressurized Water Reactor (PWR)

(Source: Reprinted with permission from Woods, D., Wise, J., and Hanes, L., "An Evaluation of Nuclear Power Plant Safety Parameter Display Systems," *Proceedings of the Human Factors Society 25th Annual Meeting*. Copyright 1981 by the Human Factors and Ergonomics Society. All rights reserved.)

In the display's design, it is important to have a unique meaning for each form. Just as the surface structure of language can be ambiguous with regard to its semantics, so can a display's form. If a display can lead to more than one interpretation, it is ambiguous and can be more easily misunderstood. The meaning of graphic format in Figure 4.3 (from Woods et al., 1981) shows this. Figure 4.3 (a) is an example of a polargraphic, iconic display developed to provide a NPP operator with a high-level overview of the status of plant safety functions. The display is driven by eight parameters (that correlate to the plant safety functions). Each parameter is represented by a spoke on the format. The full scale of the parameters' values are displayed over the length of the spoke, between the two tick marks. Points representing normal conditions are plotted as fixed points equidistant from the center of the figure. Connecting the points results in a regular geometric pattern, an octagon. The reference points are dynamically scaled, so that the reference octagon remains regular. Parameters that are higher than normal are plotted further away from the center, and those that are lower are plotted closer to the center.

When a disturbance occurs, the individual parameter values being monitored as representative of safety functions change. This changes the points on the spokes, and hence, a new "distorted" polygon is drawn. Figure 4.3 (b) shows a case where the pressurizer level decreased from the normal value of 60% to 40%. However, this situation can have more than one interpretation. For example, this decrease may be due to a leak and subsequent loss of water from the primary system, a failure of the normal pressurizer level control system, or a failure of the pressurizer level instrumentation. Thus, the same physical form can lead to distinctly different meanings.

This type of grammatical relationship does not only apply to graphic displays, although the rules for graphic displays may generally be more complicated. One of the lessons from the Three Mile Island (TMI) accident was that the display's grammar can be significant even for simple displays. The control board at TMI contained a light indicating the position of a relief valve on the pressurizer. Operators thought that the valve was physically open when the light was on and closed when it was off. However, the true meaning of the display was that the valve solenoid operator was either energized or not. During the accident, the relief valve was actually stuck open and not closed as the operators thought, even though the indicator light had gone out. There was a disconnect between the display form, the status indicator, and its meaning (solenoid energized) that contributed to a significant misunderstanding about the plant.

A polargraphic display similar to that shown in Figure 4.3 also can be useful for analysis during major transients and accidents. In this case, the semantics of the display are more involved. Figure 4.4 shows the figure resulting from a significant loss of coolant accident (LOCA) in a pressurized water reactor (PWR). In a LOCA, a major pipe break occurred in the primary system, resulting in a large loss of radioactive reactor coolant to the containment's atmosphere. In Figure 4.4, pressurizer (PRZR) level, reactor vessel (RV) level, and reactor coolant system (RCS) pressure decreased due to the water leak. Core exit temperature increased from the loss of water and resultant lack of cooling to the reactor fuel. Containment pressure also increased due to the high pressure/high temperature steam and water mix flowing into the containment from the RCS. The radiation level in the containment also increased due to radioactive water and steam in containment. As shown in Figure 4.3 (b), as the values of the individual parameter change, the polygon distorts. For the LOCA situation, the amount of distortion indicates a large deviation in many parameters from normal (still indicated by the dotted regular octagon). However, the operator cannot draw any specific conclusions from the shape of the polygon, but rather must think about the meaning of each parameter's deviation and then about what they mean in the aggregate. This requires substantial training and is aided by detailed emergency procedures.

For any information display format, it is important to clearly understand all three components of the display's grammar: the format itself, its semantics or meaning, and the rules that relate the two.

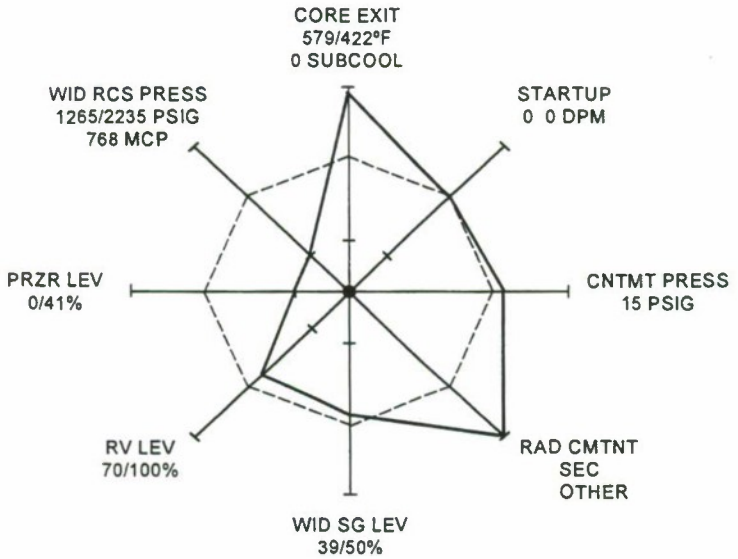


Figure 4.4 An Example of More Complex Display Semantics from a Loss of Coolant Accident (LOCA) in a Pressurized Water Reactor (PWR)

(Source: Reprinted with permission from Woods, D., Wise, J., and Hanes, L., "An Evaluation of Nuclear Power Plant Safety Parameter Display Systems," *Proceedings of the Human Factors Society 25th Annual Meeting*. Copyright 1981 by the Human Factors and Ergonomics Society. All rights reserved.)

Display Pages

Display page refers to a defined set of information that is intended to be displayed as a single unit. Typical display pages of NPPs may combine several different formats on a single VDU screen, e.g., combining bar charts and digital displays in a graphic P&ID format.

What goes into one display page, i.e., the integration of formats that make up the page, is typically meant to show some aspect of the process. For example, one page may provide a high-level status overview of the primary system.

Display pages typically have a label and designation within the computer system so they can be accessed by operators as a single "display." Section 5.5 addresses display pages.

Display Networks

Complex systems, such as NPPs, are not represented by a single graphic display. In fact, for many recently built plants, the numbers of display pages is more typically in the hundreds or thousands (O'Hara, Stubler, and Higgins, 1996). Display networks refer to an entire set of display pages within an information system.

To perform their functions and tasks, operators must access these pages. When the number of pages is large, knowing where information is located is difficult. Thus, the organizational structure of the network within the information system is an important consideration. A common type of organizational structure, for example, is by plant system. Section 5.5 addresses display networks.

4.3 Management Functions

As discussed above, display networks can include hundreds or more pages. Further, the information may be visible within a limited display area provided by video display units (VDUs). Thus, facilities, such as navigating within the display network to retrieve displays, to manipulating display pages (such as sizing or moving windows), and moving within a single display page (such as scrolling and zooming), are needed so that operators can manage the information. Generically, these are called interface management functions. While they are important considerations in information system design, they will not be addressed in this report. Interface management is being addressed in a separate project (O'Hara, Stubler, and Nasta, 1997).

4.4 Display Devices

Display devices are the media used to present information to plant personnel. Display devices include meters, gauges, VDUs, and hard-copy display devices (printers and plotters). NUREG-0700, Rev. 1 contains HFE guidance for the characteristics of these devices, such as resolution and viewing angle, that are important to crew performance. However, technology or new display devices, such as flat panel displays, is emerging and their characteristics are discussed separately (O'Hara, Stubler, and Higgins, 1996). Thus, like interface management, display devices are an important aspect of information systems, but they will not be addressed here.

4.5 Relationship to Other Aspects of HSIs

The relationship between the design features and functions of the information system and that of the other aspects of the HSI should be addressed. Modern information systems may be integrated with other HSI subsystems, such as plant controls. For example, controls may use on-screen representations that provide information through which operators can control the plant. These types of controls are referred to as soft controls. Features and functions of soft control and their impact on the design of information system is addressed elsewhere (Stubler, O'Hara, and Kramer, 2000).

Information systems also may be integrated with plant procedure systems, especially when the procedure systems are computer-based. Procedure systems that are computer-based may be fully integrated with the information system. For example, data comparisons required for evaluating procedure-step logic may be presented using trend graphs provided by the information system for that and other purposes as well. In addition, the procedure system may share the same display devices and interface management functions. Procedure systems that are computer-based and their impact on the design of information systems also is addressed elsewhere (O'Hara, Higgins, Stubler, and Kramer, 2000).

5 DEVELOPMENT OF TECHNICAL BASIS

The purpose of this section is to establish a technical basis upon which to develop review guidance for information systems and to identify human performance issues where the technical basis is insufficient for developing guidance. The review begins with a discussion of the NRC's current approach for reviewing the design of information systems (Section 5.1). This discussion provides a baseline against which new research can be compared to determine whether new guidance is necessary based on recent advances in these areas.

In Section 5.2, the generic cognitive tasks of operators are discussed to define the general scope of activities that an information system must support. Section 5.3 addresses the recent approaches to analyzing information requirements. These approaches are evaluated for their research support as well as their contribution to the NRC's existing guidance on design review. Information representation (Section 5.4) and organization (Section 5.5) are addressed next. Section 5.6 summarizes the results and conclusions.

5.1 Existing NRC Guidance for Information Systems

The NRC's approach to the review of information system requirements analysis, representation design, and evaluation will be discussed to form the basis against which to evaluate recent approaches to these topics.

Nuclear plants, like other complex human-machine systems, are generally governed by applied general systems theory (Bailey, 1982; DeGreen, 1970; Gagne and Melton, 1988; Van Cott and Kinkade, 1972; Woodson, 1981). Systems engineering has been defined as "the management function which controls the total system development effort for the purpose of achieving an optimum balance of all system elements. It is a process which transforms an operational need into a description of system parameters and integrates those parameters to optimize the overall system effectiveness" (Kockler et al., 1990). Developing a complex system begins with the mission or purpose of the system and the requirements needed to achieve the mission's objectives. The effective integration of HFE considerations into the design is accomplished by providing (1) a structured top-down approach to system development that is iterative, integrative, interdisciplinary, and requirements-driven, and (2) a management structure that details the HFE considerations in each step of the overall process.

The systems engineering approach has been used as the basis for many HFE design approaches developed by the NPP industry (EPRI, 1992; IEC, 1989; IEEE, 1988). This approach forms the basis of the NRC's review HFE methodology as well, e.g., NUREG-0711 (O'Hara, Higgins, et al., 1994) and NUREG-0700, Rev. 1. The key elements of this approach will be briefly described to understand the approach to the development of information systems. (While the key elements are essentially the same across the different documents, some of the specific details are slightly different. See Welch and O'Hara (1996) for a detailed discussion of systems engineering as it relates to NUREG-0711). The systems approach addresses all aspects of system design; however, there are six that are important to developing information systems: operating experience review, functional requirements analysis, task analysis, human reliability analysis, HSI design, and verification and validation.

Operating Experience Review

The objective of an operating experience review (OER) is to ensure that HFE-related problems and issues encountered in previous designs that are similar to the current design were identified and analyzed, so that they are avoided in developing the current design, or in the case of positive features, to ensure that they are retained.

An effective OER conducted on plants and systems that are similar to one under design will identify information requirements needed for the operators to properly perform their tasks. In particular, an OER can identify problem areas with current designs that led to incidents, and which can be addressed at the design stage.

5 DEVELOPMENT OF TECHNICAL BASIS

Functional Requirements Analysis and Function Allocation

Functional requirements analysis consists of identifying functions that must be undertaken to satisfy plant productivity and safety objectives, e.g., to prevent or mitigate the consequences of postulated accidents that could cause undue risk to the health and safety of the public. Function allocation is the analysis of the requirements for plant control and the assignment of control functions to personnel, system elements, and combinations of personnel and system elements.

The term function may be used in different ways by plant designers. It can refer to very high-level plant functions, such as critical safety functions, or the functioning of an individual piece of equipment, such as a valve or a wall-panel information display system. The former is meant here. Therefore, a function is an action that is required to achieve a desired goal. A high-level objective, such as preventing the release of radioactive material to the environment, is one that designers strive to achieve through implementing other more specific, high-level functions. Designers will strive to achieve these high-level functions through the design of the plant, and plant operators will strive to achieve them through the proper operation of the plant. Examples of these functions are reactivity control, containment integrity and control of RCS water mass inventory.

The high-level function may be described without reference to specific plant systems or to the level of human or machine intervention that is required to satisfy the function. High-level functions are usually accomplished through some combination of lower-level system actuations, such as reactor trip, safety injection, or accumulators. Manipulating lower-level systems to satisfy a higher-level function is defined here as a control function. Often plant systems are used in combination to achieve a higher-level function.

The requirements of these functions are analyzed to (1) determine the objectives, performance requirements, and constraints of the design; (2) define the high-level functions that must be accomplished to meet the objectives and required performance; (3) define the relationships between high-level functions and plant systems (e.g., plant configurations or success paths) responsible for performing the function; (4) provide a framework for understanding the role of controllers (whether personnel or system) for controlling the plant. Some of the relevant NUREG-0711 considerations for function analysis and decomposition include the following:

- The functional requirements and allocation analysis should be kept current throughout the development of the design and held until decommissioning so that it can be used as a design basis when modifications are considered. Control functions should be reallocated iteratively, in response to developing design specifics, operating experience, and the outcomes of ongoing analyses and trade-off studies.

- The functions and systems should be described. For each safety function, the set of plant system configurations or success paths that are responsible for or capable of carrying out the function should be clearly defined. Functions should be diagramed at several levels, starting at "top-level" functions, where a very general picture of major functions is described, and continuing to lower levels until a specific critical end-item requirement emerges (e.g., a piece of equipment, software, or an operator). The functional decomposition should address the following levels: (1) high-level functions (e.g., maintain reactor coolant system [RCS] integrity) and critical safety functions (e.g., maintain pressure control of the RCS) and (2) specific plant systems and components.

- Each high-level function should be described; the descriptions should include:
  - Purpose of the function
  - Conditions that indicate that the function is required
  - Parameters that indicate that the function is available
  - Parameters that indicate that the function is operating (e.g., flow indication)
  - Parameters that indicate that the function is achieving its purpose (e.g., reactor vessel level returning to normal)
  - Parameters that indicate that operation of the function can or should be terminated

Some of the functions are allocated completely or in part to plant personnel. The functions undergo additional analyses to determine human task requirements.

Task Analysis

Task analysis is the evaluation of the performance demands on plant personnel to identify the task requirements for accomplishing the functions allocated to them (Drury et al., 1987). It is a very important activity because it defines the HSI requirements for accomplishing tasks, including information requirements. Although there is no precise definition of a task with respect to the level of abstraction, a task is a group of related activities that have a common objective or goal.

Again, as in functional requirements analysis, decomposition into ever increasing levels of detail is necessary. Task analyses should begin on a gross level and involve developing detailed descriptions of what personnel must do. The nature of the input, process, and output required by and of personnel should be defined. For information requirements analysis, the detailed description of tasks should include the following:

- Gathering Information
  - Information required (e.g., parameters, units, precision, accuracy)
  - Information source (e.g., alarm, displays, verbal communication)
- Requirements for Decision Making
  - Description of the decisions to be made (relative, absolute, probabilistic)
  - Evaluations to be conducted
  - Decisions that are probable based on the evaluation (opportunities for cognitive errors, such as capture error, will be identified and carefully analyzed)

- Requirements for Response
  - Action to be taken
  - Overlap of task requirements (serial vs. parallel task elements)
  - Frequency
  - Time available for operator response based on characteristics of plant response
  - Temporal constraints (task ordering)
  - Tolerance and accuracy
  - Operational limits of personnel performance
  - Operational limits of machine and software
  - Body movements required by action taken
- Requirements for Feedback
  - Feedback required to indicate adequacy of actions taken

The task analysis should be iterative and become progressively more detailed over the design cycle. Sufficient detail is necessary to identify information and control requirements to enable specification of detailed requirements for HSI resources, such as alarms, displays, data processing, and controls.

Based on its use of functional decomposition and analysis of cognitive requirements (information gathering, decision making, response, and feedback), NUREG-0711 is consistent with recent approaches to cognitive task analysis (e.g., Roth and Mumaw, 1995).

Human Reliability Analysis

The objective of the human reliability analysis (HRA) of the HFE design is to ensure that potential effects of human error on plant safety and reliability were analyzed, that human actions important to plant risk were identified, and that human error mechanisms were addressed in the design of the HSIs, to minimize the likelihood of personnel error and to provide for error detection and recovery capability.

The HRA element of NUREG-0711 that is especially pertinent to developing information requirements is the area of risk-significant human actions. The HRA will develop those operator actions that are especially significant to risk. These actions are often associated with low-probability and high-consequence sequences of events. These actions may relate to activities that only are needed once certain failures and transients have already occurred. As a result, they would not typically be a part of task analyses that are done during the usual design process. Thus, consideration of these risk-significant human actions will often add more controls, displays, or alarms that would not have otherwise been included.

HSI Design

The HSI design process, as the term is used here, is the translation of function and task requirements into a detailed HSI design; that is, the specific design of the HSI resources identified above as well as their integration in CRs and other workplaces. This translation should be designed using a structured methodology that guides designers in the identification of what information and controls are required, the identification and selection of candidate HSI approaches, and the detailed design of the HSIs. Constraints imposed by the overall instrumentation and control (I&C) system should be considered throughout the design process.

The HSI design methodology addresses specific design activities, including:

- Development and use of guidelines for HFE design
- Functional requirement specification
- HSI concept design
- Detailed design and integration of the HSI
- Tests and evaluations of the HSI design process
- Documentation of final design

At this point the information system requirements have been defined and the representational aspect of the information system begins to be developed. Display formats are developed to meet the functional requirements with a design that reflects a combination of past operational experience (what types of formats were successful or unsuccessful), HFE guidelines, and prototype testing and evaluation.

Section 1, Information Display of Part 2 of NUREG-0700, Rev. I provides guidance for information system design review. It deals primarily with the review of visual displays, both text and graphics based. Guidance is provided in top-down fashion beginning with general display guidelines (Section I.I), and then finer levels of display details. Section I.2, Display Formats, addresses common display forms:

- Continuous Text Displays
- Tables and Lists
- Data Forms and Fields
- Bar Charts and Histograms
- Graphs
- Pie Charts
- Flowcharts
- Mimics and Diagrams

- Maps
- Graphic Instrument Panels
- Speech Displays

In addition to the display guidance in NUREG-0700, guidance for group-view displays, such as is in advanced CR wall panel displays, is available (Stubler and O'Hara, 1996).

A display format can be decomposed into a set of basic elements, such as alphanumeric characters, icons, symbols, color, highlighting, abbreviations, labels, coding, and presentation of numeric data. These are addressed in Section 1.3, Display Elements. Section 1.4 contains guidelines for reviewing the quality of data and display update rate. Section 1.5, Display Devices, addresses the hardware aspects of displays. Review guidelines are given for display devices, such as video display units, large panel displays, and hard-copy display devices (printers and plotters).

There are two significant shortcomings in the treatment of information representation: display formats do not correspond to these generic formats, and the organization of displays in a display network. For novel formats, i.e., formats not addressed in NUREG-0700, it was recommended that they be evaluated using the general display guidelines and the guidelines in Section 1.3, Display Elements. While this provides some support for design review, a review limited to these guidelines would fail to address important aspects of many novel designs, such as the relationship between their dynamic graphic elements and the underlying process dynamics that they are intended to represent. The organization of displays in an information network was not addressed at all.

HSI designs should be tested and evaluated throughout their development. This is especially important for designs that are not well defined by HFE guidance. NUREG-0711 addresses the methodology used for testing.

Verification and Validation (V&V)

V&V of HSI designs should be conducted to ensure the acceptability of the final design and to address any remaining issues. Because no one method is likely to be sufficiently comprehensive, a series of analyses may be done.

HSI Task Support Verification. This evaluation verifies that the HSI supports all identified personnel task requirements. This is determined by comparing the HSI design elements to the criteria defined by function and task analysis requirements. Problems are identified for (1) personnel task requirements that are not fully supported by the HSI, and (2) the presence of HSI components, which may not be needed to support personnel tasks.

HFE Design Verification. This evaluation verifies that the HSI is designed and implemented to account for capabilities and limitations of humans. This is determined by comparing the detailed HSI design to the criteria defined by HFE guidelines. Problems are identified if the design is inconsistent with HFE guidelines.

Integrated System Validation. This evaluation validates that the integrated HSI design enables tasks required for safe operation to be performed without imposing excessive workload. The performance criteria are derived from task, risk, and engineering analyses. Problems are identified if performance criteria are not achieved, or if the HSI imposes a high workload on plant personnel.

5.2 Cognitive Tasks Supported by Information Systems

The plant information systems provide the basis for operators to perform their role in the plant. In this section, we consider the general tasks that the information system must support. This is important in scoping out the range of cognitive activities that must be addressed in the design of information systems. This is not only important when considering requirements for design, but also for evaluating the results of research on displays for generalizability to the full range of NPP operations.

The operator's role in a NPP is that of a supervisory controller, i.e., the plant's performance is the result of the interaction of human and automatic control. Reason (1990) called this a complex multiple-dynamic configuration; in such settings, situation assessment and response planning can be difficult when things go wrong. In addition to failures of plant process, the automatic control systems and HSI also can fail. Thus, personnel must respond to failures in the plant and to the interfaces that communicate failures. One of the most significant aspects of the HSI in responding to process failures is the plant information system.

The operator's impact on plant functions, processes, systems, and components is mediated by a causal chain from the operator's physiological and cognitive processes, to operator task performance, and ultimately to plant performance through the operator's manipulation of the plant's HSI. Design of HSI, including displays, impacts plant's performance through personnel tasks in support of plant operations. The operator's role involves two types of tasks, primary tasks and secondary tasks. Primary tasks are those the operator performs as part of the functional role of supervising the plant. Operators may be required to take an action in support of the plant's performance of a higher-level function. Even when operators are not required to take an explicit action, they must monitor the performance of automatic systems and intervene when they fail or function unacceptably.

Primary tasks involve several generic cognitive tasks, i.e., situation assessment, monitoring and detection, response planning, and response implementation (Figure 5.1). When addressing primary tasks, these generic cognitive tasks are discussed rather than the detailed specific tasks, such as monitoring steam flow, starting pumps, and aligning valves.

Secondary tasks are those the operator must perform when interfacing with the HSIs or job performance aids, but which are not directed to the primary task (O'Hara, Stubler, and Nasta, 1997). Secondary tasks include navigating through an information system and manipulating windows on a VDU. To adequately perform their tasks, both primary and secondary, operators use their information processing resources, such as attention, reasoning, and memory.

The design of the information system affects each of the operator's generic cognitive primary tasks and the secondary tasks. In this section, we address situation assessment, monitoring, response planning, and response implementation.

5.2.1 Situation Assessment

When faced with an abnormal occurrence, operators actively try to construct a coherent, logical explanation to account for their observations. This cognitive activity, situation assessment, involves two related concepts: the situation model and the mental model. Operators develop and update a mental representation of the factors known, or hypothesized, to be affecting the plant's state at a given point in time. The mental representation resulting from situation assessment may be referred to as a *situation model*, the person's understanding of the specific current situation. The situation model is constantly updated as new information is received.

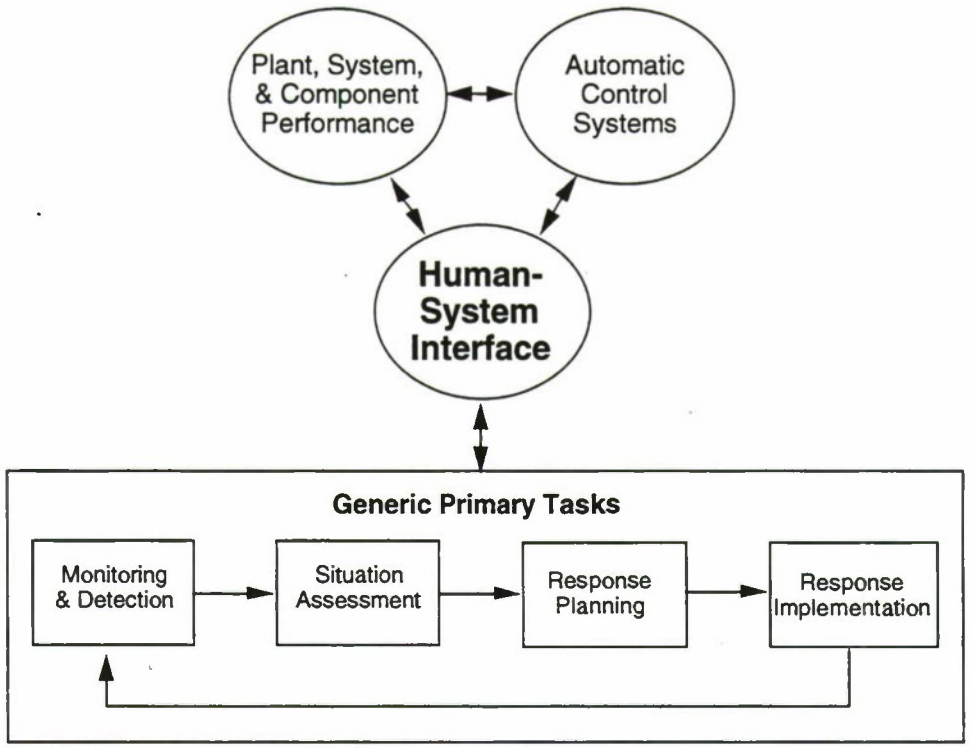


Figure 5.1 Generic Primary Tasks of a Supervisory Controller

To construct a situation model, operators use their general knowledge and understanding about the plant and how it operates to interpret the information they observe and understand its implications. Limitations in knowledge may result in incomplete or inaccurate situation models. The general knowledge governing the performance of highly experienced individuals may be referred to as a *mental model,* which constitutes the operator's internal representation of the physical and functional characteristics of the system and its operation. Mental models may not always be fully accurate or complete (Woods et al., 1994).

The mental model is built up through formal education, system-specific training, and operational experience. It is represented in the knowledge bases of long-term memory. An accurate mental model is generally considered a defining characteristic of expert performance (e.g., Wickens, 1984; Bainbridge, 1986; Moray et al., 1986; Rasmussen, 1983; Sheridan, 1976) and is extremely important to many aspects of information processing (discussed below). The mental model is thought to drive skill-based processing, control rule-based activity through the mediation of the operator's conscious effort in working memory, and provide the substantive capability to reason about and predict future plant states, which is required of knowledge-based processing (Rasmussen, 1983).

The distinctions between the mental and situation models reflect their cognitive underpinnings in long-term and working memory. The mental model is relatively permanent. By contrast, an operator's situation model is the current interpretation of the plant's status, and therefore, can be changed.

When the operator's situation model is an accurate reflection of the plant's actual state, an operator is said to have good *situation awareness*. Thus, the accuracy of situation awareness is a function of the degree of correlation between the operator's situation model and the actual plant conditions at any given time. An operator can have a good mental model (e.g., knowledge of how the plant functions), but poor situation awareness because the situation model does not match the current plant conditions. The process of situation assessment has been identified as the single most important factor in improving effectiveness of the crew in complex systems (Endsley, 1988).

For an experienced, well-trained operator, when the HSI can provide information that readily maps to knowledge in the operator's mental model, an accurate situation model is easily developed. To the extent that an easy match cannot be made between plant information and the situations defined in the mental model, situation assessment requires more working memory and attention, and cognitive workload will be high (Endsley, 1993, 1995; Fraker, 1988). However, in addition to supporting situation assessment, working memory also must support other activities, such as the selection and implementation of operator actions. Accordingly, if other tasks place high demands on working memory, situation awareness may suffer. On the other hand, the demands placed on working memory in maintaining situation awareness can be lessened if the situation is familiar (based on training or experience), and therefore, can be identified with a representation stored in long-term memory. In this case, it would not be necessary for the operator to maintain in working memory each detail of the situation.

Situation awareness and cognitive workload may vary inversely under complex, somewhat ambiguous situations. For example, under unfamiliar or otherwise difficult conditions, high cognitive workload may be associated with decreased situation awareness This may be due to a lack of available attentional resources for analyzing the situation. However, as Endsley (1993) points out, situation awareness and cognitive workload, while interrelated, may vary independently. For example, a task may be intensive, but readily recognizable. Situation awareness requires the expenditure of cognitive resources that contribute to workload, but it is not the only cognitive activity requiring such resources.

Thus, mental models enable operators to engage in situation assessment and to establish situation models. Another important aspect of mental models is that they enable operators to make predictions and form expectations that, in turn, guide monitoring and affect the interpretation of information. This is a general characteristic of human information processing; it is a synthesis of "bottom-up" processing (what an operator perceives from the environment) and "top-down" processing (what an operator expects) (Neisser, 1967). An example of bottom-up processing occurs during a disturbance when an operator monitors the HSI and processes data from the interface to determine what is wrong. At the same time, these data are used to formulate hypotheses or expectations about the status of the plant, which serve to structure the perceptual process and data gathering occurring at lower levels. This is top-down processing. Both contribute to the operator's interpretation of the situation.

The ability to make predictions using a mental model that is based on the current situation model enables the operator's performance to become more "open-loop" (Moray, 1986). "Open-loop" in this context means that behavior becomes less driven by feedback and more governed by the operator's prediction of future system behavior and the desired goal state. A NPP mental model includes such knowledge as the physical interconnections among plant systems to predict flow paths (e.g., considering piping and valve interconnections to figure out how water from one system could get into another) and knowledge of mass and energy changes in one system to predict the effect on a second system (e.g., predicting the effect that changes in secondary side steam generator levels and temperatures will have on primary system cooldown). While mental models provide the principles upon which predictions can be made, the situation model provides the starting point and becomes the basis from which expectations are developed about events that should be happening at the same time, how events should evolve over time, and effects that may occur in the future.

The operator's expectations of the near-term future state of the plant are used to guide the sampling of indicators to confirm the inference (Bainbridge, 1974). Expectations are used to search for evidence to confirm the current situation model and to explain observed symptoms. If a new symptom is observed that is consistent with operator expectations, a ready explanation for the finding will be developed, yielding greater confidence in the situation model.

While the mental model allows prediction and expectancy to guide control responses, expectancy also can make detecting subtle system failures difficult (Wickens and Kessel, 1981). When a new symptom is inconsistent with an operator's expectation, the operator may discount or misinterpret it to make it consistent with the expectations derived from the current situation model. For example, an operator may fail to detect key signals, or detect them but misinterpret or discount them, because of an inappropriate understanding of the situation and the expectations derived from that understanding. That is, operators tend to ignore or discount symptoms that are not consistent with their situation model. However, if the new symptom is recognized as an unexpected plant behavior, the need to revise the situation model will become apparent. In that case, the symptom may trigger situation assessment activity to search for a better explanation of the current observations. In turn, situation assessment may involve developing a hypothesis for what might be occurring, and then searching for confirmatory evidence in the environment. Thus, situation assessment activities can result in detecting abnormal plant behavior that might not otherwise have been observed, detecting plant symptoms and alarms that may have otherwise been missed, and identifying problems, such as sensor failures or plant malfunctions.

The situation model is constantly updated as new information is received and a person's understanding of a situation changes. In NPP applications, maintaining and updating a situation model entails keeping track of the changing factors that influence plant processes, including faults, operator actions, and automatic system responses.

The importance of mental and situation models, and the expectations that are based on them, cannot be overemphasized. They not only govern situation assessment, but also play an important role in guiding monitoring, using procedures and formulating response plans, and implementing responses.

On the basis of the above discussion, several factors can be identified that make the process of situation assessment difficult: unanticipated events, a poor mental model, a poorly designed information system, and divided attention.

- *Unanticipated events* – Mental models are established through training and experience. Situation assessment involves matching current information to those models. Therefore, situations or events that were not analyzed by designers, for which operators were not trained and have not experienced, will be difficult to assess. Vicente and Rasmussen (1992) suggested that a significant design challenge is to develop a HSI to support operators in handling unanticipated events. Since responses to NPP abnormal and emergency events are analyzed carefully in advance to design systems to handle the disturbance (e.g., engineered safety features) and operator responses (e.g., emergency operating procedures [EOPs]), the unplanned and unanticipated events pose the greatest challenge to the human-machine system. As Vicente and Rasmussen (1992) noted, "The inescapable conclusion is that unanticipated events can and do happen in large-scale industrial systems. In fact, they are the major cause of life-threatening accidents" (p. 589).

- *Poor mental model* – Even when events are anticipated, failures in training or inadequate experience can result in mental models that are not adequate to support situation assessment.

- *Poor information system design* – Even when events occur that are familiar and well understood by operators, they must recognize them. As noted above, this is accomplished by a match between information provided by the HSI and the operator's mental model. Information systems may not support such a mapping very

effectively. For example, relevant information may be lost in an information-dense display or spread out across many displays. Even when all the relevant information is available, it may be presented in a way, such as individual parameters, that operators must mentally process to get it to a level where it is able to be mapped to the mental model.

- *Divided attention* – Maintenance of situation awareness is disrupted by shifting attention between different tasks (Gaba and Howard, 1995). Attention is directed away from situation assessment to engage in other primary tasks, such as communications with coworkers, or secondary tasks, such as retrieving a display.

5.2.2 Monitoring and Detection

Monitoring and detection refer to the activities involved in extracting information from the environment. Monitoring is checking the state of the plant to determine whether the systems are operating correctly, including checking parameters indicated on the CR panels, monitoring parameters displayed by the process computer, obtaining verbal reports from operators in the plant areas, and sending operators to areas of the plant to check on equipment. Detection is the operator's recognition that something is not operating correctly and that an abnormality exists.

In a highly automated plant, much of what supervisory controllers do involves monitoring. For example, operators must monitor

- Normal conditions to determine that what is expected to happen does
- Results of actions (feedback)
- Normal and safety indications for changes or disturbances
- Performance of automated systems
- Problematic equipment
- Activities of coworkers (test and maintenance)

Ironically, despite the fact that monitoring is such a central cognitive activity, the monitoring by supervisory controllers of computer-based systems is often "unstructured" (Thurman, 1997). Operators are advised to monitor everything and given little guidance on how to accomplish this. Thus, monitoring lacks goal direction and important information can be missed. Further, display designs often fail to support monitoring because designers simply take all available status information and develop a set of displays structured around a physical representation of the system (Thurman, 1997). The cognitive basis for monitoring is discussed below.

Monitoring and detection are influenced by two factors: the characteristics of the environment and the operator's knowledge and expectations. These factors lead to two types of monitoring: data-driven and model-driven. Monitoring that is driven by characteristics of the environment is often referred to as data-driven monitoring. Data-driven monitoring is affected by the salience of the information's presentation (e.g., size, color, and loudness). For example, alarm systems are basically automated monitors that are designed to influence data-driven monitoring by using aspects of physical salience to direct attention. Auditory alerts, flashing, and color coding are examples of physical characteristics that enable operators to quickly identify an important new alarm. Data-driven monitoring also is influenced by the behavior of the information being monitored, such as the bandwidth and rate

of change of the information signal. For example, observers more frequently monitor a signal that is rapidly changing.

Model-driven monitoring is initiated by operators based on their knowledge and expectations about the most important sources of information. This type of monitoring also is referred to as knowledge-driven monitoring. Knowledge-driven monitoring can be viewed as active monitoring in that the operator is not merely responding to characteristics of the environment that "shout out" as an alarm system does, but is deliberately directing attention to areas of the environment that are expected to provide specific information.

Model-driven monitoring may be initiated by several factors. First, it may be guided by operating procedures or standard practice (e.g., control panel walk-downs that accompany shift turnovers). Second, it can be triggered by situation assessment or response planning activities, and therefore is strongly influenced by a person's current situation model. The situation model allows the operator to direct attention and focus monitoring effectively. However, such a monitoring strategy also can lead operators to miss important information. For example, an incorrect situation model may lead an operator to focus attention in the wrong place, to fail to observe a critical finding, or to misinterpret or discount an indication.

An operator is faced with an environment containing more variables than can be realistically monitored. Monitoring is challenging because there are a large number of potentially relevant things to attend to at any point in time and that the operator must determine what information is worth pursuing within a constantly changing environment (Vicente et al., 1997). In this situation, monitoring requires the operator to decide what to monitor and when to shift attention elsewhere. These decisions are strongly influenced by an operator's current situation model, which guides the allocation of attentional resources to sampling data from the environment based on its statistical properties; i.e., expected probability and correlation. The operator's ability to develop and effectively use knowledge to guide monitoring relies on an understanding of the current state of the process. As cognitive workload increases, monitoring strategies become less thorough and the capability to detect particular failures decreases (Ephrath and Young, 1981).

As discussed above, under normal conditions, situation assessment is accomplished by mapping the information obtained in monitoring to elements in the situation model. For experienced operators, this comparison is relatively effortless and requires little attention. During unfamiliar conditions, however, the process is considerably more complex. The first step in realizing that the current plant conditions are not consistent with the situation model is to detect a discrepancy between information representing the current situation and information derived from monitoring. This process is facilitated by the alarm system, which helps to direct the attention of a plant operator to an off-normal situation.

When determining whether or not a signal is significant and worth further investigation, operators examine the signal in the context of their current situation model. They must judge whether the anomaly indicates a real abnormality or an instrumentation failure. They will then assess the likely cause of the abnormality and evaluate the importance of the signal in determining their next action.

Monitoring and detection were described in terms of signal detection theory (SDT) (Green and Swets, 1988). Process control operators are in a monitoring environment that was described in SDT terms as an alerted-monitor system (Sorkin et al., 1985; Sorkin and Woods, 1988). Such a system is composed of an automated monitor and a human monitor, an operator. The automated monitor is the alarm system which monitors the system to detect off-normal conditions. When a plant parameter exceeds the criterion of the automated monitor, the operator is alerted and must then detect, analyze, and interpret the signal as a false alarm, or a true indication of a plant upset. The operator also can assess plant parameters independently of the automated monitor (the alarm system). Both

the operator and alarm system have their own specific, signal detection parameter values for sensitivity (d') and response criterion. The response criterion refers to the amount of evidence that is needed before an operator will conclude that a signaled event is actually present; this is sometimes referred to as response bias since it describes an operator's degree of conservatism. Sensitivity refers to the resolution of the system and determines the ease with which signals (represented as a statistical distribution) can be distinguished from signals and noise (also represented as a distribution).

SDT research has many implications for understanding how operators process information during a disturbance. First, the response criterion is affected by expectancy, i.e., the expected probability that an event will occur and the payoff structure (rewards and penalties for making correct and incorrect detections, respectively). While alarms can occur frequently, significant off-normal events in NPPs typically have a low probability of occurring. Therefore, operators have low expectancy about their actual occurrence, which creates a conflict between the cost to productivity for falsely taking an action that shuts down the reactor versus the cost for failing to take a warranted action. In a real-world system, disturbances have a low probability, and operators therefore rely on redundant and supplemental information to confirm the alarmed condition. Upon verification of several confirmatory indicators, the operator can accept the alarm information as indicating an actual off-normal condition (compared with a spurious condition).

There are two types of anomalies: (1) deviations from desired system function, referred to as abnormal findings, and (2) deviations from the operator's situation model, referred to as unexpected findings. The different kinds of anomalies lead to different follow-up reasoning and monitoring behavior:

- Abnormal findings lead to information processing about how to cope with the disturbance (response planning) and to monitoring behavior to see if responses to coping occurred as expected, and whether they are having the desired effect.

- Unexpected findings or process behavior lead to situation assessment activity and knowledge-driven monitoring to explain the finding.

Failures in monitoring can include failing to observe parameters, misunderstanding their significance, or failing to obtain necessary reports from plant areas. Failures in detection can include failing to recognize an abnormality despite appropriate monitoring. An error in monitoring or detection can lead to the operator's failure to respond to the event, or at least, failure to respond within the required time.

Two aspects of plant design are significant to monitoring: HSI technology and plant sophistication. HSI technology has a significant impact on monitoring. In conventional CRs, displays and controls are predominantly spatially-dedicated. They have fixed locations that cannot be changed in form or function. In such situations, operators develop scanning patterns to support monitoring. However, even with spatial dedication, monitoring and search can be difficult because information can be physically hidden from view (Barber, 1996), e.g., when displays are obscured by tags (as happened during the TMI event) or located away from the main CR. One of the major values of the detailed design reviews of CRs in the 1980s was making the search process easier (Van Cott, 1997). Improvements that facilitated interface management and reduced the chance for error were evident in the modifications based on NUREG-0700. These included better organization of indicators and controls, improved labeling, and improved demarcation of the relationships between indicators and controls through the use of board mimics. However, there was little actual manipulation of the interface – what Vicente, Mumaw, and Roth (1997) referred to as "HSI degrees of freedom." The CR information and controls were fixed and spatially dedicated in the way the HSI designer felt was most appropriate.

By contrast to conventional HSIs, advanced HSIs are flexible because they can be configured and function in various operating modes. These interfaces have several degrees of freedom. For example, based on observation of operators monitoring a relatively advanced NPP, Vicente et al. (1997) found that operators could decide "...where to put a given display, what the time scale on a trend graph should be, what the range on a trend graph should be, what form to present a variable in (e.g., trend, bar, bar-trend, digital), what variables should be graphed together, and so on. Not only can the operator make these decisions, but they can make them over and over again in the sense that these presentation parameters can be readily changed in a moment." However, operators tended to ignore the flexibility offered by the system. Instead, they selected a set of displays that they felt gave them a good overview of the plant, and left those on the VDUs, which was done, to some extent, at the expense being able to access more detailed views of the plant that may have been available. This was attributed, in part, to the effort involved in paging through displays, a task that operators felt interfered with their ability to understand the overall status of the plant.

With regard to monitoring, Vicente et al. (1997) commented:

> Computer-based HSIs can make it difficult to find information and act on the system in comparison with conventional plants...In a computer-based control room, there is a significant increase in the amount of knowledge required to operate the interface. Part of these demands arise from the fact that information is presented serially. Thus, operators need to know how to bring up the information they want to display on CRTs. The other part of the increase in knowledge demands arises from the fact that the computer-based displays are much more flexible than the hard-wired instruments. The same information can be displayed at different time scales, at different ranges, in different locations, in different forms, and in different groupings. Consequently, the operator has to have much more knowledge about the interface (not the unit) to resolve the degrees of freedom offered by the flexible design of the system...On the one hand, one might argue that the flexibility provided by the computer-based medium should result in a performance improvement because it allows operators to view information in a form that is tailored to different types of contexts. This should reduce the need for the work-arounds that operators engage in traditional control rooms to facilitate monitoring. On the other hand, one could just as well argue that this flexibility comes at the price of an increase in the time and effort that operators spend manipulating the interface rather than monitoring the unit.

The problems associated with information retrieval and control manipulation will be compounded by the fact that a small set of control actions, such as positioning a cursor, will be required for all CR activities. Vicente et al. (1997) make a similar point for monitoring. Whereas in a conventional CR, monitoring was done primarily with the eyes, in a computer-based CR, it is done with the hands, which means that considerable manipulation of the computer-input device is needed to page through displays.

Monitoring is also affected by the technological sophistication of the plant design. In fact, the classical view of monitoring is that it is a boring and tedious task that leads to vigilance difficulties associated with lack of cognitive stimulation. While this may be true in some systems, recent research in nuclear plants has shown that routine monitoring can be difficult (Mumaw et al., 1996; Vicente et al., 1997). Some factors contributing to the difficulty were identified by Mumaw et al. (1996) following a study of monitoring performance in two NPPs. The factors included the following:

- *System complexity* – There are thousands of components which interact in different situations, thus it can be difficult to understand the implications of each.

- *System reliability* – Even though the number of components is large and they are highly reliable, at any one moment there are many that are out of service or not working properly. Operators must factor these considerations into their situation assessment.

- *Display design* – Given the large number of parameter displays, it is often difficult to detect when an abnormal situation has occurred. There are several reasons for this. First, interpretation of displayed parameter values is memory intensive. Displays do not give clear referent values and few aids are provided to support recall of recent value. In addition, few emergent features are presented to enable operators to rapidly identify higher-level information from the displays provided. Complicating the use of the displays are the same reliability issues as for other components, i.e., at any time, there may be displays that do not work properly. Failed displays also can be difficult to detect.

- *Automation design* – The operation of and feedback from automated systems is not well represented in the display system. For example, the actual status of components being automatically controlled is not displayed. (Murphy and Mitchel [1986] identified a number of effects on operator's cognition of automation and their implications for display design).

These factors introduce uncertainties that make monitoring difficult. In fact, Mumaw et al. concluded that monitoring during normal NPP operations are "better cast as a problem-solving activity than a vigilance task" (1996, p. 30). It is a complex situation assessment activity dependent on imperfect, sometimes nonfunctional, displays depicting thousands of parameters.

Vicente, Mumaw, and Roth (1997) examined the generalizability of these factors to a more advanced CR. While they found the overall reliability and trustworthiness of the instrumentation to be improved, the same basic problems existed. In addition, they noted a new problem associated with a CRT-based information system, the keyhole effect, which adds difficulty in monitoring.

5.2.3 Response Planning

Response planning refers to deciding upon a course of action to address an event. Response planning can be as simple as selecting an alarm response procedure or Emergency Operating Procedure (EOP), or it may involve more thoroughly developing a plan in circumstances where existing procedures have proved incomplete or ineffective.

In general, response planning involves the operators using their situation model of the current plant state to identify goals and the transformations required to achieve them. The goal may be varied, such as identifying the proper procedure, assessing the status of back-up systems, or diagnosing a problem (Rasmussen, 1981). To achieve the goals, operators generate alternative response plans, evaluate them, and select the most appropriate one that is relevant to the current situation model.

While this is the basic sequence of cognitive activities associated with response planning, one or more of these steps may be skipped or modified based on the operator's assessment of a particular situation. When procedures are available and judged appropriate to the current situation, the need to generate a response plan in real-time may be eliminated. However, even when written procedures are available, some aspects of response planning will be done. For example, operators still need to (1) identify appropriate goals based on their own situation assessment, (2) select the appropriate procedure, (3) evaluate whether the procedure-defined actions are sufficient to achieve those goals, and (4) adapt the procedure to the situation, if necessary.

The decision making involved in situation assessment and response planning, especially in ambiguous situations, such as when available procedures do not suffice, can be a large cognitive burden and draw heavily upon working memory, long-term memory, and attentional resources. In such situations, information is consciously manipulated in working memory, and the ability to do so is a direct function of the attentional resources available. Working memory has very limited capacity, and without sustained attentional resources (or transfer of the information to

long-term memory), information decays rapidly. Information can be lost due to (1) insufficient attentional resources to keep it active, (2) overload of the working memory capacity, and (3) interference from other information in working memory. To increase the capacity of working memory, operators use memory heuristics, such as chunking, that enable them to organize various bits of information into higher-level, meaningful units. A heuristic, as used in this report, is a shortcut for information processing developed through experience and trial-and-error rather than systematic, formal analysis. Once this is accomplished, the higher-level units, not the individual elements, are stored in working memory.

Roth, Mumaw, and Lewis (1994) demonstrated the need for operators to maintain a supervisory role even when responses are largely dictated by EOPs. They investigated how operators handle cognitively demanding emergencies. Their objective was to examine the role of situation assessment and response planning on guiding crew's performance in situations where EOPs were being used. NPP operators from two different utilities performed interfacing system loss of coolant accident (ISLOCA) and loss of heat sink scenarios on training simulators, where complexities made it difficult to simply follow the appropriate procedure. The results showed the importance of high-level cognitive functions during the use of EOP. The operators developed an understanding of the plant state and confirmed their situation assessment. They also attempted to understand plant performance that was not expected based on their current situation model. These cognitive activities enabled them to evaluate the appropriateness of the EOP for the high-level goal dictated by the situation assessment. Roth et al. (1994) noted the importance of the crew's interaction and communication to these high-level cognitive functions. This was partly because of the need to obtain information from many HSIs in different locations. In addition, communication helped operators overcome the fact that EOPs do not address all the important information about the current state of the plant. Roth et al. noted that these cognitive activities made it possible for crews to evaluate the ability of a procedure to achieve its high-level goal in the context of the current plant condition. When a specific procedure failed to meet the high-level goal, operators would alter its path to better address the situation.

Thus, Roth et al. (1994) demonstrated the importance of understanding the basis of the procedure and the higher-level goals it is intended to achieve. The need to formulate modifications to procedure pathways also means that operators may not simply proceed linearly through a procedure. They may need to consider future steps, reexamine previous steps and consult other procedures to verify that their current activities are correct and will meet the high-level goals of the procedure.

Roth (1994) considered the implication of the Roth et al. (1994) study for the design of operator support systems. First, the requirement of situation assessment and response planning independent from procedure activity suggests that operators must maintain awareness of abnormal plant symptoms, determine what malfunctions could produce those symptoms, and know the manual and system actions that are being undertaken and their effects. Second, since crews have to anticipate the consequences of their actions, operator support systems could support identifying consequences and side effects of planned actions. Third, operators must understand the assumptions and logic behind the procedures, i.e., the intent of the procedures, their overall strategies, and the transition logic between them. Since operators may not move linearly between procedures, the means for navigating the information system will be important to the usefulness of such information systems in complex emergencies.

5.2.4 Response Implementation

Response implementation is the actual performance of the actions identified in response planning. This can be as simple as a single operator selecting and operating a control, or it can involve communications and coordination with teams of operators in different locations of the plant, who each then select and operate appropriate equipment controls in a centrally coordinated manner. The actions may be discrete (e.g., flipping a switch) or they may involve continuous control (e.g., controlling steam generator level).

The results of actions are monitored through feedback loops. Two aspects of NPPs can make response implementation difficult: response time and indirect observation. Time and feedback delays disrupt response implementation, because they make it difficult to determine whether control actions are having their intended effect. In such a situation, the operator's ability to predict future states using mental models can be more important in controlling responses than feedback. Further, since plant processes cannot be directly observed, their status is inferred through indications. Thus, errors in the cognitive process can disrupt performance.

Failures in response implementation can lead to operating the wrong equipment, or incorrectly operating or controlling particular components.

5.2.5 Implications For Information System Design

From a consideration of the cognitive tasks performed by operators to support their supervisory control functions, the following general observations can be made:

- Operators' information needs, especially in support of monitoring, detection, and situation assessment, are very broad, both in terms of range of activities they need to be aware of, and the level of abstraction they need to consider.

- Information should be expressed in terms that are at the level that will directly impact decision making and control. Cognitive resources should not be required to mentally process data to provide the information that is needed.

- It is important to correctly map the plant or process and the identification of information needs and their relationship to the operator's mental model. These mappings are necessary to ensure that the information representations trigger the appropriate mental representation of the situation.

- HSI design can have a strong effect on the operator's cognitive activity and can make information difficult to obtain (through poor organization, high data density, and excessive interface management demands).

The following information processing considerations for cognitive tasks were reflected in design principles supporting situation awareness developed by Endsley (1988, 1995):

- Displays should provide information that is processed and integrated to meet the operators' need to comprehend the current situation and to project future states.

- Information presentation should take into account the operator's goals and the information needed to make goal-directed decisions. That is, information should be organized in terms of what the operator is trying to accomplish and not simply the physical layout of the system.

- Since situation awareness depends on activating the appropriate mental representation for the situation, the critical cues to activating the schema should be determined and displays should make these cues salient.

- Cues with highly salient features can redirect attention away from the current goals. Such cues should be reserved for situations that require the redirection of goals and critical events.

- The display should provide global situation awareness; that is, it should give an overview of the status of all operator goals at all times as well as giving details about the current goal. This is because situation awareness suffers when operators focus on some information and fail to attend to other important information.

- Support should be given for projecting future states of the system (especially for less experienced operators). For example, displays of trends or rate of change support this process.

- Information overload should be avoided by filtering out extraneous information and using processing techniques that integrate lower-level data to provide operators with the high-level information needed for goal-directed decision making.

- To minimize divided attention, information should be grouped and embedded within objects when possible. The number of attention shifts should be minimized; thus, the number of objects should be minimized, as should the need to shift between separate displays. Ideally, all information should be available at a single glance.

- The HSI should support parallel processing by providing, for example, information through visual and auditory channels. This will help operators to do tasks requiring divided attention.

5.3 Analysis of Information Requirements

HFE guidance has been criticized for focusing on legibility and not meaningfulness. Bennett et al. (1997) stated that:

> Designs that consider only data availability often impose unnecessary burdens on the user: to collect relevant data, to maintain these data in memory, and to integrate these data mentally to arrive at a decision. These mental activities require extensive knowledge, tax limited resources (attention and short-term memory) and therefore increase the probability of poor decision making and errors. (p. 673)

However, in the last few years, the NRC has improved the traditional guidance with the issuance of NUREG-0711 and NUREG-0700, Rev. 1. These documents contain guidance for information requirements that include an operating experience review, a functional requirements analysis, a functional allocation analysis, a task analysis, and a human reliability analysis. Section 5.1 summarizes these documents.

Further, as noted in Section 5.2, Vicente and Rasmussen (1992) suggested that traditional approaches to information system design, based on preplanned evaluations of normal, abnormal, and emergency events, will fail to meet the operators' needs in the face of events that have not been planned for in advance.

Proponents of ecological interface design (EID) suggested it as an alternative approach to traditional HFE design. The EID approach has implications for identifying operator information needs as well as for developing representations to display plant information. The former is addressed in this section and the latter in Section 5.4. The intent in this section is to determine whether the EID approach provides alternative or additional methods that may be beneficial in the information requirements area.

5.3.1 The EID Approach to the Analysis of Information Requirements

The concept of an ecological approach to interface design can be traced back to Gibson's theory of visual perception (1979). The central concept in Gibson's approach is that human behavior cannot be understood as an

entity independent from the environment in which it occurs. Thus, knowledge of the context or domain within which behavior occurs is essential to understanding human performance. Gibson called this the ecological approach to behavioral analysis (1979), and his concepts have influenced the EID model of interface design. The basis for using ecological perception theory as an approach to interface design was described in several papers (e.g., Flach, 1990; Vicente and Rasmussen, 1990, 1992).

In the nuclear industry, the EID approach was supported by Vicente and Rasmussen (e.g., 1992). Rasmussen (1986) viewed human performance as representing behavior organized and controlled at various levels of abstraction, including perception, rules, and knowledge. Operators are characterized as flexible in their ability to respond to the situation. This characterization of action, being based upon various levels or depths of processing, led to the categorization of operator's performance into three classes: skill-based, rule-based, and knowledge-based (SRK scheme).

Skill-based actions means that upon perception of particular signals, the operator initiates a well-learned "over-trained" response. Pilots are trained to this level so that the they can respond quickly without the need for more abstract and time-consuming processing. Behavior in this context is largely automatic, initiated, and controlled outside of the operator's awareness.

Rule-based performance is generally more complex and consciously controlled, yet a deep level of processing is not required since the situation is interpreted as familiar and recognized as requiring a previously defined set of actions. The use of standardized procedures, on which an operator has been trained in response to a well-defined transient, reflects primarily rule-based behavior. In Rasmussen's model, most of the linkages, between skill-based performance and the "identification of a state of ambiguity" in the system, fall into the domain of rule-based performance.

Knowledge-based processing represents the highest level of abstraction and deepest level of processing. It is invoked when neither skill-based nor rule-based responses are appropriate to the situation or adequate to define the actions needed to meet the operator's goal. The situation is defined as unfamiliar or ambiguous, and operators must develop an approach to attaining goals based upon their in-depth knowledge of the plant and systems.

Higher levels of abstraction enable behavior to be goal directed. These levels can serve to define goals for lower levels. So, for example, the goal to define the present state of the system can structure the set of observations made at the lower level of abstraction. When a target or desired state is identified, it becomes a goal, and the tasks and procedures to be used to achieve that state are defined. As noted in Section 5.2, the importance of the goal-directed structure of information processing has been widely recognized in NPP operator modeling (e.g., Bainbridge, 1974, 1986). The influence of higher-level goal states and expectations on lower-level cognitive processes also recognized in basic cognitive research as well, e.g., the effects of goal states on pattern recognition (e.g., Neisser, 1976).

In designing HSIs for these types of behavior, the issue is to determine the information necessary to support them at the various levels of abstraction. Based on his observations of diagnosis and problem-solving behavior, Rasmussen (1986) noted that information about a system varied along two dimensions: abstraction and aggregation. Abstraction reflects the conceptualization of system means-ends relationships along a hierarchy consisting of five levels from physical form to functional purpose. These levels were defined as follows:

- *Functional purpose* – the purpose for which the system was designed
- *Abstract function* – the causal structure of the process in terms of mass, energy, information or value flows

Table 5. 1 Abstraction-Aggregation (A-A) Matrix

Level of Abstraction	Level of Aggregation[1]			
	Plant	System	Equipment	Component
Functional Purpose				
Abstract Function				
Generalized Function				
Physical Function				
Physical Form				

[1] Levels of aggregation as typical for a nuclear power plant, but they are examples only.

- *Generalized function* – the basic functions a system was designed to achieve
- *Physical function* – the characteristics of the components and their interconnections
- *Physical form* – the appearance and spatial location of those components.

These levels span the physical components in the system and its overall functional purpose. Since SRK behavior requires information about the plant at various levels, the abstraction hierarchy provides a framework within which to describe those needs and consider display design.

Aggregation reflects the degree of integration, from part to whole, that problem-solving performance is directed toward. The part-whole dimension also consists of levels ranging from the individual component to the entire system. These two dimensions form a cognitive matrix describing the information needs of plant personnel, called the abstraction-aggregation (A-A) matrix (see Table 5.1).

The problem solver shifts between levels of abstraction and aggregation to solve problems. This enables the problem to be conceptualized in different ways. For example, Rasmussen (1986) mapped the strategy used by a computer analyst during troubleshooting into this problem-solving space (Figure 5.2). Itoh et al. (1995) applied this two-dimensional concept to interface design for nuclear plants (Figure 5.3).

Thus, during diagnostic performance, the information needs of the operator vary within this problem space. However, the two dimensions tend to be coupled (Vicente, 1992); that is, one tends to think at lower levels of abstraction when dealing with components, and to think functionally when working at the plant level. Lower levels of abstraction support knowing what to do and higher levels support an understanding of why it is necessary.

In contrast to the information needs reflected by the A-A matrix, Rasmussen (1986) suggested that in many industrial complexes, HSIs provide only one level of abstraction, reflecting a 'one sensor – one indicator' approach.

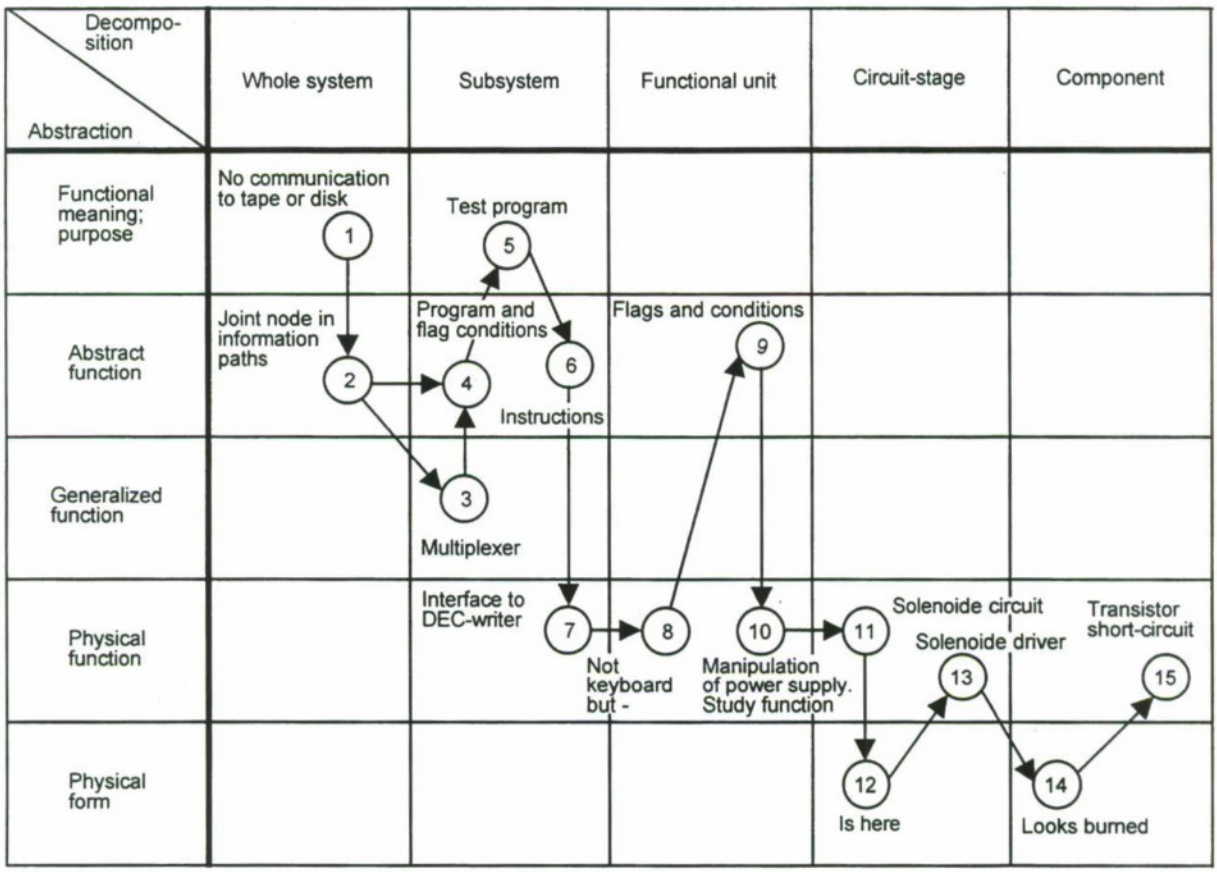


Figure 5.2 Diagnostic Strategies Used in Troubleshooting
(Source: Reprinted with the author's permission from Rasmussen, J., "Information Processing and Human-Machine Interaction," North Holland, New York, NY, 1986. All rights reserved by the author.)

This makes tasks complex because the data available often do not match the information needed. Rasmussen noted that

> In the design of human-machine interfaces for supervisory control as, e.g., industrial process control consoles, the emphasis has traditionally been on the presentation of measured data representing the physical state of the system and its processes. In complex systems, this information has been supplemented by information about the underlying functional structure by graphical means such as mimic diagrams, etc. This information is intended to serve the controller's identification of the actual state of processes bottom-up through the hierarchy. Information representing the intentions behind the system design, in terms of the purpose of functions and equipment and of constraints upon the acceptable operation, for instance, as derived from safety considerations, has only been very sparsely represented. This means that the interface system gives little or no support in the top-down derivation of the proper or acceptable states of processes. This kind of information was supposed to be immediately available to operators from their basic training. However, as systems become complex and potentially risky... this can no longer be assumed. During such situations, information about the purpose of interlocks, properties of equipment if used for untraditional purposes, etc., may be vital for ad hoc improvisations. Consequently, it becomes increasingly important to include in the support for decision making the information needed for top-down consideration of reasons. This means that the properties of the system to be controlled should be represented in terms of a consistent means-end hierarchy, systematically mapping the purpose/function/equipment relationships. (pp. 130-131)

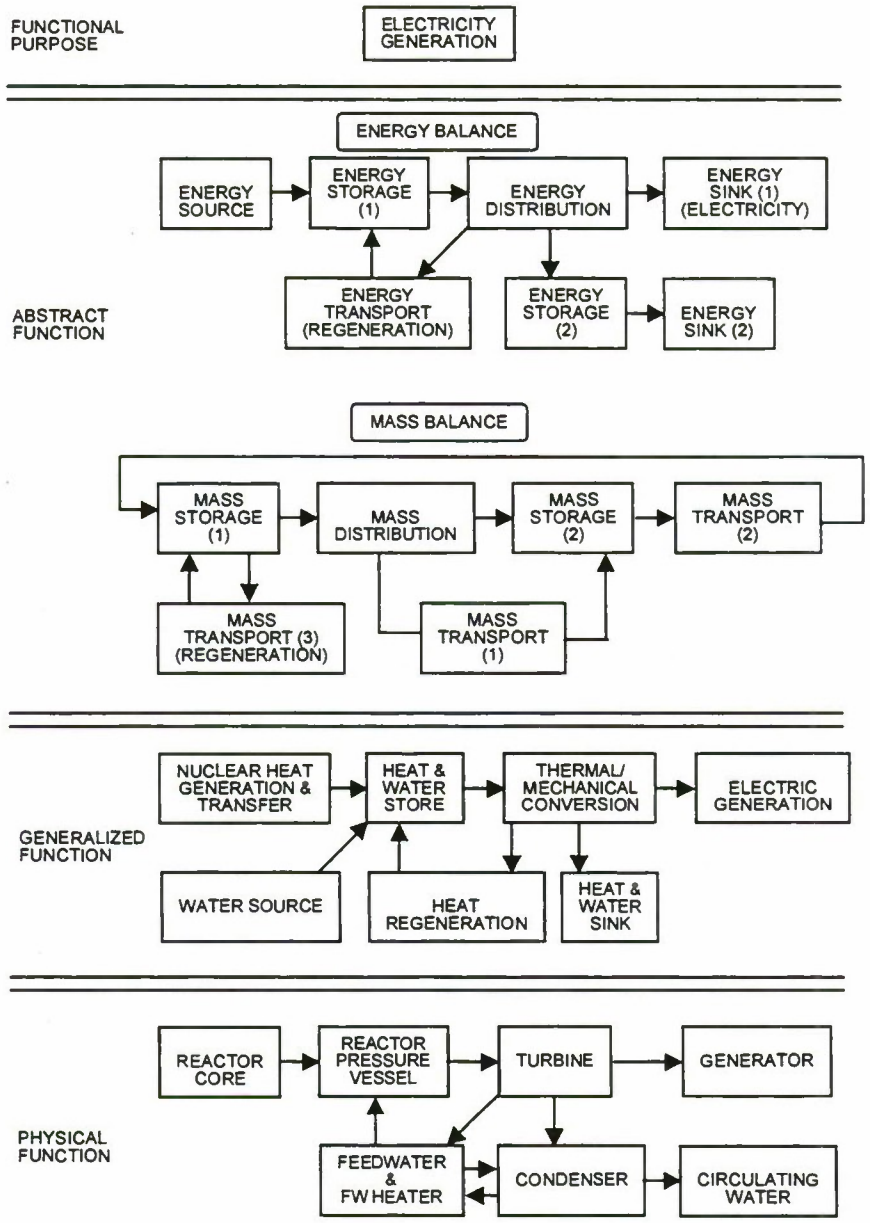


Figure 5.3 Electrical Production Abstraction Hierarchy
(Source: Reprinted from Itoh, J., Sakuma, A. and Monta, K., "An Ecological Interface for Supervisory Control of BWR Nuclear Power Plants," *Control Engineering Practice*, 3(2), 1995, Copyright 1995, with permission from Elsevier Science.)

Rasmussen indicated that this situation places the burden on operators to find the information they need to support their current activities and to structure the representation of the system that best meets their information needs.

The advantage of defining information needs using the A-A matrix is that normal plant behavior is dictated by a set of known relationships between plant parameters governed by constraints dictated by the physical nature of plant equipment, the physical laws governing the process, and the purposes for which the system was designed. Faults are revealed when these constraints are violated. By analyzing information needs according to the A-A matrix, these constraints can be represented in the design of the information system.

Vicente (1997) suggested that process control operators exist in a correspondence-driven domain where there is an external reality. This concept is in contrast to a coherence-driven domain where the human and the computer system represent a closed world and do not need to reflect external constraints. The information system should reflect the actual constraints of the process being controlled. Vicente refers to this as the "ecological compatibility principle" (in contrast to the proximity-compatibility principle, discussed in Section 5.4).

According to Vicente and Rasmussen (1988, 1992), the general goal of ecological interface design is to "...design interfaces that do not force cognitive control to a higher level than the demands of the task require, but that also provide the appropriate support for all three levels" (p. 598). The following three general principles, related to skill-, rule-, and knowledge-based behavior, are proposed to achieve this goal:

- *Skill-based behavior* – "To support interaction via time-space signals, the operator should be able to act directly on the display, and the structure of the displayed information should be isomorphic to the part-whole structure of movements" (Vicente and Rasmussen, 1992, p. 598). This means that, as far as possible, the interface should give the information necessary to allow for the appropriate use of skill-based behavior, which is the least cognitively demanding. Designs that use the natural tendencies of the user support this objective (i.e., direct-manipulation interfaces).

- *Rule-based behavior* – "Provide a consistent one-to-one mapping between the work domain constraints and the cues or signs provided by the interface" (Vicente and Rasmussen, 1992, p. 598). That is, provide a mapping between the invariant properties of the process and the format of the HSI. This principle is supported by showing contextual information in a display, such as stating the limitations of displayed information. This allows operators to identify potential inadequacies of typical responses that may be inappropriate to the current situation, thus avoiding procedural traps (Vicente, 1991).

- *Knowledge-based behavior* – "Represent the work domain in the form of an abstraction hierarchy to serve as an externalized mental model that will support knowledge-based problem solving" (Vicente and Rasmussen, 1992, p. 599). That is, display the relational structures of the processes as a functional hierarchy. This principle is supported by providing information in familiar representations, such as displaying functional relationships and information on parameters as P&IDs and in abstractions, such as subcooling margin.

In the next section, we address the effectiveness of the EID approach in the analysis of information requirements.

5.3.2 Research on the Effectiveness of EID Displays

5.3.2.1 DURESS EID Display

Vicente and colleagues conducted several studies to assess the value of the EID approach to display design. Vicente (1991) undertook the studies in part because "...no experiment has ever compared the performance of a

multilevel interface based on the abstraction hierarchy with any other type of interface" (p. 65). One series of Vicente's studies used a thermal-hydraulic process simulation called DURESS (DUal REservoir System Simulation) and DURESS II, with an updated simulation model.

The DURESS model has two redundant feedwater streams, which feed two reservoirs under various configurations. The operator tries to keep each reservoir at a specific temperature and to maintain water levels as needed based on flow rates. The operator accomplishes this task by controlling valves, pumps, and heaters. The simulation is dynamic with time lags on control variables. Faults can be introduced into the system and equipment can be damaged by improper operations (such as allowing the water level to get too low in a reservoir while it is heating).

Operators controlled the simulation using one of two interfaces: a basic physical representation (P) of the process, or a physical plus a functional display (P+F). Figures 5.4 and 5.5 show the interfaces. The P interface was a mimic-type display showing two feedwater systems (A and B), their components and status such as: P (Pump on or off), V (valve position), HTR (heating rates) for reservoirs, D (demand), and T (temperature). In addition to the representation of system components and parameters, the P+F display contained functional information identified by analyzing the abstraction hierarchy. That is, the display included information on the status of the functions that the components were serving and the mass-balance display (see the right side Figure 5.6).

The DURESS testbed provided an opportunity to experimentally study display effects in the laboratory with a simplified simulation that has many characteristics similar to actual process control systems. The simulation and the interfaces are described in detail in Vicente (1991) and in many of the other Vicente references discussed in this section. Collectively, these studies examine the effects of the following: underlying design philosophy on performance, varying the information content of displays, expertise on performance, displays on mental models, and displays on normal operation and fault management performance and strategies.

Before examining the results of these studies, we will examine the basis for the two interfaces in more detail. This is important because the studies use P (traditional design) vs. P+F (EID design) as the principal independent variable. Therefore, general conclusions about the strengths and weaknesses of EID are based on the representativeness of these designs. The design of the interfaces is discussed in detail in Chapter IV of Vicente (1991). To briefly summarize, the EID process first requires representing the domain constraints. That is, the elements of the system are described in terms of the abstraction hierarchy. Thus, for example, the functional purpose (high-level objective) of a reservoir is to maintain sufficient water to satisfy output demand and to keep the water at a temperature criterion. The next step, building an interface that represents the abstraction hierarchy, was accomplished by mapping this information into visible geometric properties of the objects in the interface. This is how the representation is thought to lessen the operator's workload by providing an external, visible model of the system. This latter step is not actually a function of EID; EID provides the requirements for the information that needs to be represented, not how to represent it. The following elements in the P+F interface (see Figure 5.6) reflect the result of this design process:

- *Functional purpose* – Demand values D1 and D2 and temperatures T1 and T2
- *Abstract function* – the rectangular graphic (to the right) representing mass balance of the reservoir
- *Generalized function* – flowrates for feedwater streams, such as FA1 and FVA
- *Physical function* – valve settings, such as VB
- *Physical form* – the spatial layout of the components and their connections

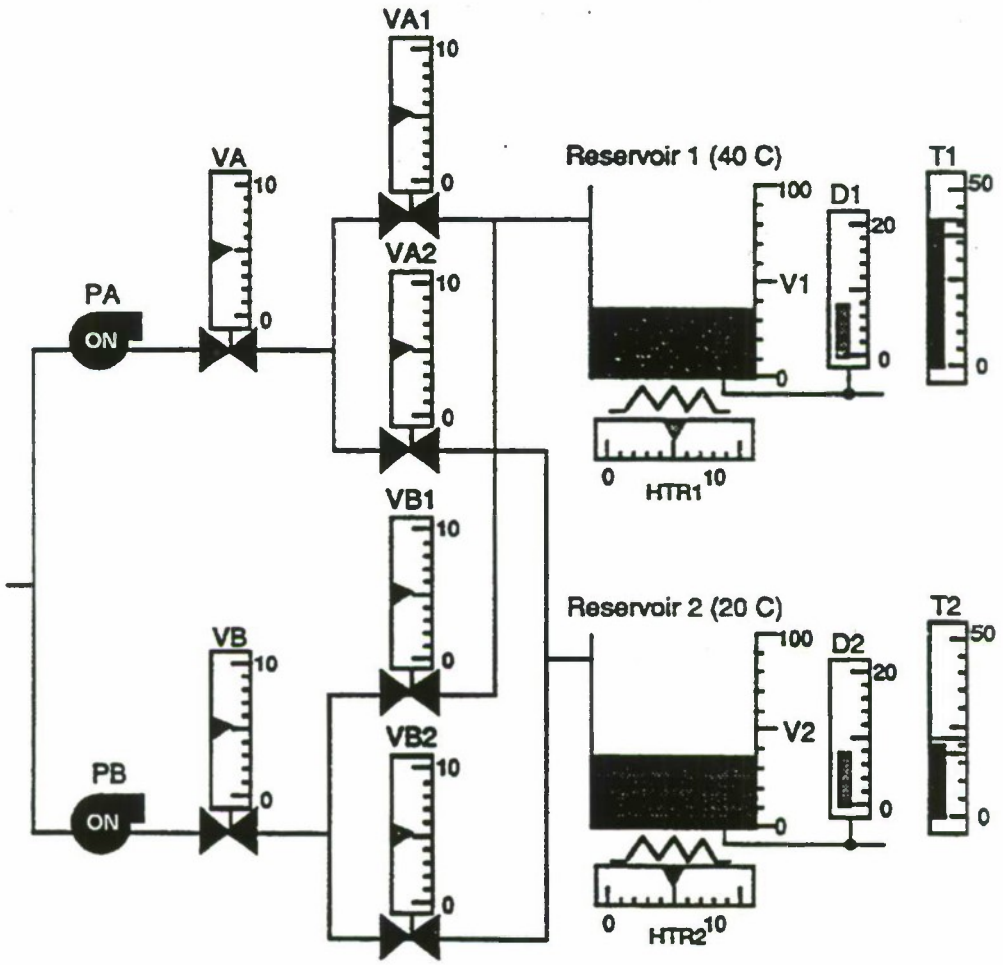


Figure 5.4 Physical Interface (P) for DURESS
(Source: Reprinted with the author's permission from Vicente, K., "Supporting Knowledge-Based Behavior Through Ecological Interface Design," (EPRL-91-01), University of Illinois, Engineering Psychology Research Laboratory, Urbana, IL, 1991.)

The P+F EID interface appears to be a well thought-out example of an EID process.

The design basis for the P interface, which is a traditional interface, is not discussed. However, it is not clear that the P interface is the product of a design approach that is an alternative to the EID process. Thus, one cannot determine why basic parameter values that appear in the P+F interface do not appear in the P interface. This latter point was discussed in an interesting exchange in *Human Factors* addressing a critique of Christoffersen, Hunter, and Vicente (1996) by Maddox (1996) and Vicente, Christoffersen, and Hunter (1996). The lack of information on flow rate either from the pump or to the reservoirs is noteworthy. Only information on valve position is given. Typical process displays would more likely include information on flow rate rather than valve position, and flow rate should be more useful for process control. If the P interface did not reflect a systems analysis or even a "traditional" task analysis, then what was used to determine the information requirements of the P interface? This

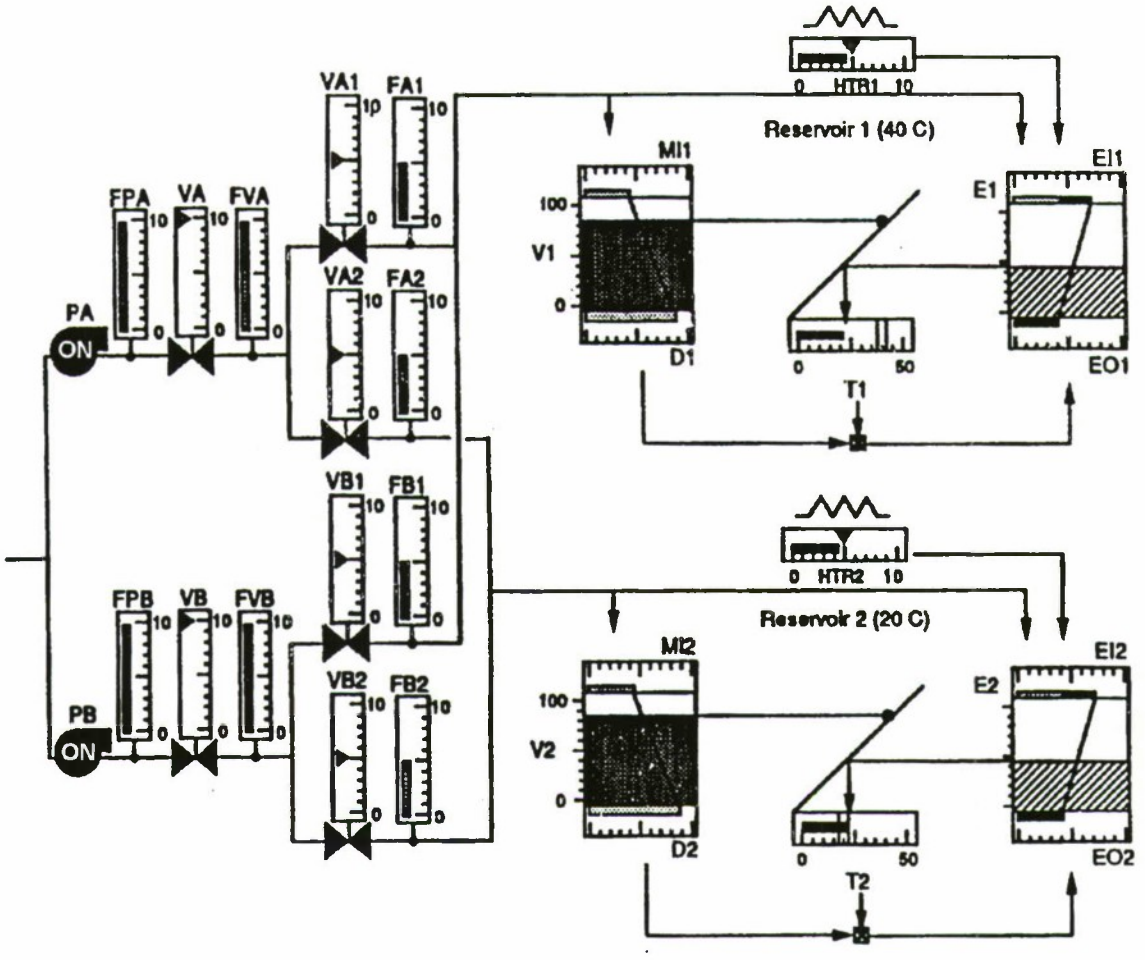


Figure 5.5 Physical + Functional (P+F) Interface for DURESS
(Source: Reprinted with the author's permission from Vicente, K., "Supporting Knowledge-Based Behavior Through Ecological Interface Design," (EPRL-91-01), University of Illinois, Engineering Psychology Research Laboratory, Urbana, IL, 1991.)

is an important question; its answer affects any conclusions on the generalizability of identified differences in performance between the P and the P+F displays.

With this issue in mind, the research related to the EID DURESS interface will be discussed. Seven different experiments of the series are discussed here.

The first experimental evaluation of the interfaces is reported in Vicente (1992) (and Experiment 1 of Vicente, Christoffersen, and Pereklita, 1995). The evaluation compared the two interfaces on fault diagnosis accuracy and a recall memory measure. A second independent variable was expertise (expert and novice). Experts were graduate students in mechanical or nuclear engineering, while the novices were graduate students who had never been enrolled in a science or engineering major. Subjects were first provided with familiarization and training on the simulator and interface. There were 12 participants in each expertise group. Participants observed the DURESS

simulation for approximately 30 seconds. In some of the trials, faults, such as reservoir leak and a blocked valve, occurred. Following the presentation, the screen went blank, and the participants were asked to recall the value of system parameters and diagnose the functional state of the system.

The results showed that the P+F interface was better than the P display in support of diagnosis. Generally, this result was stronger for experts than for novices. Vicente (1992) indicates that the superiority of diagnosis using the P+F interface supports the value of including higher-level functional information in a display, which he believes is critical to diagnosis. On the memory measures, experts had better recall than did novices; however, the effect of recall using the P+F display was only better for functional information. (The memory results were reported in more detail in Vicente [1992]. It was reported that memory for the subset of variables that were most important to the diagnosis was better for the participants using the P+F display.) Vicente also concluded that the study provided empirical support for displaying various levels of the abstraction hierarchy in an interface. That is, he concluded that the results are not due simply to the fact that the P+F display has more information than the P display, but that the additional information was specified by the EID approach as being goal relevant.

In the second study, Pawlak and Vicente (1996) compared the P and P+F displays to determine their relative effects on (1) control strategies and (2) fault detection and diagnosis. They hypothesized that the EID display would lead to the development of more effective control strategies. Twelve participants were assigned either to the P or the P+F display (six each). They practiced for an hour a day for 27 days and performed the following tasks: start-up, tuning to new setpoints, shutdown, and fault management. For some of the trials, participants had to conduct secondary tasks along with their primary tasks. The secondary task loaded on either verbal or spatial cognitive resources. Measures of primary task performance were time and analysis of verbal protocols.

The results showed that the P+F display led to more accurate diagnosis than the P display, although the time to compensate for the fault did not differ between the two groups (compensating for a fault does not necessarily require a diagnosis). Further, the strategies used by the two groups were different. Although some differences in strategy on the startup task were observed, no significant differences in general task performance were found. Analyses of the workload measures showed that the P+F display loaded more on spatial cognitive resources, while the P interface loaded more on verbal resources.

The authors identified some limitations to the study. First, it is not known whether differences in diagnostic performance were due to differences in the content or in the form of the displays. (This is a key point relevant to interface design, because the added information could easily be given in a more standard format, resulting in a very different display.) Second, the participants were not skilled in detecting faults and it is not known whether the benefits of the EID interface would hold for true operational experts.

In the third study, EID displays were compared with P&ID displays in a longitudinal examination of the performance of a variety of simulated process control tasks (Christoffersen et al., 1994, 1995, 1996). The DURESS II simulation was used and the P and P+F displays were compared. Six students participated in the study. They were assigned to either the P or the P+F condition in a between-subjects design and did the same operational tasks as described above. The participants engaged in 224 trials over 6 months. A brief crossover was performed where participants used the other group's displays. The primary performance measures were trial completion time and verbal protocols.

The most significant finding was that the EID display led to faster fault detection, more accurate fault diagnosis, and faster compensation. These differences were observed for routine as well as non-routine faults (Christoffersen et al., 1995). Also significant is that their strategies were different than the P group. The P group had difficulty distinguishing between a fault and a normal situation requiring control action. They sometimes only recognized a fault after normal control actions failed. They typically did not diagnose the failure and handled it by trial and

error. In contrast, P+F participants typically did not adopt such a strategy. Instead, they were often able to diagnose the problem, and therefore, respond appropriately.

For performance on a normal (nondisturbance) trial, there was very little difference in mean performance between the two groups. However, the P+F group was significantly less variable than the P group. Interestingly, during the crossover trials, when participants in the P+F group used the P interface, their performance variability increased. Thus, the differences were likely due to the characteristics of the interface and not the characteristics of the participants alone. This finding is important because assuming acceptable mean performance, it is important from a human reliability perspective to reduce human variability.

In the fourth study, the importance of the functional level of information was examined by having participants control the DURESS II process using a windows-based interface (Janzen and Vicente, 1997). The windows presented distinct information reflecting four of the five levels of the abstraction hierarchy: goals, principles, flow, and settings. No form level was included because the process was simulated. Only one level could be observed at a time. Of interest were which levels were used, for what purposes, and with what results. Six participants in three types of trails (normal, routine fault, and non-routine fault) operated the simulation for approximately one hour per workday for one month. The performance measures included system variables, operator actions, and verbal protocols. Regression analyses were conducted to predict process control performance, based on the participant's attention allocation strategies.

The results showed that more accurate and faster control under normal conditions was achieved when more functional levels were consulted (relative frequency of visits to the principles level). In addition, while fault detection time was not predicted, allocating attention to more levels (relative frequency of visits to the principles and flows levels) was associated with more accurate diagnosis. For fault compensation, performance was improved by dwell time in the principles level. The authors noted that to simply complete the process control task, only the settings and goals levels were necessary. To complete it quickly and stably, the principles level is necessary. Further, to handle faults, moving between multiple levels is required; i.e., most faults are revealed by switching between the settings and flows levels or between the flows and principles levels. These results showed the importance of the different levels of the abstraction hierarchy to different operating tasks.

In the fifth study, Vicente and Wang (1996) extended the comparison of effects of EID performance by comparing the following five interfaces, which included those previously described and some variations on them:

- the P display,
- the P display+trend plots (for input flow rates, level, and output flow rates for each reservoir),
- the P+F display,
- the P+F display+trend plots, and
- the P+F display+analytical redundance.

Analytical redundance is the calculation of expected parameter values using a model of system performance. The expected value is then represented in the display along with the actual value. Deviations between the two show some disturbance or abnormality of the system (Figure 5.6). The difference between the actual and expected flow rate is represented by the difference between the solid and dashed lines connecting MI and MO, which means a leak in the reservoir. Such a display directly reveals the violations of process constraints introduced by the fault.

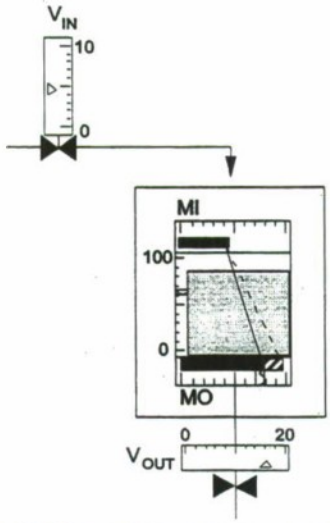


Figure 5.6 EID P+F Interface with Analytical Redundancy
(Source: Reprinted with permission from Vicente, K., and Wang, J., "Taking Full Advantage of Process Constraints in Advanced Interface Design," *Proceedings of the 1996 American Nuclear Society International Topical Meeting on Nuclear Power Plant Instrumentation, Control and Human-Machine Interface Technologies*, pp. 405-411, 1996. Copyright 1996 by the American Nuclear Society. All rights reserved.)

Participants operated DURESS under startup tuning and fault management trials. Performance measures included task times, fault detection time and accuracy, and verbal reports. The fault detection time was better for the EID+analytical redundancy, but only for reservoir leaks, as expected. They were better at fault compensation as well. For diagnosis, the three EID groups were more accurate than the P groups. Including trend plots did not clearly improve fault management, and in some cases even decreased performance.

In the sixth study, Howie and Vicente (1996) followed the expertise developed by six novice operators of the DURESS II process simulation. They anticipated greater expertise would develop in a group using an EID interface. Half were assigned to a P interface group and half to a P+F interface group. Perhaps the most interesting aspect of this study is the dependent measures developed for analyzing performance: steady-state times, complexity of action transition graph, path length of state space, mass-energy inventories, and timelines. The operators completed 224 trials over 6 months, and the first 20 trials were compared with the last 20 trials.

Performance improvements of larger magnitude were reported for the EID group, which may be because they tended to perform more poorly in the first 20 trials. By the last 20, both groups performed similarly. This pattern held for the first three measures. As an example, Table 5.2 shows the average steady-state times. Faster times show an ability to reach goals quickly and to maintain the system in the goal state. There may be two reasons for this result. First, with only three participants per group, there is no reason to believe the groups were equivalent at the start of the study. Perhaps by chance, the EID group performed more poorly at the task in the beginning. Second, the EID group may have been harder for the participants to use during early trials so they performed poorer. Over time they may have learned to use the EID display and improved. If the latter interpretation was correct, it would not represent an especially positive effect of EID displays. For the mass-energy inventory, the P+F group performed better for one of the two reservoirs in terms of percent above 1/3 capacity.

Table 5. 2 Mean Steady-State Times (in seconds)

	Initial Trials	Final Trials
P+F Group	687.6	395.1
P Group	602.2	393.3

In the seventh study, Vicente, Christoffersen, and Pereklita (1995) evaluated the hypothesis that superior fault management performance with EID interfaces occurs because these interfaces encourage knowledge-based behavior by enabling operators to (1) begin diagnosis at high levels of abstraction, reflecting functional considerations, and (2) use that information to work their way down to problematic components at the lower levels of abstraction. To evaluate this hypothesis, fault diagnosis strategies were examined as a function of type of expertise and success at fault management. It was found that the relevant expertise in managing DURESS faults was knowledge of the DURESS system and the P+F interface. Experience at controlling DURESS and thermodynamic knowledge were not well correlated with performance. For strategies of fault management, better performers began at higher levels of abstraction and slowly worked their way down to lower levels. In fact, diagnosis strategies starting at the lower levels had a negative effect on performance. In part, this is because at lower levels components have many interconnections. Thus, it is difficult to determine where a problem resides.

In summary, the main result of these studies is that fault detection and diagnosis seemed to be improved with the EID display reflecting the abstraction hierarchy. There was also a reduction in control performance variability. However, several issues make it difficult to fully interpret the results.

The first issue is generalization of the findings as representative of the strength and weaknesses of the design approaches they intended to represent. The uncertain technical basis for the P display make it unclear whether the results reflect the contribution of EID over traditional design methods, or whether they reflect the difference between a display that was designed with operator information needs defined and one that was not. Or, perhaps more likely, all three aspects of the EID displays (added information about flow rate, improved display design, and analytical redundancy) created improvements in performance, but how much each aspect contributed or which one is more important cannot be determined.

The second issue is generalization of the findings to more complex systems. DURESS is a relatively simple system compared to a NPP. Thus, all the levels of the abstraction hierarchy could be represented in a single display, which would not be possible in an actual NPP. Consequently, the amount of information (note the difference in amount of information between the P and P+F interfaces and generalize to an entire plant) and its organization (with regard to functions, systems, and levels of the hierarchy) may be an issue.

The third issue is generalization of the findings to more complex and routine tasks. The main benefits of EID were seen in knowledge-based diagnosis. In an actual plant, this cognitive activity is supported by alarm systems and other HSIs and procedures. The support of EID displays in the context of a richer HSI and task environment needs to be addressed. Further, while the effects on diagnostic performance are important, a NPP information system must support all of the cognitive activities discussed in Section 5.2. Since most of the activities are highly proceduralized, including responses to planned events and EOPs, using displays based on EID for these tasks should be evaluated.

The fourth issue is generalization of the findings to other participants, especially expert operators. Some of the studies were based on very small sample sizes, and therefore, the results may be influenced by individual differences (Howie and Vicente, 1996). Even when statistical tests are conducted to determine the significance of observed differences, there is no guarantee of the generalizability of results from small samples, because generalization is based on the assumption that randomization has resulted in equivalent groups. The confounding effects of individual differences are minimized by randomization of participants to groups. When accomplished in large numbers, the observed differences between groups can be attributed to the independent variable. When this is not accomplished, the results may be due to the manipulations of the independent variable (e.g., EID vs. traditional display) or to preexisting differences in ability between the groups (which is not accounted for in the statistical tests). Further, generalization to significant groups not represented in the studies are not supported. In this case, the effects on expert operators are unknown, and (as discussed below) they may interact differently with the displays due to their expertise.

The fifth issue is identification of an appropriate mental model. Vicente concluded that "an interface based on an abstraction hierarchy can provide more support for knowledge-based behavior than an interface based on physical variables alone because it results in a better match to the *theoretical expert's model*" (1991, p. iii, emphasis added). However, the participants in these studies were generally not experts in operations. Thus, they probably had no competing model as expert, trained process control operators might have. Training was noticeably weak in these studies. Yet training is the primary source of the mental model developed by professional process control operators.

Some of these issues, notably the use of EID displays by professional operators, were addressed in the research on the Rankine cycle display, which is discussed in the next section.

5.3.2.2 Rankine Cycle EID Display

Introduction

Abstract function representations of any process plant (such as a NPP) can be built on the conservation of energy and mass and on thermodynamic principles. One example is the Rankine cycle display (Beltracchi, 1987, 1989, 1995). Numerous other examples of such displays were developed (Duncan and Praetorius, 1992; Hollnagel et al., 1984), which show important aspects of the process cycle (e.g., heat source and heat sink) integrated into one display. The Rankine cycle display was incorporated into the information system of the Experimental Breeder Reactor (EBR II) at Argonne National Laboratory (Lindsay, 1990). The Rankine cycle display, its thermodynamic rationale, and its relationship to EID was described by Vicente et al. (1996).

The general functioning of a typical NPP, the thermodynamics behind the Rankine display, the ideal Rankine cycle, and the Rankine cycle EID display are discussed below.

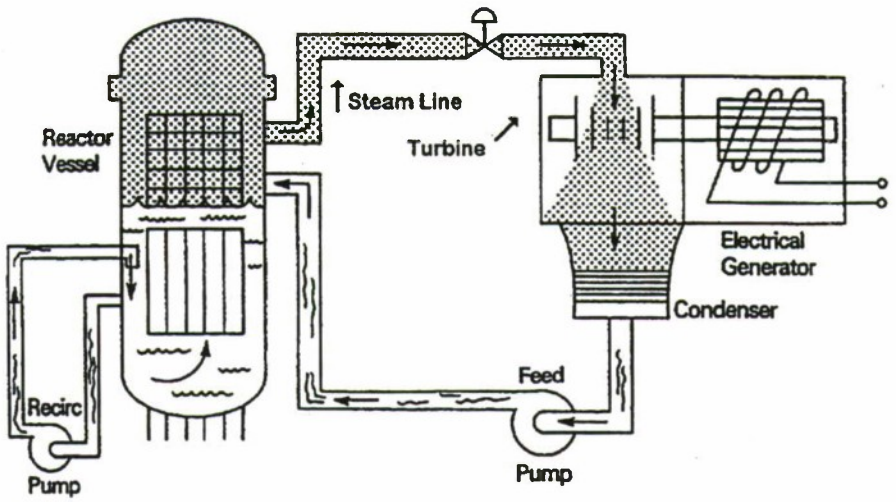


Figure 5.7 Boiling Water Reactor (BWR)

Discussion of NPP in Physical Terms

Figure 5.7 shows a top-level view of a boiling water reactor (BWR). The heat source is the nuclear reactor, in which water is boiled directly in the reactor vessel, creating steam. In a BWR, a recirculation loop and pump provides forced circulation and allows higher power levels. Steam leaves the reactor and flows down the main steam lines to the steam turbine, which is commonly used in both fossil fuel and NPPs to convert the thermal energy of the steam to rotational energy. An electrical generator is attached to the turbine shaft and converts the rotational energy to electrical power. After the steam passes through the turbine, it is cooled and condensed into water in the main condenser. The condenser is usually supplied with river, lake, or ocean water for cooling. After cooling, the water is pumped back to the reactor to complete the cycle. As will be discussed later, this process is a thermodynamic Rankine cycle (named after William J. M. Rankine, a Scottish engineer).

Figure 5.8 presents a top-level version of a pressurized water reactor (PWR). In this type of reactor, the primary water, which is heated in the reactor vessel, is kept under high pressure (typically about 2250 psia) by a pressurizer to prevent boiling and is circulated through a steam generator by reactor coolant pumps. The hot primary water (at about 600°F) serves as the heat source to the steam generator, where secondary water is boiled. The primary and secondary water do not mix. The steam produced in the steam generator then flows down the main steam lines to the turbine-generator, and condenser. After cooling, the water is pumped back to the steam generator to complete the cycle.

Discussion of Water

Water is used in both BWRs and PWRs as the reactor coolant and the fluid that is boiled and sent to the turbines to produce electric power. The water exists as a liquid, a gas (steam), and a combination of the two. Its particular state at various locations of the process systems is important for both production and safety. From a

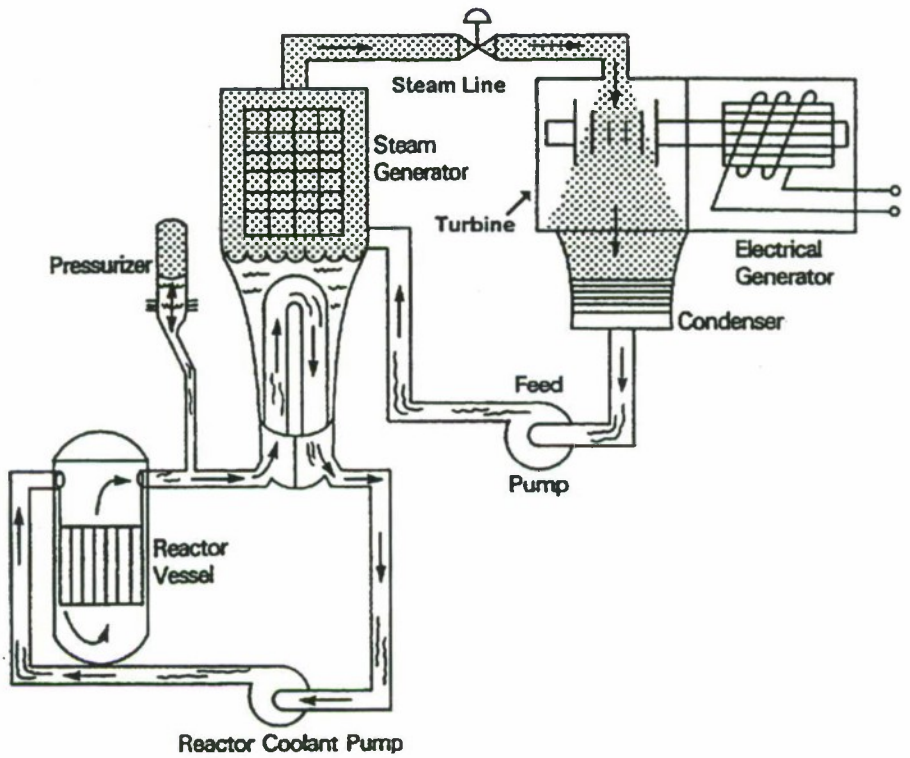


Figure 5.8 Pressurized Water Reactor (PWR)

thermodynamic standpoint, the state of water can be described using temperature, pressure, and entropy, as shown in Figure 5.9. Temperature (T) is on the y-axis and entropy (s) is on the x-axis. Entropy is a mathematically defined property of a substance that increases as heat is added. It is a measure of the disorder of a system at the microscopic level (i.e., molecules vibrating more as temperature is raised or as water boils). Constant pressure lines (P_1 to P_3) also are shown.

To the left of the curve in Figure 5.9, water is a subcooled liquid, with a temperature less than the boiling point for both unpressurized water and the primary water in a PWR. To the right of the curve, the water is superheated steam, with a temperature above the boiling point. Starting at the curve on the left side, water is saturated with a temperature at the boiling point for a given pressure. As pressure increases from P_1, to P_3, along the saturated water line, the boiling point temperature increases. For a given constant pressure, if saturated water is heated (as in a BWR reactor vessel or PWR steam generator), the water will begin to boil and its properties will move along the horizontal constant pressure lines on Figure 5.9. This shows the quality of the steam going from 0% (saturated water) through 10% steam, 90% steam, to 100% steam on the saturated steam line on the right of the curve. If more heat is added, the steam then becomes superheated.

Ideal Rankine Cycle

The power plant steam cycle is termed a Rankine cycle and can be displayed graphically on the temperature (T) versus entropy (s) plot for water. This is shown in Figure 5.10.

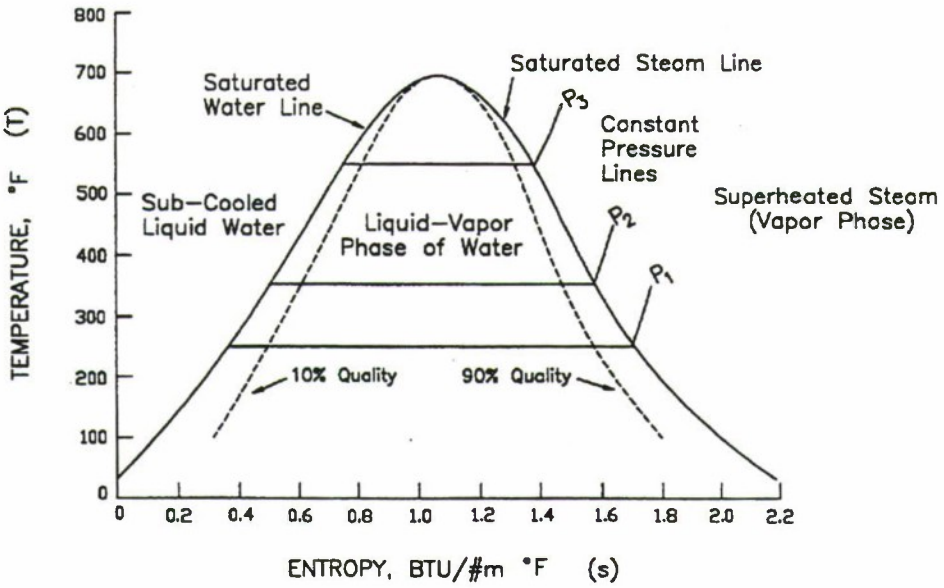


Figure 5.9 Thermodynamic Diagram of Water and Steam

Figure 5.10 shows an ideal Rankine cycle with no thermodynamic losses (such as friction). The cycle physically consists of a boiler of some type, a turbine where work is extracted from the steam (for conversion to electricity), a condenser where the exhaust steam from the turbine is condensed into liquid, and a pump where the condensed water is pumped back to the boiler to begin the cycle again. Each of these steps is shown on the figure. Step b-c is the boiler where the water is heated along a constant pressure line. The water is first heated to saturation, then boiled (following the constant temperature horizontal line), and finally the steam is superheated, following the same constant pressure line. U.S. reactors do not superheat their steam, but rather send saturated steam (at about 99.25% quality) to the turbine. The area under the line b-c represents the total heat or energy added from the boiler. Step c-d represents an ideal turbine where the energy is extracted from the steam at a constant value of entropy. A real turbine contains some losses (not all of the steam energy is converted to useful work), and hence, line c-d for a real turbine would slope to the right as entropy increases. Step d-a represents the condensation of the steam to water in the condenser across the constant temperature line, and then some subcooling of the water along a constant pressure line that is very close to the saturated water line. The area under line d-a represents the heat or energy rejected to the heat sink in the condenser, which is called unavailable heat or energy. The area between the lines b-c and d-a represents the energy converted to work in the turbine. By ratios of these areas, the theoretical efficiency of the process can be calculated. Step a-b represents the increase in pressure of the water in the condensate and feedwater pumps, as it is sent back to the boiler. In the real case, there would be some losses in the pumps and some increase in entropy, causing the line to curve slightly to the right. Processes to the left of the curve stay very close to the saturated liquid line in this figure, due to the relative incompressibility of water.

Discussion of Rankine Cycle Display

Figure 5.11 shows the display that was evaluated in the experiment described in Vicente, Moray, et al. (1996). The display, based on the Rankine cycle, represents a PWR plant which uses the following: a steam generator, a two-stage turbine with a high-pressure and a low-pressure stage, steam reheated and then superheated in between the two turbine stages, a condensate pump and a main feedwater pump to return the condensed water to the steam generator, and two stages of feedwater heaters to preheat the feedwater before its return to the steam generator.

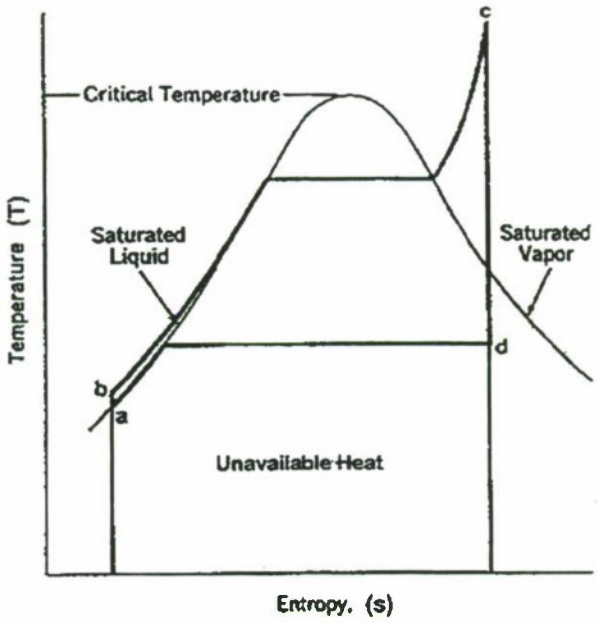


Figure 5.10 Rankine Cycle

This display reflects a real (rather than ideal) Rankine cycle, with additional information and graphics superimposed upon it. The correspondence of the display shown in Figure 5.11 to the ideal Rankine cycle (Figure 5.10) will be described first and then the added information on the display will be addressed. For discussion purposes, the letters a through g were added.

The process step b-c in Figure 5.11 represents the addition of heat and boiling in the steam generator similar to the ideal step b-c in Figure 5.10. This includes heating of the water to saturation and then boiling all the water to 100% steam. There is no superheating of the steam in the steam generator. The lines to the left of the saturated water line appear different; this will be discussed below. Step c-d in Figure 5.11 represents extracting energy from steam in the turbine. After the first drop in temperature in the high pressure turbine, reheat is added to the steam to first bring it to the saturated steam line, and then to superheat it. Next, temperature drops again in the low pressure turbine down to point d. Step d-a represents the condensation of the steam to water in the condenser across a constant temperature line and then some subcooling of the water. Finally, Step a-b represents the increase in pressure of the water in the condensate and feedwater pumps, as it is sent back to the steam generator, as well as the feedwater preheating that will be discussed below.

Figure 5.11 differs noticeably from the ideal Rankine cycle in one respect. The two lines representing extraction of energy from steam in the turbine (along step c-d) slant to the right rather than being a vertical constant entropy line, due to various losses in the process.

A substantial amount of additional information was added to the display in Figure 5.11. Points and information on the display are determined by measured parameters sensed at key points in the plant, such as temperature, pressure, and water levels. As parameter values change, the polygon display adjusts to these points as appropriate.

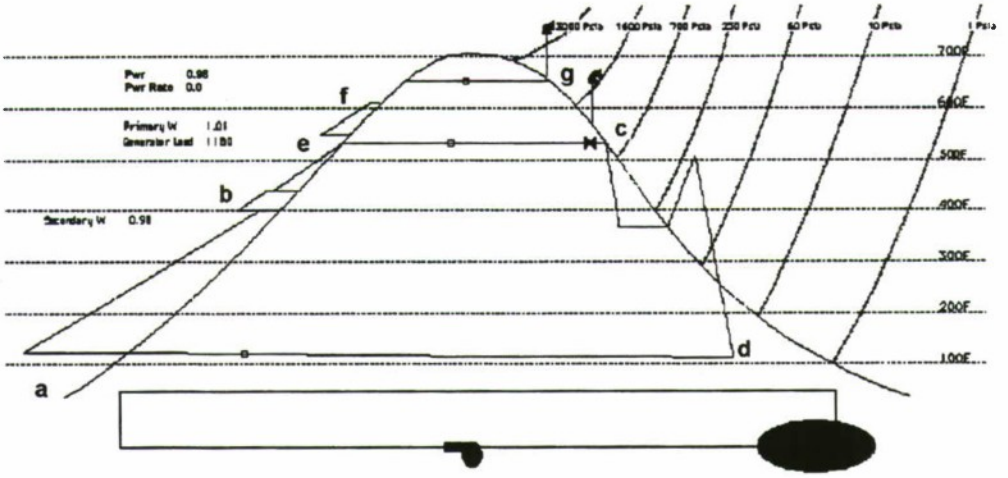


Figure 5.11 Rankine Cycle Display
(Source: Reprinted with minor modification with permission from Vicente, K., Moray, N., Lee, J., Rasmussen, J., Jones, B., Brock, R., and Djemil, T., "Evaluation of a Rankine Cycle Display for Nuclear Power Plant Monitoring and Diagnosis," *Human Factors*, 38(3), 1996. Copyright 1996 by the Human Factors and Ergonomics Society. All rights reserved.)

While the display is based on a standard temperature-entropy (T-s) chart, it does not directly display the entropy axis. The constant pressure lines are only displayed in the two-phase central portion and the superheat portion of the display, since they would all be too crowded together in the subcooled region. Also, the portion of the figure to the left of the liquid saturation line (letters a, b, e, and f) was changed to represent the degree of subcooling by distance to the left of the curve. Thus, points a and b in Figure 5.11 appear differently from Figure 5.10. Furthermore, the display in this area after the condenser represents the following: first, a pressure increase in the condensate pump, next an increase in temperature in a feedwater heater, then an increase in pressure in the feedwater pump, and a further increase in temperature in a second feedwater heater. This portion of the display is not discussed by Vicente et al. (1996).

The display also includes information on the primary loop, the pressurizer, some liquid levels, and relief valves on the primary and secondary sides, as follows. The temperatures of the primary loop (reactor coolant system or RCS) and the heat transfer from the primary to secondary sides are displayed by the small trapezoidal-shaped figure with the line e-f. The horizontal line from point e represents the cold leg of the RCS. It is drawn at the temperature of the cold leg, T_C. Also, the distance from the saturation curve line to point e represents the amount of subcooling in the cold leg. This is an important feature because the RCS in a PWR should always remain subcooled. Similarly, the line from point f represents the hot leg, and is drawn at the hot leg temperature, T_H. The subcooling is less for the hot leg than the cold leg. The distance between T_H and T_C is proportional to the heat transferred from the RCS to the steam generator. From this trapezoid, the operator can infer that the primary system is properly subcooled

and is correctly transferring heat to the secondary side. Actual values are not included here, and other displays or indicators would be needed to show, for example, the subcooling margin (how far away the primary is from saturation). As an example, a typical SPDS alarm for low subcooling margin is set at 32°F to allow a margin for instrument uncertainty.

The horizontal lines within the saturation curve represent the steam generator (the line left from point c), the condenser (the line left from point d), and the pressurizer (the line left from point g). These lines are at the correct temperature and pressure for each of those components. For example, the line left from point g for the pressurizer is at a pressure of about 2250 psia and a temperature of about 653°F. The water level in each of these three components is represented by the small square box on the horizontal line. The state of "all water" corresponds to the box at the left on the saturated water curve and "all steam" (no water) is with the box at the right on the saturated steam curve. In between, the position of the box represents a percent level.

The P&ID-like graphic under the Rankine curves represents the circulating water system that cools the condenser. Also, relief valve icons were added for a pressurizer relief valve and a steam generator relief valve, and a main steam line valve icon was added on the horizontal line for steam generator. These changed color when open or closed. Various other portions and lines on the display were color coded to aid the operators.

Thus, while the display of Figure 5.11 is based primarily on the Rankine cycle, significant additions and changes were made to give more information relevant to various aspects of the NPP.

Evaluation of EID-Type Displays

According to Lindsay (1990), the use of this EID type of display has certain advantages. The display takes advantage of human pattern recognition. However, unlike simpler configural displays, the underlying pattern is related to plant thermodynamics. The display also integrates important information together in one display, which gives a significant overview of plant's performance. A properly trained operator can use pattern recognition to detect plant disturbances by distortions in the pattern.

The effects of the Rankine cycle display on diagnosing events have been investigated (Moray et al., 1993; Moray et al., 1994; and Vicente et al., 1996). The Rankine display was compared with single-parameter, linear-meter displays and a display that included both single-parameter meter display (Figure 5.12) and a pressure vs. temperature plot. The study used three groups of 42 participants each: undergraduate engineering students, graduate engineering students, and professional NPP operators.

The procedure required the participants to monitor nine transients for two to four minutes on a desktop VDU. The data for the transients were obtained from a PWR training simulator. Each participant used only one type of display. Following each transient, the participants were given either a quantitative recall task (e.g., "what is the value of parameter x"), or a qualitative recall task (e.g., "did the primary coolant remain sub-cooled for the duration of the trial?"), and asked to indicate whether something was abnormal. If something abnormal did occur, they were asked to make a diagnosis.

For accuracy of detection, a significantly greater percent correct was obtained with the Rankine display in comparison to the other two. In addition, the NPP operators were better at detection than the other two groups. The Rankine display also led to more accurate diagnoses than the others, and operators were more accurate than the other groups.

The Rankine display also led to better qualitative recall, but the difference was not significant. Quantitative recall was better with the meter display. The authors concluded that diagnosis is more associated with qualitative

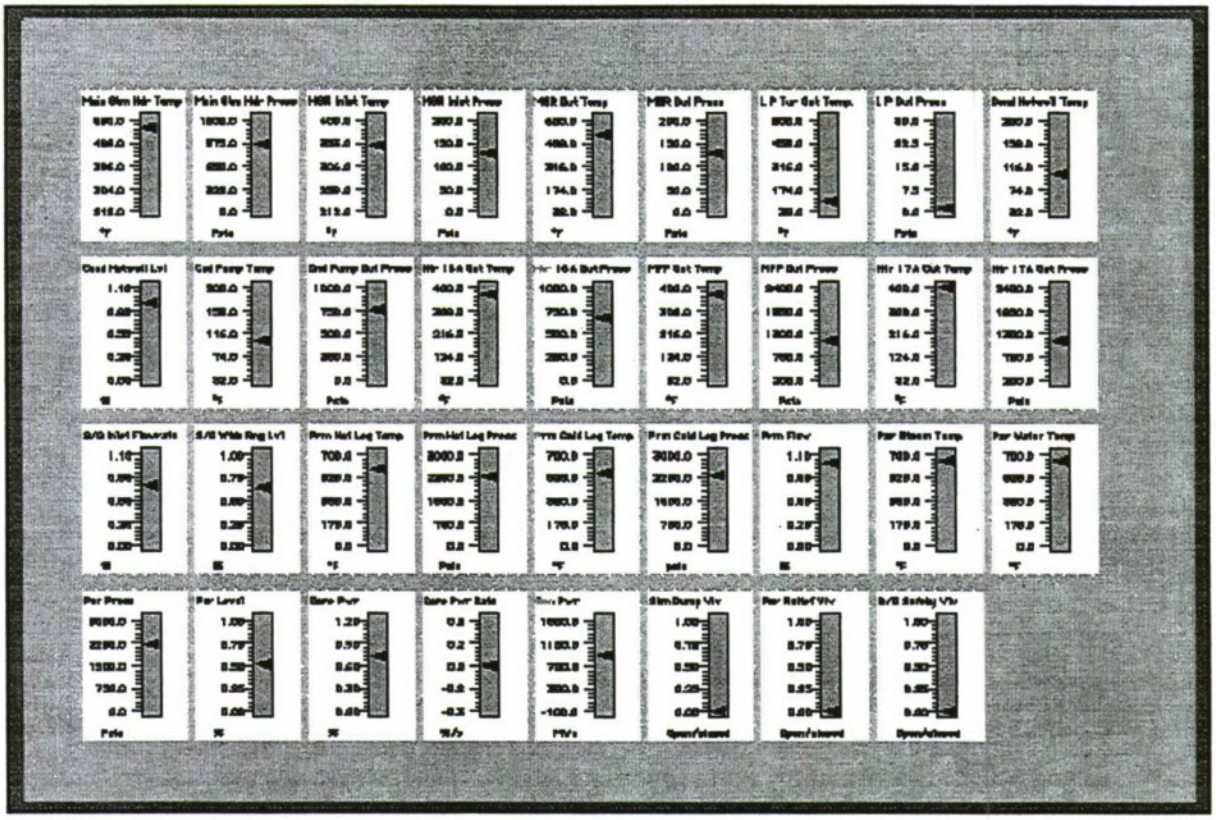


Figure 5.12 Simulated Analog Meter Display
(Source: Reprinted, with minor modification, with permission from Vicente, K., Moray, N., Lee, J., Rasmussen, J., Jones, B., Brock, R., and Djemil, T., "Evaluation of a Rankine Cycle Display for Nuclear Power Plant Monitoring and Diagnosis," *Human Factors,* 38(3), 1996. Copyright 1996 by the Human Factors and Ergonomics Society. All rights reserved.)

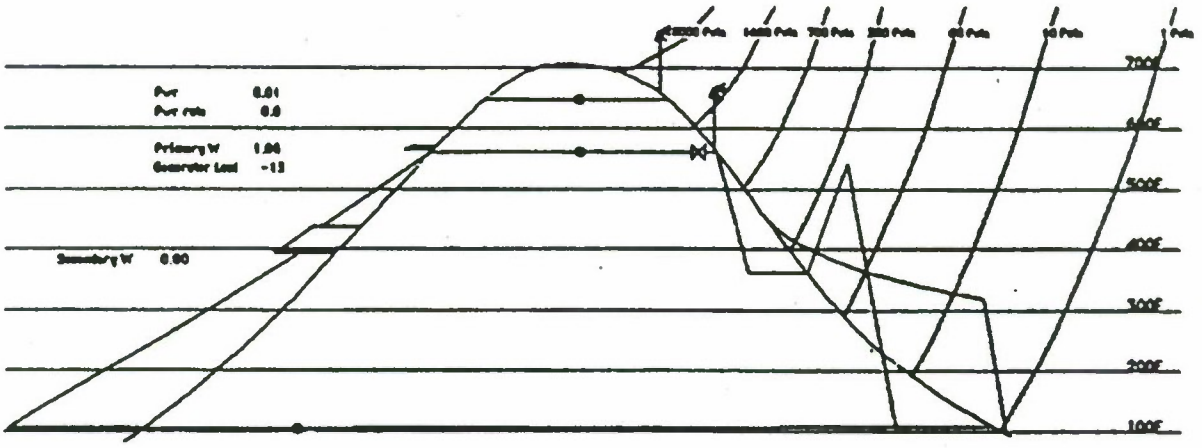
information rather than quantitative information. The Rankine display was better at supporting the diagnostic performance of experts.

It is interesting that, despite the performance effects noted above, the operators did not like the Rankine display because they were unfamiliar with it. They also claimed that they missed the alarm systems that they normally use for diagnosis. In their actual plants, the alarms are the first indication of a disturbance, and their pattern typically provides information about the nature of a disturbance.

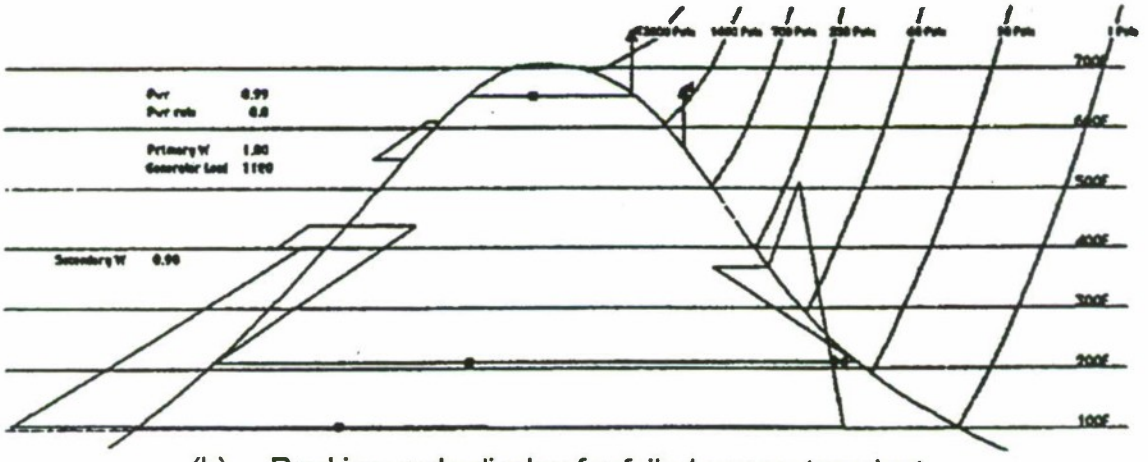
The authors suggested that failures in instrumentation can affect performance and interpretation of the display. Figure 5.13 shows two displays: one representing a real LOCA and the other a failed instrument.

While only one of thirty-five instrumentation points failed, the display was very difficult to interpret. Moray et al. (1994) noted that

> The calculations involved in coupling information from many sources to produce the DPIs [direct perception interfaces] are extremely vulnerable to certain classes of failures. Little or no research exists in this aspect of DPIs, and is urgently needed. The real advantages of such displays during normal operation and during many classes of



(a) Rankine cycle display for loss of coolant accident



(b) Rankine cycle display for failed sensor transient

Figure 5.13 Rankine Cycle Display of Abnormalities

(Source: Reprinted with permission from Moray, N., Lee, J., Vicente, K., Jones, B., and Rasmussen, J., "A Direct Perception Interface for Nuclear Power Plants," *Proceedings of the Human Factors and Ergonomics Society 38th Annual Meeting*, 1994. Copyright 1994 by the Human Factors and Ergonomics Society. All rights reserved.)

transients may be more than offset if they collapse under other classes of abnormalities. An understanding of the failure modes of DPIs (as distinct from the failure modes of the plant itself) is as necessary as an understanding of their design for normal conditions. Existence proofs of interface designs are no substitute for full empirical evaluations, and yet very few advanced DPIs have been exhaustively evaluated over a wide range of abnormal conditions. It is clear from our results that DPIs and/or ecological interfaces can fail in catastrophic ways, and it is probable that such failures may be particularly dangerous in large richly coupled systems. (p. 485)

To briefly summarize the literature for the Rankine cycle display, it clearly reflects the principles of EID and has been used in designs of new power plants (see also the development of Toshiba HSI, below) and by professional operators (see the EBR II application). There is currently only one empirical evaluation of the display, which despite some negative operator comments, was associated with better performance of detection and diagnosis than other types.

Despite the success of the experiment in beginning to address a real research need, there may be several limitations to the study. The first issue is generalization of the findings as representative of the strengths and weaknesses of the design approaches they intended to represent. There are two problems with the study. First, if the research is to provide a valid comparison of an EID approach and an alternative, the alternative approach to identifying information requirements was not clearly defined, and the alternative displays were not well designed. Second, there is a confound between information presented and display representation or format. That is, any difference between the alternative experimental conditions may be due to the information requirements analysis (EID vs. other) or to the different format (graphical display vs. single meter displays). Contrasting the Rankine-cycle display with a set of 35 individual analog meter displays (shown in Figure 5.12) is a biased comparison – even when augmented with a pressure-temperature plot.

The second issue is identification of information requirements. What cells of the abstraction hierarchy does the display represent? What information needs is this display meeting? What analysis, ecological or otherwise, led to the selection of the Rankine cycle as an appropriate mental model for operators to conduct their tasks? Are operators sufficiently familiar with thinking of the plant on these terms to effectively use the display? Another way to approach the question of information requirements is noted below in item (1) under General Issues to Consider Relevant to EIDs.

The third issue is generalization of the findings to other tasks, both complex and routine. The study was not a fully interactive dynamic simulation and operators did not have the full HSI available to them. Thus, potential interactive effects with the Rankine display in the context of other plant HSIs could not be evaluated; nor could its effects on other operational tasks.

A fourth issue relates to proper interpretation the experiments' results. It was noted that the operators commented that they did not like the Rankine EID display and would have preferred to have some of their normal HSI available, namely the alarm system. Perhaps they would have preferred to have their entire display system rather than the EID display, and would have done better with it. In fact, given the low absolute performance values (78% for detection and 45% for diagnosis) recorded by the experienced operators, they may have worked better than this with their typical HSI suite rather than with the Rankine display.

General Issues to Consider Relevant to EIDs

This experiment, and particularly the Rankine display, show a few important points to consider that are relevant to the design and implementation of EID displays. Where appropriate, the more generic aspects of these issues were included in Section 5.6, General Summary and Issues.

(1) In developing a higher-level display, one needs a clear definition of what higher-level functions and goals are to be addressed. As an example, are you addressing the goal of safety or electric production, or both? For the goal of safety, the NRC established five critical safety functions needed to achieve overall safety in NUREG-1342 (NRC, 1988), namely, reactivity control, reactor core cooling and heat removal, RCS integrity, radioactivity control, and containment conditions. Tables 2 and 3 of the NUREG give sample parameters to be monitored to address these functions for both BWRs and PWRs.

The experiment did not clearly define which goals or functions the EID was to address. Examining the five critical safety functions, one sees that three (reactivity control, radioactivity control, and containment conditions) are not addressed at all in the display. RCS integrity and reactor core cooling and heat removal are addressed somewhat, but all of the recommended parameters are not included. For example, reactor vessel level, core exit thermocouples, and residual heat removal (RHR) flow are not included. Also, the discrimination of some of the provided important parameters (reactor pressure, subcooling margin, and pressurizer level) is not fine enough to detect relatively small changes, and there does not appear to be any trending capability.

Thus, while the Rankine display gives some higher level functional information, it does not appear to provide a sufficient amount, and not nearly as much as a typical NPP SPDS implementation. Perhaps a useful experiment would compare a typical SPDS with an improved EID display based on the Rankine cycle. The improvements would be to incorporate the five SPDS functions and the related important parameters. This certainly appears to be a feasible experiment.

(2) For any higher-level display, where the information is sophisticated and a large amount of it is consolidated into one or a few graphics, training becomes very important. One needs to understand all of the aspects of the display and how it reacts to various operational transients, accidents, and instrument failures. Further, many of the items in the display are not labeled (e.g., T_H and T_C) and would be burdensome to estimate unless operators were highly familiar with the display.

(3) The effect of failures of instrumentation on EID displays was recognized as a potentially significant problem that needs to be addressed. There are several subissues associated with this problem.

- Can operators detect a failure of instrumentation?
- Can failures of instruments result in representations that are interpreted by operators as real process failures; and, perhaps more importantly, can real process failures be misinterpreted as failures of instruments?
- If operators detect a failure, should use of the display be suspended?
- Since the display integrates many parameters into a single display, what is the effect on operations of its loss, and how effectively can operators switch to backup displays?

(4) The integration of a new and significantly different EID into the remainder of the standard HSI of a CR is an important consideration that needs attention.

(5) The issue of the operator's acceptance of a new and different type of display (such as an EID) also is important, as shown by the operator's comments during the experiment. One interesting idea was introducing the displays initially in training and then perhaps gradually introducing them into the plant.

5.3.2.3 Toshiba Advanced BWR HSI

The EID approach to interface design is guiding Toshiba's development of an intelligent interface for an advanced BWR information system. A series of papers (discussed below) described the development of the information system, giving examples of the displays, and discussing some validation experiments. This application of EID is interesting because it represents an effort to develop an entire NPP information system based on EID principles. However, while the importance of the evaluation of EID displays was identified, little information on the

Table 5. 3 Operator Cognitive Activity

Level of Abstraction	Level of Aggregation			
	Plant	System	Equipment	Component
Functional Purpose	X	X		
Abstract Function	X	X	X	
Generalized Function	X		X	
Physical Function		X	X	

effectiveness of the interface is available.

The basis for the design is a cognitive task analysis reflecting the abstraction hierarchy (Itoh et al., 1990). As part of this effort, operators engaged in situation assessment, diagnosis, and response planning for simulated plant disturbances involving multifault scenarios. The scenarios were designed to elicit knowledge-based behavior. Operators were asked to verbalize their thought processes. The data were analyzed and sorted into the cells in the A-A matrix. Table 5.3 shows the envelope of cognitive activity. The correlation between the higher levels of abstraction and higher levels of aggregation is noteworthy (e.g., operators did not reason at the plant level in terms of physical form, nor did they reason about components at the functional level).

The authors concluded that information reflecting these cells is needed, at a minimum, in the interface. At each level of abstraction, the following types of information were preliminarily identified as necessary:

- Functional purpose – the goal of each function should be expressed in flow of mass, energy, and information. No information on equipment or components is necessary.
- Abstract function – information should be presented on the flow and distribution of mass and energy (the relationship between origins and destinations of substance or energy flows).
- Generalized function – information should be presented on the relationships between objects, input-output relationships, and information on the operating sequence.
- Physical function – information should be centered around the properties of objects and can be categorized in terms of underlying physical processes.
- Physical form – information should be provided on component status and appearance, and how it is accessed. For specific purposes, operators may need information on component settings and parts drawings.

Examples of displays supporting some of these levels were presented elsewhere (Sakuma et al., 1990; Monta et al., 1991). Monta et al. (1991) also discuss an intelligent "advisor" that can generate strategies and procedures after faults.

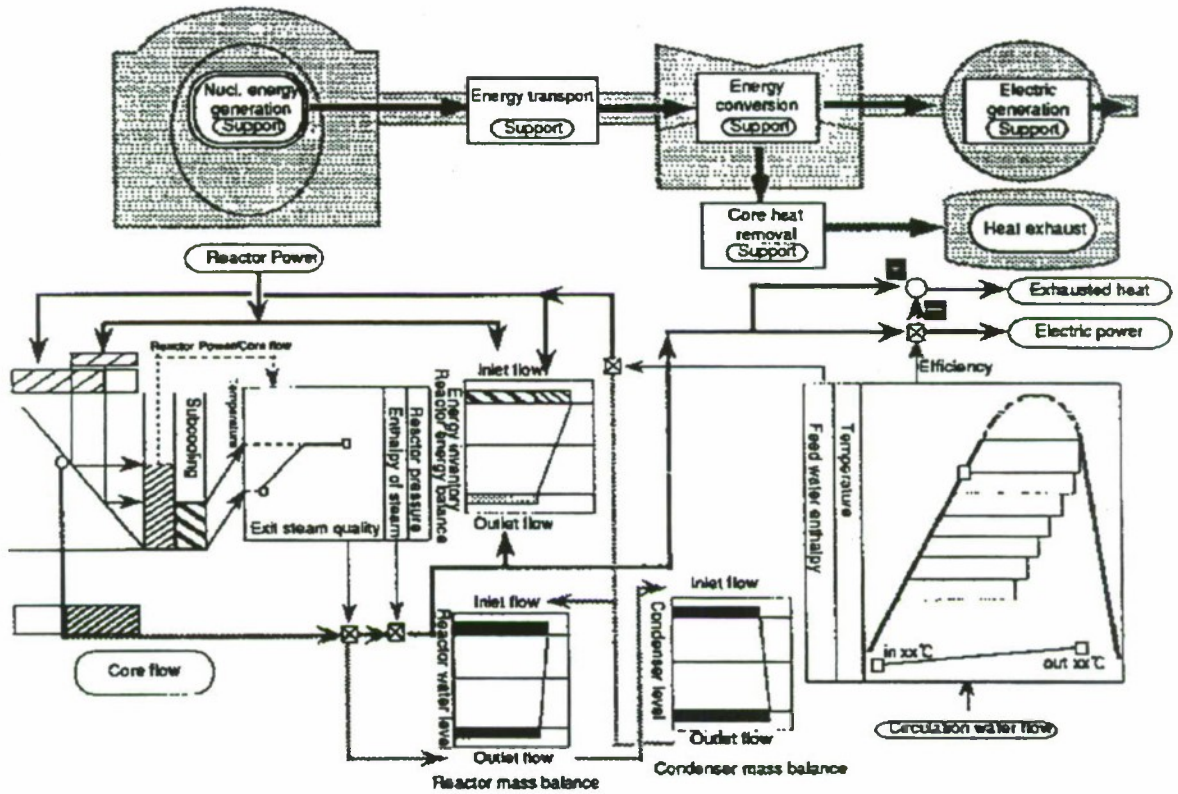


Figure 5.14 EID Production Goal and Display

(Source: Reprinted with permission from Monta, K., Takizawa, Y., Hottori, Y., Hayashi, T., Sato, N., Itoh, J., Sakuma, A. and Yoshikawa, E. (1991), "An Intelligent Man-Machine System for BWR Nuclear Power Plants," *Proceedings of the AI91 Frontiers in Innovative Computing for the Nuclear Industry.* LaGrange Park, IL: American Nuclear Society, pp. 383-392. Copyright 1991 by the Valley Litho, Idaho Falls, Idaho. All rights reserved.)

Figure 5.14 is an example of a production goal display from Monta et al. (1991). The uppermost section of the display represents the flow of electrical production. Its center shows the process for converting the energy and includes a display based on the Rankine cycle. The lower part of the display depicts the mass balance for the reactor vessel and the condenser, showing inlet and outlet flows and water levels.

This display was intended to be an externalized mental model of the process. Thus, workload should be reduced because operators do not have to recall these relationships from memory and mentally compute information related to higher-level goals.

The display was tested using a full-scope, advanced boiling water reactor (ABWR) simulator (Monta et al., 1992). Six experienced crews of utility operators were presented with simulated plant disturbances. Subjective evaluations of the interface were obtained following each trial. The operators' evaluations were generally positive; however,

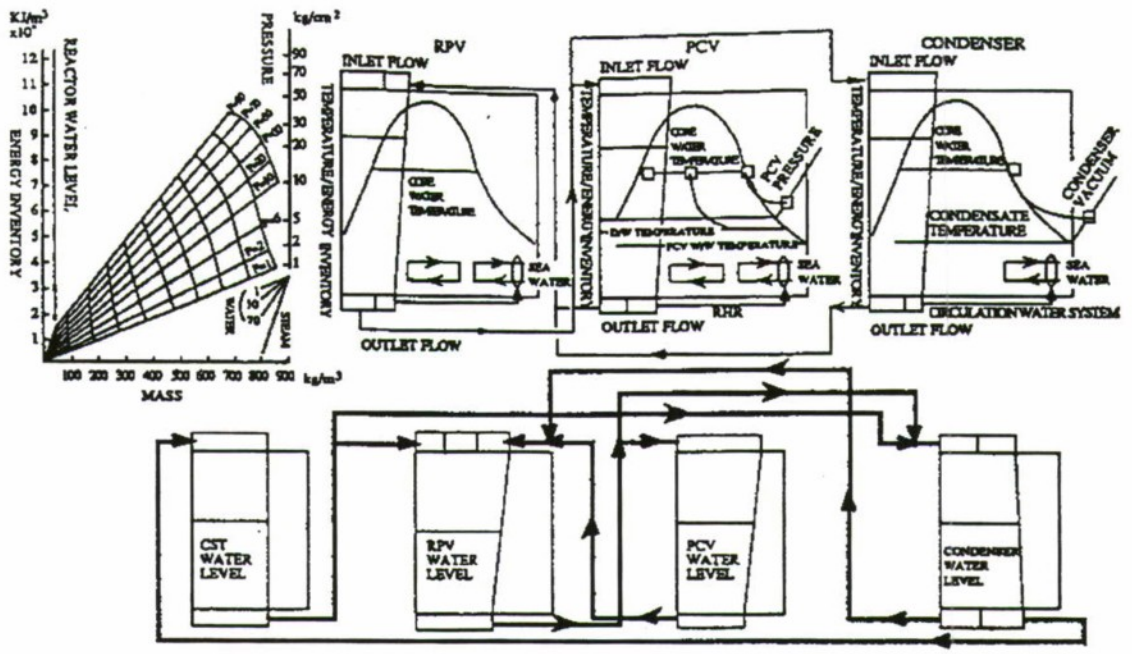


Figure 5.15 Toshiba EID Display
(Source: Reprinted from Itoh, J., Sakuma, A. and Monta, K., "An Ecological Interface for Supervisory Control of BWR Nuclear Power Plants," *Control Engineering Practice*, 3(2), 1995, Copyright 1995, with permission from Elsevier Science.)

more detailed results were not given. Itoh et al. (1995) gave additional information on the evaluation of the Toshiba EID display (Figure 5.15). This EID was subjected to an empirical evaluation (Takizawa et al., 1994).

Itoh et al. (1995) presented a typical comment from operators participating in the empirical evaluation of the display. "EID display would suit the novice operator training to build up his/her mental model. However, it is too crowded with information to easily understand the situation" (p. 238). This is not a very comforting result. Operators may have experienced difficulty understanding the plant situations shown in the displays. An independent examination of the display shows that many aspects are not self-evident and would probably require substantial training before operators could use it in operational situations. This also illustrates the importance of evaluating the relationship between the representation in the display and the operator's mental model of the domain, as well as its relationship to training.

Itoh et al. (1995) also discuss the difficulties of evaluating this type of interface. The authors stated that "evaluation of the man-machine interface, especially for new designs such as EID, is one of the most important issues, since it should guarantee that the design objectives have been completely achieved before interface usage. Its importance as well as its difficulty increases for the present case, because the main objective is to support the operator's knowledge-based behavior to cope with unanticipated events" (p. 237). Methods are needed to evaluate the technical accuracy as well as the human factors and performance aspects of the design's use.

In summary, Toshiba has put substantial resources into developing and testing an EID-based display system for the ABWR and believes that it will provide benefits over traditional displays. Since the ABWR has now been operating for some time, operating experience on the EID should soon become available. This would provide valuable information on its use in real-life situations.

5.3.2.4 Other EID Studies

This section discusses nine additional studies of EID-type displays that addressed a variety of different applications.

Edlund and Lewis (1994) compared five types of displays for controlling a simulation of a simplified steam plant. Eighteen participants were given the task to maintain boiler level and turbine speed in response to variations in load. When a fault occurred, they were to stop the simulation and make a diagnosis. The five displays (see Figure 5.16) used in the test were

- Dials display – Traditional gages were used to present process parameters. No information on constraints or relationships between parameters was given (see Fig. 5.16a).

- Fluid-tanks display – This display represents boiler and turbine levels. Feedwater, fuel, and make-up controls are shown as valves, which control flow in the system. Pipes and valves were animated to depict flow characteristics. Unlike the mimic display, the effects of parameters were not displayed as functions of commanded pumping rates (e.g., feedwater pump rate). The fluid-tank display is closest to the EID-type displays discussed above (see Fig. 5.16b).

- Seesaw display – The process is displayed as a seesaw with balances representing the fuel, feedwater, and makeup pump rates. The seesaw display is interesting because it incorrectly represents the dynamics of the process (see Fig. 5.16c).

- Mimic display – The same process parameters were presented as in the dials display, but the mimic provided a context revealing the relationships between them and their constraints (such as direction of flow). Its disadvantage was that the operator's task is to control states rather than individual components. This information is not given and the operator must mentally determine how to integrate it to manage the states (see Fig. 5.16d).

- Object display – The process parameters are integrated into a single-object display (see Fig. 5.16e).

The general results were that the best performance was obtained with the fluid-tank, dial, and mimic displays. The integrated object display fared more poorly. The authors hypothesized that this was because it presents state information with no context or process information. The seesaw display led to the worst performance, which emphasizes the importance of accurately mapping the features of the display to the dynamics they are intended to represent.

In another study, an EID display was compared with a mimic display for a chip refiner in a pulp factory (Brehmer et al., 1995). Fifteen process operators used the displays in a process simulation. The operators were divided into three groups: P&ID, EID, and EID with special training. The EID display was associated with better performance, and interestingly, no special training was found to be necessary.

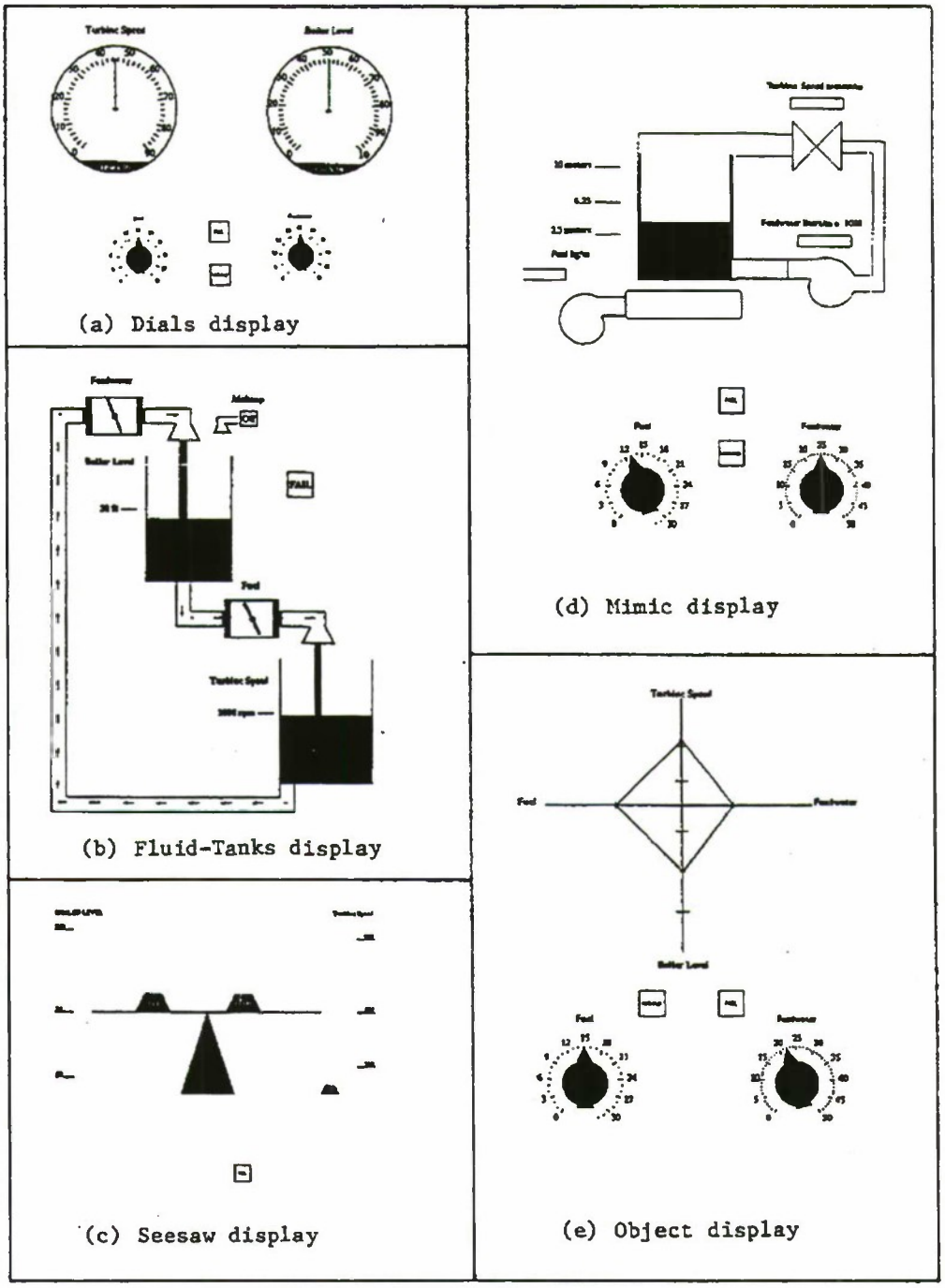


Figure 5.16 Edlund and Lewis Displays

(Source: Reprinted with permission from Edlund, C. and Lewis, M., "Comparing Ecologically Constrained and Conventional Displays in Control of a Simple Steam Plant," *Proceedings of the Human Factors and Ergonomics Society 38th Annual Meeting*, 1994. Copyright 1994 by the Human Factors and Ergonomics Society. All rights reserved.)

Similarly, Meshkati et al. (1994) evaluated the effectiveness of an ecological interface for handling process control disturbances. They found that the interface led to significantly more accurate diagnosis of events and faster response than a computer emulation of the current traditional console.

Reising and Sanderson (1996) conducted a detailed analysis of a pasteurization plant using the abstraction hierarchy. They found the following important factors for EID:

- Limitations in sensor technology may limit the designers' ability to represent, in displays, the information found in the analysis of the abstraction hierarchy.

- The displays of higher order variables and their relationships are based on computations using lower-level information, such as volume and temperature. The information displayed will be limited by the quality of the lower-level information.

- Sensor failures or errors may affect the form and content of the display.

One important contribution of a thorough analysis of abstraction hierarchy is that it can reveal not only the operators' information needs, but what sensors are needed and where in the plant they should be placed. In fact, the authors state that EID is "in a position to bring about a profoundly user-centered approach to system design in which the ultimate information needs of human controllers drive the engineering agenda of sensors and instrumentation in a feed-forward manner" (p. 296).

Based on their experience in applying the process, Reising and Sanderson (1996) concluded that building an abstraction hierarchy is an iterative process that required expertise in thinking in terms of abstraction hierarchies and in conducting the analyses. The knowledge of domain experts also is necessary. In addition, keeping track of the links in the hierarchy was very difficult and tools to support such analyses are needed. Lack of such support limits their use.

Shively (1995) examined the use of ecological approaches to 911 dispatcher interfaces. Ten experienced dispatchers completed eight trials, half with a traditional text display and half with a graphic EID display. Their task was to assign the most appropriate resource to each incident. Time and ratings of situation awareness, workload, and preference were collected. Response times did not differ; however, the operators were very experienced with the text display and had little training on the EID display. There were trends toward improved situation awareness and reduced workload with the EID display. The EID display was preferred as well.

In the medical domain, an EID display for hemodynamic monitoring was compared with a conventional display (Effken et al., 1992). The display provides clinical patient information, including current state and goal state. Data to determine the relevant information were obtained from expert clinicians. From this information, an integrated object display was developed. The display represents pressures by interconnected balloons for cardiac, venous, and arterial compartments, and cardiac flow as a bellows. This display reveals the functional relationship of the hemodynamic system. Traditionally, this information is monitored using strip chart displays of individual parameters.

Thirteen participants at three experience levels used the displays to handle simulated clinical events using a within-subjects design. Performance measures included time to initiate treatment, time to achieve target range, percent of time in target range, and the number of drugs, drug changes, and combined drug and dose changes. Compared to the strip chart display, the EID display performed better, showing the following: higher percent of problems corrected, greater percent time in target range, fewer drugs, drug changes, and combined drug and dose changes. There was an interaction with time to initiate treatment, such that the more experienced participants took

performed in parallel and some sequentially. This temporal dimension to operations may be lacking in the A-A analysis, except insofar as time is reflected in higher-level information, such as rates.

Additionally, the EID approach seems to be built around functional decomposition of means-ends relationships. How well such an approach will support common tasks or the handling of disturbances that are highly proceduralized needs to be determined. While it is important to be able to deal with unanticipated and unplanned events, still most of the operator's activities are well planned and the information system needs to support these activities as well.

(3) Information Volume and Density

Due to the extensive analytical process used for EIDs, the process, including the A-A matrix, may identify more information than can practically be displayed. Also, too many pages may be required to satisfy EID information requirements (see also discussion of density in Section 3.5). Potentially negative impacts of designing displays using the abstraction hierarchy are the potential proliferation in the number of pages and the increase in the density of information on each page.

(4) Integration of EID Displays into the Remainder of the HSI

Integrating a new and significantly different EID display into the remainder of the standard HSI of a CR is an important consideration to address.

(5) Critical Testing and Evaluation of EID Concepts

There has not been much thorough research that carefully assesses the various aspects of EID, e.g., information requirements, effect of organization of information along functional lines, display representation, and use of analytical redundancy. Studies tend to confound these characteristics or give weak assessments of the contribution of the various aspects of EID concepts.

Successfully handling unplanned or unanticipated events with EIDs, under actual operational conditions in complex systems, has not been demonstrated.

Further research also is necessary to more clearly identify which cells of the A-A matrix are important to operations.

(6) Evaluation of Operating Experience

For EID displays that were installed in operating facilities, there needs to be a thorough assessment of the operating experience and how it applies to the EID. Actual application of this approach to NPP HSI design includes the Toshiba ABWR CR (discussed earlier), a NPP feedwater system (Dinadis and Vicente, 1996), and the EBRII (Lindsey, 1990).

(7) Internal vs. External Mental Models

Carroll and Olson (1988) note, "If the interface suggests or reflects an appropriate model, then the user could conceivably learn it with less guidance and perform with fewer errors. The question is: What should the model be?" (p. 56). Compatibility of information representation and operator mental models is characteristic of "user-centered approaches to design and design review." For example, the high-level design review principle of User Model Compatibility from NUREG-0700, Rev. 1 states as follows:

> All aspects of the system should be consistent with the users' mental models (understanding and expectations about how the system behaves as developed through training, use of procedures, and experience). All aspects of the system also should be consistent with established conventions (i.e., expressed in customary, commonplace, useful and functional terms, rather than abstract, unusual or arbitrary forms, or in forms requiring interpretation). (pp. A2-3)

Vicente (1990, 1997) and others (Flach and Dominguez, 1995) criticized the "user-centered perspectives" and disagreed with the notion that the plant representations provided by displays must be compatible with the operator's mental model of the plant. Vicente argues that is because the models are incomplete and sometimes incorrect (as was discussed in Section 5.1). Thus, Vicente asks "what good is it having the computer be compatible with the agent's model if that model does not correspond to reality?" (1990, p. 496).

An example of the failures of user-centered design is the use of operators to support interface design. Vicente (1997) gives an example of a nuclear plant HSI that was designed with the aid of an "exceptional operator." When the design was shown to other operators, it was not accepted. Vicente concluded that "no two operators seemed to have the same mental model of the plant" and that "the control room in question had to be redesigned to reflect better the way in which the plant actually worked" (p. 3). Instead Vicente argues that process control operators exist in a correspondence-driven domain where there is an external reality in which the operator must exist. This is in contrast to a coherence-driven domain, where the human and the computer system represent a closed world and need not reflect external constraints. Rather than reflect the operator's model, the display should reflect the actual constraints of the process being controlled. Vicente refers to this as the "ecological compatibility principle."

We feel the criticism of the user-centered perspective takes the principles out of context. HSI design is part of a systems engineering process that attempts to capture the functions, relationships, and constraints as part of functional requirements analysis and task analysis. Further, the systems approach derives training requirements that are meant to provide operators with a concept of operations that includes an understanding of the system. Thus, for example, the NUREG-0700 principle identified above is part of a greater process described in NUREG-0711. This context was recognized by Pejtersen and Rasmussen (1997) as well, who identify one of the questions to be addressed in the evaluation of the complex system as "Does the presentation match the user's cognitive processes and mental models?" This is not the only question, and Pejtersen and Rasmussen suggest that questions on the content of the information in representations are better addressed by analytical evaluation methods, while questions addressing form are better addressed using empirical evaluation methods. In fact, other authors view EID as a movement toward user-centered design. Reising and Sanderson (1996) stated that EID is "in a position to bring about a profoundly user-centered approach to system design in which the ultimate information needs of human controllers drive the engineering agenda of sensors and instrumentation in a feed forward manner" (p. 296).

The point of user-centered principles (in their full design context) is that once the systems analyses are completed and operators are trained, the HSI should be consistent with human cognitive and physical constraints and should be compatible with the training and experience used to develop operators' expertise with the system.

Thus, we do not disagree with Vicente's ecological compatibility principle. The HSI must reflect the reality of the system being operated. Display design should reflect the systems engineering process. If it does, the process should not lead to displays based on faulty mental models of individuals. For the NPP CR design discussed above, the failure is not in the user-centered aspects of the design, but in the design process at large. Operators' input should be sought after the systems analyses to help develop representations that link display forms and functions to the way the plant works. The design process should have allowed for display requirements based on systems analyses to have been developed and for prototyping and testing alternatives of design early in the process (see

NUREG-0711). HSIs should not be developed based on the input of a single operator without the checks and balances offered by the full design process.

In fact, the representation of a system as complex as a NPP will ultimately be based on many sources of human expertise, including operators, engineers, and physicists. All of these experts are likely to have some gaps in their mental models.

An extreme expression of the ecological compatibility principle was reflected in a paper by Lindsey and Staffon (1988; from Hansen, 1995). They developed a modified Rankine cycle display and concluded that operators no longer needed to construct a mental model of the process because the display accurately depicts the plant state. While displays should certainly provide accurate representations of the systems they represent, the relationship between them also must be consistent with operator models of the system. Consider the implications of violating a principle, such as the User-Model Compatibility. There are ample data to show that when displays are not consistent with operator models and expectations are not well integrated into task environments, they will not be used, or even worse, they will be misunderstood.

Operators interpret information using their mental models, which provide meaning and coherence to information. Ignoring this information processing reality is as serious as ignoring the constraints of the system. Both need to be equally addressed designing an effective HSI. Our point is consistent with the notion of the cognitive system triad of Woods and Roth (1988), which includes the world to be acted on, the agents who will act, and the representation through which the agent acts. All three are essential parts of the overall system.

(8) Training and Qualification Implications

Christoffersen et al. (1995) concluded that "to experience the benefits of EID, it seems likely that operators need to be trained to think functionally rather than procedurally. It would seem that this would require a fundamental shift in NPP operation philosophy...it may be that operators have to possess certain types of cognitive characteristics that may not be considered in the traditional selection process in the nuclear industry" (p. 143). Concern also was expressed that EID interfaces may inhibit long-term learning and retention (Wickens, 1992).

Also, for any such display, where the information is sophisticated and a large amount is consolidated into one or a few figures, the requirements for training become very important. One needs to understand all of the aspects of the display and how it reacts to various operational transients, accidents, and failure of instruments. Finally, the long-term effects of EID-type displays on operators' performance and strategies are unknown.

(9) Operator Acceptance

The issue of operator acceptance of a new and different type of display (such as an EID display) also is important, as shown by the operators' comments during experiments. One interesting idea that was noted during the Rankine cycle experiments is introducing the displays initially in training, and then perhaps gradually introducing them into the plant.

(10) Effect of Instrumentation Failures on Interpreting Displays

The effects of failures of instrumentation on EID displays is a potentially significant problem that needs to be addressed. There are several subissues associated with this problem:

- Can a failure of instrumentation be detected by operators?

- Can failures result in representations that are interpreted by operators as real process failures, and perhaps more importantly, can real process failures be misinterpreted as instrument failures?
- If operators detect a failure, should they suspend use of the display?
- Since the display integrates many parameters into a single display, what is the effect of its loss on operations, and how effectively can operators switch to backup displays?

Many designers have implemented advanced features that address this concern to some extent. For example, the concepts of redundancy and diversity in instrumentation, coupled with automatic parameter validation and appropriate notification of operators when instruments fail their validation, have been shown to be powerful.

5.4 Research on Information Representation

As discussed in the previous section, advances in the analysis of information requirements have led to potentially enhanced methods for identifying levels of information about a plant that vary along A-A dimensions. However, it is not adequate to identify the information needed and simply make it available in the CR (Woods and Elias, 1988; Woods and Roth, 1988). Data, in and of themselves, have no inherent meaning. Meaning is acquired when data are put in context. Thus, "data availability" is distinguished from "information extraction" Further, this context should be reflected in the representation of the information. An intelligent display system would "create and manipulate the representation through which the domain problem solver sees the world" (Woods and Elias, 1988, p. 1352). Representation addresses the manner in which the information needed by the operator is displayed.

Conventional CRs present individual parameters on analog displays as separate pieces of information. The displays are usually grouped logically. However, integration and interpretation of data is mainly accomplished by the operators based on training and experience. When computer-based display technology was first introduced into CRs, the displays tended to follow well-known information presentation formats showing single parameter values, such as digital displays, multiple parameter values, such as bar charts, and simple relationships between variables, such as trend graphs vs. time. The first attempts at making displays ecological linked individual parameter displays with mimic lines to reveal their structure with respect to the plant and process they represented. While this approach was a common modification of a NPP CR following the TMI event, the tradition has continued in the first generation of digital CRs, which make extensive use of displays to show plant components and systems at low levels of abstraction; i.e., individual components may be represented by icons. Such displays can be based on a functional layout of the plant, using the format of simplified piping and instrumentation diagrams (P&IDs).

Comparisons between some of the above simple representational formats revealed differences in performance which appear to be task specific. For example, Hollands and Spence (1992) found that change was judged more quickly and accurately with line and bar graphs than with tiered bar graphs and pie charts, while the opposite results were obtained for proportion judgements. Research examining the effects of basic display representations on specific tasks is still the subject of ongoing research (e.g., Gillan et al., 1998; Hink et al., 1996; Hollands and Dyre, 1997; Hollands and Spence, 1997; Meyer, 1997; Meyer, Gopher, and Levy, 1997; Meyer, Shinar, and Leiser, 1997; Shamo et al., 1996).

The guidance on design review contained in NUREG-0700 addresses these basic representational formats fairly well. Representational formats based on graphical features that are tied to perceptual processes, such as polar graphic displays, and formats using graphic forms that reveal higher-level plant information, such as Rankine cycle displays are not addressed in sufficient detail. Thus, the main focus of this section is on representation formats that attempt to reveal plant information by making better use of human perceptual and cognitive processes.

The term *representational aiding* has been used to refer to using the capability of computer-generated displays to create novel representations of a system that can be manipulated to support operator's decision making (Woods and Roth, 1988).

Sections 5.4.1 and 5.4.2, respectively, discuss the theory and research directed to representational aiding. Section 5.4.3 gives the conclusions.

5.4.1 Theory of Representational Aiding

Direct Perception and Representational Mapping

As noted earlier, NPPs generate a great quantity of data that, at times, can overload the operator. To lower the workload associated with extracting meaningful information from data, efforts were undertaken to support the task of integrating data into more meaningful units of information. Within the context of representational aiding, the goal of display design is "...to map the domain semantics (low-level data, high-level constraints, and relevant performance goals) into the appearance and dynamic behavior of a graphic display so that this information is readily available (easily extracted or decoded by the user)" (Bennett et al., 1993, p. 73).

The success of representational aids is a function of the characteristics of the system, the tasks to be performed, and human information processing (Bennett, 1992). Woods and Roth (1988) suggested that displays can be conceptualized as involving a cognitive system triad that includes the world to be acted on, the agent who will act on the world, and the representation through which the agent acts on the world. All three are essential parts of the overall system. The representation involves the following two types of mapping (Bennett et al., 1997):

- Correspondence map between the properties and characteristics of the system to be represented and the features in the representation (how well the display communicates meaningful information about the plant that is needed by operators)

- Coherence map between the features in the representation and the physical and cognitive characteristics of the operator (how comprehensible the representation is to the operator)

The systems engineering approach (see Section 5.1) and abstraction hierarchy (see Section 5.3) provide approaches that address half of the correspondence issue – the identification of system functions and constraints that need to be represented.

In the previous section, EIDs were discussed in terms of Gibson's ecological psychology and its focus on the work domain or system to be represented. Two aspects of Gibson's approach to perception are important to representing information about the system: the concepts of direct perception and affordances (Flach, 1989; Flach and Hancock, 1992). Direct perception means that the information presented in the display has immediate meaning within the context of the operator's current information needs, including task requirements and system status. There is little need for the operator to analyze and interpret direct perception displays (see Flach, 1988, for a discussion of the use of the term "direct" in HSI design). Affordances are the features of an interface that suggest an interpretation or a response by the crew. They are a product of the interaction between the crew and the interface within the context of the ongoing tasks of the crew. This is an extension of what Gibson meant by direct perception of the physical features of the perceptual environment. Direct perception is made possible by a one-to-one mapping of affordances and domain constraints.

Thus, the degree to which a display supports operator's performance is a function of both the quality of the mapping between the emergent display features perceived by the operator and the relationships and constraints of the system. Bennett et al. (1997) stated that

> Problem solving can be critically influenced by the nature of visual representations. Building effective representations requires designers to go beyond the simple psychophysical questions of data availability to the more complex questions of information availability, where information refers to the specification of domain constraints and boundary conditions. This specification depends both on the mapping from display to human (i.e., coherence) and on the mapping from display to domain (i.e., correspondence). (p. 682)

Efforts to create direct links between graphical forms and operator actions are discussed below (these links are the affordances). Two basic approaches are discussed: the information relationships approach and the proximity-compatibility approach. The primary focus of the information relationships approach is on the mapping between display characteristics and characteristics of the system being represented, while the primary focus of the proximity-compatibility approach is the mapping between display characteristics and the characteristics of the tasks being performed.

Information Relationships: Representing Separable, Integral, and Configural Relationships

One attempt to accomplish the objective of direct perception is based on the mapping of low-level perceptual processes to the relationships between plant information. Bennett and Flach (1992) defined three potential relationships between data that can be represented in displays: separable, integral, and configural. Separable relationships are those that can be showed by individual data points. They are characterized by a lack of interaction among the data dimensions; i.e., each dimension retains its unique perceptual identity. Integral relationships are defined by a strong interaction among data dimensions such that the unique identities of individual dimensions are lost. When such a relationship exists, a change in one dimension necessarily produces a change in a second dimension. Bennett and Flach used the example of color perception, which is a function of the dimensions of hue and brightness. In color perception, the perception of each individual dimension is lost in the integration. Configural relationships refer to an intermediate level of interaction between dimensions, where each maintains its unique identity, but new emergent properties are created as a result of the interaction between the dimensions.

These three types of relationships are associated with three generic types of displays. An important goal in display design is to provide the most appropriate type based on how the operator must use information about the domain.

Separable displays are representations where each process parameter is presented individually and no relationships between the parameters are provided by the representation itself. The key aspect of separable displays is not that individual parameters are presented, but that no interaction or relationship between them is perceived. There may be, in fact, a relationship between the parameters, but the separable displays do not show it. The studies on the Rankine cycle display, discussed in Section 5.3, used a separable display – a set of individual meters – as a basis of comparison (see Figure 5.12).

Integral displays show the integration of information in such a way that the individual parameters used to generate the display are not represented in it. A display that provides information on system status by the appearance of an icon is an example. The icon may change appearance based on the computation of lower-level parameters, but these parameters are not presented. When decisions are based on the integrated information, the concept of integral display suggests that information processing is supported by integrating information into a single object (Kahneman and Triesman, 1984). Integral displays are thought to support direct perception by capitalizing on the

abilities of human pattern recognition, and thereby reduce demand on working memory associated with simultaneous consideration of many individual variables.

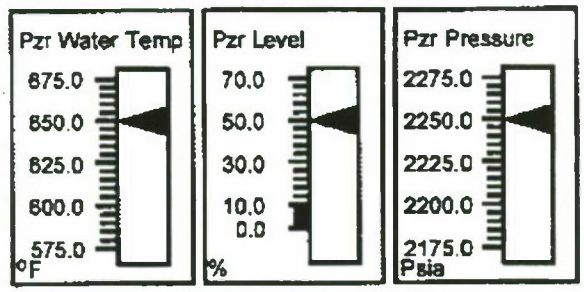
Configural displays provide a combination of the other two types. Information about the basic parameters is available; however, information on their relationships becomes evident as features emerge from the representation. An *emergent feature* is a "high-level, global perceptual feature that is produced by the interactions among individual parts or graphical elements of a display (e.g., lines, contours, and shapes)" (Bennett et al., 1993, p. 73). Configural displays often use simple graphic forms, such as a polygon. Information that could be presented by separate display formats is integrated into a single format in which each of the separate pieces of information is represented, for example, by the distance of a polygon's vertex from its center. In addition, the geometric shape of the polygon provides a high-level summary (the emergent feature) (Buttigieg et al., 1988; Sanderson et al., 1989).

The SPDS display described in Section 4 is an example of a configural display (Woods et al., 1981). By glancing at the shape of the polygon, the operator can readily see whether the plant is in a safe or unsafe mode. However, information about the individual parameter values also is still available. Such displays are thought to enhance parallel processing (lowering cognitive workload), enable operators to better understand the relationships between display elements, and ultimately lead to a more rapid and accurate awareness of the situation (Bennett and Flach, 1992; Flach and Bennett, 1992). The extraction of information for high-level task requirements is supported by the emergent features produced by a configural display.

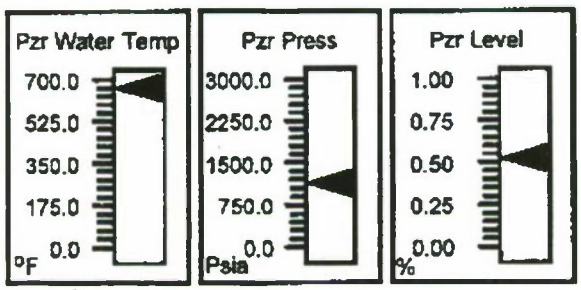
Another example of a configural display is the Rankine cycle graphic discussed in Section 5.3 (see Figure 5.11). The form of the graphic indicates overall performance, and the operator can obtain specific parameter information if needed. However, in this Rankine display, the parameters would have to be estimated from the figure, and the scales are large. This almost makes it into an integral display (without parameter values), since the operators would really need to refer to separate indicators to obtain useful specific information on pressure, temperature, or levels.

Emergent features can be formed by purely separable displays; i.e., where no specific graphic is incorporated into the display (Wickens and Carswell, 1995). A systematic pattern formed by a series of bars on a bar chart or the parallel appearance of a set of analog meters may form an emergent feature (Figure 5.17). Operators may, for example, be able to glance at a row of meters and be able to determine that all systems are properly functioning because the needles are all pointed in the same direction. Similarly, the blackboard (or darkboard) concept in alarm system design is based on an emergent feature (O'Hara et al., 1994). The darkboard concept means that when all alarmed parameters are within normal operating range, no lighted alarms can be seen (on a conventional board) or no messages appear on alarm VDUs. When the alarm system is designed in this way, the operators can glance at the alarm display and determine the general acceptability of overall plant performance. The emergent feature is effective if it conveys high-level information without requiring operators to analyze the individual parameters.

The degree to which the individual and emergent features are perceptually salient to the observer is important in allocating attention to the elements of the display. The design goal is to map meaningful aspects of the operator's task information requirements to the visual characteristics of the display (the display grammar, as discussed in Section 4). Significant aspects of domain structure and behavior must be mapped to the characteristics of the representation so that the domain's semantics are directly visible to the operator (Woods and Roth, 1988). Issues that need to be addressed include selecting, scaling, and assigning lower-order data to characteristics of the representation. The challenge is to set up a mapping so that the task-meaningful semantics are directly visible to the observer and that both normal and disturbance conditions are clearly perceived.



(a) Emergent features showing normal operating conditions



(b) Same normal operating conditions without emergent features

Figure 5.17 Separable Display With and Without Emergent Features

The value of each type of display – separable, integral, and configural – may depend on the task requirements (Bennett and Flach, 1992). That is, if operators must conduct their tasks based merely on individual parameters, then separable displays may be preferred. If they depend on the integration of individual parameters, then integral displays may be preferred. If performance is based on a combination of the two, then configural displays may be the best solution for representation.

Bennett et al. (1997, pp. 291-292) identified the following design principles based on information relationships:

(1) Each relevant process variable should be represented by a distinct element within the display. If precise information about this variable is needed, then a reference scale or supplemental digital information should be provided.

(2) The display elements should be organized so that the emergent properties (symmetries, closure, parallelism) that arise from their interaction correspond to higher-order constraints within the process. Thus, when process constraints are broken (i.e., a fault occurs), the corresponding geometric constraints also are broken (the display symmetry is broken).

(3) The symmetries within the display should be nested (from global to local) in a way that reflects the hierarchical structure of the process. High-order process constraints (e.g., at the level of functional purpose or

abstract function) should be reflected in global display symmetries; lower-order process constraints (e.g., functional organization) should be reflected in local display symmetries.

Proximity-Compatibility Principle

The proximity-compatibility principle (PCP) was developed to guide the mapping of operator task characteristics and display design (Carswell and Wickens, 1987; Wickens and Carswell, 1995). Task proximity and display proximity need to be jointly considered when designing displays to support task performance. The task and display characteristics are described in more detail below.

Task proximity can be described by several dimensions, including the following:

- Temporal proximity – the degree to which two tasks must be performed in close temporal proximity to achieve a goal
- Processing proximity – the overlap between the information processing that is needed to process different information
- Statistical proximity – the degree of covariation between information (e.g., when two parameters covary or when a change in one is reflected in a change in the other, the relationship has high statistical proximity)
- Functional proximity – the similarity of objects as represented in the operator's mental model (e.g., all parameters describing the performance of a single component have high functional proximity)

Three general categories of tasks are defined: integrative, nonintegrative processing of similar tasks, and nonintegrative processing of dissimilar tasks. Integrative processing tasks require operators to engage in (1) computational integration, i.e., combining or integrating data to make a decision or take an action; or (2) boolean integration, i.e., determining the satisfaction of boolean conditions to make a decision or take an action. In both cases, operators are using many information sources to arrive at a few decisions or to take a few actions (a *many* to *few* relationship).

In contrast to integrated tasks, nonintegrative processing of dissimilar tasks is characteristic of task independence or low task proximity. There is little similarity or interaction between the information or processing mechanisms required by two tasks. Nonintegrative processing of similar tasks is characteristic of tasks with moderate proximity.

Display proximity addresses how perceptually similar two displays are that convey information on the same task. There are several dimensions that define perceptual proximity, including spatial proximity, chromatic proximity, physical dimensions used to code information (such as length), perceptual coding (such as digital vs. analog), and geometric (integrated or separate displays) (Bennett et al., 1997). Display proximity is enhanced by (1) arranging displays close together, (2) using shared information channels, (3) adding lines to connect or enclose information channels, (4) giving related information sources the same codes, such as color and orientation, (5) integrating information so it appears as a single object (object integration), and (6) configuring homogenous features into a new pattern (configuration).

The PCP states that there should be a high correlation between task proximity and display proximity. High-proximity tasks, such as those involved in process fault detection, must be performed in a highly integrated manner. These types of tasks are conducted better using high-proximity displays, e.g., by presenting data relationships as a single object (an integral object display), because many plant variables must be considered

simultaneously. High proximity is accomplished by high integration of data. Low-proximity tasks are those in which the operator responds by focusing on individual system elements. These tasks are better supported by low-proximity displays, such as a series of bar charts. Essentially, the PCP states that low-proximity tasks will be better performed with low-proximity displays and vice versa.

The basic phenomena that account for high-proximity display support of high-proximity tasks are reduced information access cost (IAC), object integration, and emergent features (Wickens and Carswell, 1995; Wickens, 1986). Reduced IAC is accomplished by (1) allowing all display axes to be within foveal vision, thus minimizing search and scanning problems; (2) reducing the memory load associated with retaining part of the needed information while another display is accessed to get additional needed information; and (3) reducing the mental effort required to integrate the information. The more separate the information, the more IAC is involved. Emergent features and object integration enable perception to be used instead of mental computation. Emergent features, however, need to be mapped to task-related variables.

These same phenomena can make the performance of low-proximity tasks more difficult because high-proximity displays will create clutter on the screen and lead to confusion. Close spatial proximity can make it difficult to find relevant information and discriminate it from other information. When a relevant object is within one visual degree of an irrelevant object, the presence of one has a negative effect on the processing of the other (and will increase IAC). Conversely, decreasing proximity of the display makes it easier to focus attention on a single object or parameter, and thereby supports the performance of low-proximity task. Thus, the PCP places emphasis on the mapping of display characteristics to task demands. Compatibility between the two will support performance while incompatibility will detract from performance.

5.4.2 Research on the Effectiveness of Representational Aiding

In this section, we consider the research addressing these approaches to representational aiding. Where possible, published reviews of the literature were used. These reviews were supplemented with individual research reports. For discussion of the studies addressing representational aiding, the term *focused tasks* refers to tasks that are independent from each other in terms of requiring separate information, and the term *integrated tasks* is used to refer to tasks that require integrating information. The discussion below centers around two main questions: (1) what are the overall effects of integral, configural, and separable displays on performance? and (2) what are the specific design features that explain these effects?

Bennett and Flach (1992) conducted a literature review of studies examining the relative effects of configural graphical displays and separable displays on performance of integrated and focused tasks. They grouped the studies by test methodology, as follows: signal detection, multiple-cue judgement, retrospective memory probe, and system control.

In the signal detection methodology, a participant observes a display and detects an abnormality. No actual system control is performed by the participant. The results of studies using this methodology generally showed that the configural displays led to better detection performance than separable displays, especially in integrated tasks requiring higher-level information. For tasks focused on lower-level information, the results were either insignificant or favored the separable displays.

Studies using a multiple cue judgement methodology require the participants to observe a display and make a judgement about the system's status. The results were generally consistent in support of configural displays in integrated tasks. Bennett and Flach found only one study using focused tasks where performance was better with the separable display.

In studies using the retrospective memory probe methodology, participants were asked to recall information about a system based upon display conditions. Again, participants performed better with configural displays for integrated tasks, but the display differences for focused tasks were insignificant.

Finally, in the system control method, participants monitor and control a dynamic system. Performance measures reflecting performance goals are obtained. Bennett and Flach found little research using this method (see discussion of Bennett et al., 1993, below). In one area, the results from multiaxis tracking tasks supported the use of configural displays.

In summary, the review showed that better performance was found with configural displays when the task was integrated, and therefore, required performance based on abstract integration of data. For focused tasks, where performance required responses based on specific aspects of the data, a "mixed pattern of results" was found (Bennett and Flach, 1992; Bennett et al., 1997); i.e., results were either insignificant or favored separable displays.

Barnes and Suantak (1996) evaluated the effects of configural representations of complex tactical situations in comparison to conventional graphic and alphanumeric formats on the speed and accuracy of tactical decisions. Seventeen army officers made situational decisions based on the displays, and responses were faster and more accurate with the configural displays.

Bennett et al. (1993) used the system control method to compare the performance of 20 students on a simulated manual feedwater control task, using either separable or configural displays in two experiments. In experiment 1, the task was to adjust the flow rate to maintain steam generator level. Task performance was the primary dependent variable. No significant differences between the displays was observed. In experiment 2, using the same participants and control tasks, a memory task was included to examine recall for focused information (e.g., rate of steam flow) or integrated information (e.g., the difference between steam and feedwater flow). To ask the memory question, the simulation was stopped and computer screens went blank. After the memory question was answered, the simulation was resumed. The results showed that there was a significant interaction of display type and question type. The configural display significantly improved performance on the integrated information, but not on the focused information. Also, while the configural display improved memory for important high-level information, differences in actual task performance were not significant. This result may parallel those of Vicente and colleagues (discussed in Section 5.3), where the configural information in the DURESS EID display did not greatly affect the control task performance.

Coury and Boulette (1992) compared several graphical formats and found that a task's time constraint was an important factor affecting the display-task relationships. They found that "different representations of the same system data can have a profound effect on performance" (p. 707). They further stated that

> One clear conclusion from this research is that the effects of time stress complicate the selection of display formats for state identification tasks. Although designers of operator interfaces may be tempted to select the polygon display because of its apparent superiority under the most severe time constraints, such a choice would ignore a number of important trade-offs in performance. Consider changes in processing strategy. Although overall performance with the polygon display was good, the digital display was superior in many situations. (p. 723)

Hurts (1996) investigated memory for configural information. Twelve undergraduate students responded to questions about interpretation of graphed information using either separable graphs or configural graphs. Dependent measures were time and accuracy. The results revealed that while configural graphs were superior to separable graph displays when the graphs were present, the effect was reversed when retrieval from memory was required to respond to questions on lower-level information. That is, performance on the memory test was superior

with separable graphs. They also found that the effect was lessened when there was greater data-to-graph compatibility.

While integral and configural displays appear to support some aspects of integrated task performance, some questions remain. What accounts for the effects, i.e., is it that the information is integrated into objects displays, such as polygons, or is it the emergent features? Further, how might performance of focused tasks be better supported in higher-level displays? These issues are discussed below.

Flach and colleagues addressed the 'object vs. emergent feature' aspect of displays using a fault detection task (Buttigieg et al., 1988; Sanderson et al., 1989). Fault detection is a high-proximity or integrated task because many variables must be simultaneously considered. In such a situation, the PCP predicts that a high-proximity display will lead to superior performance. An integral display where all variables are integrated into a single object is a high-proximity display. The emergent features approach would predict that it is not the object per se that will lead to superior performance, but the salience of emergent features even if the individual displays are separate.

To compare these predictions, participants engaged in a fault detection task for a simple process consisting of two inputs and one output. Four displays were used. One was an integral display where the inputs and outputs were integrated into a triangle display. The other three displays were separate bar charts, which were arranged in different ways to vary the salience of the emergent feature created by the three bar charts. Reaction time and false alarms were the dependent variables. Contrary to the proximity-compatibility principle, performance was better on separate bar chart displays than with an integrated object display. The bar chart associated with the best performance had the most salient emergent feature (linearity of the bar chart arrangement).

Thus, it may not be the integration of information into an object that supports performance, but rather the emergent features. The failure of integral object displays to support focused tasks was observed as well. Montgomery and Bivona (1997) compared bar charts, two types of deviation bar charts, and an integrated object display for detecting differences in the temporal variability of information sources. Fourteen participants observed the displays and were asked to decide which of two sources was least variable. Accuracy was the dependent measure. The magnitude of the difference was varied. The deviation bar chart resulted in the best performance; the integral and standard bar chart displayed were the worst. The authors concluded that the deviation displays were more compatible with the task, which required the source variability to be considered separately.

Thus, focused tasks are not supported by integral object displays and may not be supported well by configural displays. Bennett et al. (1996) addressed methods for enhancing the extraction of lower-level information from configural displays. Configural displays with and without several enhancements were compared: (1) color coding, layering, and separation; (2) tickmarks and gridlines, (3) bar graphs and extenders, and (4) digital values. These enhancements were systematically included and excluded. Eight students participated in the experiments and performed a simulated process control task. The experimental sessions were interrupted at random intervals and participants were asked either focused memory probes (addressing lower-level information) or integration memory probes (addressing higher-level information). Latency and accuracy were the dependent variables. The results showed that the inclusion of digital values was associated with the greatest increase in performance. Another positive enhancement was the use of tickmarks on the display axes and gridlines that extended the scale information into the display area. Thus, configural displays can be designed to better support focused tasks.

Hansen (1995) also examined the enhancement of configural displays. The evaluation included the degree of configurality (configural or separable), presence of digital information (presented or not), and presence of time history information (presented or not). Configural and separable displays were compared with and without digital and time information. The experimental task was to monitor eight variables to determine an "event" defined by a

decrease in all eight. Measures of reaction time, event hit rate, and false alarm rates were obtained. The displays were compared in two experiments. In the first, the rate of change of the event was either slow or rapid. In experiment 2, the signal-to-noise ratio was varied between noisy and not. Each experiment had 11 participants, graduate students, in a within-subjects design. Overall, the results showed that configural displays were better than separable displays for event hit rate, but led to higher rates of false alarms. The addition of time information was found most useful in noisy events. In an analysis of the combined results of the two studies, providing digital information led to faster response time, but there was no effect on hit or false alarm rates. The digital information provided a means of responding when the graphic display began to indicate the event. At times, digital information interfered with the emergent features of the integral displays. Hansen (1995) concluded that there was much support for the observation that

> ...graphical representations can be effective for communicating information for controlling dynamic systems. However, there is less agreement as to the dimensions that distinguish effective graphical representations from ineffective ones. Experimental comparisons of display formats varying in degree of configurality, inclusion of supplemental digital information, and inclusion of explicit time dimensions were found to have significant effects on the detection of temporal events and the ability to detect trends. For example, it was observed in some conditions the inclusion of digital information in an integral graphical display can detract from its emergent features. (p. 539)

Several studies focused on polygon displays. Woods et al. (1981, 1982) compared a safety panel composed of a configural polar graphic display (see Section 4) and a plant mimic display to one composed of trend graphs of safety parameters. Eight crews of professional operators experienced transients on a NPP simulator during their normal training sessions. No quantitative comparisons of the displays were performed. In a qualitative analysis, the trend display did not support operator decision making because of implementation problems, e.g., the update rate was too slow. The polar graphic display gave a useful overview of the plant's safety status, but the authors felt that lack of familiarity limited its use. The mimic display was the most effective and frequently used display.

Other studies found an effect of polygons on performance. Performance on a fault detection task was found to be better with the polygon display (Hughes and MacRae, 1994). Greaney and MacRae (1996) evaluated the effect of polygon displays on fault diagnosis. As the number of vertices increased, the reaction time for diagnosis increased. Reaction time also increased as a function of polygon regularity, that is, the more irregular the display, the longer it took to diagnose a fault. Thus, such displays may be of more value for indicating higher-level information than for the display of individual parameters that must be assessed separately.

Green and Logie (1996) examined the use of polygon displays to indicate the physiological status of a patient in intensive care. Polygons of eight to ten sides were developed. They found that information on status could quickly be derived from the displays and that performance was better for simpler polygons. They also observed that physicians were more attentive to information reflected by the top of the polygon; that is, patient information represented by the upper part of the polygon was more salient. In another experiment, polygons were developed to indicate specific medical conditions that were typically observed in intensive care units. Physicians were readily able to use these displays for diagnosing the nature and severity of the conditions.

Pionek et al. (1997) investigated the effects of polygon characteristics on reaction time. The characteristics were color (color vs. no color), size (large vs. small, 30% of large), and number of vertices (6 or 12). Fourteen engineering students viewed the polygon displays to identify the presence of an abnormal state using reaction time as a measure. The results showed that color and size were significant, as was the interaction of color and number of vertices.

Coury et al. (1989) found that, for fault diagnosis, a polygon display was worse than a bar chart display, but was superior to a digital display. Casey (1986) also found a polygon display worse than an integrated bar chart display.

Coury and Pietras (1989) compared the following three display formats: graphic, alphanumeric, and multiple formats. Performance in a simulated process control task was worse with graphic displays and best with the multi-format display. Thus, the overall results on the effectiveness of polygon displays are mixed.

5.4.3 Conclusions

In general, we agree with the conclusion of Bennett and Flach (1992) that configural displays support integrated task performance, and that a mixed pattern of results is found when focused tasks are performed (sometimes separable displays are better for focused tasks). Further, it appears that configural displays can be enhanced to better support focused task performance, such as by the inclusion of digital information. However, including digital information can detract from the emergent features, so it must be done cautiously.

The aggregate of the studies related to information representation appears to support the PCP that performance is best supported when both the types of displays and their details closely match operators' tasks. Operators of NPPs have a wide variety of tasks, from high-level fault detection and diagnosis to lower-level component manipulation. Thus, one can conclude that operators should have a variety of different levels of displays that span the A-A hierarchy. (A careful review of NPP instrumentation and displays shows that to some extent this already exists). The operators should be able to select from this suite of displays or be able to reconfigure the level of displays, based on the task at hand. When this level of diversity of displays and flexibility in selection is provided, performance issues naturally arise (see Issue [6] below).

In general, while the research reported in this section was more rigorous from a standpoint of experimental methodology than the EID studies, these studies also were limited in generalizability, because of the following factors:

- *Domain representation* – The domains represented by the displays did not address the complexity of real systems. While there were exceptions (e.g., Woods et al., 1982), in many of the studies the domains represented were very simple. Since the emergent features are meant to map to constraints of the system, increasing the complexity of the system can be expected to make the mapping considerably more complex.

- *Tasks* – In part due to simplifications of the domain, the tasks also were simple. Even the fault detection in several studies was simplified and based on only a few variables. Further, the studies did not address a wide range of tasks.

- *Participants* – More often than not, the participants were students and not domain experts. Further, they did not receive the training that, for example, Vicente's participants did. Thus, issues associated with the contribution of mental models to interpreting the displays did not reflect the complexity of interpretation that would arise in NPP operations.

The limits on generalizability give rise to several possible research issues, as noted below. Resolving them is necessary for developing further guidance.

(1) Lack of Specific HFE Guidance

Bennett and Flach (1992) concluded that "Although there is general consensus that this type of display has the potential to improve human-machine system performance, there is less agreement on the principles or heuristics that should be used as design guidelines" (p. 514). The research on advanced graphic forms is at an early stage,

and while we can formulate a few general guidelines, the research is not yet substantial or definitive enough to provide a solid technical basis on which to develop a complete set of guidelines.

(2) System Complexity and Emergent Features

As the number of vertices in a polygon display increased, the displays became complex and performance was reduced. Further, emergent features can be affected by unpredictable interactions between component parts and produce unintended effects that may be misunderstood (Hansen, 1995). This illustrates the issue of increasing the complexity of the underlying domain to which integral and configural displays map. For complex dynamic systems, such as NPPs, not much is known about the dynamic aspects of the emergent features that may be used to represent them. In addition, as the graphic representation increases in complexity, so does the display grammar.

(3) Perceptual Resolution

Configural and integral displays require a perceptual process to take place, such as recognizing a change in an emergent feature. However, the degree to which a geometric form needs to change, before it is perceived as a distortion, is not well understood.

(4) Elements of Configural Display

The research discussed above suggested that configural displays could be enhanced, especially in support of focused tasks, for example, by including digital information. Research is needed to better understand the effects of display elements on performance and the effects of their interactions with other types of displays.

(5) Evaluation of Display

More comprehensive methods of evaluation are needed; this was also noted in Section 5.3 on the evaluation of EID displays. For example, the lack of definitive review guidance will need to be compensated for with dynamic evaluations. The criteria for the evaluations will have to be addressed. Hansen (1995) suggested a signal detection approach, i.e., an examination of hits, false alarms, and misses, because there is some evidence that subjects may generally be less conservative using configural displays under some situations, so that the hits as well as the false alarms increase.

(6) Operator Use of a Large Span and Variety of Displays

If and when the operators of a NPP have a large variety of different levels of displays from which to choose, how does the designer decide how many displays are enough? Have the operators been given too much information, either in a single display or in the entire suite of displays that are available? Will the operators be able to select the appropriate display for the task or tasks at hand? Will operators tend to choose a few "favorite" displays even though they may not be the most appropriate for the tasks? If operators do switch displays based on varied tasks, will they pick the proper display? What sort of training should be developed to address these concerns?

5.5 Organization of Displays

The investigation of display representations discussed in Section 5.4 addressed predominantly simple systems, where task performance was accomplished with a single display. Even the studies directed at complex systems such as NPPs (discussed in Section 5.3) looked at performance with a single display page. However, real-world complex systems cannot be represented with a single graphic display (Bennett et al., 1997), and this is certainly

true of NPPs, where display pages number in the hundreds and thousands (O'Hara et al., 1996). Thus, in complete information systems, representations are combined into display pages and pages into networks.

There are two characteristics of computer-based HSIs that impact the organization of information: information volume and available display area. Computer-based HSIs equipped with digital I&C systems typically provide much more real-time information than conventional CRs. Gaddy et al. (1991) observed "a common occurrence that often accompanies the introduction of computer-based technologies is an order-of-magnitude increase in the quantity of information at the user's fingertips" (p. 256).

An interesting paradox is that while the volume of information increases considerably, it is available through the very limited viewing area provided by workstation VDUs. This characteristic has been referred to as the "keyhole effect" (Woods et al., 1990), since at any given time most of the information is hidden from view; i.e., the operator has only a glimpse of the current plant information through the display devices. Therefore, operators must know what information and controls are available in the virtual information space, where they are, and how to navigate and retrieve them. If insufficient viewing area is available for operators to accomplish their tasks, they may have to frequently repeat navigation tasks. A problem related to the keyhole effect is that access to controls and display tends to be serial, e.g., only a few controls can be accessed at one time, which is in contrast to the parallel presentation of controls and displays in conventional CRs.

Thus, to present plant information in a limited viewing area, multiple levels of display pages are needed, and each must be accessed from a large network of pages before it is viewed. This way of presenting information may interfere with the ability of operators to quickly scan indications and assess plant conditions. Not all desired information may be presented at one time via the HSI. Because information in computer-based CRs must be retrieved from display networks, operators must know where to look to obtain status information. That operators may only monitor what they can observe and may ignore information not immediately presented has been identified as a human performance concern associated with computer-based systems (Fujita, 1992; Elm and Woods, 1985; Stubler et al., 1991).

Therefore, decisions on the design of display pages and their organization into networks are important considerations. This section will address these two aspects of display organization.

5.5.1 Organization of Display Pages

The limited display area in VDU-based systems means that when information is needed by an operator, it may be contained on more than one display page, which may require the operator to make rapid transitions between pages, try to remember values, or write values on paper. Compared to the sweeping wall-to-wall panels of older conventional CRs, CRs using advanced information systems have a more restricted view, even when multiple display devices are provided. Thus, the design of individual pages is critical to performance. The design review issues related to display pages are (1) the information to be combined into a single display page, and (2) the interaction of different display formats within a display page. However, very little research was identified that addressed these issues.

Information Requirements for Single Pages

In Section 5.2, the cognitive tasks supported by the information system were discussed. Those tasks included situation assessment, monitoring and detection of process disturbances, response planning, and response implementation. The information requirements for each of these activities are different and a task analysis, perhaps augmented by an analysis of the abstraction hierarchy, will help define the operator's information needs

for performing these cognitive activities. After developing the overall information needs, the specific organization and coordination of the information into distinct pages must be addressed.

Design considerations for display pages are highly related to and dependent on other factors, notably the following:

- Design of information (how much information is packed into individual display pages)
- Amount of display area that is available
- Interface management functions (how operators move within the organization to retrieve information)

These characteristics also interact with each other. Since the amount of information is large and the display area limited, more information-dense displays lead to fewer pages and less need to manage the interface. The tradeoff is that very dense displays can reduce the salience of important information and make it difficult to locate needed information within the display page.

Recent research showed a preference for a high density of information in displays. Thomas et al. (1998) evaluated the design of a wall panel information system for an advanced CR. A mimic-type display was compared with a display with considerably more information at various levels of abstraction. They found the crew's situation awareness increased and workload decreased with the more dense design. In addition, operators preferred the new, more dense design. In this study, however, operators did not have control over the amount of information on the display.

In another study (Roth and O'Hara, 1998), operators had control over the amount of information they could put on the display. They tended to cram their VDUs with information. For example, they would place multiple trend plots on a single VDU. It was not unusual for operators to divide a VDU screen into two windows and place four trend plots in each. Since each trend plot could have up to 4 parameters trended, operators could have up to 32 parameters trended per VDU. They were observed putting up multiple windows per VDU, occasionally overlapping and covering up one display with another. Covering up information by overlapping or covering one display with another was not found to be a problem in this study.

An important reason for preferring information-dense displays was that operators rarely modified or pulled up new displays once a scenario was started. Rather, they tended to select a set of trend plots to display at the beginning of a scenario and kept that arrangement. This finding is consistent with the finding that operators are generally reluctant to engage in interface management tasks in high workload situations (O'Hara et al., 1997).

Another aspect of information requirements for single pages is how complex information that extends beyond the physical limits of single pages, such as a detailed P&ID or procedure flow chart, should be divided to form individual pages. Again, tradeoffs must be considered with approaches for interface management.

Representational Format Interactions

While operators appear to prefer information-dense displays (to reduce interface management tasks), very little research has been conducted on the effects of mixing representation formats. Payne and Lang (1995) examined the effects of mixed vs. pure format displays on performance of focused vs. separable tasks. In pure format display, all indicators within a display are the same, either words (such as "fifty-five"), digital (such as "55"), or analog (graphic representation). In mixed format displays, a variety of formats are presented. They hypothesized that performance on focused tasks would be better supported with mixed formats. Undergraduate students visually monitored a dynamic simulated system. Their task was to indicate whether an indicator exceeded the safe range.

Accuracy and latency were the dependent variables. Responses were faster with the analog displays than with verbal or digital displays. There was no support for the contention that mixed format displays would better support focused tasks. In fact, more errors were committed in the mixed condition. Thus, mixing formats may have undesired effects on performance. However, the results of this study are suggestive only. The displays, participants, and tasks were not representative of a NPP context.

5.5.2 Organization of Networks

As previously noted, NPPs can have hundreds or even thousands of display pages. Therefore, their organization into a network is essential for rapidly and efficiently retrieving information. A variety of schemes for organizing information are possible: e.g., by physical equipment layout, systems, functions, and operator tasks. While there has not been a great deal of research on the organization of information in a display network, numerous organizational schemes have been criticized. Endsley (1995) criticizes physical organization, and Heslinga and Herbert (1993, 1995) criticize a plant systems organization.

The most common organization scheme for display networks in NPPs is by plant functions and systems. Such organizations were effective for the layout of conventional plants, but a recent survey of power plants suggests it may not be effective for organizing display networks. Heslinga and Herbert (1993, 1995) surveyed designers, managers, and operators of plants of various types from eight European countries on their experiences with the introduction of advanced HSI technology, either as part of new plant design or plant modernization. They found that the displays differed between a system-based hierarchal organization (e.g., an organization around plant systems with displays arranged hierarchically from overview to detailed levels) and a task-oriented organization (e.g., an organization around operator tasks). In comparison to task-oriented displays, operators reported having problems finding information in system-based organizations. This preference was especially true for non-routine operations. The authors suggested that operators' information needs were not centered along the system hierarchy, but along task requirements. Since the system-based organization did not conveniently provide the information needed for task performance, operators had to search through multiple displays. Heslinga and Herbert (1993) concluded that displays "dedicated to a certain task instead of the currently used system-based displays, could be a valuable alternative" (p. 33). For non-routine situations, there was insufficient time to search for information and controls within a hierarchy of displays, leading to the operators' reluctance to search through functionally-oriented sets of display pages. However, it may be more difficult to establish task-based displays for non-routine situations, due to their unpredictable nature and potentially large number. While Heslinga and Herbert's observations are important, we found no research that specifically addressed and manipulated the organization of display pages.

Woods and Roth (1988) proposed using multiple organizational schemes. They discussed fixed vs. adaptive collections of information. Given that there is too much data to see all at once, the question is how can the representational design be manipulated to help the operator find the right set at the right time? While needed data may be available in the system, the data needs to be grouped based on some criterion, such as where the device is located, physical system boundaries, time, or function.

When the designer preselects fixed collections of data, the effect on performance depends on the amount of searching that the operator must do across the predefined groupings, which in turn, depends on (1) the degree to which the designer's choice of criteria anticipates the questions to be asked by the operator, (2) the degree to which links between data sets and domain questions vary, and (3) the characteristics of the representation in which the search occurs (e.g., parallel vs. serial display).

Since the questions asked may vary, adaptive collections of data may be best. In adaptive collections, the grouping of data can change as a function of the state of the plant or of the operators' intent. Suppressing alarms based on

plant mode is an example of grouping changes based on the plant's state. Operators, however, may make changes to individual display pages, create new ones, or even globally change the grouping of pages. Such global changes could be predefined (e.g., normal operations, startup, normal shutdown, post-scram) and then invoked at the operators' discretion.

5.5.3 Conclusions

While the issues of organization of pages and networks are important and interact with many other design considerations, little data were found on the organization of large, complex information systems. Some information seemed to contradict current HFE guidance and nuclear practice. That is, very dense displays were found to lead to better performance and to be preferred by operators. The common industry practice of network organization by function and system was found to inadequately support operators' task performance.

Both of these findings may reflect the effects of workload associated with interface management, i.e., that operators seek to minimize the demands of interface management. Less dense displays increase the number of display pages and the amount of interface management needed to retrieve information. Similarly, organizing display pages by plant systems increased the interface management workload associated with performing tasks. A further complicating factor may be the flexibility of the HSI, which may inhibit the development of an accurate model of the display structure. If operators can view the display network in many different ways, it may be more difficult to understand its organization, and as a result, navigation plans may be less predictable. Thus, the organization of display pages and of networks remain human performance issues and further research to address them is warranted.

5.6 General Summary and Issues

The purpose of Section 5 was to establish a technical basis upon which to develop review guidance for information systems and to identify human performance issues where the technical basis is insufficient for developing guidance. To accomplish this objective, we examined research in the following four areas: (1) generic, operator cognitive tasks that an information system must support, (2) analysis of information requirements, (3) representation of information, and (4) organization of information. Section 5.6.1 summarizes the results of this research, and Section 5.6.2 gives the remaining research issues.

5.6.1 Information System Design and Operator Performance

Cognitive Tasks

The plant information systems provide the basis for operators to perform their role in the plant. The general tasks that the information systems must support include situation assessment, monitoring and detection, response planning, and response implementation. The following general observations were made:

- Operators' information needs, especially in support of monitoring, detection, and situation assessment, are very broad, both in terms of the range of activities that operators need to be aware of, and the level of abstraction they need to consider.

- Information should be expressed in terms that are at the level that will directly impact decision making and control. Cognitive resources should not be required to mentally process data to obtain information that is needed.

- It is important to correctly map the plant or process and the identification of information needs and their representation to the operator's mental model. These mappings are necessary to ensure that the representations of information trigger the appropriate mental representation of the situation.

- HSI design can strongly affect the operator's cognitive activity and can make information difficult to obtain (through poor organization, high data density, and excessive interface management demands).

The information processing basis for the operators' cognitive tasks should be considered in the guidance for reviewing information system designs. The way in which these needs are reflected in the information system's design is through analysis of information requirements, representation, and organization.

Analysis of Information Requirements

In NPP design, a systems engineering approach was recommended to identify information requirements. In such an approach, plant functions are decomposed based on performance requirements and allocated to human and machine resources. Human functional requirements are further analyzed in task analyses to better define the information requirements of task performance.

Such traditional approaches to information system design were criticized because the information requirements they define could fail to meet the operator's needs in the face of unplanned events. EID was identified as a potential alternative approach. There are four aspects of the EID approach (Section 5.3):

- Specification of information requirements

- Organization of information among the levels of an abstraction hierarchy

- Development of innovative displays to show functionality

- Addition of analytical redundancy

Each may have some performance-enhancing features.

In specifying information requirements, using the A-A matrix may provide a framework for identifying information needs by giving a structure that specifies levels of functional decomposition. Further, it appears that interfaces based on EID provide better support for knowledge-based behavior than those based on physical variables alone. By using EID goals, the relevant system requirements, constraints, and parameters can be evaluated and represented.

Developing innovative displays to show functionality may not be considered purely a feature of EID, but once the levels of functionality that should be displayed are specified, the designers should develop appropriate displays. Such displays will probably not be found in the design engineer's tool box of past successful applications, and thus will likely need to be developed for the particular application in question.

The addition of analytical redundancy is another feature of EIDs that is not always applied, but which appears to be quite valuable. This is a particularly effective method of verifying that higher level functions and goals are, in fact being met, and if they are not being met, determining why and what to do about it.

While several methodological issues were raised related to the studies of EID effects, EID designs have shown some beneficial effects. These effects may be stronger for fault diagnosis and disturbance handling than for normal operations, and these aspects may be important to safety. Several issues remain to be addressed; they are summarized in Section 5.6.2.

Representation of Information

Once information requirements are identified, they must be represented in the information system. That is, display formats are developed to communicate the information to the operators. The success of representational aids was discussed as being a function of the characteristics of the plant, the operators, and the representation through which the operators view and act on the plant. All three are essential parts of the overall system. The representation involves the following two types of mapping:

- Correspondence map between the properties and characteristics of the system to be represented and the features in the representation (how well the display communicates meaningful information about the plant that is needed by operators)

- Coherence map between the features in the representation and the physical and cognitive characteristics of the operator (how comprehensible the representation is to the operator)

Three generic types of displays were identified: separable, integral, and configural displays. Separable displays are representations where each process parameter is presented individually and no relationships between the parameters are provided by the representation itself. Integral displays are displays which show the integration of information in such a way that the individual parameters used to generate the display are not represented in it. Configural displays provide a combination of the other two types. Information about the basic parameters is available; however, information on their relationships becomes evident as features emerge from the representation. An *emergent feature* is a "high-level, global perceptual feature" that is produced by the interactions among individual parts or graphical elements of a display.

Research studies tended to compare these display types based on the types of tasks participants performed. Focused tasks are independent from each other in terms of requiring separate information. Integrated tasks required the integration of information.

In general, the research found that configural displays support integrated task performance, and that a mixed pattern of results is found when focused tasks are performed (sometimes separable displays are better for focused tasks). The studies found that performance is best supported when the representation of information matches operator's tasks. Operators of NPPs have a wide variety of tasks, from high-level fault detection and diagnosis to lower-level component manipulation. Thus, one can conclude that operators should have available to them a variety of different levels of displays that span the A-A hierarchy.

However, most of the studies of information representation also were found to be limited in generalizability due not to methodological issues, but to the use of simple systems, tasks, and inexperienced participants. Thus, the extension of the research findings to complex systems such as NPPs must be made with caution.

Organization of Information

While organization of display pages and networks is important, little data on organization of large, complex information systems were found. The study of these issues is complicated due to the interaction of the

information's organization and other design considerations, such as display area available and interface management functions.

Some of the research seemed to contradict current HFE guidance and nuclear practice. That is, very dense displays were found to lead to better performance and were preferred by operators. Additionally, the common industry practice of organization by functions and systems was found to be difficult for operators to use in some studies.

Both of these findings may reflect the effects of workload associated with interface management, i.e., operators seek to minimize the demands of interface management. Less dense displays increase the number of display pages and the amount of interface management needed to retrieve information. Similarly, organizing display pages for plant systems increased the workload of interface management associated with performing tasks. A further complicating factor may be flexibility of the HSI, which may inhibit the development of an accurate model of the display's structure. If operators can view the display network in many different ways, it may be more difficult to understand its organization, and as a result, navigation plans may be less predictable. Thus, the organization of display pages and of networks are human performance issues, and further research is needed to address them.

5.6.2 Issues

This section summarizes the human performance issues associated with information systems that were identified based on the literature review. The issues, as described below, are not mutually exclusive. They overlap, and some are more general than others; thus, some may be considered secondary to others. As the issues all pertain to the interactions within an integrated human-machine system, interdependencies are unavoidable. The issues are organized into the following three sections below:

- Technical Basis Issues
- Design Review Issues
- Operator-Related Issues

From a researcher's standpoint, these issues represent topics for which research is necessary before additional guidance can be developed. From a regulatory review perspective, many of them can be addressed on a case-by-case basis as part of the design process review discussed in Part 2 of this document.

5.6.2.1 Technical Basis Issues

There were five issues identified in the Technical Basis area.

(1) Lack of a Well-Defined EID Process

While the EID approach may be a promising advance for the system engineering process, developing a well-defined process for conducting an analysis using the abstraction hierarchy is important to its broader application to the design process.

(2) Lack of Specific Representation Guidance

The research on advanced graphic forms is still at an early stage, and while a few general guidelines can be established, the research is not yet substantial or definitive enough to provide a solid technical basis on which to develop a complete set of guidelines.

(3) Evaluation of Operating Experience

For those EID displays which were installed in operating facilities, the operating experience and its application to EID should be thoroughly assessed. Such experience is important to formulating criteria for design review to address EID aspects of the HSI.

(4) Critical Testing and Evaluation of EID Concepts

There has not been much thorough research that carefully assesses the various aspects of EID, e.g., information requirements, effect of organization of information along functional lines, display representation, and use of analytical redundancy. Studies tend to confound these characteristics or provide weak assessments of the contribution of the various aspects of EID concepts.

The successful handling of unplanned or unanticipated events with EID displays under actual operational conditions in complex systems has not been demonstrated.

Further research also is necessary to more clearly determine which cells of the A-A matrix are important to operations.

(5) Evaluation of Displays

More comprehensive methods for evaluating displays are needed. For example, the lack of definitive review guidance will need to be compensated for with dynamic evaluations. The criteria for the evaluations will have to be addressed. For example, signal detection approaches (i.e., an examination of hits, false alarms, and misses) were recommended. This is due to some evidence that subjects may generally be less conservative using configural displays under certain situations, so that the hits as well as the false alarms increase (Hansen, 1995).

5.6.2.2 Design Review Issues

There were ten issues identified in the area of Design Review.

(1) Task and Temporal Considerations

The A-A matrix and the EID approach address the plant at a functional level rather than on a task or temporal basis. However, the importance of presenting information consistent with task requirements has been a fundamental basis of the systems approach, and deviating from it is a problem in many new plant information systems (where information is organized around plant systems rather than operator tasks).

Much of the operators' goal-directed activity is centered around temporal constraints, which is one reason operators like trend displays. The operators' tasks unfold along a temporal continuum with some tasks being performed in parallel and some sequentially. This temporal dimension to operations may be lacking from the A-A analysis, except where time is reflected in higher-level information, such as rates.

Additionally, the EID approach seems to be built around functional decomposition of means-ends relationships. How well will this relate to common tasks and disturbances, that are highly proceduralized, such as in EOPs? While it is important to be able to address unanticipated and unplanned events, still most of the operator's activities are well planned and the information system needs to support these activities as well.'

The proper role of task-based information in the design of displays and how it is integrated into the EID approach needs to be addressed.

(2) Volume of Information

Due to the extensive analytical process used in EID, there is the potential that the process, including the A-A matrix, may lead to identifying more information than can be displayed practically. Also, too many display pages may be required to satisfy information requirements identified by EID.

(3) Density of Display Information

The increase in information may be linked to an increase in the density of information on individual displays. While this may be done to minimize the need for interface management tasks, such as navigating to retrieve additional display pages, the density may be associated with a lack of salience of important information. Another issue with dense displays is that, for any given operator task, the amount of irrelevant information increases, and from a human performance perspective, performance decreases as the amount of irrelevant data increases (Mitchell and Miller, 1983).

(4) Operator Use of a Large Span and Variety of Displays

If and when the operators of a NPP have a large variety of different levels of displays from which to choose, how does the designer decide how many displays are enough? Have the operators been given too much information, either in a single display or in the entire suite of displays that is available? Will the operators be able to select the appropriate display for the task or tasks at hand? Will operators tend to choose a few "favorite" displays even though they may not be the most appropriate for the tasks? If operators do switch displays based on varied tasks, will they pick the proper one? What sort of training should be developed to address these concerns?

(5) System Complexity and Emergent Features

As the number of vertices in a polygon display increased, the displays became complex and performance was reduced. Further, emergent features can be affected by unpredictable interactions between component parts and produce unintended effects that may be misunderstood (Hansen, 1995). This illustrates the issue of increasing the complexity of the underlying domain to which integral and configural displays map. For complex dynamic systems, such as NPPs, not much is known about the dynamic aspects of the emergent features that may be used to represent them. In addition, as the graphic representation increases in complexity, so does the display's grammar.

(6) Perceptual Resolution

Configural and integral displays require a perceptual process to take place, such as recognizing a change in an emergent feature. However, the degree to which a geometric form needs to change before it is perceived as a distortion is not well understood.

(7) Elements of Configural Display

The research suggested that configural displays could be enhanced, especially in support of focused tasks, for example, by including digital information. Research is needed to better understand the effects of display elements on performance and the effects of their interactions with other types of displays.

(8) Effect of Instrumentation Failures

The effects of instrumentation failures on EID displays is a potentially significant problem that needs to be addressed. There are several subissues associated with this problem.

- Can operators detect a failure of instrumentation?
- Can failures of instruments result in representations that are interpreted by operators as real process failures; and, perhaps more importantly, can real process failures be misinterpreted as failures of instruments?
- If operators detect a failure, should they suspend use of the display?
- Since the display integrates many parameters into a single display, what is the effect of its loss on operations and how effectively can operators switch to backup displays?

Many designers have implemented advanced features that address this concern. For example, the concepts of redundancy and diversity in instrumentation, coupled with automatic parameter validation and appropriate notification of operators when instruments fail their validation, were demonstrated successfully.

(9) Organization of Information

The issues related to organization of display pages and networks remain as important research topics.

(10) Integration of EID Displays into Remainder of HSI

The integration of a new and significantly different EID display into the remainder of the standard HSI of a CR is an important consideration that needs to be addressed.

5.6.2.3 Operator-Related Issues

There were three Operator-Related issues.

(1) Implications for Training and Qualification

Christoffersen et al. (1995) concluded that "...to experience the benefits of EID, it seems likely that operators need to be trained to think functionally rather than procedurally. It would seem that this would require a fundamental shift in NPP operation philosophy...it may be that operators have to possess certain types of cognitive characteristics that may not be considered in the traditional selection process in the nuclear industry" (p. 143). Concern was also expressed that EID interfaces may inhibit long-term learning and retention (Wickens, 1992).

Also, for any display where the information is sophisticated and a large amount is consolidated into one or a few figures, the requirements for training become very important. One needs to understand all of the aspects of the

display and how it reacts to various operational transients, accidents, and instrument failures. The long-term effects of EID-type displays on operators' performance and strategies are unknown.

The training aspects of Design Review Issue (4), Operator Use of a Large Span and Variety of Displays, should also be addressed.

(2) Acceptance by Operators

The issue of operators' acceptance of a new and different type of display is also important, as shown by their comments during experiments. One suggestion from the Rankine cycle experiments was to introduce the displays initially in training and then perhaps gradually into the plant.

(3) Internal vs. External Mental Models

Section 5.3 discussed the issue of the appropriate model(s) to apply as a basis for designing the display. Providing a model that accurately characterizes the process and its supporting systems, yet that reflects operators' training, experience, and cognitive capabilities, is an important factor. Designing displays that characterize the system in ways that may not reflect the cognitive requirements of plant operators to perform situation assessment, monitoring and detection, response planning and response implementation, may result in negative performance. Achieving this balance will require additional research.

6 DEVELOPMENT OF GUIDANCE

NUREG-0711 provides the high-level design process criteria used by the NRC for reviewing the overall HFE programmatic goals and objectives. NUREG-0711 does not address the detailed review of final HSI designs as implemented, such as displays, control, or procedures; rather, it references NUREG-0700 for detailed guidance. In Part 1 of NUREG-0700, Rev. 1, the design process is covered. The general framework of NUREG-0711 was used to structure the design review process developed in NUREG-0700. However, Part 1 also considers aspects of the design process of the HSI review in general terms; i.e., it does not identify the specific considerations that may be important in reviewing an individual technology, such as information systems. The only detailed HSI technology-specific guidelines are in Part 2 of NUREG-0700. They relate to the detailed form and functional characteristics of HSIs, such as displays and controls, and not the unique design process considerations.

For information systems, both types of guidance are necessary to perform a design review. That is, while there is a sufficient technical basis to develop detailed guidance for design implementation for some characteristics of information systems, as is typical in NUREG-0700, several limitations in the technical basis were identified (see Section 5.6.2.1). Thus, there are many issues remaining for which typical NUREG-0700 guidance could not be developed. Until it can, these issues can be addressed for specific information systems. To support the latter, considerations were identified for reviewing the information system design process. Thus, guidance was developed to address both the design process and human factors engineering design. Each is described below.

6.1 Guidance for Reviewing the Information System Design Process

Guidelines were developed to address important design process considerations identified in the literature, and to provide a place where human performance issues could be identified and assessed, case-by-case, during a design review. The format of the guidelines corresponds to the NRC's general design process guidance NUREG-0711. They were organized into the following sections:

- Operating Experience Review
- Function and Task Analysis
- Human-System Interface Design
- Training Program Development

These guidelines are contained in Section 9.

6.2 Guidelines for HFE Design Review

A draft set of guidelines was developed from the findings and source materials discussed in Section 5. The methodology was conservative in the sense that guidelines were developed only for those aspects of display design that, in our interpretation, are supported by the literature. Many of the research studies evaluated were either weak in experimental methodology or limited in generalizability to complex systems. This situation constrains the development of new HFE guidelines.

The guidelines adopted the standard format in NUREG-0700, Rev. 1. An example is presented below:

10.1-1 Correspondence Mapping

There should be an explicit mapping between the characteristics and functions of the system to be represented and the features of the display representation, i.e., changes in the appearance of the display form should have a one-to-one relation with the plant states it represents. These changes should result from explicit rules relating the physical form of the display and its meaning with respect to the plant state represented.

ADDITIONAL INFORMATION: Correspondence mapping addresses how well the display communicates meaningful information about the plant to operators. The physical form and functions of the display should be explicitly tied to its meaning with respect to the plant's functions and states. The meaning of the display must consider the instrumentation and the data processing that drives the display format. If a single display can lead to more than one interpretation, the display is ambiguous and can be more easily misunderstood. Changes in the graphic display should be unambiguously related to the plant's state. The same graphic change should not be associated with more than one interpretation.

Discussion: Woods and Roth (1988) conceptualized displays as involving a cognitive-system triad consisting of the world to be acted on, the agents who will act on the world, and the representation through which the agents act on the world. The success of a representation is a function of two types of mapping (Bennett et al., 1997): correspondence and coherence. (Coherence is addressed in Guideline 10.1.3.) The importance of providing consistent one-to-one mapping between the work domain's constraints and the features of the display was identified as an important principle derived from research on representing complex systems (Bennett, Nagy, and Flach, 1997; Vicente and Rasmussen, 1992).

Each of the guidelines is composed of the following components:

Guideline Number – Within each section, individual guidelines are numbered consecutively. Each guideline has a number which reflects its section and subsection location, followed by a dash, and then its unique number.

Guideline Title – Each guideline has a brief, unique, descriptive title.

Review Criterion – Each guideline contains a statement of an HSI characteristic so that the reviewer may judge the HSI's acceptability. The criterion is not a requirement, and discrepant characteristics may be judged acceptable based on the procedures in the review process.

Additional Information – For many guidelines, there is additional information which may address clarifications, examples, exceptions, and details on measurements, figures, or tables. This information is intended to support the reviewer's interpretation or application of the guideline.

Discussion – This section summarizes the technical basis on which the guideline was developed. It may identify the primary source documents, the technical literature such as journal articles, or the general principle from which the guideline was derived. This section will be removed when the guidance is integrated into NUREG-0700.

In place of the Discussion section will be a Source field.

Source – The source field identifies the NUREG or NUREG/CR (or other document) containing the technical basis and development methodology for the guideline. As is the standard practice, the source field will cite this document as it will appear in its final form.

The guidelines were organized into the following sections:

- Guidelines for General Display

- Display Format
  - Integral Formats
  - Configural Display Formats

The guidance was submitted for peer review and was revised accordingly.

The new review guidelines for information system design will be integrated with the information system guidance in NUREG-0700, Rev. 1.

7 GENERAL SUMMARY

The objective of this study was to develop HFE review guidance for information systems based on a technically valid methodology for guidance development. To support this objective, the following tasks were performed:

- Development of a framework for describing key design characteristics of information systems
- Development of a technical basis using human performance research and analyses pertinent to information systems and related areas
- Development of HFE review guidelines for information systems in a format consistent with NUREG-0700, Rev. 1, and other NRC review guidance
- Identification of remaining issues regarding information systems for which research was insufficient to support the development of NRC review guidance

The status of each will be briefly addressed below.

Characterization Framework for Information Systems

The first step in guidance development was to identify the areas for which guidance was needed. Existing information systems were reviewed to identify the dimensions and characteristics along which such systems can be defined. Characterization was important because it provided a structure within which the reviewer could request information about a system, and with which to structure the guidance.

The characterization of information systems included the following major components: information requirements, representation system, management functions, and display devices. Representation systems were further hierarchically broken down into display elements (basic building blocks of displays, such as axes, alphanumeric elements, and icons), display format (such as P&ID and trend graphs), display pages (a defined set of information that is intended to be displayed as a single unit), and display networks (the organization of display pages). This report mainly addressed information requirements and representation.

Technical Basis Development

The development of detailed review guidelines began with the collection of technical information on which to base the guidance. Research in the following areas was examined: (1) generic cognitive tasks that an information system must support, (2) analyses of information requirements, (3) representation of information, and (4) organization of information.

The plant's information systems are the basis for operators to perform their roles. The general tasks that the information system must support include situation assessment, monitoring and detection, response planning, and response implementation.

The information processing requirements of the operators' cognitive tasks have to be reflected in the design review guidance for the information system. The way in which these needs are reflected in designing information systems is in analyses of information requirements, the representation of information, and the organization of information.

In NPP design, a systems engineering approach has been recommended for identifying information requirements. Plant functions are broken down based on performance requirements and allocated to humans and machines. Human functional requirements are further analyzed to better define the information required to perform the tasks.

7 GENERAL SUMMARY

EID was identified as a potential additional approach. Its four aspects, discussed to varying extents in the studies reviewed in Section 5.3, are the following:

- Specification of information requirements
- Organization of information among the levels of an abstraction hierarchy
- Development of innovative displays to show functionality
- Addition of analytical redundancy

Each of them may have some performance-enhancing features. However, the associated research had methodological weaknesses that limited the conclusions that could be drawn.

Once information requirements are identified, they must be represented in the information system; that is, display formats are developed to communicate the information to the operators. The success of representational aids was discussed as being a function of the characteristics of the plant, the operators, and the representation through which the operators view and act on the plant. All three are essential parts of the overall system.

A variety of approaches to representation were discussed, including separable displays (individual parameters displayed in unrelated form), integral displays (individual parameters integrated into object display where the individual ones are not visible), and configural displays (individual parameters are displayed, but emergent perceptual features are created by the arrangement and organization of parameters).

In general, some research support was found for the representation principles; however, most of the studies could not be generalized due to the use of simple systems and tasks, and inexperienced participants. Thus, extending the research findings to complex systems such as NPPs must be done with caution.

While the organization of the display page and network are important, there were few data on organizing large, complex information systems. Such studies are complicated due to the interactions between informational organization and other design considerations, such as the display area available and interface management functions. Further, some research seemed to contradict current HFE guidance and nuclear practice; that is, very dense displays were found to lead to better performance and were preferred by operators, and the industry's common practice of function-system network organization was found to be difficult for operators to use when performing certain tasks.

HFE Review Guidelines

Once the technical information was assembled, a draft set of guidelines was developed. The guidelines were organized and specified in a standard format and are given in Part 2 of this document. In general, guidelines were only developed for those aspects of display design that, in our interpretation, are supported by the literature. As discussed in Section 5, many research studies were either weak in experimental methodology or limited in generalizability to complex systems. This situation constrains the development of new HFE guidelines.

Guidance was developed to support (1) Design Process Review, and (2) HFE Design Review, both of which are needed to evaluate an information system design. While there was a sufficient technical basis to develop detailed design-implementation guidance, as is typical in NUREG-0700, several limitations in the technical basis were identified, and so, many issues remain for which typical NUREG-0700 guidance could not be developed. However,

until it can be developed, these issues should be addressed for specific information systems case-by-case. To support reviewing such issues, design process review guidance was developed.

The new guidance will be integrated into the existing guidance on information systems in NUREG-0700, Rev. 1.

Information Systems Issues

Where there was insufficient information to provide a technical basis upon which to develop valid design review guidance, an issue was defined. There were several human performance issues associated with information systems (in Section 5.6.3). The issues were organized into three topic areas:

- Technical Basis Issues
  - Lack of a Well-Defined EID Process
  - Lack of Specific Representation Guidance
  - Evaluation of Operating Experience
  - Critical Testing and Evaluation of EID Concepts
  - Evaluation of Displays
- Design Review Issues
  - Task and Temporal Considerations
  - Volume of Information
  - Density of Display Information
  - Operator Use of a Large Span and Variety of Displays
  - System Complexity and Emergent Features
  - Perceptual Resolution
  - Elements of Configural Display
  - Effect of Instrumentation Failures
  - Organization of Information
  - Integration of EID Displays into the Remainder of the HSI
- Operator-Related Issues
  - Implications for Training and Qualification
  - Acceptance by Operators
  - Internal vs. External Mental Models

8 REFERENCES

Bailey, R. (1982). *Human-performance engineering: A guide for system designers.* New Jersey: Prentice-Hall, Inc.

Bainbridge, L. (1986). What should a good model of the NPP operator contain. In *Proceedings of the International Topical Meeting on Advances in Human Factors in Nuclear Power Systems.* LaGrange Park, IL: American Nuclear Society.

Bainbridge, L. (1974). Analysis of verbal protocol from a process control task. *The human operator in process control.* London, England: Taylor and Francis.

Barber, C. (1996). Human factors of human-computer interaction techniques in the control room. In N. Stanton (Ed.) *Human factors in nuclear safety.* London, England: Taylor and Francis.

Barnes, M. and Suantak, L. (1996). Configural display of tactical information for instantaneous decision making. In *Proceedings of the Human Factors and Ergonomics Society 40th Annual Meeting.* Santa Monica, CA: Human Factors Society.

Beltracchi, L. (1996). Display navigation design issues. In *Nuclear Plant Instrumentation, Control, and Human-Machine Interface Technologies.* LaGrange Park, IL: American Nuclear Society.

Beltracchi, L. (1995). An OLE interface concept for Rankine cycle based heat engines. In *Proceedings of the Topical Meeting on Computer-Based Human Support Systems: Technology, Methods and Future.* LaGrange Park, IL: American Nuclear Society, Human Factors Division.

Beltracchi, L. (1989). Energy, mass, model-based displays, and memory recall. *IEEE Transactions on Nuclear Science, 36,* 1367-1382.

Beltracchi, L. (1987). A direct manipulation interface for water-based Rankine cycle heat engines. *IEEE Transactions on Systems, Man and Cybernetics, 17,* 478-487.

Bennett, K. (1992). Representation aiding: Complementary decision support for a complex, dynamic control task. *Control Systems,* 19-24.

Bennett, K. and Flach, J. (1992). Graphical displays: Implications for divided attention, focused attention, and problem solving. *Human Factors, 34,* 513-533.

Bennett, K., Nagy, A., and Flach, J. (1997). Visual displays. In G. Salvendy (Ed.), *Handbook of human factors and ergonomics* (Second Edition). New York, NY: John Wiley and Sons.

Bennett, K., Nittoli, B., and Walters, B. (1996). Design techniques to offset potential costs in configural displays. In *Proceedings of the Human Factors and Ergonomics Society 40th Annual Meeting.* Santa Monica, CA: Human Factors and Ergonomics Society.

Bennett, K., Toms, M., and Woods, D. (1993). Emergent features and graphical elements: Designing more effective configural displays. *Human Factors, 35,* 71-97.

Brehmer, A., Hill, J., and Brehmer, B. (1995). Using process operators to compare a traditional interface with a three dimensional interface for better process control. In *Proceedings of 5th European Conference on Cognitive*

8 REFERENCES

Science Approaches to Process Control, VTT Symposium 158. Espoo, Finland: VTT Automation Finnish Psychological Society.

Buttigieg, M., Sanderson, P., and Flach, J. (1988). Object vs. separate displays for process failure detection: The emergent features approach. In *Proceedings of the Human Factors Society 32nd Annual Meeting*. Santa Monica, CA: Human Factors Society.

Carroll, J. and Olson, J. (1988). Mental models in human-computer interaction. In M. Helander (Ed.), *Handbook of human-computer interaction.* New York, NY: Elsevier Science Publishers.

Carswell, C. and Wickens, C. (1987). Information integration and the object display – an interaction of task demands and display superiority. *Ergonomics, 30*, 511-527.

Casey, E. (1986). Visual display representation of multidimensional systems: The effect of information correlation and display integrality. In *Proceedings of the Human Factors Society 30th Annual Meeting*. Santa Monica, CA: Human Factors and Ergonomics Society.

Christoffersen, K., Hunter, C., and Vicente, K. (1996). A longitudinal study of the effects of ecological interface design on skill acquisition. *Human Factors, 38*, 523-541.

Christoffersen, K., Hunter, C., and Vicente, K. (1995). Ecological interface design and fault management performance: Long-term effects. In *Proceedings of the Human Factors and Ergonomics Society 39th Annual Meeting*. Santa Monica, CA: Human Factors and Ergonomics Society.

Christoffersen, K., Hunter, C., and Vicente, K. (1994). *Research on factors influencing human cognitive behavior* (CEL 94-05). Toronto, Canada: University of Toronto (Cognitive Engineering Laboratory).

Coury, B. and Boulette, M. (1992). Time stress and the processing of visual displays. *Human Factors, 34*, 707-725.

Coury, B., Boulette, M., and Smith, R. (1989). Effect of uncertainty and diagnosticity on classification of multidimensional data with integral and separable displays of system status. *Human Factors, 31*, 551-569.

Coury, B. and Pietras, C. (1989). Alphanumeric and graphic displays for dynamic process monitoring and control. *Ergonomics, 32*, 1373-1389.

DeGreene, K. (1970). *Systems psychology*. New York, NY: McGraw-Hill Book Company.

Dien, Y. and Montmayeul, R. (1995). Taking Account of Human Factors in Control-Room Design. In *Proceedings of the Topical Meeting on Computer-Based Human Support Systems: Technology, Methods and Future*. LaGrange Park, IL: American Nuclear Society.

Dinadis, N. and Vicente, K. (1996). Ecological interface design for a power plant feedwater subsystem. *IEEE Transactions on Nuclear Science, 43*, 266-277.

Drury, C., Paramore, B., Van Cott, H., Grey, S., and Corlett, E. (1987). Task analysis. In G. Salvèndy (Ed.), *Handbook of human factors*. New York, NY: Wiley-Interscience.

Duncan, K. and Praetorius, N. (1992). Flow displays representing complex plant for diagnosis and process control. *Reliability Engineering and System Safety, 36*, 239-244.

Eckenrode, R. (1991). Technical note: Safety parameter display systems - 10 years later. *Nuclear Safety, 32*, 65-67.

Edlund, C., Hume, S., and Lewis, M. (1995). Ecological design for a network scheduling interface. In *Proceedings of the Human Factors and Ergonomics Society 39th Annual Meeting.* Santa Monica, CA: Human Factors and Ergonomics Society.

Edlund, C. and Lewis, M. (1994). Comparing ecologically constrained and conventional displays in control of a simple steam plant. In *Proceedings of the Human Factors and Ergonomics Society 38th Annual Meeting.* Santa Monica, CA: Human Factors and Ergonomics Society.

Effken, J., Kim, N., Kadar, E., and Shaw, R. (1992). Enhancing computer displays to support coordination of hemodynamic monitoring and treatment. In *Proceedings of the Human Factors Society 36th Annual Meeting.* Santa Monica, CA: Human Factors Society.

Elm, W. and Woods, D. (1985). Getting lost: A case study in interface design. In *Proceedings of the Human Factors Society 29th Annual Meeting.* Santa Monica, CA: Human Factors Society.

Endsley, M. (1988). Design and evaluation for situation awareness enhancement. In *Proceedings of the Human Factors Society 32nd Annual Meeting.* Santa Monica, CA: Human Factors Society.

Endsley, M. (1995). Toward a theory of situation awareness in dynamic systems. *Human Factors, 37*, 32-64.

Ephrath, A. and Young, L. (1981). Monitoring vs. man-in-the-loop detection of aircraft control failures. In J. Rasmussen and W. Rouse (Eds.), *Human detection and diagnosis of system failures.* New York, NY: Plenum Press.

EPRI (1993). *Advanced light water reactor utility requirements document, Volume III, passive plant (Revision 6).* Palo Alto, CA: Electric Power Research Institute.

EPRI (1992). *Advanced light water reactor utility requirements document, Volume II, evolutionary plant (Revision 4).* Palo Alto, CA: Electric Power Research Institute.

Flach, J. (1990). The ecology of human-machine systems I: Introduction. *Ecological Psychology, 2*, 191-205.

Flach, J. (1989). An ecological alternative to egg-sucking. *Human Factors Society Bulletin, 32 (9)*, 4-6.

Flach, J. (1988). Direct manipulation, direct engagement and direct perception: What's directing what? In *Proceedings of the Human Factors Society 32nd Annual Meeting.* Santa Monica, CA: Human Factors Society.

Flach, J. and Bennett, K. (1992). Graphical interfaces to complex systems: Separating the wheat from the chaff. In *Proceedings of the Human Factors Society 36th Annual Meeting.* Santa Monica, CA: Human Factors Society.

Flach, J. and Dominguez, C. (1995). User-centered design: Integrating the user, instrument, and goal. *Ergonomics in Design, 4*, 19-24.

8 REFERENCES

Flach, J. and Hancock, P. (1992). An ecological approach to human-machine systems. In *Proceedings of the Human Factors Society 36th Annual Meeting.* Santa Monica, CA: Human Factors Society.

Fracker, M. (1988). A theory of situation assessment: Implications for measuring situation awareness. In *Proceedings of the Human Factors Society 32nd Annual Meeting.* Santa Monica, CA: Human Factors Society.

Fujita, Y. (1992). Time for tailoring human-machine interface technology to humans. *1992 IEEE Conference on Human Factors and Power Plants.* New York, NY: Institute of Electrical and Electronics Engineering.

Gaba, D. and Howard, S. (1995). Situation awareness in anesthesiology. *Human Factors, 37,* 20-31.

Gaddy, C., Taylor, J., and Fray, R. (1991). Human factors considerations in digital control room upgrades. In *Proceedings of the American Power Conference.* Chicago, IL: Illinois Institute of Technology.

Gagne, R. and Melton, A. (1988). *Psychological principles in system development.* New York, NY: Holt, Rinehart and Winston.

Gibson, J. (1979). *The ecological approach to visual perception.* Boston, MA: Houghton Mifflin, Co.

Gillan, D., Wickens, C., Hollands, J., and Carswell, C. (1998). Guidelines for presenting quantitative data in HFES publications. *Human Factors, 40,* 28-41.

Greaney, J. and MacRae, A. (1996). Diagnosis of fault location using polygon displays. *Ergonomics, 39,* 400-411.

Green, C. and Logie, R. (1996). Aberdeen polygons – computer displays of physiological profiles for intensive care. *Ergonomics, 39,* 412-428.

Green, D. and Swets, J. (1988). *Signal detection theory and psychophysics.* New York, NY: J. Wiley and Sons.

Hansen, J. (1995). An experimental investigation of configural, digital, and temporal information on process display. *Human Factors, 37,* 539-552.

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

Heslinga, G. and Herbert, M. (1993). *Experience with the introduction of new systems for human-machine interaction from a human factors perspective* (CORECH-HMI Summary Report). Netherlands: KEMA.

Hink, J., Wogalter, M., and Eustace, J. (1996). Display of quantitative information: Are grables better than plain graphs or tables? In *Proceedings of the Human Factors and Ergonomics Society 40th Annual Meeting.* Santa Monica, CA: Human Factors and Ergonomics Society.

Hollands, J. and Dyre, B. (1997). Bias in proportion judgments with pie charts: The cyclical power model. In *Proceedings of the Human Factors and Ergonomics Society 41st Annual Meeting.* Santa Monica, CA: Human Factors and Ergonomics Society.

Hollands, J. and Spence, I. (1997). Integral and separable dimensions in graph reading. In *Proceedings of the Human Factors and Ergonomics Society 41st Annual Meeting.* Santa Monica, CA: Human Factors and Ergonomics Society.

Hollands, J. and Spence, I. (1992). Judgments of change and proportion in graphical perception. *Human Factors, 34,* 313-334.

Hollnagel, E., Hunt, G., Praetorius, N., and Yoshimura, S. (1984). *Reports from the pilot experiment on multilevel flow modeling displays using the GNP simulator* (HWR 114). Halden, Norway: OECD Halden Reactor Project.

Howie, D. and Vicente, K. (1997). Using self-explanation to exploit ecological interface design. In *Proceedings of the Human Factors and Ergonomics Society 41st Annual Meeting.* Santa Monica, CA: Human Factors and Ergonomics Society.

Howie, D. and Vicente, K. (1996). Measuring the impact of ecological interface design on operator skill acquisition. In *Proceedings of the Human Factors and Ergonomics Society 40th Annual Meeting.* Santa Monica, CA: Human Factors and Ergonomics Society.

Hughes, T. and MacRae, A. (1994). Holistic peripheral processing of a polygon display. *Human Factors, 36,* 645-651.

Hurts, K. (1996). The effect of configural graphs on concurrent and retrospective performance. In *Proceedings of the Human Factors and Ergonomics Society 40th Annual Meeting.* Santa Monica, CA: Human Factors and Ergonomics Society.

IAEA (1994). *Development and implementation of computerized operator support systems in nuclear installations* (Technical Reports Series No. 372). Vienna: International Atomic Energy Agency.

IEC (1989). *Design for control rooms of nuclear power plants* (IEC-964). Geneva, Switzerland: International Electrotechnical Commission (Bureau Central de la Commission Electrotechnique Internationale).

IEEE (1996). *Guide for the application of human factors engineering in the design of computer-based monitoring and control displays for nuclear generating stations* (IEEE Std. P1289, Draft 13). Piscataway, NJ: Institute of Electrical and Electronics Engineers.

IEEE (1988). *IEEE guide to the application of human factors engineering to systems, equipment, and facilities of nuclear power generating stations* (IEEE Std. 1023-1988). New York, NY: Institute of Electrical and Electronics Engineers.

Itoh, J., Sakuma, A., and Monta, K. (1995). An ecological interface for supervisory control of BWR nuclear power plants. *Control Engineering Practice, 3(2),* 231-239.

Itoh, J., Yoshimura, S., Ohtsuka, T., and Masuda, F. (1990). Cognitive task analysis of nuclear power plant operators for man-machine interface design. In *Proceedings of Advances in Human Factors Research on Man/Computer Interactions: Nuclear and Beyond.* Nashville, TN: American Nuclear Society.

Janzen, M. and Vicente, K. (1997). Attention allocation within the abstraction hierarchy. In *Proceedings of the Human Factors and Ergonomics Society 41st Annual Meeting.* Santa Monica, CA: Human Factors and Ergonomics Society.

8 REFERENCES

Kahneman, D. and Triesman, A. (1984). Changing views of attention and automaticity. In R. Parasuraman and R. Davies (Eds.), *Varieties of attention.* New York, NY: Academic Press.

Kockler, F., Withers, T., Podiack, J., and Gierman, M. (1990). *Systems engineering management guide* (Department of Defense AD/A223 168). Fort Belvoir, VA: Defense Systems Management College.

Lee, J. (1995). Ecological interface design: Applications in the maritime industry. In *Proceedings of the International Symposium on Human Factors on Board: Man-Machine Interface on Safety of Navigation.* Bremen, Germany.

Lindsay, R. (1990). A display to support knowledge based behavior. In *Proceedings of the Topical Meeting on Advances in Human Factors Research on Man/Computer Interactions: Nuclear and Beyond.* LaGrange, IL: American Nuclear Society.

Lindsey, R. and Staffon, J. (1988). A model based display system for the Experimental Breeder Reactor-II. *ANS Transactions, 57,* 264-265.

Liner, R. and DeBor, J. (1987). *Progress review of six safety parameter display systems* (NUREG/CR-4797). Washington, DC: U.S. Nuclear Regulatory Commission.

Lorenzo, D. and Brune, R. (1985). Computer-based controls can reduce operator errors. In *7th International System Safety Conference.* San Jose, CA.

Maddox, M. (1996). Critique of "A longitudinal study of the effects of ecological interface design on skill acquisition." *Human Factors, 38,* 542-545.

Malin, J., Schreckenghost, D., Woods, D., Potter, S., Johannesen, L., Holloway, M., and Forbus, K. (1991). *Making intelligent systems team players: Case studies and design issues. Volume 1: Human-computer interaction design.* (NASA Technical Memorandum 104738). Houston, TX: National Aeronautics and Space Administration.

Meshkati, M., Buller, B., and Azadeh, M. (1994). Simulation and experimental studies of operator's decision styles and crew composition while using an ecological and traditional user interface for the control room of a nuclear power plant. In *Proceedings of the Twenty-Second Water Reactor Safety Information Meeting.* Washington, DC: U.S. Nuclear Regulatory Commission.

Meyer, J. (1997). A new look at an old study on information display: Washburne (1927) reconsidered. *Human Factors, 39,* 333-340.

Meyer, J., Gopher, D., and Levy, J. (1997). Discrimination between functions in tables and graphs. In *Proceedings of the Human Factors and Ergonomics Society 41st Annual Meeting.* Santa Monica, CA: Human Factors and Ergonomics Society.

Meyer, J., Shinar, D., and Leiser, D. (1997). Multiple factors that determine performance with tables and graphs. *Human Factors, 39,* 26-286.

Mitchell, C. and Miller, R. (1983). Design strategies for computer-based information displays in real time control systems. *Human Factors, 25,* 353-369.

Monta, K., Itoh, J., and Makino, M. (1992). An advanced man-machine system for BWR nuclear power plants. In *Proceedings of the 1992 IEEE Fifth Conference on Human Factors and Power Plants*. Monterey, CA.

Monta, K., Takizawa, Y., Hottori, Y., Hayashi, T., Sato, N., Itoh, J., Sakuma, A., and Yoshikawa, E. (1991). An intelligent man-machine system for BWR nuclear power plants. In *Proceedings of the AI91 Frontiers in Innovative Computing for the Nuclear Industry*. LaGrange Park, IL: American Nuclear Society.

Montgomery, D. and Bivona, L. (1997). The effects of graphical display formats on observer's accuracy in detecting differences in source variability. In *Proceedings of the Human Factors and Ergonomics Society 41st Annual Meeting*. Santa Monica, CA: Human Factors and Ergonomics Society.

Moray, N. (1995). Information needs in the control of continuous and discrete processes. *Fifth European Conference on Cognitive Science Approaches to Process Control*. Finland: Valtion Teknillinen Tukimuskeskus (VTT).

Moray, N. (1986). Monitoring behavior and supervisory control. In K. Boff, L. Kaufman, and J. Thomas (Eds.), *Handbook of Human Perception and Performance*. New York: Wiley.

Moray, N., Lootsteen, P., and Pajak, J. (1986). Acquisition of process control skills. *IEEE Transactions on Systems, Man, and Cybernetics, 16*, 497-504.

Moray, N., Jones, B., Rasmussen, J., Lee, J, Vicente, K., Brock, R., and Djemil, T. (1993). *Development of a performance indicator for the effectiveness of human-machine interfaces for nuclear power plants* (NUREG/CR-5977). Washington, DC: U.S. Nuclear Regulatory Commission.

Moray, N., Lee, J., Vicente, K., Jones, B., and Rasmussen, J. (1994). A direct perception interface for nuclear power plants. In *Proceedings of the Human Factors and Ergonomics Society 38th Annual Meeting*. Santa Monica, CA: Human Factors and Ergonomics Society.

Mumaw, R., Roth, E., Vicente, K., and Burns, C. (1996). *A model of operator cognition performance during monitoring in normal operations*. Pittsburgh, PA: Westinghouse Science and Technology Center (prepared for the Atomic Energy Control Board).

Murphy, E. and Mitchell, C. (1986). Cognitive attributes: Implications for display design in supervisory control systems. *International Journal of Man-Machine Studies, 25*, 411-438.

NAS (1995). *Digital instrumentation and control systems in nuclear power plants: Safety and reliability issues*. Washington, DC: National Academy Press.

Neisser, U. (1976). *Cognition and reality*. San Francisco, CA: W. H. Freeman & Co.

Neisser, U. (1967). *Cognitive psychology*. New York, NY: Appleton-Century Crofts.

O'Hara, J. (1994). *Advanced human-system interface design review guideline: Volume 1: General evaluation model, technical development, and guideline description* (NUREG/CR-5908). Washington, DC: U.S. Nuclear Regulatory Commission.

O'Hara, J., Brown, W., Higgins, J., and Stubler, W. (1994). *Human factors engineering guidelines for the review of advanced alarm systems* (NUREG/CR-6105). Washington, DC: U.S. Nuclear Regulatory Commission.

8 REFERENCES

O'Hara, J., Brown, W., Stubler, W., Wachtel, J., and Persensky, J. (1996). *Human-system interface design review guideline* (NUREG-0700, Rev. 1). Washington, DC: U.S. Nuclear Regulatory Commission.

O'Hara, J., Brown, W., and Nasta, K. (1996). *Development of the human-system interface design review guideline* (BNL Technical Report L1317-2-12/96). Upton, NY: Brookhaven National Laboratory.

O'Hara, J., Higgins, J., Stubler, W., Goodman, C., Eckenrode, R., Bongarra, J., and Galletti, G. (1994). *Human factors engineering program review model* (NUREG-0711). Washington, DC: U.S. Nuclear Regulatory Commission.

O'Hara, J., Stubler, W., Brown, W., and Higgins, J. (1997). *Integrated system validation: Methodology and review criteria* (NUREG/CR-6393). Washington, DC: U.S. Nuclear Regulatory Commission.

O'Hara, J., Stubler, W., and Higgins, J. (1996). *Hybrid human-system interfaces: Human factors considerations* (BNL Technical Report J6012-T1-4/96). Upton, NY: Brookhaven National Laboratory.

O'Hara, J., Stubler, W., and Nasta, K. (1997). *Human-system interface management: Effects on operator performance and issue identification* (BNL Technical Report W6546-1-1-7/97). Upton, NY: Brookhaven National Laboratory.

Patrick, J. (1987). Information at the human-machine interface. In J. Rasmussen, K. Duncan, and Leplat, J. (Eds.), *New technology and human error*. New York, NY: John Wiley and Sons.

Pawlak, W. and Vicente, K. (1996). Inducing effective operator control through ecological interface design. *International Journal of Human-Computer Studies, 44,* 653-688.

Payne, D. and Lang, V. (1995). Mixed versus pure display format in integration and nonintegration visual display monitoring tasks. *Human Factors, 37,* 507-527.

Pejtersen, A. and Rasmussen, J. (1997). Effectiveness testing of complex systems. In G. Salvendy (Ed.), *Handbook of human factors and ergonomics* (Second Edition). New York, NY: John Wiley and Sons.

Pionek, J., Heidenreich, M., Shanahan, M., and Schoepke, D. (1997). Factors affecting user response to polygon displays. In *Proceedings of the Human Factors and Ergonomics Society 41st Annual Meeting.* Santa Monica, CA: Human Factors and Ergonomics Society.

Rasmussen, J. (1986). *Information processing and human-machine interaction.* New York, NY: North Holland.

Rasmussen, J. (1983). Skills, rules, knowledge: Signal, signs, and symbols and other distinctions in human performance models. *IEEE Transactions on Systems, Man, and Cybernetics, 13,* 257-267.

Rasmussen, J. (1981). Models of mental strategies in process control. In J. Rasmussen and W. Rouse (Eds.), *Human detection and diagnosis of system failure.* New York, NY: Plenum Press.

Reason, J. (1990). *Human error.* New York, NY: Cambridge University Press.

Reising, D. and Sanderson, P. (1996). Work domain analysis of a pasteurization plant: Using abstraction hierarchies to analyze sensor needs. In *Proceedings of the Human Factors and Ergonomics Society 40th Annual Meeting.* Santa Monica, CA: Human Factors and Ergonomics Society.

Reynolds, A. and Flagg, P. (1977). *Cognitive psychology.* Cambridge, MA: Winthrop.

Roth, E. (1994). Operator performance in cognitively complex simulated emergencies: Implications for computer-based support aids. In *Proceedings of the Human Factors and Ergonomics Society 38th Annual Meeting.* Santa Monica, CA: Human Factors and Ergonomics Society.

Roth, E., Bennett, K., and Woods, D. (1987). Human interaction with an "intelligent" machine. *International Journal of Man-Machine Studies, 27,* 479-525.

Roth, E. and Mumaw, R. (1995). Using cognitive task analysis to define human interface requirements for first-of-a-kind systems. In *Proceedings of the Human Factors and Ergonomics Society 39th Annual Meeting.* Santa Monica, CA: Human Factors and Ergonomics Society.

Roth, E., Mumaw, R., and Lewis, P. (1994). *An empirical investigation of operator performance in cognitively demanding simulated emergencies* (NUREG/CR-6208). Washington, DC: U.S. Nuclear Regulatory Commission.

Roth, E. and O'Hara, J. (1998). *Integrating digital and conventional HSIs: Lessons learned from a control room modernization program* (BNL Report J6012-3-4-5/98). Upton, NY: Brookhaven National Laboratory.

Sakuma, A., Sato, N., Mizukami, M., Yoshikawa, E., and Ikeda, J. (1990). An intelligent man-machine interface for supporting operator knowledge-based behavior. In *Proceedings of the ANS Topical Meeting on Advances in Human Factors Research on Man/Computer Interactions: Nuclear and Beyond.* LaGrange Park, IL: American Nuclear Society.

Sanderson, P., Flach, J., Buttigieg, M., and Casey, E. (1989). Object displays do not always support better integrated task performance. *Human Factors, 31,* 183-198.

Shamo, M., Meyer, J, and Gopher, D. (1996). Predicting values and trends from tables and graphs. In *Proceedings of the Human Factors and Ergonomics Society 40th Annual Meeting.* Santa Monica, CA: Human Factors Society.

Sheridan, T. (1976). Toward a general model of supervisory control. In T. Sheridan and G. Johannsen (Eds.), *Monitoring behavior and supervisory control.* New York: Plenum Press.

Shively, R. (1995). Emergency (911) dispatcher decision making: Ecological display development. In *Proceedings of the Human Factors and Ergonomics Society 39th Annual Meeting.* Santa Monica, CA: Human Factors and Ergonomics Society.

Sorkin, R., Kantowitz, B., and Kantowitz, S. (1988). Likelihood alarm displays. *Human Factors, 30,* 445-459.

Sorkin, R. and Woods, D. (1985). Systems with human monitors: A signal detection analysis. *Human Computer Interaction, 1,* 49-75.

Stubler, W., Higgins, J., and O'Hara, J. (1996). *Evaluation of the potential safety significance of hybrid human-system interface topics* (BNL Technical Report J6012-T2-6/96). Upton, NY: Brookhaven National Laboratory.

Stubler, W. and O'Hara, J. (1996). *Group-view displays: Functional characteristics and review criteria* (BNL Technical Report E2090-T4-4-12/94). Upton, NY: Brookhaven National Laboratory.

8 REFERENCES

Stubler, W., O'Hara, J., and Kramer, J. (2000). *Soft controls: Technical basis and human factors review guidance* (NUREG/CR-6635). Washington, DC: U.S. Nuclear Regulatory Commission.

Stubler, W., Roth, E., and Mumaw, R. (1991). Evaluation issues for computer-based control rooms. In *Proceedings of the Human Factors Society 35th Annual Meeting*. Santa Monica, CA: Human Factors Society.

Takizawa, Y. et al. (1994). An intelligent man-machine system for future nuclear power plants. *Nuclear Technology, 107*, 72-82.

Thomas, V., Sugibayashi, N., Lin, L., and Roth, E. (1998). Enhanced operator support through integrated resources and large wall panel display application within a compact main control room. In *Proceedings of the 11th Pacific Basin Nuclear Conference.*

Thurman, D. (1997). The Interactive Monitoring and Control (IMAC) design methodology: Application and empirical results. In *Proceedings of the Human Factors and Ergonomics Society 41st Annual Meeting*. Santa Monica, CA: Human Factors and Ergonomics Society.

Van Cott, H. (1997). Were the control room design reviews worth it? In *1997 IEEE Sixth Conference on Human Factors and Power Plants: Global Perspectives of Human Factors in Power Generation*. New Jersey.

Van Cott, H. and Kinkade, R. (1972). *Human engineering guide to equipment design*. Washington, DC: U.S. Government Printing Office.

Vicente, K. (1997). Should an interface always match the operator's mental model? *CSERIAC Gateway, 8 (1)*, 1-4.

Vicente, K. (1996). Evaluation of a Rankine cycle display for nuclear power plant monitoring and diagnosis. *Human Factors, 38*, 506-521.

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

Vicente, K. (1991). *Supporting knowledge-based behavior through ecological interface design* (EPRL-91-01). Urbana, IL: University of Illinois, Engineering Psychology Research Laboratory.

Vicente, K. (1990). Coherence- and correspondence-driven work domains: Implications for systems design. *Behavior and Information Technology, 9*, 493-502.

Vicente, K., Christoffersen, K., and Hunter, C. (1996). Response to Maddox critique. *Human Factors, 38*, 546-549.

Vicente, K., Christoffersen, K., and Pereklita, A. (1995). Supporting operator problem solving through ecological interface design. *IEEE Transactions on Systems, Man, and Cybernetics, 25(4)*, 529-545.

Vicente, K., Moray, N., Lee, J., Rasmussen, J., Jones, B., Brock, R., and Djemil, T. (1996). Evaluation of a Rankine cycle display for nuclear power plant monitoring and diagnosis. *Human Factors, 38*, 506-521.

Vicente, K., Mumaw, R., and Roth, E. (1997). *Cognitive functioning of control room operators - final phase* (Report prepared for the Atomic Energy Control Board). Toronto: University of Toronto.

Vicente, K. and Rasmussen, J. (1992). Ecological interface design: Theoretical foundations. *IEEE Transactions on Systems, Man, and Cybernetics, 2*, 589-606.

Vicente, K. and Rasmussen, J. (1990). The ecology of human-machine systems II: Mediating 'direct perception' in complex work domains. *Ecological Psychology, 2(3)*, 207-249.

Vicente, K. and Rasmussen, J. (1988). On applying the skills, rules, knowledge framework to interface design. In *Proceedings of the Human Factors Society 32nd Annual Meeting.* Santa Monica, CA: Human Factors Society.

Vicente, K. and Wang, J. (1996). Taking full advantage of process constraints in advanced interface design. In *Proceedings of the 1996 American Nuclear Society International Topical Meeting on Nuclear Power Plant Instrumentation, Control and Human-Machine Interface Technologies.* La Grange Park, IL: American Nuclear Society.

Welch, D. and O'Hara, J. (1996). Human factors in the process of developing nuclear power plant systems. In N. Stanton (Ed.), *Human factors in nuclear safety.* London: Taylor and Francis.

Wickens, C. (1992). *Computational models of human performance* (Report ARL 92-4). Champaign, IL: University of Illinois.

Wickens, C. (1986). *The object display: Principles and experimental findings* (Report CPL-86-6). Champaign, IL: University of Illinois.

Wickens, C. (1984). *Engineering psychology and human performance.* Columbus, OH: Merrill Publishing Company.

Wickens, C. and Carswell, C. (1995). The proximity compatibility principle: Its psychological foundation and relevance to display design. *Human Factors, 37*, 473-494.

Wickens, C. and Kessel, C. (1981). The detection of dynamic system failures. In J. Rasmussen and W. Rouse (Eds.), *Human detection and diagnosis of system failures.* New York, NY: Plenum Press.

Woods, D. and Elias, G. (1988). Significance messages: An integrated display concept. In *Proceedings of the Human Factors Society 32nd Annual Meeting.* Santa Monica, CA: Human Factors Society.

Woods, D., Johannesen, L., Cook, R., and Sarter, N. (1994). Behind human error: Cognitive systems, computers, and hindsight. *CSERIAC, 94-01,* SOAR.

Woods, D., Potter, S., Johannesen, L., and Holloway, M. (1991). *Human interaction with intelligent systems: Volume I–trends, problems, new direction* (CSEL Report 1991-001). Columbus, OH: Cognitive Systems Engineering Laboratory.

Woods, D. and Roth, E. (1988). Cognitive systems engineering. In M. Helander (Ed.), *Handbook of human-computer interaction.* New York, NY: North-Holland.

Woods, D., Roth, E., Stubler, W., and Mumaw, R. (1990). Navigating through large display networks in dynamic control applications. In *Proceedings of the Human Factors Society 25th Annual Meeting.* Santa Monica, CA: Human Factors Society.

8 REFERENCES

Woods, D., Wise, J., and Hanes, L. (1982). *Evaluation of safety parameter display concepts* (NP-2339, Vol. 1). Palo Alto, CA: Electric Power Research Institute.

Woods, D., Wise, J., and Hanes, L. (1981). An evaluation of nuclear power plant safety parameter display systems. In *Proceedings of the Human Factors Society 25th Annual Meeting*. Santa Monica, CA: Human Factors Society.

Woodson, W. (1981). *Human factors design handbook*. New York, NY: McGraw-Hill Book Company.

Xu, W., Dainoff, M., and Mark, L. (1996). Externalizing a work domain structure using an abstraction hierarchy: An alternative approach for hypertext interface designs. In *Proceedings of the Human Factors and Ergonomics Society 40th Annual Meeting*. Santa Monica, CA: Human Factors and Ergonomics Society.

PART 2

Review Guidelines for Information System Design

9 REVIEW GUIDANCE FOR THE INFORMATION SYSTEM DESIGN PROCESS

Guidance for reviewing the design process for information systems was developed to address important design process considerations identified in the literature and to provide a means whereby human performance issues may be assessed during a design review (see Section 6.1). The review guidelines were formatted to correspond to the NRC's general design process guidance in NUREG-0711. The guidelines are organized into the following sections:

- Operating Experience Review
- Function Analysis
- Task Analysis
- Human-System Interface Design
- Training Program Development.

Guidelines may specify that some aspect of an information system needs to be "evaluated." General approaches to evaluation methods and criteria development are defined in NUREG-0700. Since the guidance in this section will eventually be incorporated into that document, the methods by which such evaluation should be performed and by which criteria should be identified are not repeated below.

9.1 Operating Experience Review (OER)

(1) Available operating experience with advanced information systems should be reviewed to take advantage of lessons learned in the operational use of the systems, as well as to ensure that problematic aspects of their design implementation are addressed.
Discussion: There has not been much operating experience with advanced graphic displays in NPPs. An analysis of the available experience will help ensure the design supports the intended aspects of operational performance. This is consistent with the NUREG-0711 criterion to review the operating experience associated with approaches for implementing HSI designs.

9.2 Function and Task Analysis

(1) The function analysis and task analysis criteria by which information requirements are defined should be clearly documented.
Discussion: In developing a higher-level display, such as one based on EID principles, a clear definition is needed of what higher-level functions and goals are addressed, e.g., electric production and safety. For the latter goal, the NRC established five critical safety functions needed in NPPs to achieve overall safety: reactivity control, reactor core cooling and heat removal, RCS integrity, radioactivity control, and containment conditions (NUREG-1342 - NRC, 1988). These should be addressed in high-level safety displays; Tables 2 and 3 of NUREG-1342 give sample parameters for both BWRs and PWRs.

(2) The information requirements established in advanced graphical displays should be based on the operators' cognitive tasks (i.e., situation assessment, monitoring and detection, response planning and response implementation).

Discussion: Advanced graphical displays are integral and configural displays that use novel graphic forms to convey plant information, such as the Rankine cycle display. Information defined by requirements analyses, such as task analysis and abstraction-hierarchy analysis, should consider the operator's use of the information and the specific cognitive tasks it will be used for. This will help ensure that the information is specified at the appropriate level for the operators' needs.

(3) The analysis of information requirements should consider the different needs of individual staff in the control.
Discussion: Roth and O'Hara (1998) identified the different information needs of the shift supervisor, reactor operator, balance-of-plant operator, and shift technical advisor. They vary both in terms of specific information requirements, as well as in the level of abstraction needed.

9.3 Human-System Interface Design

(1) Explicit guidance should be available defining the relationship between the physical form of the display and its meaning with respect to the plant's status.
Discussion: NUREG-0711 specifies the need for the HSI design to reflect HFE guidelines in supporting standardization and consistency of design. Explicit guidance defines the relationship between the physical form and functions of the display and its meaning with respect to the plant's functions and states. These rules should consider the instrumentation and the data processing driving the display's format. If a single display can have more than one interpretation, it is ambiguous and can be more easily misunderstood.

(2) The information presented and its organization into display pages should be based on considering operators' tasks when using the displays. Display pages should include as much information as can be efficiently represented and interpreted to minimize the need for operators to retrieve additional pages.
Discussion: Display pages should reflect operators' information needs. Performance can suffer when information is missing (Fujita, 1992; Elm and Woods, 1985) or when the interface management workload makes operators reluctant to retrieve information (O'Hara, Stubler, and Nasta, 1997).

(3) When more than one display format is used on a display page, an evaluation should determine whether the user's perception of one format is negatively impacted by the presence of the other one(s).
Discussion: There has been little research on interactions between formats; however, some evidence indicates that unwanted interactions can occur (Payne and Lang, 1995). For example, including two graphic formats may create an unintended emergent feature. An emergent feature is a high-level, global perceptual feature generated by the interactions among individual parts or graphical elements (e.g., lines, contours, and shapes) to produce perceptual properties, such as symmetries, closure, and parallelism (see Figure 5.17).

(4) The density of information on a display page should be evaluated to ensure that important information is readily perceived, and needed information is rapidly identified.
Discussion: It is difficult to precisely specify the information density of graphic displays. Operators may prefer displays of greater density to minimize the need to retrieve information from other pages (Roth and O'Hara, 1998; Thomas et al., 1998). However, there are trade-offs between density and perceptual clutter, and a greater chance of making errors when information is not found. For example, operators experienced difficulty in understanding plant situations depicted in the Toshiba EID displays (Itoh, Sakuma, and Monta, 1995), partly because the pages were too crowded with information. This tradeoff needs to be evaluated in designing pages.

(5) The organization scheme of display pages within the network should be readily apparent to operators.

Discussion: In a computer-based HSI, there can be many displays; thus, the organization of pages is important. Operators need to know the organizational scheme of display pages to locate and retrieve the appropriate ones. Consideration may be given to providing the operators with variable, operator-selectable, schemes which could enable them to adapt the organization of data to meet their current needs (Woods and Roth, 1988).

(6) The effects of instrumentation failures on graphic displays should be analyzed. Potential failure problems should be evaluated with respect to the following:

- Can operators detect a failure of instrumentation?
- Can instrument failures result in representations that are interpreted by operators as real process failures; perhaps more importantly, can real process failures be misinterpreted as instrument failures?
- If operators detect a failure, should use of the display be suspended?
- Since the display integrates many parameters into a single display, what effect does its loss have on operations and how effectively can operators transition to backup displays?

Discussion: The failure modes of the display and their effects on plant operations must be carefully examined, especially with complex graphical displays. The effects of instrumentation failures need to be understood to ensure that they do not lead to incorrect situation assessment; i.e., operators mistakenly interpreting a graphic change due to an instrument failure as a change in process state.

(7) Access to displays within a network should be evaluated to ensure rapid, efficient retrieval of information needed to support operators' tasks.
Discussion: Operators have experienced difficulty in gaining access to information to support their tasks. Heslinga and Herbert (1993, 1995) found that information organized by systems was sometimes problematic for operators, and required excessive interface management.

(8) Unwanted effects of integrating a new, novel graphic representation into a conventional HSI (other displays, other control room HSIs, and environmental considerations such as lighting levels) should be evaluated and minimized.
Discussion: Just as graphic displays can interact within display pages, they can interact with other information sources in the control room; such interactions are not fully understood. Since there is no technical basis for guidance on these interactions, they should be examined case-by-case during the design process.

(9) The following aspects of information system design should be carefully analyzed and evaluated:

- Number of VDUs – to ensure that the display area is sufficient to show the important information needed by operators without them having to perform extensive interface management
- Interface management functions – to ensure that the HSI features are easy to use and provide explicit interface management support
- Flexibility of HSI and display features and functions – to ensure that the flexibility of the system does not unduly burden operators, nor increase the chance of misunderstandings and errors.

Discussion: The keyhole effect resulting from the operator's limited view of plant information through VDUs, the interface management tasks, and computer-system flexibility all significantly impact performance. These factors have also affected the design of display pages and network organizations. Digital instrumentation and control systems typically provide much more information than do conventional systems. Operators must know what information and controls are available in the virtual workspace, where they are, and how to navigate and retrieve them. Information is viewed through the limited display area of workstation VDUs; this is the so-called "keyhole effect" (Woods et al., 1990). Consequently, most information is hidden from view. Operators may have to frequently repeat interface management and navigation tasks which can distract them from their primary task of monitoring and controlling the plant. For example, a problem related to the keyhole effect is that access to controls and displays tends to be serial, i.e., only a few can be accessed at one time. This contrasts with the parallel presentation of controls and displays in conventional systems, where HSIs are predominantly spatially dedicated and their form and function does not change. Advanced HSIs are flexible; they can be configured and can function in various operating modes.

The flexibility of computer-based HSIs and their lack of spatial dedication can be problematic for operators. As discussed in O'Hara, Stubler, and Nasta (1997), one reason may be the reduction of the automaticity of operators' performance. When there is a good match between the information available and the operator's mental model of the task, performance becomes somewhat automatic, i.e., it requires little attention and cognitive resources. When the situation is unclear, more cognitive resources are needed to assess it and to plan responses. With spatially dedicated HSIs, operators can use automatic information processing capabilities, such as scanning and pattern recognition, to rapidly assess situations. Flexibility and lack of spatial dedication increases the dependence of interface management tasks on controlled information processing. Flexibility also makes it easier for the operator to mistake one display for another.

(10) Methods should be specified for assuring that plant modifications (such as changes in instrumentation or systems) are incorporated into the display and do not introduce inconsistencies in how they correspond to plant situations, or lead to technical inaccuracies and, possibly, invalid displays.
Discussion: Methods should be specified for assuring that plant changes do not introduce errors or changes in the relationship between displays and their representations of plant situations. For example, the information system may depend upon specific sensor data to generate a graphic form. To maintain the integrity of the information system, it is critical that the implications of changing any plant feature or software calculation is traceable and controllable.

(11) If display formats are developed for a generic plant design or as an "off-the-shelf" product, any plant-specific inputs to display characteristics need to be analyzed to ensure that the display correctly reflects the relationship between changes in the display format and the changes in the specific plant it is intended to represent.
Discussion: Plant-specific features may affect the relationship between the appearance of the display format and the plant conditions being represented in it. It is important to make sure the intended relationship between the two is preserved once plant-specific details are incorporated into the information system.

9.4 Training Program Development

(1) The knowledge, skills, and abilities that the operators need to use and understand the information system should be specified.
Discussion: Research on the use of complex displays, such as the Rankine cycle display and DURESS EID display, illustrated the importance of training (Brehmer, Hill, and Brehmer, 1995). Itoh, Sakuma, and

Monta (1995) found that operators experienced difficulty understanding the plant situations depicted in the Toshiba EID displays. These studies demonstrated the importance of evaluating the relationship between the representation in the display and the operator's mental model of the domain, on the implications for training.

Where the information is sophisticated and a large amount is consolidated into one or a few graphics, training requirements become very important (Itoh, Sakuma and Monta, 1995). Operators need to understand all aspects of the display, and how it reacts to various operational transients, accidents, and instrument failures. Christoffersen, Hunter, and Vicente (1995) stated that "...to experience the benefits of EID, it seems likely that operators need to be trained to think functionally rather than procedurally. It would seem that this would require a fundamental shift in NPP operation philosophy" (p. 143). They further suggest that "...it may be that operators have to possess certain types of cognitive characteristics that may not be considered in the traditional selection process in the nuclear industry" (p. 143).

(2) Operators should be trained on the relationship between the display form and the plant states it is intended to represent, including failure modes and their effect on graphical representation.
Discussion: Where large amounts of information at various levels of abstraction are consolidated into one or more graphic formats, training requirements become very important. Operators need to understand all of the aspects of the display and how it reacts to various operational transients, accidents, and instrument failures. Training should cover design features of the information system, relationships between graphic elements and plant status, and the effects of failures.

(3) Users should be trained in using the interface management features of the information system, including navigation within and between displays, manipulation of on-screen features such as windows, and use of user-definable characteristics and features.
Discussion: Successful use of complex information systems depends to a great extent on the user's ability to understand the characteristics of the interface and effortlessly use its features (O'Hara et al., 1997). These aspects of HSIs are often neglected in training, so they are used inefficiently.

(4) Users should be trained to an acceptable level of proficiency with unfamiliar graphic displays before using them in the control room to ensure that operators are sufficiently familiar with them to correctly assess their meaning.
Discussion: The issue of operators' acceptance of a new and different type of display is important. Introducing the displays initially in training and then gradually into the plant will help ensure their acceptance and proper use.

10 REVIEW GUIDELINES FOR THE INFORMATION SYSTEM HFE DESIGN

The guidelines presented in this section follow the characterization of information systems described in Section 4 of this document. They also reflect the results of the literature review discussed in Section 5. Following the HSI design review procedure described in Part 1 of NUREG-0700, Rev. 1, the first step is to select the subset of guidelines relevant to the unique aspects of the particular design being evaluated. It is recognized that there is a wide range of information system designs, and that some may not include all of the characteristics and functions addressed in these guidelines. The reviewer will have to determine, case-by-case, the importance of information system features that are covered in the guidelines, but that are not part of the system being reviewed.

Guidelines were developed from the findings and source materials that were reviewed in Section 5. They are constructed in the standard format adopted in NUREG-0700, Rev. 1 (see Section 6.2 of this report). The guidelines are organized into the following sections:

- General Display Guidelines
- Display Format
  - Integral Formats
  - Display Formats

These new guidelines for review of information system designs will be integrated with the information system guidance in NUREG-0700, Rev. 1.

Guidelines may specify that some identified aspect of an information system needs to be "evaluated." General approaches to evaluation methods and criteria development are defined in NUREG-0700. Since the guidance in this section will eventually be incorporated into that document, the methods by which such evaluation should be performed and by which criteria should be identified are not repeated here.

10.1 General Display Guidelines

10.1-1 Correspondence Mapping

There should be an explicit mapping between the characteristics and functions of the system to be represented and the features of the display representation, i.e., changes in the appearance of the display form should have a one-to-one relation with the plant states it represents. These changes should result from explicit rules relating the physical form of the display and its meaning to the plant state represented.
ADDITIONAL INFORMATION: Correspondence mapping addresses how well the display communicates meaningful information about the plant to operators. The physical form and functions of the display should be explicitly tied to the plant's functions and states. The display form and function must consider the instrumentation and the data processing that drive the display format. If a single display can lead to more than one interpretation, it is ambiguous and can be easily misunderstood. Changes in the graphic display should be unambiguously related to the plant's state. The same graphic change should not be associated with more than one interpretation.
Discussion: Woods and Roth (1988) conceptualized displays as involving three essential parts of an overall cognitive system triad that includes the world to be acted on, the agents who will act on the world, and the representation through which the agents act on the world. The success of a representation is a function of two types of mapping (Bennett et al., 1997): correspondence and coherence. (Coherence is addressed in Guideline 10.1.3.) The importance of providing consistent one-to-one mapping between the

work domain's constraints and the features of the display has been identified as an important principle derived from research on representing complex systems (Bennett, Nagy, and Flach, 1997; Vicente and Rasmussen, 1992).

10.1-2 Levels of Abstraction

Displays should provide information at the levels of abstraction necessary to meet the operators' requirements relative to their task goals.
ADDITIONAL INFORMATION: Information should be presented in accord with the operator's goals and the information needed to address them.
Discussion: This guideline reflects considerations of the information processing basis of situation awareness support (Endsley, 1988, 1995). In addition, to support knowledge-based behavior, Vicente and Rasmussen (1992) suggest that the information system should represent the work domain as an abstraction hierarchy to serve as an externalized mental model. Further, to do this, Endsley and others (Heslinga and Herbert, 1993 and 1995) noted that consideration of tasks involves more than simply the physical layout of the system.

10.1-3 Coherence Mapping

The characteristics and features of the display used to represent the process should be readily perceived and interpreted by the operator.
ADDITIONAL INFORMATION: Coherence mapping addresses how comprehensible the representation is to the operator. Unambiguous relationships between the display and the process are of little value if they also are not readily perceived by the operators and easily understood.
Discussion: See discussion of Guideline 10.1-1.

10.1-4 Understandability of Higher-Level Information

The methods by which lower-level data are analyzed to produce higher-level information and graphical elements should be understandable to users.
ADDITIONAL INFORMATION: Users must be able to judge the acceptability of higher-level information and how it relates to lower-level information.
Discussion: To maintain their role as system supervisors, operators need to be able to understand and evaluate the appropriateness and validity of the information being displayed.

10.1-5 User Verification of Higher-Level Information

Operators should have access to the rules or computations that link process parameters and graphical features, and to an explanation of how the information system produces higher-level information.
ADDITIONAL INFORMATION: When graphical features change in ways not completely understood by operators, they should be able to access the rules that produce the graphic forms. Operators should be able to review any analysis performed by the information system.
Discussion: To maintain their role as system supervisors, operators need to be able to access information enabling them to determine the appropriateness and validity of information displayed. Access to the rules and computations that relate the system and the display (the correspondence map) should be available to operators to support situation assessment. In general, computer-based systems often are not sufficiently observable. That is, they do not make clear their analysis basis and do not have adequate communication facilities to enable operators to verify system performance (Dien and Montmayeul, 1995; IAEA, 1994; Malin et al., 1992a; Roth, Bennet, and Woods, 1987).

10.1-6 Salience Levels

The salience of graphic features should reflect the importance of the information.

ADDITIONAL INFORMATION: The most salient features of a graphic display should be those aspects of the representation that are most important. Less important information should not be more perceptually salient than more important information.
Discussion: This guideline reflects considerations of the information processing basis of situation awareness support (Endsley, 1988, 1995), and research by Bennett, Nagy, and Flach (1997) on the salience of emergent features. Situation assessment depends on activating the appropriate mental representation for the situation; thus, the critical cues to such activation should be determined, and displays should make these cues salient.

10.1-7 Display of Goal Status
The information system should provide for global situation awareness (i.e., an overview of the status of all the operator's goals at all times) as well as supplying details about the current specific goal.
ADDITIONAL INFORMATION: Situation assessment can suffer when operators focus on some information and fail to attend to other important data.
Discussion: This guideline reflects considerations of the information processing basis of situation awareness support (Endsley, 1988, 1995).

10.1-8 Display of Future Status
The information system should support the user's ability to project future states of the system when this is required to safely operate the plant.
ADDITIONAL INFORMATION: Situation assessment involves not only understanding the current state of the plant, but projecting its future state. Displays such as trend graphs can support these projections.
Discussion: This guideline reflects considerations of the information processing basis of situation awareness support (Endsley, 1988, 1995).

10.1-9 Minimize Attention Shifts
Information needed by the operator to accomplish a task should be grouped and perceptually related, when possible.
ADDITIONAL INFORMATION: To minimize the disadvantages of divided attention, the number of attention shifts should be minimized, both within a display page and between them.
Discussion: This guideline reflects considerations of the information processing basis of situation awareness support (Endsley, 1988, 1995). Interface management tasks necessary to retrieve displays and to shift between them are distracting, and can degrade performance. Such distractions should be minimized.

10.1-10 Analytical Redundancy
Analytical redundancy should be considered to help ensure the appropriateness of displayed values.
ADDITIONAL INFORMATION: Analytical redundancy is the calculation of expected parameter values using a model of system performance. The expected value is then represented in the display, along with the actual value. Deviations between the two indicate some disturbance or abnormality of the system.
Discussion: Vicente and Wang (1996) found that fault detection time was reduced and the ability of study participants to compensate for the fault was improved when a display had analytical redundancy.

10.1-11 Failure Recognition
Information system failures (due to sensors, instruments, and components) should result in distinct display changes which directly indicate that depicted plant conditions are invalid.
ADDITIONAL INFORMATION: The information system should be designed so that failures in instrumentation are readily recognized by operators. This may be more difficult to determine in complex graphics, and thus, should be carefully evaluated.

Discussion: Moray et al. (1994) noted that graphical interfaces are "extremely vulnerable" to this type of failure and that understanding their failure modes is as necessary as understanding their design for normal conditions.

10.1-12 Navigational Links to Related Information
Navigational links to and from high-level and lower-levels of information and to reference and supporting information should be provided when needed for operators' tasks.
Discussion: Navigation to and from related information can be time consuming, distracting, and error prone. Computer support, such as hyperlinks, for these activities can reduce the workload.

10.2 Display Format

10.2.1 Integral Formats

10.2.1-1 Appropriate Use of Integral Displays
Integral formats should be used to communicate high-level, status-at-a-glance information where users may not need information on individual parameters to interpret the display.
ADDITIONAL INFORMATION: Since integral displays do not display individual parameters, they are most appropriate for general status monitoring.
Discussion: NPP operators almost always need information on individual parameters, except for general monitoring. Integral displays best serve this purpose because they do not show individual parameters.

10.2.1-2 Reference Aids for Object Displays
A perceptually distinct reference aid should be provided in an object display to support operators in recognizing abnormalities in the object's characteristics.
ADDITIONAL INFORMATION: When a change in an object's characteristics (e.g., its shape) is the perceptual feature that indicates a fault or abnormal condition, perceptual cues can assist operators in detecting the change. If shape is used, the graphic display should include the normal reference point to which operators can compare the current shape. Reference points are especially useful when the abnormality is slow to evolve, and the integral object is changing slowly.
Discussion: There is little research guidance on how much a graphic form must change to be perceptually recognized. Thus, if a referent is not present, it may be difficult to ensure that a change is recognized. Recognition is supported by including the comparison referent.

10.2.2 Configural Display Formats

10.2.2-1 Appropriate Use of Configural Displays
Configural formats should be used when operators must rapidly transition between high-level functional information and specific parameter values.
ADDITIONAL INFORMATION: Configural displays provide lower-level information, such as parameter values, and higher-level information conveyed through emergent features. Since both are present in a single display, operators can easily move between them.
Discussion: The value of configural features is their ability to convey multiple levels of information in a single display. Therefore, when operators must be cognizant of more than one level of abstraction of information, configural displays are preferred.

10.2.2-2 Representation of Emergent Features
The display elements should be organized so that the emergent features that arise from their interaction correspond to meaningful information about the process or system, e.g., when the aspect of the system represented by the emergent is disturbed, the disturbance is visible in the emergent feature.
ADDITIONAL INFORMATION: An emergent feature is a high-level, global perceptual feature generated by interactions among individual parts or graphical elements of a display (e.g., lines, contours, and shapes) to produce perceptual properties, such as symmetries, closure, and parallelism. Displays cannot always be organized to provide emergent features, but they should be considered where feasible.
Discussion: This guideline is was developed by Bennett, Nagy, and Flach (1997) from reviewing research on configural displays.

10.2.2-3 Levels of Emerging Features
The emergent features or patterns within the display should be nested (from global to local) in a way that reflects the hierarchical structure of the process.
ADDITIONAL INFORMATION: High-order aspects of the process (e.g., at the level of functional purpose or abstract function) should be reflected in global display features; lower-order aspects of the process (e.g., functional organization) should be reflected in local display features.
Discussion: This guideline is was developed by Bennett, Nagy, and Flach (1997), who reviewed research on configural displays.

10.2.2-4 Salience of Emerging Features
Each emergent feature should be clearly distinguishable for other emergent features and from information on individual parameters.
Discussion: This guideline is was developed by Bennett, Nagy, and Flach (1997) based on a review of research on configural displays.

10.2.2-5 Reference Aids for Configural Displays
A perceptually distinct reference aid should be provided in a configural display to support operators in recognizing abnormalities in emergent features.
ADDITIONAL INFORMATION: When a change in an object's characteristics (e.g., its shape) is the perceptual feature that indicates a fault or abnormal condition, perceptual cues can assist operators in detecting the change. If shape is used, the display graphic should include the normal reference point against which operators can compare the current one. Reference points are especially useful when the abnormality is slow to evolve, and the integral object is slowly changing.
Discussion: See discussion of Guideline 10.2.1-2.

10.2.2-6 Representation of Individual Parameters
Each relevant process parameter should be represented by a perceptually distinct element within the display.
Discussion: Since configural displays provide both high- and low-level information, all relevant lower-level parameters should be given. This will minimize the need for operators to retrieve supplemental information directly relevant to the configural display from another one.

10.2.2-7 Use of Lower-Level Information
The display should support the user in performing tasks requiring lower-level information.
ADDITIONAL INFORMATION: When the operator must perform tasks using lower level information, the display should provide such support. For example, if precise information about a variable is desirable, then a scale or digital information should be provided.

Discussion: Providing information to support detailed use of lower-level information will minimize the chance for error in deriving the lower-level information from the display, and minimize the need to retrieve supplemental information from another display.

10.2.2-8 Complexity

The emergent features and their interactions should not be so complex as to be susceptible to misinterpretation.

ADDITIONAL INFORMATION: The value of emergent features is that they provide a direct perception of higher-level information. They substitute perception for mental calculation. The shift toward perceptual cognition requires careful design, so that misunderstandings are unlikely to occur.

Discussion: Configural displays can get complex and can be misunderstood by operators (Itoh, Sakuma, and Monta, 1995).

GLOSSARY

Analytical Redundancy – The calculation of expected parameter values using a model of system performance.

Coherence Mapping – A map between the features in the representation and the physical and cognitive characteristics of the operator (how comprehensible the representation is to the operator).

Configural Display – A display in which information dimensions are uniquely represented, but where new emergent properties are created from interactions between the dimensions. Configural display representations often use simple graphic forms, such as a polygon.

Correspondence Mapping – A map between the properties and characteristics of the system to be represented and the features in the representation (how well the display communicates meaningful information about the plant to operators).

Display Devices – The media used to present information to personnel, including meters, gauges, VDUs, and hard-copy display devices (printers and plotters).

Display Element – The basic building blocks used to make up display formats, such as abbreviations, labels, icons, symbols, coding, and highlighting.

Display Format – The general class of information presentation. Examples of general classes are continuous text (such as a procedure display), mimics and piping and instrumentation diagram (P&ID) displays, trend graphs, and flowcharts.

Display Network – An group of display pages within an information system and their organizational structure.

Display Page – A defined set of information that is intended to be displayed as a single unit. Typical NPP display pages may combine several different formats on a single VDU screen, such as putting bar charts and digital displays in a graphic P&ID format. Display pages typically have a label and designation within the computer system so they can be accessed by operators as a single "display."

Emergent Feature – A high-level, global perceptual feature produced by the interactions among individual parts or graphical elements of a display (e.g., lines, contours, and shapes).

Information System – Those aspects of the HSI that provide information on the plant's systems to the operator.

Integral Display – A display that depicts the integration of information in such a way that the individual parameters used to generate the display are not explicitly represented in it.

Level of Abstraction – A hierarchy consisting of levels increasing in abstraction:

- Physical form – the appearance and spatial location of the components
- Physical function – the characteristics of the components and their interconnections
- Generalized function – the basic functions a system was designed to achieve
- Abstract function – the causal structure of the process in terms of mass, energy, information or value flows
- Functional purpose – the purpose for which the system was designed; the functional characteristics of the plant as opposed to physical characteristics.

GLOSSARY

Object Display – A type of integral display that uses a geometric object to represent parameter values graphically, but where the individual information dimensions or data contributing to the object are not displayed.

Separable Display – Each process parameter is presented individually and no relationships between the parameters are shown by the representation itself. The key aspect of separable displays is not that individual parameters are presented, but that no interaction or relationship between them is perceived.

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11. ABSTRACT *(200 words or less)*

Plant information systems provide operators with information supporting situation assessment, monitoring and detection of disturbances, response planning, and response implementation. The importance of the design of information systems for human performance and reliability has long been recognized. Recent advances in design go beyond the 'one sensor – one indicator' display systems of conventional plants. Computer-based systems provide a variety of ways to process and present data. These characteristics of design represent a trend toward making displays more immediately meaningful to personnel by mapping display representations to important aspects of plant processes and to underlying cognitive mechanisms, such as perceptual processes and mental models. The objective of this study was to develop guidance for human factors review of advanced information systems based on a technically valid methodology for developing guidance. To support this objective, we developed a characterization framework for describing key design characteristics of information systems. The characterization includes the following major components: information requirements, representation systems, interface management functions, and display devices. Representation systems were further hierarchically divided into display elements (basic building blocks of displays, such as axes, alphanumeric elements, and icons), display formats (such as mimic displays, configural displays, and novel graphics), display pages (a defined set of information that is intended to be displayed as a single unit), and display networks (the organization of display pages). Then, we examined research in the following areas: (1) generic cognitive tasks that an information system must support, (2) information requirements analysis, (3) information representation, and (4) information organization. This research was used to provide the technical basis on which guidelines for review of design were developed. These guidelines address both the design process and the implementation of advanced information systems. However, there were aspects of information systems for which the technical basis was insufficient to support the development of guidance. These were identified as issues to be addressed in future research.

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