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Advanced Human-System Interface Design Review Guideline

General Evaluation Model, Technical Development, and Guideline Description

Prepared by
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Prepared for
U.S. Nuclear Regulatory Commission

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ABSTRACT

Advanced control rooms will use advanced human-system interface (HSI) technologies that may have significant implications for plant safety in that they will affect the operator's overall role in the system, the method of information presentation, and the ways in which operators interact with the system. The U.S. Nuclear Regulatory Commission (NRC) reviews the HSI aspects of control rooms to ensure that they are designed to good human factors engineering principles and that operator performance and reliability are appropriately supported to protect public health and safety. The principal guidance available to the NRC, however, was developed more than ten years ago, well before these technological changes. Accordingly, the human factors guidance needs to be updated to serve as the basis for NRC review of these advanced designs. The purpose of this project was to develop a general approach to advanced HSI review and the human factors guidelines to support NRC safety reviews of advanced systems. This two-volume report provides the results of the project. Volume 1 describes the development of the Advanced HSI Design Review Guideline (DRG) including (1) its theoretical and technical foundation, (2) a general model for the review of advanced HSIs, (3) guideline development in both hard-copy and computer-based versions, and (4) the tests and evaluations performed to develop and validate the DRG. Volume 1 also includes a discussion of the gaps in available guidance and a methodology for addressing them. Volume 2 provides the guidelines to be used for advanced HSI review and the procedures for their use.

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EXECUTIVE SUMMARY

Background

Advanced control room (ACR) concepts are being developed in the commercial nuclear industry as part of future reactor designs and as improvements to current control rooms. The ACRs will use advanced human-system interface (HSI) technologies that may have significant implications for plant safety in that they will affect the operator's general role (function) in the system, the method of information presentation, the ways in which the operator interacts with the system, and the requirements on the operator to understand and supervise an increasingly complex system. The U.S. Nuclear Regulatory Commission (NRC) reviews the HSI aspects of control rooms to verify that they are designed to good human factors engineering (HFE) principles and that operator performance and reliability are appropriately supported to ensure public health and safety. The principal review guidance available to the NRC (NUREG-0700), however, was issued in 1981, well before many of these technological changes. Accordingly, the human factors guidance needs to be updated to serve as the basis for NRC review of these advanced designs. The objective of the project described in this report was to develop an approach for the evaluation of advanced HSIs called the Human Factors Engineering Program Review Model (HFE PRM) and an Advanced Human-System Interface Design Review Guideline (DRG).

This summary addresses the development and evaluation of the HFE PRM and the DRG.

HFE Program Review Model

In order to develop an approach for the evaluation of HSIs, it was necessary to consider: (1) standardization of nuclear power plant (NPP) designs, (2) the trends in advanced NPP HSIs, (3) the human factors issues associated with advanced technology, and (4) the state-of-the-art of human factors guidelines for advanced HSIs. Considering these issues, it was concluded that safety reviews of the HFE aspects of advanced reactor designs should: (1) be performed throughout the design of the plant; (2) extend beyond checklist-based evaluations to include a variety of assessment techniques; and (3) accommodate a broad range of CR "types" and a diversity of approaches to advanced HSI technology.

These factors have led to the development of the HFE PRM. It is largely based on applied general systems theory and represents a top-down approach to the review of HSIs. This approach starts with plant goals/functions and leads to the detailed design and validation. The HFE PRM is composed of eight elements and is divided into four review phases: HFE program planning, design analysis, interface design, and verification & validation. The review process allows the tracking of the design from initial conception through final design implementation. Within the context of the HFE PRM, the role of DRG is to provide the review guidance for evaluation of advanced HSIs to assure their conformance to accepted human factors engineering principles, standards, and guidelines.

DRG Development Methodology

Following a review of research and industry experience related to the integration of personnel into advanced systems, a set of "High-Level Design Review Principles" was developed. These principles identify the important design goals for maximizing primary task performance (i.e., the operator's process monitoring, decision-making, and control tasks); minimizing secondary task effects (i.e., the distracting effects of tasks such as configuring a workstation) which are unrelated to the primary task; and minimizing human error and making systems more tolerant to human errors when they occur. Then more detailed review guidance was developed for specific HSI implementations (e.g., graphic displays, touch screens, and expert systems).

The effort to develop detailed guidelines began with an identification of human factors guidance documents for advanced HSIs. Through a review of the human factors literature and contact with organizations that sponsor such research, over 50 guideline efforts were identified. The next step was to select those documents that would serve as the "primary sources" for the initial set of guidelines to be incorporated in the DRG. A high priority was given to establishing the validity of the guidelines; i.e., assuring that they were based upon empirical research and/or accepted human engineering practice. Validity was defined in terms of two aspects of document development. "Internal" validity was evaluated by the degree to which the individual guidelines within a document were based upon research and an audit trail to the research maintained. "External" validity was evaluated as a function of the degree to which the guidelines were subjected to independent peer review. The peer review process was considered a good method of screening guidelines for conformance to accepted human engineering practices. Documents which had strong validity were considered primary source documents to serve as a basis for the DRG.

The guidelines from the primary sources were edited to combine similar guidelines and to transform the material into a standardized format. Where compound guidelines were encountered (several guidelines in a single statement) an effort was made to break them into logical units and represent the units as separate guidelines. Conflict resolution between guidelines was handled on a case-by-case basis.

The guidelines were sorted into seven major sections described below. Some sections are currently empty pending the completion of other NRC projects that are developing new guidelines in those areas. Each of these sections contains a set of general guidelines and more detailed guidelines addressing specific HSI applications.

The seven sections are:

- **Information Display** - This section deals primarily with the formatting of visual displays, both text-based and graphics-based. Following a section of general guidelines, guidance is provided in top-down fashion beginning with display formats (such as mimic displays and trend graphs), display format elements (such as labels, icons, symbols, color, text, coding, etc.), data quality and update rate, and display devices (such as video display terminals and large board displays).

- **User-System Interaction** - This section addresses the modes of interaction between the operator and the HSI. Topics include dialog format, navigation, display controls, entering information, system messages, prompts, and system response time. This section also contains guidelines concerning methods for ensuring the integrity of data accessed through the user interface. Guidance covers prevention of inadvertent change or deletion of data, minimization of data loss due to computer failure, and protection of data such as setpoints from unauthorized access.

- **Process Control and Input Devices** - This section addresses information entry, operator dialogue, display control, information manipulation, and system response time. Considerations of display-control integration are also included here.

- **Alarms** - This section is a place holder for the results of another NRC research project to develop review guidance in the area of advanced alarm systems.

- **Analysis and Decision Aids** - This section addresses the use of knowledge-based systems.

- **Inter-Personnel Communication** - This section contains guidelines for activities related to speech and computer-mediated communication between plant personnel, e.g., preparing, addressing, transmitting and receiving messages.

- **Workplace Design** - This section addresses the organization of displays and controls within individual workstations, control room configuration, and environment.

In addition to a hard-copy document, the DRG has been developed as an interactive, computer-based review aid. The interactive document will simplify guideline access and review, editing, compilation of individual guidelines for a specific review, and incorporation of new guidelines as they become available. Availability of the DRG on a portable computer will also facilitate on-site reviews.

The guidelines are stored in a database composed of several primary fields: guideline number, title, guideline statement, additional information, and source (link to primary source document). Other "reviewer-support" fields are also provided, e.g., a note pad for reviewers to append comments related to specific guidelines. The interactive review aid provides for many document functions such as instant table of contents (ToC) access, context index, glossary, and placemarkers. Reviewers can automatically go to desired sections by clicking on the ToC or index entry. DRG evaluation summary and reporting functions are also available.

DRG Test and Evaluation

The DRG has been evaluated with respect to its scope and technical content (i.e., adequacy for the review of advanced HSI technology), and usability (i.e., DRG presentation, interactive document functionality, and user interfaces). The test and evaluation (T&E) program consisted of three methodologies: Development Test, User Test, and Peer-Review Workshop. The Development Test provided a preliminary evaluation of the DRG and an opportunity to correct interface problems before subsequent testing. The User Test was a field test of the DRG in advanced control room environments by experienced human factors reviewers. The third evaluation was a Peer-Review Workshop. The workshop provided a different type of evaluation than the two testing tasks and addressed the broader aspects of the DRG, such as the validity and technical basis for the DRG.

The general results supported the DRG's validity. The primary source documents were considered an appropriate technical basis upon which to develop the DRG. However, several further developments were recommended including a reduction in the total number of guidelines, the specification of a review process or procedure to facilitate DRG usage by a review team, and development of additional guidelines for several topics that were not adequately addressed (such as computer-based alarm processing systems).

With respect to the interactive version of the DRG, most interface characteristics thought to be indicative of usability (such as visual clarity, consistency, explicitness, ease of use, ease of learning, low memory load, etc.) were rated highly. Some difficulties were encountered, mainly concerning input devices, reporting and help functions.

Based upon the results of the T&E program, modifications were made to address the identified considerations.

Final Version of the DRG

Based upon the results of the T&E program, modifications were made to the technical content of the guidelines. These included reducing the number of guidelines and "layering" the guidelines into (1) general principles, (2) general guidelines in each of the major sections, and (3) more detailed guidelines addressing specific HSI implementations, techniques, and formats. The DRG was also revised to eliminate redundancy and standardize terminology to ensure consistency throughout the document. Procedures were developed for use of the DRG to evaluate (1) a plant-specific HSI guideline or design specification document and (2) an actual ACR design.

Many modifications have been made to the interactive document. These include the development of a review planning aid to support the identification and selection of guidelines for a specific review and improvements in the review functions to mitigate the troublesome characteristics of the interface identified in the evaluations. In addition, a maintenance function was developed to enable easy export of the guidelines to a text file for editing and import of the revised guideline.

Conclusion

A general framework for the review of advanced HSI technology and design review guidelines was developed to support NRC staff reviews of advanced HSI technology. The methodological approach established for the development of advanced HSI design review guidance will support the further refinement of the DRG to ensure that the document is maintained up-to-date and with valid human factors review guidance.

The report consists of two volumes. Volume 1 provides the technical basis for the guideline development. Volume 2 provides the HFE guidelines and the procedures for their use.

PREFACE

This report was prepared for the Human Factors Branch of the Nuclear Regulatory Commission's Office of Nuclear Regulatory Research. The U.S. Nuclear Regulatory Commission (NRC) Project Manager for this effort is Jerry Wachtel. This document is submitted as part of the work performed for the "Advanced Control Room Design Review Guideline" project (FIN L-1317).

The objective of the project was to develop an Advanced Human-System Design Review Guideline (DRG). The results are reported in a two-volume NUREG/CR. The contents of each are briefly described below.

Volume 1: General Evaluation Model, Technical Development, and Guideline Description
Volume 1 provides an overview of the project. Section 1 outlines the tasks performed as part of the DRG development. Section 2 describes the general issues, regulatory considerations, and theoretical factors that provided the context for both general model and guideline development. Section 3 describes the development of a general model for the review of advanced NPP human factors. The model is called the Human Factors Engineering (HFE) Program Review Model (PRM). Section 4 describes the methodology used to develop the design review guidelines for advanced HSIs that are available in the DRG. This section also briefly describes the organizational structure of the guidelines, an overview of guideline content, and procedures for DRG usage. Section 5 describes the development of the interactive, computer-based version of the DRG and briefly explains its present functions and user interfaces. Section 6 describes the tests and evaluations performed as part of DRG development and validation. Section 7 describes review needs and a methodology for the development of additional guidance.

Volume 2: Evaluation Procedure and Guidelines for Human Factors Engineering Reviews
Volume 2 contains the detailed guidelines and procedures for their use. It is divided into two technical parts. Part 1 provides a brief background to the use of the DRG within the context of the overall HFE PRM, the intended use and limitations of the DRG, and a description of the DRG's contents. Also included in Part 1 are procedures for using the Guideline for the review of (1) a design-specific guideline or detailed design specification, and (2) an HFE verification of an implemented HSI design. Part 2 contains the guidelines used to conduct reviews of advanced HSIs. In addition to a set of high-level design review principles, the guidelines are divided into seven sections: (1) Information display, (2) User-system interaction, (3) Process control and input devices, (4) Alarm systems, (5) Analysis and decision aids, (7) Inter-personnel communication, and (7) Workplace design. Volume 2 also contains a detailed glossary and index to support DRG use.

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We also extend our gratitude to our colleagues at Brookhaven National Laboratory who provided insights, assistance, and constructive reviews of all work associated with the project: Robert Hall, James Higgins, Sonja Haber, and William Stubler. Special thanks are given to Kathleen Nasta for her tremendous assistance in preparing the manuscript.

ACRONYMS

ABWR	Advanced Boiling Water Reactor
AC	Alternating Current
ACR	Advanced Control Room
ACRS	Advisory Committee for Reactor Safeguards
AECL	Atomic Energy of Canada, Limited
AI	Artificial Intelligence
ALWR	Advanced Light Water Reactor
ASLB	Atomic Safety and Licensing Board
BNL	Brookhaven National Laboratory
BWR	Boiling Water Reactor
CE	Combustion Engineering
CII	Carlow International Incorporated
COL	Combined Operating License
CFR	Code of Federal Regulations
CR	Control Room
CRT	Cathode Ray Tube
DAC	Design Acceptance Criteria
DCRDR	Detailed Control Room Design Review
DI	Debriefing Interview
DMS	Data Management System
DoD	Department of Defense
DRG	Design Review Guideline
DQ	Debriefing Questionnaire
EDF	Electricite de France
EOP	Emergency Operating Procedure
EPG	Emergency Procedure Guidelines
EPRI	Electric Power Research Institute
FAA	Federal Aviation Administration
FSER	Final Safety Evaluation Report
GE	General Electric
GEMS	Generic Error Modelling System
GL	Guideline
HED	Human Engineering Discrepancy
HFE	Human Factors Engineering
HFE PRM	Human Factors Engineering Program Review Model
HFES	Human Factors and Ergonomics Society
HRA	Human Reliability Analysis
HSI	Human System Interface
HWR	Heavy Water Reactor

ACRONYMS (Cont'd.)

I&C	Instrumentation and Control
IAEA	International Atomic Energy Agency
IEC	International Electrotechnical Commission
IEEE	Institute of Electrical and Electronics Engineers
INEL	Idaho National Engineering Laboratory
INSAG	International Nuclear Safety Advisory Group
IP	Information Processing
ITAAC	Inspections, Tests, Analyses, and Acceptance Criteria
KWIC	Key Word in Context
LCS	Local Control Station
LMR	Liquid Metal Reactor
LWR	Light Water Reactor
LTM	Long-Term Memory
MHTGR	Modulated High Temperature Gas Reactor
NASA	National Aeronautics and Space Administration
NPP	Nuclear Power Plant
NRC	U.S. Nuclear Regulatory Commission
NSSS	Nuclear Steam Supply System
OECD	Organization for Economic Cooperation and Development
OER	Operating Experience Review
ORNL	Oak Ridge National Laboratory
OSAC	Operations Sequence Accomplishment Checklist
P&ID	Piping and Instrumentation Diagram
PC	Participant Comments
PIUS	passive inherently ultimate safe
PRA	Probabilistic Risk Assessment
PRISM	power reactor inherently safe module
PSF	Performance Shaping Factor
PWR	Pressurized Water Reactor
RARS	Requirements Analysis Rating Scale
SA	Situation Awareness
SAIC	Science Applications International Corporation
SBWR	Simplified Boiling Water Reactor
SDT	Signal Detection Theory
SME	Subject Matter Expert
SPDS	Safety Parameter Display System
SRP	Standard Review Plan
SSAR	Standard Safety Analysis Report

ACRONYMS (Cont'd.)

T&E	Test and Evaluation
TCO	Test Conductor's Observations
TMI	Three-Mile Island
TTC	U.S. NRC Technical Training Center
UIRS	User Interface Rating Scale
USAF	United States Air Force
V&V	Verification and Validation
VDU	Video Display Unit
WM	Working Memory

1. INTRODUCTION

1.1 Background

The importance of a well-designed human-system interface (HSI) to reliable human performance and nuclear safety is widely acknowledged. The National Academy of Sciences (Moray and Huey, 1988) reported that one of the first insights from studies of the Three Mile Island (TMI) accident was that errors caused by operators in the control room (CR) are a significant contributing factor to nuclear power plant (NPP) incidents and accidents. The errors at TMI were due to several factors including a poorly designed CR and inadequate provisions for monitoring the basic safety parameters of plant functioning. The International Nuclear Safety Advisory Group (INSAG, 1988) of the International Atomic Energy Agency (IAEA) in their basic safety principles indicated that "...one of the most important lessons of abnormal events, ranging from minor incidents to serious accidents is that they have so often been the result of incorrect human action" (page 19). Further, "...continued knowledge and understanding of the status of the plant on the part of operating staff is a vital component of defense in depth." This conclusion led to the safety principle that:

> Parameters to be monitored in the CR are selected, and their displays are arranged to ensure that operators have clear and unambiguous indications of the status of plant conditions important to safety, especially for the purpose of identifying and diagnosing the automatic actuation and operation of a safety system or the degradation of defense in depth (page 43).

In the United States (U.S.), the Nuclear Regulatory Commission (NRC) reviews the human factors engineering (HFE) aspects of CRs to ensure that they reflect "state-of-the-art human factors principles" (10 CFR 50.34/f/2/iii) and that the operator's performance and reliability are appropriately supported. In response to the investigations following TMI, the NRC developed an action plan (U.S. NRC, 1980a and 1980b) to address safety-significant deficiencies in commercial NPPs. In addition, a formal human factors program was initiated in the NRC. There were two significant outgrowths of the post-TMI planning with respect to HSI. First, all licensees and applicants for commercial NPP operating licenses were required to conduct a detailed CR design review (DCRDR) including reviews of remote shutdown panels to identify and correct human-factors design deficiencies. Extensive guidelines, published in NUREG-0700, "Guidelines for Control Room Design Review" (U.S. NRC, 1981b), were prepared in support of these evaluations. Second, all licensees and applicants were required to install a plant Safety Parameter Display System (SPDS) to aid operators to rapidly and reliably determine the safety status of the plant, something they were unable to do during the accident at TMI. The minimum information required was reactivity control, reactor core cooling, and heat removal from the primary system; reactor coolant system integrity; radioactivity control; and containment conditions. The NRC provided guidance on SPDS design and implementation (U.S. NRC, 1980c, 1981a). Analogous requirements for SPDS and human engineering of CRs were established for new plant designs in 10 CFR 50.34. In addition to requiring licensees to conduct DCRDRs and install SPDSs, the evaluation of licensees' compliance on these issues became part of the NRC's Standard Review Plan (SRP) (U.S. NRC, 1984a), Sections 18.1 and 18.2, respectively. The SRP describes the review procedures and acceptance criteria that the NRC uses for each area covered.

The DCRDRs produced a great deal of information on human engineering discrepancies (HEDs) that existed in NPPs. A study by the Electric Power Research Institute (EPRI) evaluated 25 DCRDRs from the 1980s to identify and categorize problems based upon the categorization scheme in NUREG-

0700 (Seminara, 1988). A total of 4,345 HEDs were evaluated by EPRI. Table 1.1 summarizes the HEDs within each category. There was a steady increase in the number of HEDs per CR reported between 1981 and 1986 as NUREG-0700 became increasingly applied to the DCRDRs. In general, the HSI issues associated with NPPs are broad, and cover all aspects of CR design.

Table 1.1. Summary of Human Error Deficiencies (HEDs) Found in 25 DCRDRs*

NUREG-0700 SECTION	TOTAL HEDs	AVERAGE PER PLANT
6.1 Workspace	641	26
6.2 Communications	160	6
6.3 Annunciators	488	20
6.4 Controls	558	22
6.5 Displays	1085	43
6.6 Labels	638	26
6.7 Computer	335	13
6.8 Panel Layout	328	13
6.9 C/D Integration	112	4

* From Seminara, 1988.

Problems also were reported following the review of SPDS interfaces (Liner and DeBor, 1987). The main purpose of SPDS is to assist operators in detecting, interpreting, and tracking process disturbances by providing a concise display of key parameters and giving them the ability to track changes in real time. However, poor information displays that confuse or mislead operators have led to poor acceptance of these systems in some plants.

Following the completion of DCRDR- and SPDS-related reviews, attention focussed on research areas for which there were insufficient scientific data to support regulation. One such area was the introduction of advanced, computer-based HSI technology which was not used in TMI-era NPPs.

Advanced, computer-based HSI designs are emerging in NPPs as a result of several factors including: (1) incorporation of computer-based systems (such as SPDS), (2) upgrading of current CRs with new control and display technologies, when existing hardware is no longer supported by equipment vendors, and (3) development of advanced CR (ACR) concepts as part of new (evolutionary and revolutionary) reactor designs. The first two activities result in a hybrid CR, reflecting a mix of conventional and advanced technologies. ACRs will be developed primarily with advanced instrumentation and controls based upon digital technology and will substantially differ from conventional and hybrid CRs. These developments may have significant implications for plant safety in that they will affect the operator's overall role (function) in the system, the method of information presentation, the ways in which the operator interacts with the system, and the requirements of the operator to understand and supervise an increasingly complex system.

To help assure that advanced technology is incorporated in both new and existing CRs in a way that emphasizes the potential safety benefits of the technology and minimizes the potential negative effects on performance and plant safety, the NRC reviews the design and implementation of significant changes to CRs and reviews the human engineering aspects of new CR designs. However, the principal guidance (NUREG-0700; U.S. NRC, 1981b) available to the NRC was developed more than ten years ago, well before these technological changes, and it was tailored to the technologies used in "conventional" CRs. Accordingly, the human factors guidance needs to be updated to serve as the basis for NRC review of these advanced designs.

1.2 Project Objective and Overview

The overall purpose of this project was to develop human factors guidelines for reviewing advanced HSIs in NPPs. Accordingly, several objectives were identified:

1. Evaluate the factors that impact the review of advanced HSIs and determine if/how they are different from those impacting reviews of conventional HSIs (e.g, DCRDRs). From this evaluation, if determined to be appropriate, develop a general framework for the regulatory review of advanced HSI. The framework developed is called the "Human Factors Engineering Program Review Model" (HFE PRM).

2. Develop an Advanced HSI Design Review Guideline (DRG), including review procedures and acceptance criteria, based upon accepted HFE principles, standards, and guidelines to support staff reviews of advanced HSIs.

3. Develop an interactive, computer-based version of the DRG to facilitate the use and update of the review guidance.

4. Test and evaluate the DRG to support its technical validity, scope, content, and functionality.

5. Identify additional HFE review needs; i.e., areas that are important to reviewing advanced NPP HSIs that are not adequately addressed in the DRG.

6. Use the results of this effort to support the NRC review of ACR designs. Although this objective has been accomplished, it will not be discussed in this report.

The project had five major tasks, each one corresponding to the first five objectives listed above:

- Task 1 - General HFE PRM
- Task 2 - DRG Development
- Task 3 - Interactive Document Development
- Task 4 - Test, Evaluation, and DRG Modification
- Task 5 - New Guidance Development

Figure 1.1 illustrates these general tasks, and shows the revisions to the DRG (shown in the bold-outlined boxes) leading to the present document. A brief overview of these tasks follows (a more detailed description is contained in the remaining sections of this report).

The purpose of Task 1, General HFE PRM Development, was to evaluate the issues that impact the performance of HFE reviews of advanced technology. These issues include specific factors that affect the NRC's regulatory responsibility, as well as general issues related to the impact of advanced technology on the operating crew's performance in high-reliability and complex supervisory-control systems. From an analysis of these issues, a broad evaluation model was developed. The HFE PRM is expressed in fairly broad terms, and was not fully developed in this project. Instead, one aspect of the model was selected for detailed development in Task 2, the DRG.

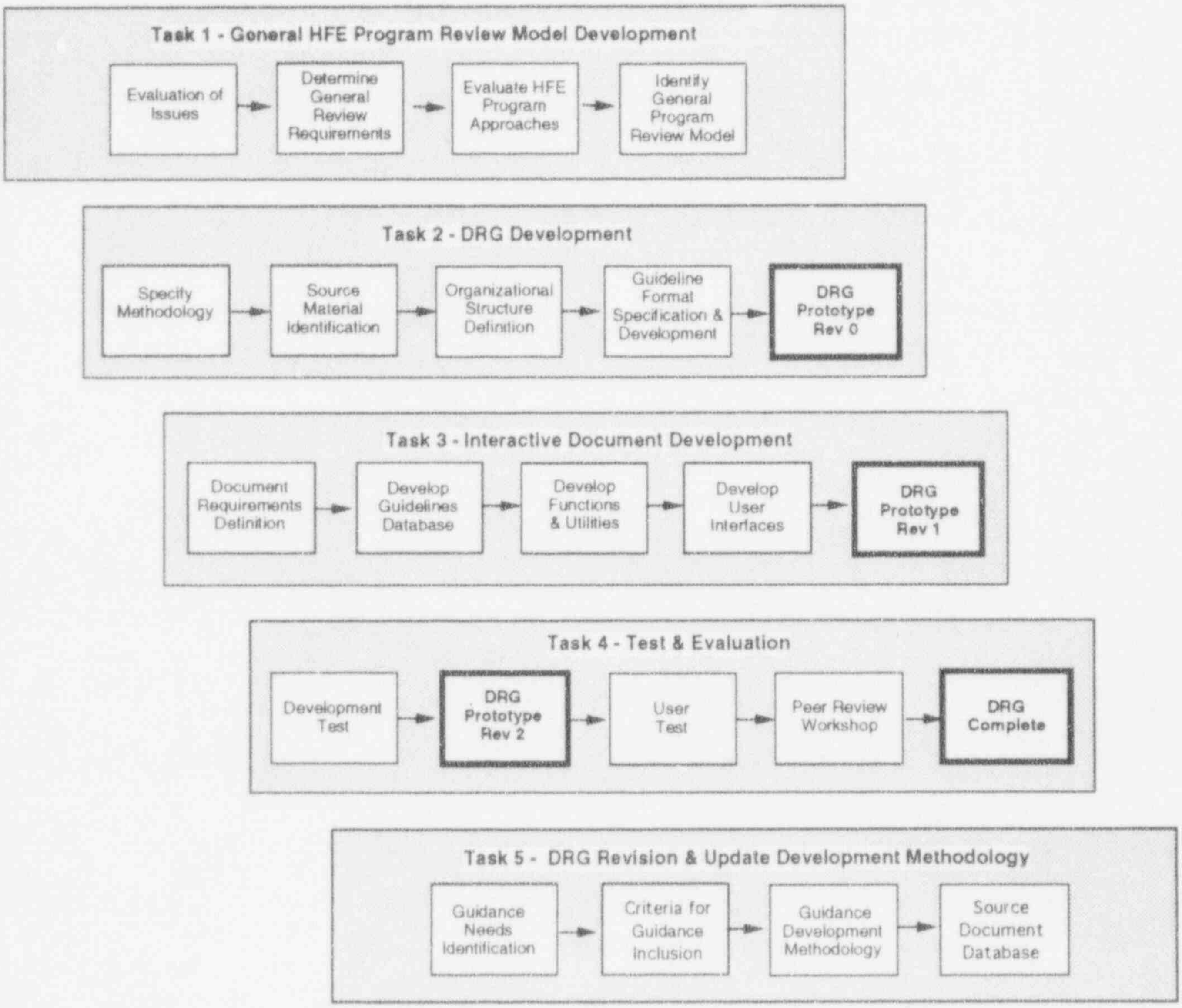

Figure 1.1. DRG development tasks

As part of Task 2, DRG Development, a guideline development methodology was established and individual guidelines for the review of advanced HSIs were assembled into an organizational structure and standardized format. In addition, a procedure was developed to use the DRG.

In Task 3, Interactive Document Development, the DRG was implemented as an interactive document in an electronic database to support guideline access and to provide reviewer aids to support preparation/planning, the conduct of evaluations, preparation of reports, and DRG maintenance.

In Task 4, Test and Evaluation, the scope and technical content of the DRG was evaluated. The user interfaces and functionality of the computer version of the DRG were evaluated as well. Three different evaluations were conducted and the DRG was modified based on the results. The DRG was tested by the project staff (Development Test) and a selected group of volunteers from facilities employing advanced HSIs (User Test). In addition, the DRG was evaluated in a peer-review workshop. Using the results of the User Test and the Workshop, the present version of the DRG was developed.

Task 5, DRG Revision and Update Development Methodology, addressed the development of new guidance. Through DRG development, test, and evaluations, gaps in the guidelines were identified. A methodology to address the development and incorporation of new guidelines in the DRG was developed.

1.3 Organization of the Report

The DRG is contained in two-volumes. The purpose and contents of each are briefly described below.

Volume 1: General Evaluation Model, Technical Development, and Guideline Description

The purpose of Volume 1 is to provide an overview of the technical development and basis of the guidelines. This is accomplished in the following sections. Section 2 describes the general issues, regulatory considerations, and theoretical factors that provided the context for both HFE PRM and guideline development. Section 3 describes the development of the HFE PRM for the review of advanced NPP human factors. Section 4 describes the methodology used to develop the design review guidelines for advanced HSIs that are available in the DRG. This section also briefly describes the organizational structure of the guidelines, an overview of guideline content, and procedures for DRG usage. Section 5 describes the development of the interactive, computer-based version of the DRG and briefly explains its functions and user interfaces. Section 6 describes the tests and evaluations performed as part of DRG development and validation. Section 7 describes the areas of guidance for which the DRG is weak and a methodology for the development of additional guidance. Section 8 contains the references.

Table 1.2 shows the relationship between the project objectives described in Section 1.2 above and those sections of Volume 1 where these efforts are described. For some tasks, more detailed information is available elsewhere, thus Table 1.2 also references these additional sources.

Volume 2: Evaluation Procedure and Guidelines for Human Factors Engineering Reviews

The purpose of Volume 2 is to provide the detailed guidelines and procedures for their use. The volume is divided into two technical parts. Part 1 provides a brief background, the intended use and limitations of the DRG, and a description of the DRG's contents. Also included in Part 1 are procedures for using the Guideline for (1) the review of a design-specific guideline or detailed design specification, and (2) an HFE verification of an implemented HSI design. Part 2 contains the guidelines used to conduct reviews of advanced HSIs. In addition to a set of high-level design review principles, the guidelines are divided into seven sections: (1) Information display, (2) User-system interaction, (3) Process control and input devices, (4) Alarm systems, (5) Analysis and decision aids, (6) Inter-personnel communication, and (7) Workplace design. Volume 2 also contains a detailed glossary and index to support DRG use.

Table 1.2. Report Organization and Sources of Additional Project Information

OBJECTIVE AND TASK	SECTION	ADDITIONAL INFORMATION
Background Issues	2	
General Model Development	3	O'Hara, Higgins, and Stubler, 1994
DRG Development	4	Volume 2 of this report
Interactive Document Development	5	
Test and Evaluation	6	Various BNL Technical Reports (referenced in Section 6)
DRG Weaknesses and Update Methodology	7	

2. FACTORS AFFECTING THE REVIEW OF ADVANCED REACTOR HUMAN FACTORS ENGINEERING

This section describes the general issues, regulatory considerations, and theoretical factors that provided the technical basis and context for developing the general model and the guidelines. To develop an approach to reviewing the human factors engineering (HFE) of advanced nuclear power plants (NPPs), it was necessary to consider the factors that can be expected to impact such reviews. Several sources of information were searched to identify significant issues, including:

- Current NRC regulations governing advanced reactor certification reviews,
- Research reports and publications on the advanced technology being developed for human-system interfaces (HSIs) in process control applications,
- Information on advanced NPP control room (CR) designs,
- Advanced instrumentation and controls surveys conducted for the NRC (Carter and Uhrig, 1990), the IAEA (Neboyan and Kossilov, 1990), and the OECD (Kennedy, 1988),
- General publications on human information processing and the effects of advanced technology on human performance, and
- Existing literature on human-factors standards and guidelines for advanced HSI.

From the above material, many factors were identified that had implications for the development of an approach to review the HFE of advanced HSI. These factors are organized into four categories: regulatory issues (Section 2.1), trends in NPP HSIs (Section 2.2), human information processing and performance factors (Section 2.3), and advanced HSI guidelines issues (Section 2.4). The implications of these factors and issues for the HFE review are summarized in Section 2.5.

2.1 Regulatory Considerations

Two factors are considered in this section:

- NRC review of standardized plant designs under 10 CFR Part 52,
- Scope of human factors reviews.

2.1.1 NRC Review of Standardized Plant Designs Under 10 CFR Part 52

NRC reviews of CRs typically have been directed toward existing CRs or existing systems (such as SPDS). However, the NRC and the commercial nuclear power industry have embarked on an effort to improve and standardize future designs of commercial nuclear power plants. The NRC issued 10 CFR Part 52, entitled "Early site permits; standard design certifications; and combined licenses for nuclear power plants," to encourage standardization and to streamline the licensing process. Nuclear plant designers and vendors have begun to design advanced standard plants, that are being submitted to the NRC for review and approval under Part 52. The General Electric (GE) Advanced Boiling Water

Reactor (ABWR), the Combustion Engineering (CE) System 80+ and the Westinghouse AP600 are examples of designs undergoing such review.

The licensing process of Part 52 consists of a Final Design Approval by the NRC and the Advisory Committee for Reactor Safeguards (ACRS) followed by a Standard Design Certification that is issued as an NRC Rule. The latter will require formal rule-making and include the opportunity for a public hearing before the Atomic Safety and Licensing Board (ASLB). The certification would be valid for 15 years, and would be renewable. During its tenure, neither the NRC nor the designer can change or impose new requirements on the standard design certification without a new rule-making. Utilities would have the option of purchasing the standard design and using it as already approved by the NRC.

To ensure that a plant, as built, conforms to the standard design certification, inspections, tests, analyses, and acceptance criteria (ITAAC) must be specified as part of the standard design certification. Then, the utility building the plant and the NRC will ensure that the ITAAC are performed and met. A utility desiring to license and operate a NPP under Part 52 will obtain a Combined Operating License (COL) that authorizes both construction and operation in one step. The COL applicant may propose a new design or refer to an existing standard design certification. To obtain a standard design certification under Part 52, a designer must submit a Standard Safety Analysis Report (SSAR) to the NRC. The NRC's review of the SSAR is issued as a Final Safety Evaluation Report (FSER) which will form the basis for the Final Design Approval and the Standard Design Certification.

A major issue to emerge from the initial CR reviews under the certification process was that detailed HSI design information was not available for staff review as part of the design certification evaluation. To address the lack of detail, the NRC made a review based partially on the preliminary design (key features) and partially on a final design and implementation process plan that describes the HFE program elements required to develop the key features into an acceptable, detailed, design specification. Along with the design process, the NRC requires the applicant for design certification to submit a form of ITAAC, called Design Acceptance Criteria (DAC), that ensures the design process is properly executed by the COL applicant. The NRC specified that the design and implementation process should contain descriptions of all required human factors activities that are necessary and sufficient to develop and implement the HSIs. It also should include an identification of predetermined NRC conformance review points, the DAC, and ITAAC for the conformance reviews.

This process is very different from the typical HSI reviews conducted by the NRC and is unprecedented in the commercial nuclear power industry. The present NRC review criteria provided by Chapter 18 of the Standard Review Plan (SRP) and NUREG-0700 provide little information to the reviewer for this type of evaluation; i.e., the criteria for review are not addressed by current regulations and guidance documents. Thus, HFE guidance for advanced reactor reviews must support the review of HSIs through the design and implementation process, and must be able to support the review of proposed standardized designs, as well as modifications to existing CRs.

2.1.2 Scope of Human Factors Reviews

While the focus of NUREG-0700 reviews was the CR (including reference to remote shutdown panels), the NRC also has been evaluating the human factors characteristics of local control stations (LCSs) in connection with Emergency Operating Procedures (EOPs) reviews, Appendix R (Safe Shutdown) reviews, and reviews of events occurring at low power/shutdown (which are more LCS-intensive than full-power operations). Within the context of this report, a LCS is an operator interface related to NPP process control that is not located in the main CR. This includes multi-function panels as well as single-function LCSs, such as controls (e.g., valves, switches, and breakers) and displays (e.g., meters) that are operated or consulted during normal, abnormal, or emergency operations. In addition, the NRC is investigating the safety significance of LCS design (Persinko and Ramey-Smith, 1986; O'Hara et al., 1991; Brown et al., 1993). Since the results of these reviews and studies indicate that LCSs have safety significance and frequently significant HEDs, the review of advanced NPP human factors should encompass the HSIs outside as well as inside the main CR and at remote shutdown stations.

2.2 Tren' · Advanced NPPs

Two ... are considered in this section:

- Diversity of advanced reactor technology
- CR evolution and major trends in HSI technology

2.2.1 Diversity of Advan... ...actor Technology

The current generation of commercial NPPs in the United States, consisting of over 100 plants, is based upon light water reactor (LWR) technology. The LWR plants were either boiling water reactors (BWRs) or pressurized water reactors (PWRs). There were two gas-cooled commercial reactors, Peach Bottom-1 and Fort St. Vrain, but these are now shut down.

Advanced reactors are being developed with a broader technical basis include: LWRs, heavy water reactors (HWRs), liquid metal reactors (LMRs), and gas-cooled reactors, such as the modular high-temperature gas reactor ...GR). Each reactor type is envisioned as a standard plant design from which a number of reacto... ould be built. However, the diversity of reactor types raises new issues about their design and operation. These issues include reactivity control and other reactor physics issues; core thermal hydraulics; natural cooling of the core; different types of safety systems and safety system control and operation; smaller plants and multiple units (as many as nine per site); different dominant accident sequences; new hazards (e.g., sodium-water reactions and very high tritium levels); new equipment (liquid sodium pumps, gas circulators, and "passive" components); and advanced instrumentation and controls.

Thus, as these new types of reactors are designed and built, new and different systems are being incorporated, and so many new features must be addressed, both from the standpoint of reactor physics and plant engineering. A main objective in designing the next generation of reactors is to develop plants which are simpler, safer, and more reliable than the current generation. One important initiative to improve safety and reliability has been the move from active safety features toward more passive safety features, some of which use natural physical processes such as convection flow, radiational cooling, and gravity. If these designs are successful, there will be less opportunity for equipment failure or operator error to create hazardous situations. However, the operator's role in such systems and the means by which the operator will monitor and interact with such systems is not fully known.

The first advanced reactors to be proposed are extensions of current BWR and PWR technology and thus, have been termed evolutionary advanced reactors (GE's ABWR and CE's System 80+ PWR). These plants have incorporated technological improvements but still rely on primarily active safety systems. Beyond these are reactor designs using "simplified passive" features (such as GE's simplified BWR (SBWR) and Westinghouse's AP-600 PWR) that have eliminated active pumps for emergency coolant injection but still have some active components; i.e., valves. These designs use pressurized tanks and gravity flow to inject the coolant, but they still require various valves to actively cycle to permit the flows and to depressurize the reactor. Further along the spectrum toward fully passive design are the "revolutionary designs" (such as the power reactor inherently safe module (PRISM) liquid metal reactor and the passive inherently ultimate safe (PIUS) LWR) which submerge the primary reactor systems in large pools of coolant that can provide natural circulation cooling in an accident. The containment systems also are designed to provide natural circulation cooling to remove heat generated inside containment during accidents. The PIUS reactor has gone even further toward passive design, with the reactor internals directly in contact with the emergency shutdown and cooling pool and isolated only via density differences. These density locks will immediately break on any overheating in the core.

These advanced passive features introduce new and different systems for operators to control, test, and monitor, and they require different types of instrumentation. There are questions as to how the reliable functioning of these passive systems can be verified by the operators during operation. Also, the role of the operator during transients and accidents changes considerably with these new passive systems. Important high-level questions include:

- How do operators verify that these systems are ready during normal operation?
- How can proper operation be confirmed when the systems are called upon?
- What parameters should be monitored?
- What is the proper operator's response when the passive systems do not function properly?

These questions will result in different CRs, different roles and tasks for the operator, and different operator-control interfaces. One implication of this diversity is that a prescriptive approach to reviewing interface design based upon specific operator tasks is not possible in an NRC guidance document that must support reviews of all designs and a great variety of operator functional roles in the system.

2.2.2 CR Evolution and Major Trends in HSI Technology

Several important trends emerged from the review of literature on developments in advanced HSI in the nuclear industry:

- The greater use of automation that shifts the operator's role more toward that of a system monitor, supervisor, and back up to automated systems.
- Greater centralization of controls and displays into "compact" digital workstations.
- Use of large-screen display panels that can be seen from anywhere in the CR to present high-level information and critical parameters.
- Operator interface with the plant systems mediated through a data management system (DMS) with little direct interaction with components.

- Use of data integration and graphic displays.

- Use of information-processing and decision-support aids.

With increased application of digital control technology comes an enhanced ability to automate tasks traditionally performed by an operator. It is generally presumed that automation will enhance the overall reliability of the system by removing or reducing the need for human action. The operators' interaction with the system is believed to be improved by freeing them from tasks which are routine, tedious, physically demanding, or difficult. Thus, operators can better concentrate on supervising the overall performance and safety of the system.

The trends toward using a CR composed of large-screen display panels, together with one or more "compact," computer-based workstations, is characteristic of many new designs. The large overview display, designed to be seen anywhere in the CR, provides information, such as high-level plant status, key parameter values (such as SPDS), major alarms, and status of important safety equipment. The operator is located at a workstation that serves as the locus of CR operations. Typically, such workstations include centralized and integrated controls and displays; color graphics; high levels of data integration; display devices such as cathode ray tubes (CRTs) and flat panels; new input devices such as the mouse and touch screen; multifunction ("soft") controls; workstation flexibility; and an emphasis on information management and software-interface issues.

Intelligent operator-aids based on expert systems and other artificial intelligence-based technologies are being applied to process control. These applications include aids for alarm processing, diagnostics, accident management, plant monitoring, and procedure tracking. In fact, many recent articles on advances in NPP CR technology specifically address intelligent operator aids.

As these technologies are increasingly applied, the range of CR types will expand beyond that with which the industry is familiar. CRs reflect an evolutionary continuum, but can generally be thought of as falling into four groups:

Conventional CR - A CR containing analog and primarily hardwired controls (e.g., switches, knobs, handles) and displays (e.g., gauges, linear scales, indicator lights).

Hybrid CR - A conventional CR that has introduced digital technology for new systems and to replace selected analog systems. Thus, the CR represents a mixture of analog and digital technology. Increasingly, CRs in U.S. NPPs are evolving to hybrid CRs.

Advanced CR - An ACR is based primarily on digital technology and computer-based interfaces. Some analog and hardwired interfaces may remain for safety critical or backup functions. Data processing functions are available to assist the operator with processing of lower-level information. Computer-based decision aids may be available to the operator, but will not be in the control loop.

Intelligent CR - The generation of CRs to be developed beyond ACRs will include various artificial intelligence (AI) and related capabilities to further automate the operators' supervisory control, and decision-making functions.

Related to CR evolution is the wide range of technological approaches to implement HSI in computer-based CRs. In part, this is due to the capability of software-driven interfaces to provide alternative data display and control. The options for display expand the hardware media choices (e.g., computer-driven displays which mimic conventional gauges and meters, video display units, and computer-driven large screen displays). Further, the formats in which to display data are extremely varied (e.g., lists, tables, flow charts, graphs, iconic graphics, speech). Operator input to the system has seen similar expansion in diversity including, for example, conventional controls, miniature controls, keyboards, touch screens, mice, joy sticks, light pens, and voice controls. With interactive graphic displays, the traditional distinction between controls and displays becomes blurred. For example, an operator may open a valve or start a pump via computer graphic mimic of the system and touching the icon of the desired component. In addition, data processing and integration are more significant in ACRs providing the operator with higher-level displays.

The DRG must support the review of new CRs and modifications to existing CRs that reflect these industry trends.

2.3 The Effects of Advanced Technology on Human Performance and Reliability

The introduction of advanced instrumentation and control (I&C) and HSI technology promises to improve the safe operation of nuclear power plants. The potential advantages of advanced technology over conventional CR technologies include:

- Support for data access and presentation, e.g.,
  - Rapid, highly reliable, validated data transfer
  - Large amounts of data at the operator's fingertips
  - Precise digital data displays
  - Use of color and graphic displays to facilitate the operator's assimilation of important information
- Support for the operator's processing of information, e.g.,
  - Data integration providing the operator with high-level, more meaningful information
  - Parameter trend displays
  - Decision aids
- Support for process control, e.g.,
  - Hierarchical levels of control
  - Use of automation to reduce operator workload
- Workstation design, e.g.,
  - HSI in a compact workstation
  - Flexibility in control and display operations

While such advanced technology is generally considered to enhance system performance, computer-based operator interfaces also have the potential to negatively impact human performance, spawn new types of human errors, and reduce human reliability (Coblentz, 1988; Rasmussen, Duncan, and Leplat, 1987; and Wiener and Nagel, 1988; Woods et al., 1990). There have been many attempts over the past 20 years to identify the causes of error. The main conclusion from the work is that few human errors represent random events; instead, most can be explained on the basis of human cognitive mechanisms (Reason, 1988; Rasmussen, 1986). Therefore, it is important to understand how operators perform their tasks from an information-processing point of view and how human information processing relates to HSI design and human error. However, because the contributors to unreliability in an ACR (such as function allocation and automation, supervisory control, and human-software-computer interactions) differ from those that are familiar contributors to human error in conventional CRs, they are less obvious and generally less well understood (O'Hara and Hall, 1990, 1991; Stubler et al., 1991). Cognitive issues and human information processing are emerging as more significant than the physical and ergonomic considerations that dominated the design of conventional HSIs.

While these issues have been long recognized, their full implication to human performance and system safety have only recently begun to be investigated, and there is not a long history of practical operational experience to draw upon. Thus, the National Academy of Sciences identified areas, such as automation, supervisory control, and human-computer interfaces, as high-priority research areas for the human factors community in general (Pew et al., 1983) and for the commercial nuclear industry in particular (Moray and Huey, 1988). More recently, issues that significantly impact the integration of human operators with advanced systems were identified as high priority research topics in an effort to improve safety in the civilian aviation industry by the U.S. Federal Aviation Administration (U.S. FAA) in their "National Plan for Aviation Human Factors" (U.S. FAA, 1990). The plan represents a major effort involving the U.S. FAA, National Aeronautics and Space Administration (NASA), U.S. Department of Defense (U.S. DoD), and industry.

Because of the rapidly increasing use of these technologies in complex, high-reliability systems such as NPPs and civilian aircraft, the knowledge base for understanding the effects of advanced HSI technology on human performance and system safety is limited, and further information is needed. Some factors have been identified which are discussed in the next section. This section presents a general framework for examining the effects of advanced HSI technology on human, system, and plant performance.

2.3.1 Human Information Processing

In the remainder of this section, issues related to the effects of selected design features on human performance and error are considered. These effects are discussed in terms of human cognitive processes. Therefore, the discussion is preceded by a brief overview of information processing and human error.

2.3.1.1 General Model

Human performance theories typically consider errors as one indicator of performance along with other measures, such as time, accuracy, and workload. However, error has special significance in the NPP domain due to its incorporation and quantification in risk models. Therefore, within the context of the present discussion, human errors are distinguished from other aspects of human performance. The error event (whether omission or commission) is the end product of an information processing sequence, i.e., a result of normal information processing characteristics that, under certain circumstances, lead to error predisposition by altering information processing strategies. This process is depicted in Figure 2.1. Also shown in the figure are significant characteristics of each step in the process. These characteristics will be discussed in the following discussion. The focus of HSI effects on human performance can be directed to both errors themselves (that are infrequently observed in skilled operators) and to the information processing precursors that give rise to them (that are more readily measurable). To identify and interpret the effects of advanced technology on human error and performance, it is helpful to utilize a model of information processing.

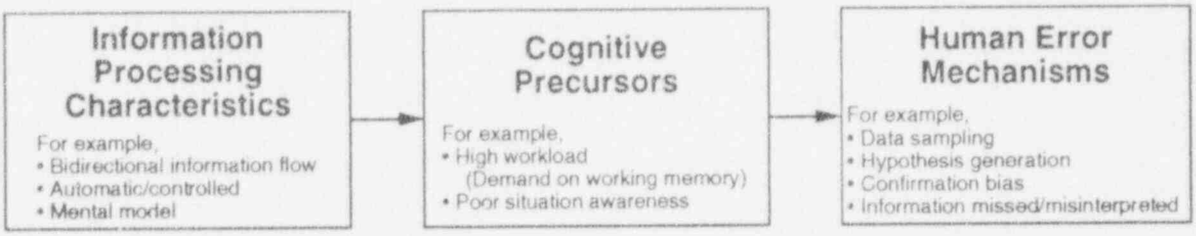

Figure 2.1. Human cognitive error mediators

Many models of information processing (IP) have been proposed (e.g., Broadbent, 1958; Atkinson and Shiffrin, 1968); they differ in specificity with respect to the aspects of IP they attempt to explain, as well as the types of studies used for validation. A model frequently used in human engineering was proposed by Wickens (1984). It is general in the sense that it borrows features that are common to many models of human cognition that have good empirical support. Figure 2.2 presents an adaptation of Wickens' model to a supervisory control task. The model is briefly reviewed below to identify those aspects of cognition that are important to HSI design and evaluation in supervisory control systems where an automatic control system exerts an influence (generally the primary control) on the system. The model in Figure 2.2 is simplified, and not all interconnections between the elements are shown. While it is depicted showing the flow of information through the system from left to right, the complex interaction between cognitive elements is more complex, thus, the figure is a simplification.

During a typical monitoring task, information about the system is made available to the operator through the HSI and through communications via the operator's sensory organs. Each sense has a short-term storage capability, usually on the order of milliseconds, during which a large quantity of information is represented. Some of this information is perceived, which implies (1) that a stimulus pattern was associated with a meaningful pattern based on information stored in the knowledge base or long-term memory (LTM) (see path from LTM to perception in Figure 2.2), or (2) the stimulus was so intense (such as very loud noise or very bright flash) that attentional resources were drawn to it through the "orienting response" (typical, measurable physiological changes such as a change in the electroencephalogram pattern that occur when a person detects a change in the environment). The pattern recognition process is quite robust in that to make a perceptual identification, a stimulus pattern need not be an exact match in the knowledge base. Instead, knowledge is represented in prototypical or schematic form. The specific information available to the operator is evaluated in terms of the probability that it represents an exemplar of a known pattern in LTM. Pattern recognition becomes more difficult when the number of dimensions that are required to make the recognition increases.

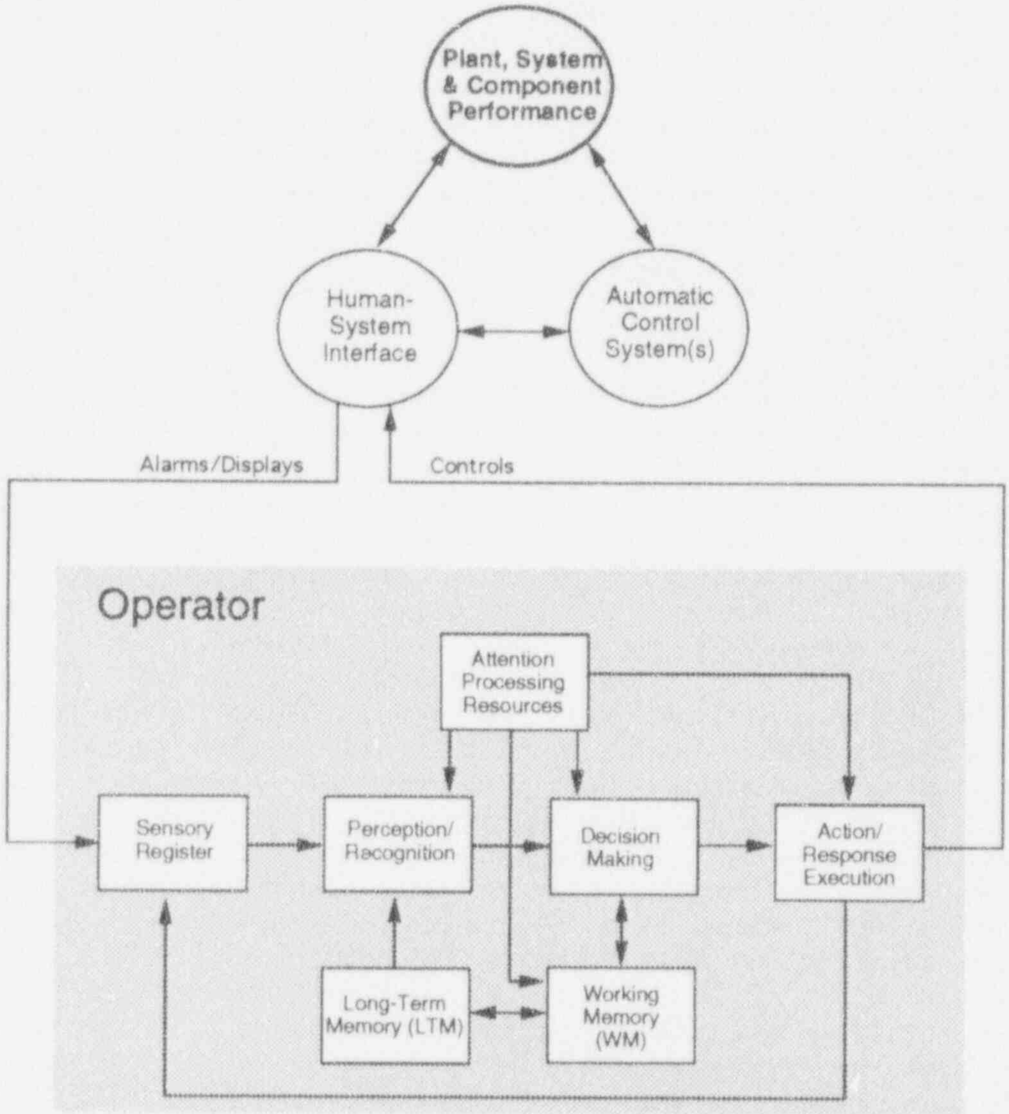

Figure 2.2. Simplified supervisory control information processing model (Adapted from Wickens, 1984)

The knowledge base is relatively permanent, has a large capacity, and can process information in parallel. There are many theories as to how information is stored in the knowledge base. One of the most widely held is that information is stored in knowledge structures which have traditionally been called schemas (Bartlett, 1932), and more recently, frames (Schank and Abelson, 1977). Classically, a schema is an abstract representation containing the general properties, identifying characteristics, actions, and rules associated with a group of related concepts or events (Bartlett, 1932). Schemas are themselves organized by the meaning ascribed to them, and they constitute our understanding of the perceived events. Schemas tend to organize actions and behavior either through their direct activation based on perceptual data (skill-based action) or through their identification in the decision-making process (rule- and knowledge-based process). When the schema are properly identified and actuated, the operator can be said to understand the situation and its appropriate goals. The schema also defines the actions required to achieve the goal and initiate their execution.

A network of schemas related to skilled behavior may be referred to as the "mental model" (the operator's internal representation of the physical and functional characteristics of the system and its operation). The mental model is complex and contains a vast amount of technical information and experience. It is built up through formal education, system specific training, and operational experience. An accurate mental model is considered the defining characteristic of skilled performance in general (e.g., Wickens, 1984) and for NPP operations in particular (e.g., Moray, et al., 1986; Bainbridge, 1986; Rasmussen, 1983; Sheridan, 1976). The mental model is thought to directly drive skill-based processing, to control rule-based activity through the mediation of the operator's conscious effort in working memory, and to provide the substantive capability to reason and predict future plant states required of knowledge-based processing (Rasmussen, 1983). Moray (1986) argued that a well-developed mental model enables the operator's performance to become more "open-loop" and thus, system control to become smoother. "Open-loop" in this context means that behavior becomes less driven by feedback and more governed by the operators prediction of future system behavior and desired goal state. The mental model allows prediction and expectancy to guide control responses; however, expectancy can also make the detection of subtle system failures difficult (Wickens and Kessel, 1981). Similarly, Bainbridge (1974) stated that the operator of a NPP uses the mental model to predict the near-term future state of the plant and then uses this inference to guide sampling of indicators to confirm the inference.

Information is cognitively manipulated in working memory (WM) that has a very limited capacity relative to the knowledge base. Information in WM remains for only a brief period and is processed serially. An operator's current interpretation of a system's status, as represented in WM, may be referred to as situation awareness (SA) (Fraker, 1988). SA is the degree of correlation between the operator's understanding of the plant's condition and its actual condition at any given time. An operator can have a good mental model (e.g., knowledge of how the plant functions) but poor situation awareness (understanding of its current status). SA has also been identified as the single most important factor in improving crew effectiveness in complex systems (Endsley, 1988).

Under normal conditions, monitoring is accomplished by scanning the information presented by the HSI and comparing it to the mental model. If no discrepancies are identified, monitoring continues. The operator's SA represents the outcome of the comparison represented in WM. SA of normal conditions is the default condition if no discrepancy with the mental model is detected. For skilled operators, this comparison is relatively effortless and requires little attention. If no deviation is detected from is expected, the operator may not be aware of making the comparison.

Information processing during off-normal conditions is considerably more complex. The first step in detecting such conditions is to detect a discrepancy between the mental model of the information pattern representing normality and the information pattern detected on the HSI. In a NPP, this process is facilitated by the alarm system that directs the operator's attention to an off-normal situation.

Monitoring has been described in terms of signal detection theory (SDT) (Green and Swets, 1988). The early stages of the operator's detection of alarms and off-normal situations are basically issues of signal detection. Process control operators are in a monitoring environment that has been described in SDT terms as an alerted-monitor system (Sorkin et al., 1985 and 1988). Such a system is composed of an automated monitor and a human monitor. The automated monitor in a NPP is the alarm system that monitors the system to detect off-normal conditions. When a plant parameter exceeds the criterion of the automated monitor, the human monitor is alerted and must then detect, analyze, and interpret the signal as a false alarm or a true indication of a plant upset. The human monitor also can assess plant parameters independently of the automated monitor (the alarm system). Both the human and automated monitors 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 signalled 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 that determines the ease with which signals (represented as a statistical distribution) can be distinguished from signals and noise (also represen [illegible] distribution).

SDT research has many implications for understanding how operators process alarm system data. 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). Off-normal events in NPPs typically have a low probability of occurring, and 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. Since, in the real-world system, disturbances have a low probability, operators 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).

Information processing is typically a synthesis of both "top-down" processing (what an operator expects) and "bottom-up" processing (what an operator perceives from the environment) (Neisser, 1967). For example, during an off-normal situation, an operator monitors the HSI and processes data from the interface to determine what is wrong. This is bottom-up processing. At the same time, these data are used to formulate hypotheses or expectations about the status of the plant. These hypotheses or expectations 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. While the situation remains normal, much of the operator's information processing occurs automatically, i.e., with very little attention and conscious effort. As an off-normal situation is detected, information processing demands a great deal of attentional resources and effort. This is an important distinction which is explained below.

Once a situation is detected and perceived, the operator must decide what to do by defining a goal state and the transformations required to achieve that state. The goal state may be varied to identify the proper procedure, to assess the status of back-up systems, or to diagnose a problem (Rasmussen, 1981). Decision-making is a burden and draws heavily upon WM, the knowledge base, and attentional resources. Information is consciously manipulated in WM, and the ability to do so is a direct function of attentional resources available. Data to be manipulated may come from sensory input or information recalled from long-term memory, or some combination of the two. As indicated above, WM has very limited capacity and without sustained attentional resources (or transfer of the information to LTM), information decays rapidly. (A heuristic, as used in this report, means an aid to information processing developed through experience and trial-and-error rather than systematic, formal analysis.) Information can be lost due to (1) loss of attentional resources to keep it active, (2) overload of WM's limited capacity. (3) interference from other information in WM. If greater attentional resources are required by the operator to interact with the system, less will be available for decision-making and situation analysis in WM. To increase the capacity of WM, operators use memory heuristics, such as chunking, that enables them to organize various bits of information into higher-level meaningful units. Once this is accomplished, the higher-level units are stored in WM, not the individual elements.

For an experienced, well-trained operator, when the HSI can provide information to activate appropriate schemas in the operator's mental model, the demands on WM and attention are greatly reduced. To the extent that this is not the case, more WM and attention are required. Since the processing capacity of WM and attentional resources are limited, it will be very difficult to maintain good SA.

Attention is currently viewed as a finite limited resource that is distributed across the elements of cognition associated with perceptual mechanisms, WM, decision making, and action execution of (see Figure 2.2) which compete for this limited resource; any process that requires a high amount of attention will be executed at the expense of other processes. Attention also is generally associated with the experience of mental effort (Kahneman, 1973) and is, therefore, frequently associated with cognitive workload.

While attention tends to be conceptualized as a single resource (Kahneman, 1973), research on divided attention tasks (where operators perform more than one task at a time) suggests that this is not the case (Navon and Gopher, 1979; Wickens, 1984, 1987). Wickens (1984) proposed a multiple-resource model with attentional processing resources divided along three dimensions: (1) Processing Stage, i.e., perceptual and central processes require different resources than response processes; (2) Input Modality, i.e., visual processes require different resources from auditory processes; and (3) Information Code Type, i.e., spatial and analog mental representations require different resources from linguistic information. A secondary task competing for the same resources as the primary task will be performed less well than one requiring separate resources.

Secondary task approaches to cognitive workload assessment, for example, assume that the primary task and the secondary task draw from the same attentional resources, and that if the performance of the primary task is maintained, the secondary task is performed with the spare attentional processing capacity. The logic of the secondary task approach is simple. Assume that total capacity is equal to one and that the operator's primary task will utilize "x" amount of the total capacity. The spare capacity (1-x) is left in reserve and can be applied to the secondary task. The capacity limits of WM can be tied largely to limitations in attentional resources since it is these resources that keep information active in WM.

Research on selective attention (Moray, 1986; Wickens, 1987) suggests the following. First, two tasks competing for the same resources will be performed less well than if they required separate resources. Thus, for example, it is easier to drive a car and talk with a passenger than it is to drive and manually tune an analog radio. While both involve two simultaneous tasks, the former situation involves less competition for common processing resources than the latter. Second, the allocation of attentional resources to sampling data from the environment is guided by the operator's mental model that contains expectations regarding the statistical properties of the environment; i.e., expected probability and correlation. Third, as cognitive workload increases, capability to detect failures decreases (Ephrath and Young, 1981).

During the early stages of an off-normal condition, the operator is likely to have poor SA; i.e., the operator knows something is wrong but may not know what. The HSI is scanned to identify a pattern of alarms and displays that, as a result of training and experience, match a known failure pattern in the mental model. Assuming a successful match is found, the activated schema will provide the operator with knowledge as to the appropriate course of action, and accurate SA will be established.

Execution of the response is the carrying out of actions that guided by either operating procedures or an operator's plan to get from the current plant state to the goal state. The results of actions are monitored through feedback loops. In a slowly responding, supervisory control system, this is more difficult than in direct, rapid-response systems such as aircraft where responses can be better guided by feedback. In a NPP, as in other slowly responding systems, the operator's ability to predict future states can be more significant in controlling responses than feedback.

Action execution also draws attentional resources and depends on information code types. When the response demands are incompatible with information code types, operator performance can be impaired. A good example of this problem comes from research on telerobotics (human control of remote robotic manipulator systems). One of the most demanding aspects of telerobot operation is the simultaneous control of manipulator arms and cameras in environments, such as space, where the entire system may be operated by a single person. Efforts have been made to use advances in computer-based voice recognition to enable an operator to control cameras through voice commands rather than manually; thus, overall system performance would be improved by completing the tasks faster with fewer errors. However, research has indicated that time and errors increase when voice operations are introduced (Bejczy et al., 1982; O'Hara, 1986; Bierschwale, et al., 1989). This finding can be understood in terms of two aspects of the multiple resource theory. The first is competition for processing resources. Operators cannot make judgements about the spatial displacement of manipulator arms at the same time as they make judgements about positioning the camera. Both tasks draw on the same cognitive processing resources: perceptual/central processes of visual information requiring spatial/analog mental representations. While it is true that the response modality is different, operators perform the tasks serially. Second, the poor match between the demands of the task and the response modality increased the error rate. Voice commands are not well suited to continuous spatial control tasks. Controlling a camera by voice is like trying to tell someone how to tie their shoes - easy to do manually but difficult to do verbally. An excessive amount of language is required to accurately position cameras, making the execution workload very high. Language is much better suited to discrete rather than continuous control.

Operator tasks should be structured to take into account the cognitive processing resources required, and to assure that tasks expected to be performed in parallel have minimal competition for common resources. The HSI should support maximum use of cognitive processing resources.

2.3.1.2 Human Error Mechanisms

As discussed initially, most human errors can be explained on the basis of a relatively small number of cognitive mechanisms (Reason, 1988; Rasmussen, 1986). An identification of these mechanisms can contribute to the specification of design principles that will reduce the probability of error and make the system more error-tolerant.

While error data can be collected in studies evaluating the effects of HSI on the performance of the operating crew, it is not practical within the context of any one experiment to collect enough data to confidently estimate long-term, low-likelihood errors under the myriad of possible plant conditions. However, the cognitive prerequisites of human error can be measured to determine whether HSI design characteristics differ in error likelihood. Noteworthy in the specification of human error mechanisms has been the work of Norman, Rasmussen, and Reason, which can be interpreted within the general information processing model described above.

Norman (1981, 1983) classified errors into three categories, based upon the cognitive mechanisms involved. Description errors result from the operator's characterization of a situation at too high a level of abstraction. This occurs because it takes less mental effort than constructing a detailed characterization. At such a high level of description, the operator may not have enough detail to select the appropriate actions. Premature diagnosis of a problem is an example of this type of error. The second type is activation or trigger errors, that occur when an intention leads to the activation of a schema, but the operator does not keep track of the resulting actions, or the automated sequence is interrupted in favor of another action. Failure to restore a valve to its proper position after maintenance may be an example of this type of error. The third type is capture errors that occur when the environmental cues are similar to those associated with a well-developed schema which is inappropriately activated. Changes in equipment or procedures in the CR make an operator susceptible to this type of error, if well-learned responses in the old CR are inappropriate in the new one. Also, similarity in the display of information patterns between two plant states can lead to capture errors.

Like Norman, Rasmussen (1986) has noted that errors are a function of the cognitive control of behavior and further, that they are manifestations of the efficient human adaptation to system characteristics. Four categories of error and their importance in system design were defined. The first category is the result of random human variability. However, these are few and usually they have lower safety significance because they are single events, not correlated to other activities. The second category is errors related to inadequate processing resources; this is most important in knowledge-based processing since it is the most resource-dependent mode of processing. However, even rule-based activity requires attentional resources, and when there are insufficient resources available, errors become more likely. Therefore, this category of error is related to workload. Workload's association with error has been frequently noted in the literature (Sheridan, 1980; Wickens, 1987). The third category of error is associated with interference between internal control structures or schemas. Thus, this category is similar to the capture error described by Norman. The final category is related to human learning mechanisms that reflect the operator's adaptation to the system and, Rasmussen argues, cannot be completely eliminated. A major purpose for having operators in the system is to respond to unanticipated events through adaptation and innovation. Instead, HSI design should be made error-tolerant, i.e., the system should make errors observable so their consequences can be mitigated by operator's (or system's) intervention. The use of human error models to design interfaces that minimize certain types of errors and make the system tolerant to other types of errors was recommended by several researchers (Hollnagel et al., 1986; Thompson, 1981).

Reason (1987 and 1988) presented a fairly well-defined model of human error that, in its current version, embodies most of the main points of Norman's and Rasmussen's work. The central thesis is that error is predictable and based upon a tendency to overutilize cognitive processes that serve to simplify complex information tasks by applying previously established heuristics. Two heuristics (called computational primitives) used by operators to retrieve information from the knowledge base are assumed to exert a strong influence on human performance, and therefore, human errors. They are similarity matching and frequency gambling. Operators use these heuristics in situations of high workload that results from the demands on, and limitations of, WM and when data are insufficient to clearly identify appropriate schemas. Similarity matching reflects the tendency for WM to attempt to match a perceived information pattern (such as a pattern of indicators) with an already existing knowledge structure (schema) in the knowledge base. The operator cognitively tries to establish a link with a stored knowledge structure since it contains a previously identified successful action sequence; this saves the operator the effort of knowledge-based reasoning that is resource intensive. When the perceived information partially activates more than one schema, the discrepancy is resolved by selection of the one most frequently used in the past. This is the frequency-gambling heuristic.

According to Reason, these computational primitives cause basic error tendencies in human performance which account for most human errors: (1) similarity bias - errors reflecting the undue influence of salient features of the current situation (resulting in premature identification of the situation) or the intention/expectation of the operator (resulting in a bias to see only confirmatory data), (2) frequency bias - in ill-defined situations, the most frequently performed action will be selected, (3) bounded rationality - the processing limitations of WM cause information to be lost, (4) imperfect rationality - IP will favor heuristics over knowledge-based processing, (5) reluctant rationality - IP acts to minimize cognitive effort and strain, and (6) incomplete/incorrect knowledge - schemas rarely contain highly accurate models of the system.

Reason has developed a Generic Error Modelling System (GEMS) to account for performance errors (1987, 1988, 1990). It is not given in detail here because it is structurally similar to the WM and to knowledge-base elements of the information processing model presented earlier. Reason postulates that the search to identify and solve problems occurs in parallel with automatic matching in the knowledge base and conscious search in WM. The model varies somewhat, based upon the configuration of the problem. The NPP operator is confronted with what Reason refers to as a complex multiple-dynamic configuration, that is, a situation where the configuration changes as a result of the operator's actions and the system's own actions. This interaction creates a great deal of variability in overall plant behavior. This is the most difficult problem-solving situation and the one in which the IP system is most likely to rely on heuristics. In a situation like a NPP emergency, a typical problem-solving sequence assumes the following structure: (1) initial scanning is started by signals from the alarm system, and the operator's attention is divided among a variety of data-gathering activities, (2) the operator focusses in on a specific group of indicators and makes an initial diagnosis, (3) the operator now structures attentional resources to seek data confirming the hypothesis, and (4) the operator becomes fixated on the hypothesis and can fail to notice changes in the plant's state or new developments. The operator eventually may become aware of subsequent changes, but the process is hampered by focal attention being directed toward the current hypothesis and the overall processing limitations of WM.

The model provided by Reason accounts for many of the error tendencies identified by other researchers, such as cognitive tunnel vision (Sheridan, 1980), operator failure to effectively use information about what has not failed (Rouse, 1980), description errors (Norman, 1988), capture errors (Norman), activation (Norman)/interference (Rasmussen) errors, and inadequate processing-resources errors (Rasmussen and Wickens).

In summary, human errors are not typically random but are the result of basic characteristics and limitations of the human information processing system. Aspects of IP that were identified as especially significant are bidirectional information processing, attention, WM limitations, SA, and cognitive workload. Many errors reflect the system's response to high information/high complexity situations that result in high demands on attentional resources and WM. The IP system attempts to handle these high workload situations through the application of heuristics, such as those described by Norman, Rasmussen, and Reason, which reduce overall load on the IP system but can also lead to error. The HSI should help prevent heuristic-initiated errors which often reflect incomplete processing and tunnel vision. For example, operator decision-support aids that indicate when (1) unexpected events (based upon the current pattern) occur, and (2) expected events (based upon the current pattern) do not occur, would call the operator's attention to plant conditions which are likely to be missed due to the information processing bias toward capture errors.

2.3.2 Design-Related Factors Impacting Performance

In Section 2.3.1, it was stated that knowledge about the effects of advanced technology on human performance was limited. While this is the case, many issues have been identified in the literature. In this section, these issues are considered with respect to the model of human cognitive processes and error discussed above:

- Automation and Allocation of Function
- System Complexity and Operator Skills
- Display Design
- Data Management System (DMS) Design and Data Access
- Workstation Flexibility and Interface Management

Automation and Allocation of Function

A major trend in ACR design is to increase automation of those tasks traditionally performed by the operator. Increases in automation shift the operator's function from that of a direct manual controller to a supervisory controller and system monitor, largely removed from direct control. This type of role change is typically viewed as positive from a reliability standpoint, because the human operator is considered one of the more unpredictable components in the system. The operator's performance in the system is believed to be improved by freedom from tasks that are routine, tedious, physically demanding, or difficult. Thus, the operator can better concentrate on supervising the overall performance and safety of the system.

However, functions often are allocated to automated systems largely on the capability of the technology to reliably and safely execute the function. This allocation strategy does not consider whether a function should be automated with respect to the human operator's ability to perform as part of the overall plant, even though the human-factors problems associated with automation have been known for some time (Edwards, 1977) and new types of human and system errors have emerged (Wiener and Curry, 1980; Wiener, 1988). Wiener grouped these problems into six categories: (1) failures of automatic equipment, such as autopilot; (2) automation-induced errors compounded by crew's error, such as an error following the crew's attempt to recover from the failure of an automated system; (3) crew's error in setting up automated systems, such as keying in the wrong information/data, (4) action taken by the crew in response to a false alarm, (5) failure of the crew to pay attention to an automatic alarm, and (6) failure to properly monitor the automated system (Wiener and Curry, 1980). In civil aviation, Sexton (1988) observed that if "...decisions are automatically made without providing the rationale to the pilot, the ability to stay ahead of the aircraft is lost. Complacency and inability to take timely and proper action result." In general, increases in automation have been associated with loss of vigilance by the operator and a corresponding increase in human errors (Warm and Parasuraman, 1987). Similar concerns have been raised in the nuclear industry (IAEA, 1991).

The problems with operator intervention in an automated system have been associated with poor SA (Kibble, 1988). Maintaining SA is difficult when the operator is largely removed from the control loop; i.e., shifting the operator's role from an active, in-the-loop, manual controller to an out-of-the-loop supervisor and monitor (Wickens and Kessell, 1981; Ephrath and Young, 1981).

The shift in roles has other significant effects on the operator, such as a shift from high physical to high cognitive workload (rather than the expected reduction in overall workload), workload transition effects when the situation shifts from normal to off-normal (i.e., going from low activity monitoring to a highly active, more uncertain time at the beginning of a process disturbance), and the potential erosion of the skills needed to perform the task if the automated system fails. Since many advanced NPP designs still require the operator to assume control if there is a severe transient and to act as one line of defense, the consequences of poor integration of the operator in the plant design can be serious.

Generally, allocation of system functions should not be based on technological capability alone but also on maintaining the degree of operator involvement in the functions required to support accurate SA. Toward this end, it has been frequently argued that allocation of function need not be simply a choice between operator and automated system. Rather, there are functions where a combination of human and system task allocation best serve the overall productivity and safety of the system (Price et al., 1985).

System Complexity and Operator Skills

There is a somewhat paradoxical relationship between the skills an operator requires to successfully understand and supervise complex, technologically-advanced systems, and the day-to-day monitoring tasks they are required to perform in a highly-automated plant. Monitoring is typically considered very boring and not something people do particularly well (e.g., vigilance is difficult to maintain). Yet the skills required of operators to evaluate the performance of advanced systems, to know their limitations, and to assume manual control when necessary requires very capable individuals and extensive training. Operators still will be required to understand reactor physics and the functioning of system hardware. The advanced reactor goal of simplifying the plant and system may help. However, as plants become more automated and increasingly utilize intelligent systems, operators will be required to understand the complex software routines (to be an effective supervisory controller). The selection of operators and development of training programs will have to reflect these demands. Yet, there is a risk that the carefully selected, highly trained operators may be required to perform a boring, monotonous job.

Display Design

Human performance and reliability are especially influenced by the design of the human-computer interface and, in particular, the information displays. For computer-based interfaces, "...even slight changes in both the nature of the information available and the manner in which it is represented might have serious effects on performance" (Patrick, 1987). Therefore, computer-based HSI design requires the specification of cognitive requirements and processing resources that the operator must use in performing tasks; i.e., cognitive task analysis. The variety of ways that data/information can be processed and displayed is vast. Information may be presented in processed form; i.e., raw data parameters are processed and integrated into a higher level of information, thus potentially obscuring their meaning. Poorly designed displays will be ignored or, worse, will mislead and/or confuse the operator. Thus, the design of the interfaces can have very significant effects on human performance. These types of problems have been observed in reviews of SPDS interfaces (Liner and DeBor, 1987); in some cases, poor information displays have led to poor operator acceptance.

Data Management System Design and Data Access

The operator in an ACR typically has much more information available in real time than in a conventional CR. Yet, not all data is significant to all situations, and identifying the relevant information can be very difficult (Woods, 1986, 1991). Establishing context sensitivity to assist operators is a critical aspect to data display in data-rich systems (Woods, 1984; Lupton et al., 1991). If the data are not properly organized and presented, this can pose an excessively high cognitive workload, or worse, it can be overwhelming. Information in an ACR will typically be resident in a computer system, rather than in dedicated spatial locations spread out across control stations. The operator has only a glimpse of its contents through a display device at any one time. This is sometimes referred to as the keyhole effect (Woods et al., 1990). A poorly designed interface can make it difficult to locate and navigate through data.

Workstation Flexibility and Interface Management

The flexibility of software-driven interfaces often allows information to be displayed in a variety of formats and locations. Sometimes this flexibility is a positive feature, allowing operators to customize the interface. However, it can also increase the workload in managing the interface, which competes with the operator's primary task of monitoring and supervising the system for cognitive processing resources. The interface management workload should be minimized in ACRs. Cook, Woods, and Howie (1990) found that operators of a computer-based information system in a surgical operating room often used the flexibility of an interface to "convert the device to a static, spatially dedicated display."

Summary

While advanced technology may have the potential to improve operator's performance, the literature indicates that numerous problems have been observed in advanced systems associated with failure to properly integrate operators into the system and to provide interfaces that support performance. The major issues include:

- Increase in the cognitive workload associated with information management
- Inability to use the type of well-learned scanning patterns associated with analog displays
- Difficulty understanding how a complex system works (poor mental model)
- Confusion over the meaning of high-level displays
- Loss of vigilance and boredom from prolonged monitoring
- Loss of situation awareness in supervisory control situations
- Workload transition when automated systems fail
- Loss of skill proficiency
- Emergence of heuristics and error mechanisms to cope with an overloaded system
- Increase in the secondary tasks associated with managing the HSI due to workstation flexibility
- Navigation difficulties

2.3.3 Implications for Design Support of Crew Performance

The literature on the cognitive factors underlying crew errors and their contributing factors has implications for the design of systems. Hollnagel (1992) identified several general system-design goals to support human performance in complex systems:

- Prevent overload of the human IP system;

- Improve operational support by using design features, such as expert systems, to present intelligent information, to manage dialogues, and for diagnosis;

- Design and allocate tasks so humans perform ones they are well suited for and not those for which they are not suited; and

- Make systems fault tolerant by:

  - providing automatic counteractions,
  - limiting the consequences of errors through design interlocks and automatic shutdown mechanisms,
  - providing for early error detection by improving feedback and lengthened recovery periods, and
  - providing multiple avenues for corrective action.

Reason (1990) offers a set of similar design principles for "minimizing error affordances" that include:

- Insuring consistency between the designer's model of the system and that of the user,

- Simplifying task structures to minimize cognitive demands,

- Making available to the user information on the options and consequences of actions,

- Anticipating that errors will occur and designing methods to allow for recovery, and

- Employing standardization.

Reason (1990) and others have argued that an ecological approach is important to developing interface designs that support crew's performance. Flach (1990) stated that "...there appears to be a convergence of opinions that an ecological approach is most appropriate for the problems of human-machine systems." 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; thus, knowledge of the context within which behavior occurs is essential to understanding human performance. Gibson called this the ecological approach to behavioral analysis (1979), and his concepts have been influential in the understanding of human error and the research of Reason, Rasmussen, and Norman.

Two aspects of Gibson's approach to perception are important in designing human factors and system interfaces: the concepts of "affordances," and of "direct perception" (Flach, 1989). 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. The concept of direct perception within the context of HSI design pertains to the information provided in a display that is immediately "understood." This is an extension of what Gibson meant by direct perception which refers to physical features of the perceptual environment.

The basis for using ecological perception theory as an approach to interface design was described in several papers (e.g., Flach, 1990; Vincente and Rasmussen, 1990, 1992). According to Vincente and Rasmussen (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). 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" (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 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" (p. 598). This principle is supported by showing contextual information in a display, such as 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 (Vincente, 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" (p. 599). This principle is supported by providing information in layers and in familiar representations (such as displaying functional relationships and parameter information in the form of piping and instrumentation-type displays (P&IDs)) (see Kieras 1992, for an example of the characteristics of diagrammatic displays that support performance).

With respect to NRC design reviews, this research emphasizes the importance of evaluating the interface in terms of the joint interaction between the task's domain and the IP characteristics of the operating crew.

2.4 Advanced HSI Guideline-Based Reviews

Woods (et al., 1992) observed that the value of guidelines "...lies in the degree to which the guidance can be said to constitute a useful synthesis of the state of knowledge in the field, and in the degree to which it assists in detecting and correcting flaws in the design of human-machine systems." Two important aspects of guidelines are reflected in this statement: their technical basis and their usefulness in the performance of HSI reviews.

In general, there are several reasons for using HFE guidelines in safety reviews:

1. HFE guidelines help assure that the design accommodates general human physiological and cognitive capabilities (assuming the guidance accurately synthesizes existing knowledge, Woods et al., 1992).

2. HFE guidelines generally represent knowledge concerning HSI characteristics that support operating crew tasks, derived from a large array of systems developed over many years. HFE guidelines capture years of lessons learned from system design and research.

3. HFE guideline reviews highlight design characteristics than can detract from human performance. When the review addresses a designer's preliminary design specification or prototype, these characteristics can be addressed in a timely fashion well before the design becomes fixed and difficult to change.

4. HFE guideline reviews provide an evaluation which may be applicable to all uses of an HSI, as contrasted with integrated system validation which will generally be more limited due to the time and effort required to conduct crew-in-the-loop tests.

5. HFE guideline reviews can benefit from a comparison to HSIs in other systems standardized to the same set of design principles.

While HFE guideline reviews provide valuable data to support safety determinations, this type of evaluation has its limitations (Karat, 1989; Potter et al., 1990; Reaux and Williges, 1988; Smith, 1988, Woods et al., 1990; Woods et al., 1992). It is essential that the strengths and weaknesses of HFE guideline reviews be understood. Some of the general limitations of guidance-based safety reviews are:

1. An HFE guideline review is a necessary, but not sufficient, basis to determine if the crew can monitor and operate the HSI to adequately perform system functions.

2. HFE guidelines are not sensitive to the time required to perform a task.

3. Because establishing a validated set of guidelines requires professional consensus from research and industry, HFE guidelines always will be incomplete in scope and in their coverage of advanced technology (where research and lessons learned from practical applications are too limited to fully address all technological applications).

4. HFE guidelines are generally insensitive to the interactive effects of multiple guidelines or their tradeoffs, e.g., between requirements for consistency and flexibility.

When guidelines are used to review advanced HSIs, the following considerations must be included:

- The technical basis for advanced-technology guidelines,
- The degree of abstraction of advanced-technology guidelines,
- The dependency on thorough task descriptions for using review guidelines, and
- The new challenges to reviewers posed by advanced HSI reviews.

HFE guidelines for "conventional" technology, such as NUREG-0700, are primarily concerned with human interfaces for the hardware characteristic of conventional CRs. The development of guidelines to review advanced and primarily computer-based, HSIs is not a straightforward extension of those earlier guidelines. Further, the technical basis and knowledge needed for developing review guidance is different for advanced technology applications. The design of conventional CRs was based upon decades-old technology. When NUREG-0700 was developed, the human factors guidance (such as MIL-STD-1472B) was long-standing, tested through many years of design experience. By contrast, ACRs are based upon relatively new and rapidly changing technology. Consequently, the guidelines available for advanced technology have a weaker technical basis and have not been validated through many years of design application that provides valuable lessons learned. Thus, they are less firm and typically stated with less definitive criteria.

The contrasts between guidelines for human-software interfaces when compared with human-hardware interfaces were elaborated by Smith (1988). Hardware guidelines are generally based upon human physiology, e.g., visual acuity, reach envelopes, while software guidelines are generally based on cognition and information processing. Hardware design is limited by technology while software design is mainly limited by human understanding of the tasks to be performed; thus, a thorough knowledge of the task design is needed to apply these guidelines. Further, the cognitive task requirements are less familiar to designers and reviewers (Karat, 1989; Woods et al., 1990). Since this information is seldom known before a review of a specific system, human-software guidelines tend to be stated in more general-abstract terms relative to human-hardware guidelines which are relatively clear and specific. It was found that designers use abstractly worded guidelines less (Mosier and Smith, 1985) and that a good system cannot be designed by guidelines alone (Gould, 1988).

The same guideline characteristics that present problems for designers can make the reviewers' job more difficult. Reaux and Williges (1988) compared reviewers' ability to detect guideline violations in a computer-display prototype as a function of their wording - concrete vs. abstract. Almost twice as many violations in concrete guidelines were detected compared with abstract guidelines. Further, reviewers were less confident in their evaluations using abstract guidelines. Potter et al., 1990, reached a similar conclusion in evaluating a computer-based system using only abstract guidelines. Thus, ACR evaluations need to be broader than an evaluation based solely on guidelines.

Software-based HSI designs are generally very flexible in terms of what and how information is presented, while hardware is much less flexible. Finally, and perhaps most significant to the review of human-software interface, is that the most important design features are often hidden (to the reviewer, transparent to the operator), while important hardware design features are usually readily observable. In a conventional CR, the design of the HSI is readily apparent from the physical layout of the controls and displays. In an ACR, the physical layout of the video display units (VDUs) and computer input devices is significantly less important than the design of the human-software interface; i.e., the information management system and the methods by which information is displayed to the operator. This information can be displayed in a complex network of hundreds, or even thousands, of computer displays and flexible, operator-defined display formats. This difference in focus creates a whole new set of problems in data access and navigation for the crew (O'Hara and Hall, 1990; Woods et al., 1990) and for the reviewer. In addition, the computer display may be an end product of integration and processing of data into higher-level displays (in contrast to the single sensor/single display characteristic of conventional CRs).

Thus, the review of ACRs based largely on human-software interfaces is more complex and difficult than the review of hardware interfaces.

3. HFE PROGRAM REVIEW MODEL

3.1 Considerations for the Review of Advanced HSIs

Consideration of the HFE and advanced reactor issues discussed in Section 2 led to the identification of the following issues regarding the safety review of HFE aspects of advanced HSI designs.

1. The HSI evaluation methodology should have broad application to review upgrades to existing plants, as well as new HSI design concepts.

2. The methodology should encompass the review of a broad range of CR "designs" and the diversity of approaches to advanced HSI technology. The DRG should focus heavily on the human-software interface because this is where the most significant human performance issues reside, and where NRC review guidance is most deficient.

3. The methodology should provide guidance for conducting reviews throughout the design life cycle, i.e., proposed/conceptual design to final design. This is because:

   - Advanced reactor design certification reviews may be based on ACRs described only at conceptual levels of detail,

   - Many significant human factors issues arise early in design, e.g., initial goals/objectives of the design and allocation of function.

4. Reviews of the final HSIs should extend beyond checklist-based, HFE guideline evaluations. Reviews should include validations of the fully-integrated system under realistic, dynamic conditions using experienced operators who perform the types of tasks for which the HSI was designed (including various types of failures and transient conditions). The reasons for this include:

   - Studies have shown that a comparison of a final design against HFE guidelines alone is not sufficient to ensure a safe, acceptable design (e.g., Potter et al., 1990).

   - The state of knowledge about the effects of advanced technology on human performance, especially under abnormal plant conditions, is limited; correspondingly, the technical basis for developing complete, comprehensive, and valid guidelines is limited.

5. HFE review guidelines cannot be used in the abstract, i.e., a thorough knowledge of crew tasks is required to properly interpret them.

6. Reviews of advanced HSIs place great burdens on the judgement of the reviewers and their ability to adapt and interpret the guidelines in the context of a particular review. Thus, HSI reviews of advanced systems will have to be performed by experienced human factors evaluators. The reasons for this include:

   - Violations of human-software guidelines are more difficult to detect than violations of hardware guidelines (e.g., Reaux and Williges, 1988).

- Human factors guidelines for advanced HSI technology are more general and abstract than those for conventional technology.

- Since the guidelines need to support reviews of diverse reactor designs and operators tasks, it cannot be prescriptive.

These issues led to the conclusion that reviews of advanced HSI would be broader than those traditionally conducted by the NRC, and that a broad review model will be required to achieve a safety finding for advanced HSIs. The HFE PRM was developed to serve as a framework for conducting advanced HSI reviews. The remainder of this section provides a brief overview of the HFE PRM's rationale, development, and contents. The reader is referred to the HFE PRM for a more detailed discussion (O'Hara, Higgins, and Stubler, 1994).

3.2 HFE PRM Overview

3.2.1 HFE PRM Rationale

The design review approach of the HFE PRM is analogous to the defense in depth approach. When reviewing a design in order to make a safety evaluation, evidence is collected and weighted toward or against an acceptable finding. The reviewer would like to collect as much information as possible from different sources in order to establish "convergent validity" (Campbell and Fisk, 1959); i.e., to establish a consistent finding across different types of information each with its own sources of bias and error.

Reviews of the types of information that can provide assessments of HSI adequacy include:

- HFE planning (including an HFE design team, program plans and procedures),

- Design analyses and studies (including functional requirements analysis and allocation, task analysis, technology assessments, trade-off studies, etc.),

- Design specifications and descriptions, and

- Verification and validation (V&V) analyses of the final design (e.g., compliance with accepted HFE guidelines and operation of the integrated system with operators performing the required tasks under actual (or simulated) conditions).

These types of information all have their strengths and weaknesses. A reviewer can place the greatest confidence in a finding that a design is acceptable (and assures plant safety) if the design has all of the following characteristics: (1) it was developed by a qualified HFE design team including all the skills required using an acceptable HFE program plan; (2) it resulted from appropriate HFE studies and analyses which provide accurate and complete inputs to the design process and inputs to V&V assessment criteria; (3) it was designed using proven technology based upon human performance and task requirements incorporating accepted HFE standards and guidelines; and (4) it evaluated with a thorough V&V test program.

3.2.2 HFE PRM Development

Since it was concluded that reviews should be based, in part, on the design process, it was important to identify which aspects of the process was required to assure that HFE design goals in support of safe plant operation were achieved and to identify the review criteria by which each element could be assessed. The HFE PRM was developed to address this need. The specific objectives of the HFE PRM development effort were:

1. To develop a *technical basis* for the review of an applicant's HFE design process and final design implementation. The HFE PRM should be: (1) based upon currently accepted HFE practices, (2) well-defined, and (3) based on an approach which has been validated through its application to the development of complex, high-reliability systems.

2. To identify the HFE *elements* in a plant/system development, design, and evaluation process that are necessary and sufficient requisites to successful integration of the human in complex systems.

3. To identify the *components* of each HFE element that are key to a safety evaluation.

4. To specify the *review criteria* by which HFE elements can be evaluated.

A review of current HFE guidance and practices was conducted to identify important human factors program plan elements relevant to the technical basis of a design process review. Several types of documents were evaluated:

- Systems theory and engineering - general literature providing the theoretical basis for systems engineering, e.g. Gagne and Melton, 1988.

- NPP regulation - the regulatory basis for NPP review and related NRC literature, e.g., 10CFR50, 10CFR52, NUREG-0800, and NUREG-0700 - Appendix B.

- General HFE guidance - HFE guidance developed to be generally applicable to the design and evaluation of complex systems, e.g., Military handbook (MIL-H) 46855 (DoD, 1979).

- NPP HFE guidance - standards, guidance, and recommended practices developed in the NPP industry, e.g., The Institute of Electrical and Electronics Engineers (IEEE) STD 1023-1988 (IEEE, 1988), International Electrotechnical Commission (IEC) 964 (IEC, 1989), and EPRI Advanced Light Water Reactor Requirements (ALWR) Utility Requirements Document (EPRI, 1990).

From this review an HSI development, design, and evaluation process was defined. Then key HFE elements were identified and general criteria were developed by which these elements could be assessed. The general criteria were based upon a review of current literature and accepted practices in the field of human factors engineering. The HFE PRM development was based largely on applied general systems theory (Bailey, 1982; DeGreen, 1970; Gagne, et al., 1988; Van Cott and Kinkade, 1972; Woodson, 1981) and the DoD system development process which is rooted in systems theory (DoD, 1979; DoD, 1990a,b; Kockler et al., 1990).

Applied general systems theory provides a broad approach to system design which is based on a series of clearly defined developmental steps, each with defined goals, and with specific management processes to attain them. System 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). DoD design requirements reflect approach. Personnel are identified as a specific component of the total system (DoD, 1990a) and all system components (hardware, software, personnel, support, procedures, and training) are given detailed consideration in the design process. Since the military has been applying HFE longer than industrial/commercial system developers, the process is more formalized and contains detailed design process requirements.

Within the DoD system, the development of a complex system begins with the mission or purpose of the system, and the capability requirements needed to satisfy mission objectives. The effective integration of HFE considerations into the design is accomplished by: (1) providing a structured top-down approach to system development which is iterative, integrative, interdisciplinary and requirements driven, and (2) providing a management structure which details the HFE considerations in each step of the overall process. A structured top-down approach to NPP HFE is consistent with the approach to new CR design described in Appendix B of NUREG-0700 (U.S. NRC, 1981b) and the more recent nuclear industry standards (IEC, 1989; IEEE, 1988) for advanced CR design. The approach is also consistent with the recognition in the nuclear industry that human factors issues and problems emerge throughout the NPP design and evaluation process and, therefore, human factors issues are best addressed with a comprehensive top-down program (for example, see Beattie and Malcolm, 1991; Stubler, Roth, and Mumaw, 1991).

The applied general systems theory was expanded to develop an HFE PRM to be used for the ACR design and implementation process review by the incorporation of applicable NRC HFE requirements.

3.2.3 General Description

The HFE PRM is composed of 10 review elements:

- Element 1 - HFE Program Management
- Element 2 - Operating Experience Review
- Element 3 - Functional Requirements Analysis and Allocation
- Element 4 - Task Analysis
- Element 5 - Staffing
- Element 6 - Human Reliability Analysis
- Element 7 - Human-System Interface Design
- Element 8 - Procedure Development
- Element 9 - Training Program Development
- Element 10 - Human Factors Verification and Validation

This section summarizes the general purpose and objectives of the HFE PRM elements (see O'Hara et al., 1994 for a complete description and review criteria).

Element 1 - HFE Program Management

The overall purpose of the human factors engineering program review is to assure that:

- The applicant has integrated HFE into plant development and design.
- The applicant has provided HSIs which make possible safe, efficient, and reliable performance of operation, maintenance, test, inspection, and surveillance tasks.
- The HSI reflects "state-of-the-art human factors principles" [10 CFR 50.34(f)(2)(iii)) as required by 10 CFR 52.47(a)(1)(ii)] and satisfies all specific regulatory requirements as stated in 10 CFR.

State-of-the-art human factors principles are defined as those principles currently accepted by human factors practitioners. "Current" is defined with reference to the time at which a program management or implementation plan is prepared. "Accepted" is defined as a practice, method, or guide which is (1) documented in the human factors literature within a standard or guidance document that has undergone a peer-review process or (2) justified through scientific research and/or industry practices.

To accomplish these programmatic objectives, an adequate HFE program plan is required which is carried out by a qualified HFE design team. The objective of this review is to ensure that the applicant has an HFE design team with the responsibility, authority, placement within the organization, and composition to ensure that the design commitment to HFE is achieved. Also, the team should be guided by an HFE Program Plan to assure the proper development, execution, oversight, and documentation of the HFE program. This plan should describe the technical program elements assuring that all aspects of HSI are developed, designed, and evaluated based upon a structured top-down systems analysis using accepted HFE principles. Element 1 review topics include:

- General HFE Program Goals and Scope,
- HFE Team and Organization,
- HFE Process and Procedures,
- HFE Issues Tracking, and
- Technical Program.

Element 2 - Operating Experience Review

The main purpose of the operating experience review (OER) is to identify HFE-related safety issues. The OER provides information regarding the performance of fully-integrated predecessor systems. This approach is analogous to full-mission validation tests, which provide information about the achievement of HFE design goals in support of safe plant operation for the integrated system under review. The issues and lessons learned from previous operating experience provide a basis for improving the plant design in a timely way; i.e., at the beginning of the design process.

The objective of this review is to assure that the applicant has identified and analyzed/HFE-related problems and issues encountered in previous designs that are similar to the current design under review. In this way, negative features associated with predecessor designs may be avoided in the current design while positive features are retained. The OER should address the predecessor systems upon which the design is based, selected technological approaches (e.g., if touch screen interfaces are planned, HFE issues associated with their use should be reviewed) , and NPP HFE issues (e.g., those identified in unresolved safety issues, generic safety issues, TMI Issues, and NRC Generic Letters and Information Notices).

Element 3 - Functional Requirements Analysis and Allocation

This element involves two distinct review activities: functional requirements analysis and function allocation. Functional requirements analysis is the identification of those functions which must be performed to satisfy plant safety objectives, i.e., to prevent or mitigate the consequences of postulated accidents that could cause undue risk to the health and safety of the public. A functional requirements analysis is conducted to: (1) determine the objectives, performance requirements, and constraints of the design; (2) define the functions which must be accomplished to meet the objectives and required performance, (3) define the relationships between functions and plant processes (e.g., plant configurations or success paths) responsible for performing the function, and (4) provide a framework for understanding the role of controllers (whether personnel or system) for controlling plant processes.

Function allocation is the analysis of the requirements for plant control and the assignment of control functions to (1) personnel (e.g., manual control), (2) system elements (e.g., automatic control and passive, self-controlling phenomena), and (3) combinations of personnel and system elements (e.g., shared control and automatic systems with manual backup). Function allocation seeks to enhance overall plant safety and reliability by exploiting the strengths of personnel and system elements including improvements that can be achieved through the assignment of control to these elements with overlapping and redundant responsibilities. Function allocation should be based upon HFE principles using a structured and well-documented methodology that seeks to provide personnel with logical, coherent, and meaningful tasks.

The objective of this review is to assure that the applicant has defined the plant's safety function requirements and that the function allocations take advantage of human strengths and avoid allocating functions which would be negatively impacted by human limitations.

Element 4 - Task Analysis

Plant personnel perform tasks to accomplish their functional responsibilities. 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 since it defines the HSI requirements for supporting personnel task accomplishment and, by exclusion, what is not needed in the HSI.

The objective of the review is to assure that the applicant's task analysis identifies the behavioral requirements of the tasks that the personnel subsystem is required to perform. The task analysis should:

- Provide one of the bases for making design decisions; e.g., determining before hardware fabrication, to the extent practicable, whether system performance requirements can be met by combinations of anticipated equipment, software, and personnel,
- Assure that human performance requirements do not exceed human capabilities,
- Be used as basic input for developing procedures,

- Be used as basic information for developing staffing, training, and communication requirements of the plant, and

- Form the basis for specifying the requirements for the displays, data processing and controls needed to carry out tasks.

Element 5 - Staffing

Plant staffing is an important consideration throughout the design process. Initial staffing levels may be established as design goals early in the design process based on experience with previous plants, customer requirements, initial analyses, and government regulations. However, staffing goals and assumptions should be examined for acceptability as the design of the plant proceeds.

The objective of the staffing review is to ensure that the applicant has analyzed the requirements for the number and qualifications of personnel in a systematic manner that includes a thorough understanding of task requirements and applicable regulatory requirements.

Element 6 - Human Reliability Analysis

Human Reliability Analysis (HRA) seeks to evaluate the potential for and mechanisms of human error that may affect plant safety. Thus, it is an essential element in the achievement of the HFE design goal of providing operator interfaces that will minimize operator error and will provide for error detection and recovery capability. HRA has quantitative and qualitative aspects, both of which are useful for HFE purposes. HRA should be conducted as an integrated activity in support of both HFE/HSI design activities and probabilistic risk assessment (PRA) activities. The PRA/HRA should be initially performed early in the design process to provide design insights and guidance both for systems design and for HFE purposes. The quality of the HRA depends in large part on the analyst's understanding of personnel tasks, the information related to those tasks, and the factors which influence human performance of those tasks. As a result, the HRA could be performed iteratively as the design progresses.

The development of information to facilitate the understanding of causes and modes of human error is an important human factors activity. The HRA analyses should make use of descriptions and analyses of operator functions and tasks as well as the operational characteristics of HSI components. HRA can provide valuable insight into desirable characteristics of the HSI design. Consequently the HFE HSI design effort should provide special attention to those plant scenarios, critical human actions, and HSI components that have been identified by HRA/PRA analyses as being critical to plant safety and reliability.

The objectives of the HRA review are to assure that:

- The applicant has analyzed the potential effects of human error on plant safety and reliability in a manner that is consistent with current, accepted principles and practices of HFE and HRA/PRA and has identified human actions that are important to plant risk.

- The applicant has addressed human error mechanisms in the design of the plant HFE, i.e., the HSIs, procedures, shift staffing, and training in order to minimize the likelihood of personnel error and to provide for error detection and recovery capability.

- The HRA activity effectively integrates the HFE program activities and PRA/risk analysis activities.

Element 7 - Human-System Interface Design

The selection of available HSIs and the design of new HSIs should be the result of a process which considers function/task requirements, operational considerations (e.g., the full-mission context within which the HSI will be used), and the crew's personal safety. The HSI should be designed using a structured methodology. The methodology should guide designers in the identification of what information and controls are required, the identification and selection of candidate HSI approaches, and final design of HSIs. It should address the development and use of HFE guidelines and standards that are specific to the HSI design and provide guidance for resolving differences between different HFE guidelines. It should also address the use of analysis and evaluation methodologies for dealing with design issues. The availability of an HSI design methodology will help ensure standardization and consistency in the application of HFE principles.

The objective of this review is to evaluate the process by which HSI design requirements are developed and HSI designs are selected and refined. The review should assure that the applicant has appropriately translated function and task requirements to the alarms, displays, controls, and aids that are available to the crew. The applicant should have systematically applied HFE principles and criteria (along with all other function/system/task design requirements) to the identification of HSI requirements, the selection and design of HSIs, and the resolution of HFE/HSI design problems and issues. The process and the rationale for the HSI design (including the results of trade-off studies, other types of analyses/evaluations, and the rationale for selection of design/evaluation tools) should be documented for review.

Element 8 - Procedure Development

While in the nuclear industry, procedure development has historically been considered the responsibility of individual utilities, the rationale for including a procedure development element in the HFE PRM is that procedures are considered an essential component of the HSI design and should be a derivative of the same design process and analyses as the other components of the HSI (e.g., displays, controls, operator aids) and subject to the same evaluation processes. In the current fleet of plants, technically detailed, human-factored emergency operating procedures (EOPs) were an improvement after the accident at Three Mile Island (TMI) to support safe operations. After TMI the NPP owners groups developed generic technical guidance (GTG) and then utilities produced emergency procedures based on the GTGs. Thus, procedure development programs were conducted by the individual utilities and have not been part of HSI design activities. However, since procedures were developed after the plant HSI (e.g., control room) design, they were essentially upgraded to suit the existing interface. Further, since procedures were developed by individual utilities, there was great variation in their development and final implementation. As a result, human factors problems existed and identification, access, interpretation, and validation of procedures remained a problem for years in some plants (as indicated by the NRC emergency operating procedure (EOP) inspection series) (Lapinsky, 1989; Galletti and Sutthoff, 1992). In addition, inconsistencies between procedures and the HSI have been a source of difficulty for operators.

For new plant designs and advanced reactors, these problems should clearly be addressed and solved as part of the design process. To accomplish this objective, EPGs and, if possible, procedures should be developed as part of the same design process as the other components of the HSI to assure their full integration as part of the HSI. The same human factors analyses, such as task analysis, should be used to guide procedure as well as control panel development. The same human factors principles should be applied to both aspects of the interface to assure complete integration and consistency. Further, procedures should be evaluated in conjunction with the HSI; i.e., procedures are a significant aspect of system verification and validation (Element 10).

The objective of this review is to assure that the applicant's procedure development program will result in procedures that support and guide human interaction with plant systems and control plant-related events and activities. Human engineering principles and criteria should be applied along with all other design requirements to develop procedures that are technically accurate, comprehensive, explicit, and easy to utilize.

Element 9 - Training Program Development

Training of plant personnel is an important factor in assuring safe and reliable operation of NPPs. Advanced nuclear power plants may pose demands on the knowledge, skills, and abilities of operational personnel that are different than those posed by traditional plants. These demands stem from differences in operator responsibilities resulting from advanced plant design features (e.g., passive systems and increased automation) and differences in operator task characteristics due to advances in HSI technologies.

A systems approach to the training, as defined in 10 CFR 55.4, is required of plant personnel by 10 CFR 52.78 and 50.120. Training design is to be based on the systematic analysis of job and task requirements. The HFE analyses associated with HSI design process provides a valuable understanding of the task requirements of operations personnel. Therefore, the training development should be coordinated with the other elements of the HFE design process.

The objective of this review is to assure that the applicant establishes an approach for the development of personnel training that incorporates the elements of a systems approach to training, and:

- Evaluates the knowledge and skill requirements of personnel.
- Coordinates training program development with the other elements of the HFE design process.
- Implements the training in an effective manner that is consistent with human factors principles and practices.

Element 10 - Human Factors Verification and Validation

Verification and validation (V&V) evaluations seek to comprehensively determine that the design conforms to HFE design principles and that it enables plant personnel to successfully perform their tasks to achieve plant safety and other operational goals.

This review involves five V&V evaluations, the objectives of which are to assure that:

- The HFE/HSI design provides all necessary alarms, displays, and controls to support plant personnel tasks (HSI Task Support Verification),

- The HFE/HSI design conforms to HFE principles, guidelines and standards (HFE Design Verification),

- The final HFE/HSI design including procedures can be effectively operated by personnel within all performance requirements (Integrated System Validation).

- The HFE/HSI design resolves all identified HFE issues in the tracking system (Human Factors Issue Resolution Verification).

- The final product "as built" conforms to the verified and validated design that resulted from the HFE design process (Final Plant HFE/HSI Design Verification).

3.3 Relationship Between the HFE PRM and the DRG

The general application of the DRG to NRC HSI reviews is discussed in Section 4.1, DRG Application and Technical Scope. The purpose of the following section is to describe the specific relationship of the DRG to the HFE PRM. HSI reviews that require the DRG are mainly associated with three HFE PRM elements:

- Element 7 - Human-System Interface Design,
- Element 8 - Procedure Development, and
- Element 10 - Human Factors Verification and Validation.

Element 7 - Human-System Interface Design addresses the selection of available HSIs and the design of new HSIs using a structured methodology. One aspect of the methodology involves the vendor/designer's development and use of HFE guidelines and standards to help ensure standardization and consistency in the application of HFE principles. The DRG provides the criteria for performing a review of such a document. The procedures for the use of the DRG for performing HFE Design Verification are presented in Volume 2, Section 4 of this report. In addition, the NRC may perform preliminary reviews of HSI design prototypes and mockups of design concepts. The DRG can be used to support this type of review using HFE Design Verification methodology as discussed below. (Review of the final design is addressed in Element 10 Verification and Validation.)

Element 8 - Procedure Development addresses the information context and physical representation of plant procedures.

Element 10 - Human Factors Verification and Validation involves five V&V analyses each addressing a different aspect of HFE. In HFE Design Verification the HSI design is evaluated for conformance to HFE principles, guidelines and standards. The DRG provides the criteria for reviewing many aspects of the HSI design. The reviewer should consult other NRC review guidance for aspects of the design n . addressed by the DRG, such as NUREG-0700 for conventional HSI technology. The procedures fo: .ne use of the DRG for performing HFE Design Verification are presented in Volume 2, Section 5 of this report.

4. HSI DESIGN REVIEW GUIDELINE DEVELOPMENT

4.1 DRG Application and Technical Scope

The purpose of the DRG is to provide the technical basis for HFE reviews of advanced HSI designs to assure that they support safe plant operation (that the controls, displays, and data processing support provided by the HSI are appropriate to the crew's tasks, and designed according to accepted HFE guidelines, standards, and principles). Two general applications of the DRG include:

- NRC review of design-specific guidelines and specifications
- NRC HFE verification review of preliminary and final HSI designs

From the strengths and limitations of HFE guidelines-based reviews (discussed in Section 2.1.4), it is important to recognize two issues when using HFE guidelines. First, design-specific discrepancies from the guidelines are not necessarily problematic; their importance has to be considered within the context of the individual review. Second, other methods of evaluation (such as dynamic performance evaluation) should be considered in conjunction with guideline reviews as the foundation for the safety evaluations of detailed and detailed advanced HSI designs. This approach is consistent with the multi-method approach to evaluation presented in Section 3.

The technical scope of the DRG primarily focusses on the review of advanced HSI, i.e., the crew's interface with:

- Information/data, e.g., with the displays of system status and parameter trends;
- Software, e.g., with the plant control systems, data management systems, and interface controls such as menus, windows, and navigation through display hierarchies; and
- Computer hardware devices, e.g., VDUs, mice, and touch screens.

Guidelines for "conventional" technology HSIs are covered in NUREG-0700. The guidelines pertain to the HFE aspects of HSI design and do not address I&C, software, and related issues.

With respect to the specific topic areas addressed by the DRG, it was deemed inappropriate to restrict the types of technology and HSI design approaches that would be included in the DRG; therefore, only in obvious cases were guidelines screened out as inapplicable to an NPP. As discussed in Section 2, the HSI designs and dialogue modes in advanced systems are very diverse. Also, there is diversity in the types of tasks operators may be called upon to perform and in the ways those tasks may be carried out. Thus, the guidelines in the DRG are broader than expected in a NPP review guideline. For example, guidelines for reviewing text processing are included, although it may seem unlikely that text processing would be a significant operator task in advanced plants. These guidelines were included in the DRG to provide a basis for reviewing a particular application using this type of operator activity (such as operator interface with knowledge-based systems or computer-based interaction with maintenance crews). Guidelines that are inappropriate to a particular design review need not be used by the reviewer.

4.2 Guideline Development and Description

4.2.1 Approach and General Principles

In Section 2, the human-performance issues associated with advanced technology systems were discussed. The HSI should be designed to support the operators' primary task of monitoring and controlling the process, without imposing an excessive secondary workload for interfacing with the HSI (window manipulation, display selection, and navigation, for example). The HSI also should support recognition, tolerance, and recovery from human errors when they occur. Ideally, a design review guideline would evolve directly from this research and generate guidelines to support reviews of how these design goals have been achieved. As an intermediary step between research on human performance issues and detailed design review guidelines, a set of "high-level" design-review principles were developed (see Figure 4.1). These principles were based, in part, on the literature reviewed in Section 2, and also on HSI design guidance and evaluation literature (Smith and Mosier, 1986; Ravden and Johnson, 1989; Shneiderman, 1987; U.S. DoD, 1989). Thus, the principles represent the generic HSI characteristics necessary to support the crew's performance.

The principles are not specific review *guidelines*, but are intended to be used to support the interpretation of the significance of individual discrepancies in the guidelines and the identification of significant HSI issues (as is discussed in Volume 2 this document). The principles are divided into four categories (see Table 4.1):

- *General Principles* - These principles ensure the HSI supports personnel safety and is compatible with general cognitive and physiological capabilities.

- *Primary Task Design* - These principles support the operator's primary task of process monitoring, decision-making, and control to maintain safe operation of the plant.

- *Secondary Task Control* - These principles minimize secondary tasks, i.e., tasks the operator must perform when interfacing with the system but that are not directed to the primary task. Examples include efforts the crew must expend managing the interface, such as navigation through displays, managing windows, and accessing data. Although necessary, performance of secondary tasks detracts from the crew's performance of primary tasks, so their effects must be controlled.

- *Task Support* - These principles support the operator's use of the HSI, such as providing (1) HSI flexibility so tasks can be accomplished in more than one way, (2) user guidance, and (3) error mitigation.

The individual principles within each category are described in the following pages.

General Principles

Personnel Safety - The design should minimize the potential for injury and exposure to harmful materials.

Cognitive Compatibility - The operator's role should have a level of workload that is not so high as to negatively affect performance, but sufficient to maintain vigilance and familiarity by carrying out purposeful and meaningful activities.

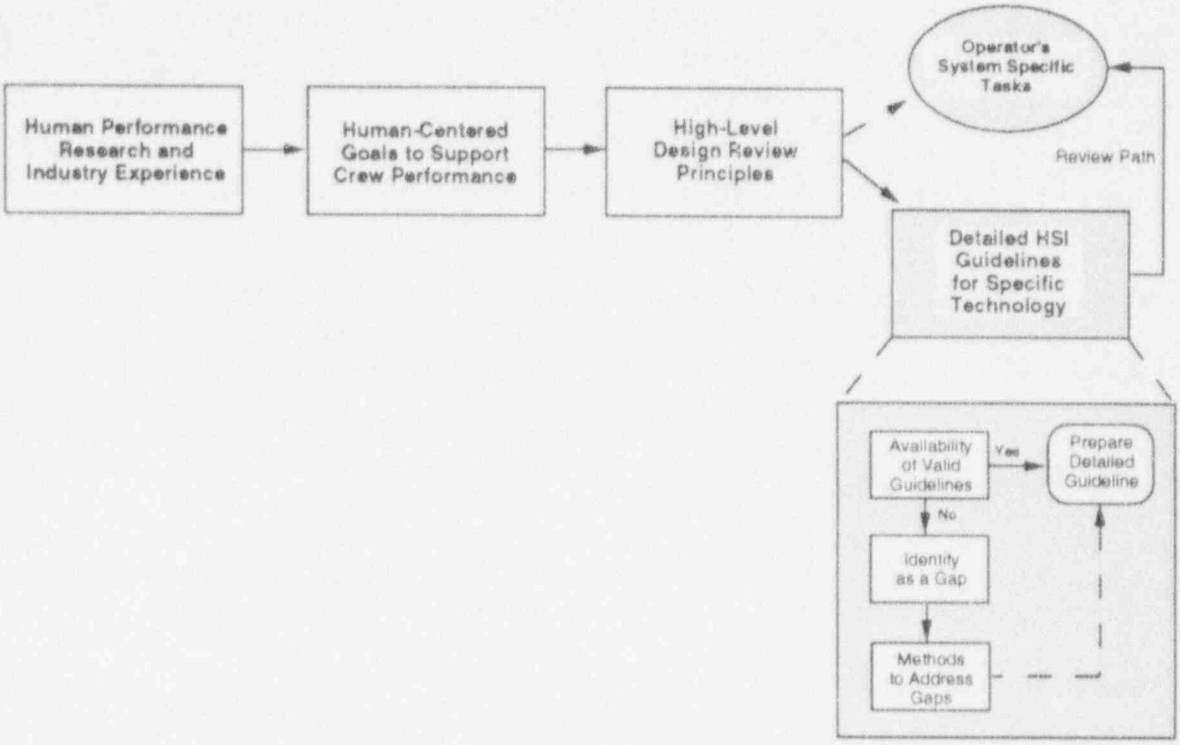

Figure 4.1. Guideline development strategy

Table 4.1. High-level Design Review Principles

CATEGORY	PRINCIPLE
General	Personnel Safety Cognitive Compatibility Physiological Compatibility Simplicity of Design Consistency
Primary Task Design	Situation Awareness Task Compatibility User Model Compatibility Organization of HSI Elements Logical/Explicit Structure Timeliness Controls/Displays Compatibility Feedback
Secondary Task Control	Cognitive Workload Response Workload
Task Support	Flexibility User Guidance and Support Error Tolerance and Control

Physiological Compatibility - The design of the interface should reflect consideration of human physiological characteristics including visual/auditory perception, biomechanics (reach and motion), characteristics of motor control, and anthropometry.

Simplicity of Design - The HSI should represent the simplest design consistent with functional and task requirements.

Consistency - There should be a high degree of consistency between the HSI, the procedures, and the training systems. The way the system functions and appears to the operating crew always should be consistent and reflect a high degree of standardization and be fully consistent with procedures and training.

Primary Task Design Principles

Situation Awareness - The information presented to the users by the HSI should be correct, rapidly recognized, and easily understood (e.g., "direct perception" or "status at a glance" displays) and support higher-level goals of user awareness of the status of the system.

Task Compatibility - The system should meet the requirements of users to perform their tasks (including operation, safe shutdown, inspection, maintenance, and repair). Data should be presented in forms and formats appropriate to the task (including the need to access confirmatory data or raw data in the case of higher-level displays) and control options should encompass the range of potential actions; there should be no unnecessary information or control options.

User Model Compatibility - All aspects of the system should be consistent with the users' mental models (understanding and expectations about how the system behaves developed through training, use of procedures, and experience) and 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).

Organization of HSI Elements - The organization of all aspects of the HSI (from the elements in individual displays, to individual workstations, to the entire control room) should be based on user requirements and reflect the general principles of organization by importance, frequency, and order of use. Critical safety-function information should be available to the entire operating crew in dedicated locations to ensure its recognition, and to minimize data search and response time.

Logical/Explicit Structure - All aspects of the system (formats, terminology, sequencing, grouping, and operator decision support aids) should reflect an obvious logic based on task requirements or some other non-arbitrary rationale. The relationship of each display, control, and data processing aid to the overall task/function should be clear. The structure of the interface and its associated navigation aids should make it easy for users to recognize where they are in the data space and should enable users to rapidly access data not currently visible (e.g., on other display pages). The way the system works and is structured should be clear to the user.

Timeliness - The system design should take into account users' cognitive processing capabilities as well as process-related time constraints to ensure that user tasks can be performed within the time required.

Information flow rates and control performance requirements that are too fast or too slow may diminish performance.

Controls/Displays Compatibility - The data entry and control requirements should be compatible with the displays.

Feedback - The system should provide useful information on system status, permissible operations, errors and error recovery, dangerous operations, and validity of data.

<u>Secondary Task Control Principles</u>

Cognitive Workload - The information presented by the system should be rapidly recognized and understood; therefore, the system should minimize the cognitive capacities that the user must allocate to making mental calculations or transformations and use of recall memory (recalling lengthy lists of codes, complex command strings, information from one display to another, or lengthy action sequences). Raw data should be processed and presented in directly usable form (although raw data should be accessible to the user for confirmation).

Response Workload - The system should require the minimum number of necessary actions required to accomplish an action; e.g., single vs. command keying, menu selection vs. multiple command entry, single input mode (keyboard, mouse) vs. mixed mode. In addition, the system should not require the entry of redundant data, nor the re-entry of information already in the system, or information the system can generate from already resident data.

<u>Task Support Principles</u>

Flexibility - The system should give the user multiple means to carry out actions (and verify automatic actions) and permit display/control to be formatted in a configuration most convenient for the task. Flexibility should be limited to situations where it offers advantages in task performance (such as to accommodate different levels of experience of the users); it should not be provided for its own sake because there is a trade-off with consistency and the imposition of interface management workload (which detracts from monitoring and operations tasks).

User Guidance and Support - The system should provide an effective "help" function. Informative, easy-to-use, and relevant guidance should be provided on-line and off-line to help the user understand and operate the system.

Error Tolerance and Control - A fail safe design should be provided wherever failure can cause damage to equipment, injury to personnel or inadvertent operation of critical equipment. Therefore, the system should generally be designed such that a user error will not have serious consequences. If an error is made, its negative effects should be controlled and minimized. The system should offer simple, comprehensible notification of the error, and provide simple, effective methods for recovery.

Since the principles are stated in general terms, they must be made more application-specific through detailed design-review guidance. That is, the general principles must be translated into terms that can be applied to specific reviews of advanced technology in NPPs, e.g., graphic displays, touch screens, and expert systems. Detailed guidance can be developed from many sources (see Section 7), the most cost-effective means being to adapt guidance already tested for similar complex, high-technology systems.

While there is still much to be learned about the effects of advanced technology interfaces on human performance, many governmental and professional groups (e.g., NASA, U.S. DoD, Human Factors and Ergonomics Society (HFES)) have started developing design guidelines and evaluation methodologies to incorporate advanced technology into the HSI. Over the past ten years, the NRC has sponsored several studies addressing the evaluation of various aspects of ACR technologies (Gilmore, 1985; Rankin et al., 1985; U.S. NRC, 1984b). In addition, NRC has been a member of the Halden Project that has been very active in testing and evaluating computer-based CR technology and in developing evaluation criteria for it (see Kennedy, 1989, for an overview of this work). More recently, the nuclear industry has been developing principles, guidelines, and standards for advanced technology interfaces (e.g., IEC, 1989; EPRI, 1990; Mumaw, Woods, and Eastman, 1992).

Several efforts to develop human factors guidance for advanced HSI were based on multi-year studies incorporating peer review of guidelines. While the HSI requirements in NPPs are unique in many ways, a critical review and adaptation of relevant efforts in other fields will maximize the NRC's guidance development efforts. Such an approach will enable the available resources to be specifically directed toward resolving those issues that are either unique to NPPs, or have not been adequately addressed elsewhere. Further, there are many similarities between advanced HSIs in NPPs and other advanced workstation applications, such as telecommunications-network control centers, space-system workstations, advanced aircraft cockpits, and military "command, control, communications and intelligence" (C^3I) workstations. This trend toward increasing similarity of command and control complexes for diverse applications has been referred to as "convergent evolution" (Wiener, 1988) and is, in part, being brought about by digital technology; this commonality gives a basis for a technology transfer strategy.

The guidelines described in this report reflect this development philosophy; details of the effort are described in the rest of this section.

4.2.2 Guidance Documents Identification and Selection

The methodology used to identify human factors guidelines for advanced HSI technology was based on the following methods:

- Searches were conducted of human factors literature including journal articles, conference papers, special-interest-group newsletters, and announcements of recent book publications, as well as computerized databases.

- Direct contact was made with organizations (such as U.S. DoD, NASA, and HFES) who sponsor such research as well as individuals in the advanced human factors technology field.

No effort was made to identify documents developed before 1980 because: (1) significant guidelines from this period were absorbed into more recent documents, and (2) HSI and computer technology changed dramatically during the 1980s so that many of the earlier guidelines are not applicable.

The search process resulted in many documents that were then entered into a computerized "HFE Source Document Database." New documents are added to the database as they become available. A sample of these is contained in Table 4.2.

Each document is stored as a record with the following 10 fields:

1. First Author
2. Other Authors
3. Publication Date
4. Document Title
5. Document Number
6. Publisher
7. Sponsoring Organization
8. Performing Organization
9. Class
10. Synopsis

The meanings of the first eight fields are self-explanatory. The *Class* field represents the classification with respect to validity assessments discussed below. The *Synopsis* field contains a brief description. An effort was made to include all key terms, table of contents items, and abstract information that would enable a user to search on terms within the synopsis to locate potentially applicable documents. However, some documents have incomplete information.

Once advanced HSI documents were identified, selection was made of those documents to serve as the basis for the guidelines to be incorporated in the DRG. Although many documents were identified and included in the database, no attempt was made to include all of them in the development of the DRG for two reasons. First, the sheer volume of documents would have made their incorporation too resource-intensive. Second, there was great diversity in the validity of individual documents. Therefore, a strategy was developed to classify the documents for selection purposes, and is explained below.

To select primary source documents to serve as the technical basis for the DRG, a high priority was given to the guidelines' validity. Validity was not used here in the classic scientific sense (Cook and Campbell, 1979). For this discussion, validity is defined in terms of two aspects of potential source document development: internal and external validity.

Internal validity was evaluated by the degree to which the individual guidelines were based on research, and where the research was referenced to provide a trail from each guideline back to the original data. The availability of an audit trail makes it possible to evaluate the source documents' appropriateness within the context of a particular review. A document based on referenced empirical literature was considered to have good internal validity.

External validity was evaluated by the degree to which a document had been peer reviewed, which was considered a good method to screen guidelines' conformity to accepted human engineering practices. A document that had undergone thorough peer review was considered to have good external validity. Internal and external validity were evaluated at the document level, not at the level of individual guidelines. Note that the evaluation of internal and external validity are somewhat judgmental; that is, both dimensions are continuums.

Table 4.2 Sample of Database Contents

(Page 1 of 2)

AUTHOR	DATE	DOC. NUMBER	TITLE
Apple Computer	1987	ISBN: 0-201-17753-6	Human-Interface Guidelines: The Apple Desktop Interface
Banks, W.	1983	NUREG/CR-3003	HE Design Considerations for CRT-Generated Displays (Vol II)
Banks, W.	1982	NUREG/CR-2496	Human Eng. Design Considerations for CRT-Generated Displays
Berson, B.L.	1981	DOT/FAA/RD-81/38,II	Aircraft Alerting Systems Standardization Study - Volume II
Blackman, H.	1984	NUREG/CR-3767	Interactive Simulator Evaluation for CRT-Generated Displays
Blackman, H.	1983	NUREG/CR-3556	Non-interactive Simulation Evaluation for CRT-Generated Displays
Blackman, H.	1983	NUREG/CR-3557	CRT Display Evaluation: The Checklist Eval. of CRT-Generated
Boff, K.R.	1990		Engineering Data Compendium: Human Perception and Performance
Brown, C.	1988	ISBN: 0-89391-332-4	HC Interface Design Guidelines
Brown, C.	1983	LMSC-D877141	Human Factors Engineering Standards for Info. Proc. Systems
Coats, R.	1987	ISBN: 0-632-01542-X	Man-Computer Interfaces: An Introduction to Software Design
Denchak, M.	1981	NUREG/CR-1994	Techniques for Displaying Multivariate Data on CRTs
DoD	1990	DOD-HDBK-761A	Human Engineering Guidelines for Management Inform. Systems
DoD	1990	MIL-STD-1800A	Human Engineering Performance Requirements for Systems
DoD	1989	MIL-STD-1472D	Human Engineering Design Criteria for Military Systems, Equipment,
DoD	1987	MIL-STD-1801	User/Computer Interface
DoD	1985	CSC-STD-002-85	Department of Defense Password Management Guideline
DoD	1981	MIL-STD-12D	Abbreviations for Use on Drawings, and in Specs., Standards,
Dumas, J.	1988	ISBN: 0-13-201971-X	Designing User Interfaces for Software
Fuey, P.	1984	EPRI NP-3701 V1	Computer Generated Display System Guidelines - Volume I
Galitz, W.	1985	ISBN: 0-89435-119-2	Handbook of Screen Format Design (2nd Edition)
Gertman, D.	1982	NUREG/CR-2942	CRT Evaluation: The Multidimensional Rating of CRT-Generated
Gilmore, W.	1989	Book	The User-Computer Interface in Process Control: A Human Factors
Gilmore, W.	1985	NUREG/CR-4227	Human Engineering Guidelines for the Evaluation & Assessment of VDUs
Helander, M.	1988	ISBN: 0-444-70536-8	Handbook of Human-Computer Interaction
Hendler, J.A.	1988	ISBN 0-89391-429-0	Expert Systems: The User Interface
HFS.	N/A		HCI Standards Efforts
IEC	1989	IEC 964	International Standard
ISO WG	N/A	ISO II 064	Ergonomic Design of Control Centers
Ivergard, T.	1989	ISBN 0-85066-454-3	Handbook of Control Room Design and Ergonomics
Keane, J.	1992	ADA 253 475	Human Computer Interface Style Guide (Version 1.0)
Kinkade, R.G.	1984	EPRI NP-3659	Human Factors Guide for Nuclear Power Plant Control Room Development
Lapinsky, G.	1989	NUREG-1342	A Status Report Regarding Industry Implementation of SPDS
Lewis, J.	1984	NUREG/CR-3621	Safety System Status Monitoring
Liner, R.	1987	NUREG/CR-4797	Progress Reviews of Six Safety Parameter Display Systems
McCauley, A.	1991	ISA S18.1	Annunciator Sequences and Specifications
Mosier, J.N.	1986	N/A	Application of Guidelines for Designing User Interface Software
NASA	1988	USE 1000, V 2.1	Space Station Freedom H-C Interface Guide (Version 2.1)
NASA	1987	NASA-STD-3000	Man-Systems Integration Standards

Table 4.2 Sample of Database Contents
(Page 2 of 2)

AUTHOR	DATE	DOC. NUMBER	TITLE
NRC Staff	1984	NUREG-0800	Human Factors Review
NRC Staff	1981	NUREG-0700	Guidelines for Control Room Design Reviews
Norman, D.A.	1986	ISBN 0-89859-781-1	User Centered System Design
Pankrantz, D.	1986	EPRI NP-4874	Graphic Display Development Methodology Volume I: Theory
Patterson, R.D.	1982	CAA Paper 82017	Guidelines for Auditory Warning Systems on Civil Aircraft
Perlman, G.	1989		The Checklist Method of Applying Guidelines to Design and Evaluation
Peterson, R.	1982	NUREG/CR-2916	An Empirical Examination of Evaluation Methods for Computer Generated Displays
Rankin, W.	1985	NUREG/CR-3987	Computerized Annunciator Systems
Rouse, W.	1984	EPRI NP-3701 VII	Computer-Generated Display System Guidelines - Volume II
Rupp, B.	1984		Human Factors of Workstations with Visual Displays
Salvendy, G.	1987	ISBN: 0-471-88015-9	Handbook of Human Factors
Schneiderman, B.	1987	ISBN: 0-201-16505-8	Designing the User Interface: Strategies for Effective Human
Shields, N.	1980	MSFC-PROC-711A	Spacelab Display Design and Command Usage Guidelines
Sidorsky, R.	1984	NTIS No. AD A153 231	Design Guidelines for User Transactions with Battlefield Automation
Smith, S.	1986	ESD-TR-86-278	Guidelines for Designing User Interface Software
Smith, S.	1984	ESD-TR-84-358	A Design Evaluation Checklist for Interface Software
Snyder, H.L.	1988	ANSI/HFS 100-1988	American National Standard for Human Factors Engineering of
Williges, B.	1984		Dialogue Design Considerations for Interactive Computer Systems
Wise, J.A.	1987	EL-4960	Display Design for Dispatch Control Centers in Electric Utilities: Handbook
Woods, D.	1982	EPRI NP-2239	Evaluation of Safety Parameter Display Concepts (UI)
N/A	N/A	DIN 66234 (Part 8)	Principles of Dialog Design
N/A	1981	ISO 6385	Ergonomic Principles in the Design of Work Systems First Edition
N/A	1983	S5.3	Graphic Symbols for Distributed Control/Shared Display Instrumentation, Logic, and Computer Systems
N/A	1985	DIN 33414 PT 1	Ergonomic Design of Control Rooms; Seated Work Stations; Terms and Definitions, Principles, Dimensions
N/A	1985	ISA S5.5	Graphic Symbols for Process Displays
N/A	1987	MIL-STD-1801	User/Computer Interface
N/A	1988	DIN 66234 PT 8	VDU Work Stations: Principles of Ergonomic Dialogue Design
N/A	1988	MIL-STD-1280 Notice	Keyboard Arrangements
N/A	1990	ISO DIS 9241-3.2	VDTs Used for Office Tasks - Ergonomic Requirments - Part 3: Visual Display Requirements
N/A	1991	DD 202 ISO 6385	1991 AMD O Ergonomic Principles in the Design of Work Systems (L)
N/A	1991	MIL-STD-1478	Task Performance Analysis
N/A	1992	ISO DIS 9241 PT 1	Ergonomic Requirements for Office Work with Visual Display Terminals (VDTs) - Part 1
N/A	1992	ISO DIS 9241 PT 2	Ergonomic Requirements for Office Work with Visual Display Terminals (VDTs) - Part 2
N/A	1992	MIL-HDBK-759B	HFE Design for Army Materiel (Metric)

Internal and external validity were used to sort documents into three classes (see Table 4.3). In general, documents that had both good internal and external validity were considered primary source documents. If they had either internal or external validity (but not both), they were considered secondary sources. Documents that had neither internal or external validity were classified as tertiary sources. This classification was used to specify documents in the guidelines compilation process. While internal validity and external validity are important factors, there are additional factors that affect a particular document's evaluation compared to others. A document was considered better based on:

- Authorship - if it was developed by a panel of experts under the auspices of a recognized institution (such as the Human Factors & Ergonomics Society).

- Recency - if it was developed recently (1985-present).

- Industry - if it was developed for the nuclear industry.

These factors were used to prioritize documents and to facilitate resolution of conflicting guidance.

The primary source documents used as a basis for DRG development are listed in Table 4.4. Many are general human factors guidelines that are the products of U.S. government-sponsored work or the activities of standards organizations. The Gilmore text and the NASA document had a slightly different background. Gilmore et al. (1989) was based, in part, upon work performed at the Idaho National Engineering Laboratory (INEL) for the NRC and reported in NUREG/CR-4227 (Gilmore, 1985). The work is significant because it: (1) is specifically directed toward process control applications, (2) provides an excellent research basis for the guidelines presented, and (3) draws heavily from source material developed in the nuclear industry.

Table 4.3. Document Classification

DOCUMENT CLASS	VALIDITY	
	Internal	External
Primary	Yes	Yes
Secondary	Yes	No
Secondary	No	Yes
Tertiary	No	No

The Space Station Freedom Human-Computer Interface Guide (NASA-HCIG-1000) was developed for a specific application and was much more prescriptive than the other documents. This source was used, however, because it had an excellent research base and extensive, recent, peer review. For the DRG, these guidelines were modified to present general principles rather than an equipment-specific requirement. NASA's Man-Systems Integration Standard (NASA-STD-3000) was also identified as a primary source document, but it is not listed in the table because no guidelines were actually included in the DRG.

4.2.3 Guideline Organizational Structure

The organizational structure of the primary source documents was reviewed. Typically, these documents used a generic function-based approach; that is, the guidelines were organized by high-level functions the operator performs with the system, such as data entry, data display, dialogue, communication, and data protection. In addition, a section on integration of these functional elements was usually provided. Several of these documents address the human interface issues peculiar to computer systems. The more general documents, such as MIL-STD-1472D, also include guidelines for hardware required for computer functions (e.g., keyboards, CRTs). NUREG-0700 follows a similar approach; the list of interface guidelines is organized into the following sections: Control Room Workspace, Communications, Annunciator Warning Systems, Controls, Visual Displays, Labels and Location Aids, Process Computers, Panel Layout, and Control-Display Integration.

Table 4.4. DRG Source Documents

LTR CODE*	AUTHOR	DOC. NUMBER	YEAR	TITLE
A	U.S. DoD	DoD-HDBK-761A	1990	Human Engineering Guideline for Management Information Systems
B	Gilmore et al.	ISBN 0-12-283965-X	1989	User-Computer Interface in Process Control
C	U.S. DoD	MIL-STD-1472D	1989	Human Engineering Design Criteria for Military Systems, Equipment, & Facilities
D	NASA	USE-HCIG-1000	1988	Space Station Freedom Human-Computer Interface Guide
E	U.S. DoD	ESD-TR-86-278	1986	Guidelines for Designing User Interface Software
F	HFS	ANSI/HFS-100-1988	1988	American National Standard for Human Factors Engineering of Visual Display Terminal Workstations
G	U.S. NRC	NUREG-0800	1984	Standard Review Plan

Note: DoD = United States Department of Defense
NASA = National Aeronautics and Space Administration
HFS = Human Factors Society (now called the Human Factors and Ergonomics Society)
U.S. NRC = United States Nuclear Regulatory Commission

* Each DRG source document was given a letter code. For each individual guideline, these letter codes were used to identify the source documents from which the guideline was developed, where applicable.

The DRG's structure is organized into three "layers." The first layer is the set of high-level design review principles discussed in Section 4.2.1 above. The second and third layers are organized into HSI functional areas (see Table 4.5): a set of general guidelines, such as for displays (layer 2), and more detailed guidelines for design-specific implementations, such as graphs, labels, color coding, and touch screens (layer 3). The DRG's structure also contains a few selected "placeholders" that do not currently contain guidelines. These were included to provide the following:

- Placeholders for ongoing NRC research projects that are currently developing guidelines to eventually be integrated with the DRG.

- A reference in a location where a reviewer may logically expect the information, but where the relevant guidelines are contained elsewhere. Thus, the section provides a cross-reference to another section. For example, under Volume 2, Part 2, Section 1.5, Display Devices, a reviewer might expect to find guidelines for the review of audio display devices. However, a cross-reference is provided to indicate that these guidelines are located in Section 6.2, Speech-Based Communication.

- Internal completeness within a section. For example, input formats, such as command and direct manipulation dialogue modes, are addressed in Volume 2, Part 2, Section 2.1. While speech is a potential mode of user input to the system, no guidelines were available. Section 2.2.7, Natural Language, was added for completeness.

For the remainder of Section 4.2.3, all references are to the sections that contain the actual guidelines in Volume 2, Part 2.

Section 0 - High-Level HSI Design Evaluation Principles

This section contains the 18 general design review principles that were described in Section 4.2.1.

Section 1 - Information Display

This section deals primarily with the visual displays review, both text- and graphics-based. Guidance is provided in top-down fashion beginning with general display guidelines (Section 1.1), and then proceeding to finer levels of display details. Section 1.2, Display Formats, addresses review guidelines for common display forms such as continuous text, mimics/P&IDs, trend graphs, and flowcharts. If novel formats are encountered in a review, they can be evaluated using the general display guidelines and the guidelines in Section 1.3, Display Elements. Any 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, as shown in Section 1.3, Display Elements. Guidelines for the review of data quality and display update rate are contained in Section 1.4. Section 1.5, Display Devices, addresses the hardware aspects of displays. Review guidelines for display devices, such as video display units, large panel displays, and hardcopy display devices (printers and plotters) are provided. Section 1.5, Audio Display Devices, is included for cross-reference purposes to Section 6.2, Speech-Based Communication, that contains guidelines for these devices.

Table 4.5 DRG Organizational Structure

1.0 INFORMATION DISPLAY
- 1.1 General Display Guidelines
- 1.2 Display Formats
  - 1.2.1 Continuous Text Displays
  - 1.2.2 Tables and Lists
  - 1.2.3 Data Forms and Fields
  - 1.2.4 Bar Charts and Histograms
  - 1.2.5 Graphs
  - 1.2.6 Pie Charts
  - 1.2.7 Flowcharts
  - 1.2.8 Mimics and Diagrams
  - 1.2.9 Maps
  - 1.2.10 Graphic Instrument Panels
  - 1.2.11 Speech Displays
- 1.3 Display Elements
  - 1.3.1 Alphanumeric Characters
  - 1.3.2 Abbreviations and Acronyms
  - 1.3.3 Labels
  - 1.3.4 Icons and Symbols
  - 1.3.5 Numeric Data
  - 1.3.6 Scales, Axes, and Grids
  - 1.3.7 Borders, Lines, and Arrows
  - 1.3.8 Color
  - 1.3.9 Size, Shape, and Pattern Coding
  - 1.3.10 Highlighting by Brightness and Flashing
  - 1.3.11 Auditory Coding
- 1.4 Data Quality and Update Rate
- 1.5 Display Devices
  - 1.5.1 Video Display Units
  - 1.5.2 Large Screen Displays
  - 1.5.3 Printers and Plotters
  - 1.5.4 Audio Display Devices

2.0 USER-SYSTEM INTERACTION
- 2.1 General User Interaction Guidelines
- 2.2 User Input Formats
  - 2.2.1 Command Language
  - 2.2.2 Menu Selection
  - 2.2.3 Function Keys
  - 2.2.4 Macros/Programmable Function Keys
  - 2.2.5 Forms
  - 2.2.6 Direct Manipulation
  - 2.2.7 Natural Language
  - 2.2.8 Query Language
  - 2.2.9 Question and Answer
  - 2.2.10 Speech
- 2.3 Cursors
  - 2.3.1 Appearance
  - 2.3.2 Controls
  - 2.3.3 Movement
  - 2.3.4 Multiple Cursors
  - 2.3.5 Pointing Cursors
  - 2.3.6 Text Entry Cursors
- 2.4 System Response
  - 2.4.1 General
  - 2.4.2 Prompts
  - 2.4.3 Feedback
  - 2.4.4 Cautions and Warnings
  - 2.4.5 Error Messages
  - 2.4.6 User Guidance/Help
  - 2.4.7 System Response Time
- 2.5 Managing Displays
  - 2.5.1 Display Selection & Navigation
  - 2.5.2 Display Control
  - 2.5.3 Display Update/Freeze
  - 2.5.4 Display Suppression
  - 2.5.5 Scrolling and Paging
  - 2.5.6 Windows
- 2.6 Managing Information
  - 2.6.1 Editing Documents
  - 2.6.2 Saving Files
  - 2.6.3 Temporary Editing Buffer
  - 2.6.4 Excerpt File
- 2.7 Prevention/Detection/Correction of Errors
  - 2.7.1 Validating User Input
  - 2.7.2 Correcting Information/Command Entries
  - 2.7.3 Confirming Entries
  - 2.7.4 Protecting Data
- 2.8 System Security
  - 2.8.1 User Identification
  - 2.8.2 Information Access

3.0 PROCESS CONTROL & INPUT DEVICES
- 3.1 General Control Guidelines
- 3.2 Input Devices
  - 3.2.1 Alphanumeric Keyboards
  - 3.2.2 Function Keys
  - 3.2.3 Trackballs,Joysticks, and Mice
  - 3.2.4 Touch Screens, Light Pens, and Graphics Tablets
  - 3.2.5 Speech Input Devices

4.0 ALARM SYSTEMS

5.0 ANALYSIS AND DECISION AIDS
- 5.1 Knowledge-Based Systems

6.0 INTER-PERSONNEL COMMUNICATION
- 6.1 General Communication Guidelines
- 6.2 Speech-Based Communication
- 6.3 Computer-Based Communication
  - 6.3.1 General
  - 6.3.2 Preparing Messages
  - 6.3.3 Sending Messages
  - 6.3.4 Receiving Messages

7.0 WORKPLACE DESIGN
- 7.1 Workstation Configuration
- 7.2 Control Room Configuration
- 7.3 Environment

Section 2 - User-System Interaction

Section 2 is the largest and most diverse section of the DRG, composed of eight subsections on various approaches to user interaction with the HSI. Section 2.1 provides general review guidelines for user-system interaction with an emphasis on user inputs to the HSI. Section 2.2 provides review guidelines for user input and dialogue formats such as menus, direct manipulation, and command language, that address the issue of sequence control commands to the system. Sequence control refers to operator input that initiates or interrupts transactions (i.e., system functions). Such command inputs are made via the transaction dialogue. A poorly-designed operator dialogue will inhibit operators from moving efficiently from one task to the next and from interacting effectively with the system by imposing unnecessary constraints on selecting or sequencing actions. Input format types addressed are:

Command Language - A command language dialogue requires the operator to specify the functions to be performed without prompting; the operator is assumed to be aware of the available options, the proper command syntax, etc.. A command language dialogue is appropriate when a great deal of flexibility is required regarding the sequencing and content of operator inputs, and the operator is very familiar with the system.

Menus - A menu dialogue presents the operator with a number of options from which the desired action is chosen (e.g., by positioning the cursor, entering a keystroke code, etc.). This style of dialogue is appropriate when the number of options is limited and speed and accuracy are critical.

Function Keys - Function keys are dedicated to a single option or action and are, therefore, best used to select from among a small number of frequently-used options that are available at any point in the operator/system interaction (i.e., functions that are available only in certain modes of system operation are typically not assigned to function keys).

Macros/Programmable Function Keys - Macros are user-defined strings (or chains) of commands which are executed upon a single user command. Often macros are assigned to programmable function keys which execute the command string upon a single key press.

Form - A form-filling dialogue requires the operator to enter data in predefined fields presented on the display. This style of interaction is, therefore, appropriate to situations in which the categories of data to be input can be specified, but flexibility is required with respect to the data to be input. It is an appropriate method for entry of information into a computer system when that information already exists in hardcopy forms.

Direct Manipulation - A direct manipulation or graphic interface typically displays pictographic icons to represent control actions and options; actions and options not easily represented in pictographic form are presented in menus. Icons or menu items are "selected" by positioning a cursor, usually by means of a pointing device (i.e., a mouse or trackball).

Natural Language - A natural language interface allows instructions or requests to be entered through the keyboard using "everyday" vocabulary with few requirements as to syntax.

Query Language - Query language is a specialized type of command language used to retrieve information from a system.

Question and Answer - In a question and answer dialogue, the system poses questions for the operator to answer. This style of interaction is appropriate when the types of information to be input are specified, and the order in which the data are to be input is predefined.

Speech - A speech interface allows users to input information and commands through voice rather than through some manual input as in natural language, query and question/answer dialog formats. The system utilizes a speech-recognition system to parse and understand the speech input from the user.

Section 2.3, Cursors, provides review guidelines for this aspect of the HSI. When interacting with a computer-based system, the appearance and behavior of the on-screen cursor (or more generally, the follower, the on-screen image that tracks the user's input) can significantly affect performance.

Section 2.4, System Response Review Guidelines, addresses prompts (including routine messages), operator guidance (feedback and on-line help), and decision aids (e.g., expert systems). Well-designed prompts indicate not only that input is expected, but also the proper format and means of performing the entry. Useful error messages clearly convey the nature of the problem and facilitate its correction. The overall goal of prompting and user guidance is to ensure that operators, at any point in the interaction, are aware of what type of action is appropriate, what their options are, how they should proceed, and how they can request help. Also covered in this section are response time guidelines, which address the necessity of the system to respond promptly.

Section 2.5, Managing Displays, contains guidelines of a variety of display interactions and modes (e.g., selection, freezing, updating, paging, scrolling) and windows. The objective of the design of display control functions is to allow the operator to access the specific information required for the task at hand while maintaining awareness of the ongoing process and the display/control context.

Section 2.6, Managing Information, addresses manipulation of data in the system, including the processing of text.

Section 2.7, Protection/Detection/Correction of Errors, contains guidelines of methods to ensure data integrity. Guidance covers prevention of inadvertent change or deletion of data, minimization of data loss due to computer failure, and protection of data, such as setpoints from unauthorized access. Measures taken to protect data will usually involve trade-offs between security and ease-of-use.

Section 2.8, Systems Security, contains guidelines for the review of safeguards to prevent unauthorized users from gaining access to system information, data, and controls.

Section 3. Process Controls and Input Devices

This section provides review guidelines for general control guidelines in Section 3.1, and for input devices in Section 3.2. Section 3.2, is focused on computer-input devices: keyboard devices (including special and variable function keys); direct manipulation controllers (including trackballs, joysticks, and mice); and pointing devices (including touch screens, light pens, and graphics tablets). The final section addresses speech input devices and provides a cross reference to Section 6.2, Speech-Based Communication, containing guidelines for these devices.

Section 4, Alarm Systems

At present, no guidelines are included in this section; it is a placeholder for the results of an NRC research project to develop review guidance in the area of advanced alarm systems.

Section 5, Analysis and Decision Aids

This section addresses the aids provided to the operator for situation analysis and decision making. Guidelines for knowledge-based aids are provided. These address the functional requirements of such systems, such as explanation and simulation facilities, and the desirable characteristics of their user interfaces.

Section 6, Inter-Personnel Communication

Section 6.1, General Communication Guidelines, contains general guidelines for communications between plant personnel. Detailed guidelines are provided for speech-based (Section 6.2) and computer-mediated (Section 6.3) communication among plant personnel, e.g., preparing, addressing, sending, and receiving messages. Speech-based communication guidelines address the characteristics of speech input and output devices. Computer-mediated communication guidelines minimize the demands placed on system operators while providing flexibility.

Section 7, Workplace Design

Section 7 is a placeholder pending further development. At present, limited review guidance is presented in Sections 7.1, Workstation Configuration, and 7.3, Environment. Section 7.1 addresses workstation configuration, i.e., the integration of individual control and display devices into a console (such as VDU viewing distance, viewing angle, and glare). Section 7.2, Control Room Configuration, is empty, but will address the integration of individual workstations, supervisors' consoles, and large-screen displays into an integrated CR. Section 7.3, Environment, is also limited and only addresses illumination in the workstation area.

4.2.4 Individual Guideline Formulation

There was considerable overlap in the guidelines contained in the primary source documents. Where appropriate, similar guidelines were combined into a single guideline. Where compound guidelines were found (several guidelines together in a single statement), an effort was made to decompose the guideline into logical units, representing individual guidelines. The objective was to make each individual guideline a clear and distinct criterion. Thus, it would be easier for a reviewer to use, by reducing ambiguity if an interface was acceptable with respect to one aspect of a guideline, but discrepant with another. The primary source document from which each guideline was derived was recorded to maintain an audit trail. Occasionally, primary source documents differed in the guidance recommended. Conflict resolution was handled case-by-case using the factors previously discussed. In those instances where conflicts still existed between guidelines, the more conservative guideline was used.

The guidelines were standardized into the format shown below.

1.1.-1 Display Screen Partitioning for HSI Functions
A standard organization should be adopted for the location of various HSI functions (such as a data display zone, control zone, message zone) from one display to another.
ADDITIONAL INFORMATION: Consistent display formats will help establish and preserve user orientation. Reserved screen areas, for example, might be used for a display title, data output by the computer, display control options, instructions, error messages, and user input and command entry. Display formats should be consistent with accepted usage and existing user habits.[E,B,D]

The components of the standard format are described below:

- *Guideline Number* - Within sections/subsections, individual guidelines are numbered consecutively from 1 to n. Each guideline has a unique number that reflects its section/subsection location followed by a dash and its unique number. For example, in Guideline 1.1-1, Display Screen Partitioning for HSI Functions, "1.1" reflects its location in Section 1.1, General Display Principles, and "-1" indicates it is the first guideline in the section.

- *Guideline Title* - Each guideline has a brief unique title.

- *Guideline Statement* - Each guideline contains a concise statement of the criterion/ characteristic the HSI should embody.

- *Additional Information* - For many guidelines, additional information is provided such as clarifications, examples, exceptions, details regarding measurement, figures, or tables. This information supports the reviewer's interpretation or application of the guideline.

- *Source* - The primary source document(s) from which the guideline was developed is shown in superscripts. To conserve space, the source documents are indicated using letter codes. Table 4.4 provides the reference for each letter code.

4.3 Procedures for Guideline Usage

The procedures for conducting an HSI safety review are as important as the guidelines themselves. As discussed in Section 4.1, there are two general applications of the DRG in NRC safety reviews: review of design specific guidelines/specifications and HSI design reviews. Procedures for both types of reviews were developed. Since these procedures are described in detail in Volume 2 of this document, they will not be discussed here. The reader is referred to Volume 2, Part 1, Sections 4 and 5.

5. INTERACTIVE COMPUTER-BASED DRG DEVELOPMENT

The purpose of this section is to describe the interactive, computer-based version of the DRG in terms of: rationale (Section 5.1), design objectives analysis (Section 5.2), and development prototyping (Section 5.3). A description of the prototype's data structure, functions, and interfaces can be found in Appendix A.

5.1 Rationale

There is a trend in the human factors community to make HFE guidelines available in computer-based form. The U.S. military's primary human factors guideline (MIL-STD-1472D) and Smith and Mosier's (1986) human-software interface guidelines, for example, are available in hypertext-type databases, and NASA's Man-System Integration Standard (NASA-STD-3000) is available in a relational database. The U.S. Air Force has a program to provide the Human Engineering Compendium and HSI guidelines in computer-based form. Computerization provides the flexibility required to handle advanced HSI guidelines. Thus, in addition to a hard copy of the DRG, the guidelines are available in an interactive electronic format. The interactive version of the DRG was developed to facilitate:

- access and review of guidelines for review planning,
- compilation of individual guidelines to assemble the subset of guidelines appropriate for a specific review,
- report preparation and review audit trail aid to a reviewer conducting human factors audits of ACR technology, and
- guideline updates and maintenance.

The detailed purposes and objectives of interactive document development are provided in the next section.

5.2 Design Objectives Analysis

An analysis of the HSI review task and the variety of ways the DRG would be used was performed to identify the desirable characteristics of an interactive document. They were organized into four categories: review task objectives, general usability objectives, electronic document functionality objectives, and general hardware objectives to support prototype development of the system (summarized below).

5.2.1 Review Task Requirements Objectives

Based upon an analysis of an NRC reviewer's activities, the following objectives were identified.

- *Support All Review Phases* - the document should support all phases of HSI review including:

  Preparation (such as the review of general details of the plant, specific HSI information and procedures, record of earlier evaluations, activity preparation, and customization of guidelines so that reviewers can prepare a subset of guidelines in advance of an audit).

- On-Site Review (such as interview support; review of plant documentation; equipment inventory; comparison of interfaces with guidelines; issue identification).

- Report Writing and Issuance (such as documentation of all areas reviewed, persons contacted, specific findings, and organization of information into canned formats).

- *Support Several "Document Utilization Modes,"* such as:

  - Emulate DRG - The capability to provide a high-fidelity emulation of the hardcopy document, including navigation aids (i.e., table of contents and index), glossary, and standard page layout (reviewer sees "raw document" that is similar to the hard copy version to facilitate familiarity with the content).

  - Perform Review - Reviewer sees only those aspects of the document needed for the various phases of review, but can easily access others; the ability to proceed through guidelines without secondary data such as Comment, Source, and Classification fields. These should be accessible through "push buttons" or menu options.

  - Edit Guidelines - For document updating, available only to authorized individuals so that the document's content can be controlled.

5.2.2 Usability Objectives

Several high-level usability objectives have been identified for the interactive document that were derived from the types of high-level guidance discussed in Section 4.

- *Fast learning* - minimize the time it takes the reviewers to learn to use the interactive document, regardless of computer experience.

- *Minimize reviewer errors* - reduce the number of possible errors the reviewers might make.

- *Good retention* - maximize document use retention when it is used on an intermittent basis.

- *Minimal memory load* - memorize commands, modes, key sequences or other actions not inherent in the inspection process.

- *Minimal reviewer input* - permit the reviewer to access the guidelines with a minimum of inputs, such as typing, accomplished with pull-down menus of keywords, "point and click" access to the table of contents and glossary, and "point and click" search term entry.

- *On-line help* - provide guidance to reviewers on how to use the system. The on-line help should be accessible from anywhere within the document and have some measure of context sensitivity.

- *Meaningful error feedback* - provide meaningful feedback to the reviewer in the event of a reviewer error, including a description and action required to correct it.

- *High satisfaction* - reviewers should be satisfied with the interface.

5.2.3 Electronic Document Functional Objectives

The following functions were deemed highly desirable based on a consideration of how the document will be used:

- *Graphics support* - capability to display graphic images (e.g., figures, illustrations).

- *Automatic "go to"* - cross-referenced, indexed, and table of contents materials activated upon reviewer request.

- *Rapid search initiation* - ability to "point and click" at a word to designate it as the current search term, and initiate a search for the first instance of that term minimizing the amount of typing to access the guidelines.

- *Restricted field search* - enables the reviewer to search for words restricted to a single field. For example, the reviewer requests a search for the term "vision" only in the "Sub-area" field.

- *Exact and approximate word search* - capability to select whether the function will search for an exact or approximate match. For example, in an exact match, if the reviewer entered "display" as the search term, "displays," "displayed," and "displaying" would not be selected. These terms, however, would all be considered "hits" for an approximate match.

- *Keyword list* - a given keyword list with the capability for the reviewer to develop, access, and modify an individualized keyword list for his/her own use for frequently used terms and phrases.

- *Browse* - a mechanism to allow the reviewer to page through the document by sequentially accessing other related guidelines based on reviewer-specified terms and phrases.

- *Location landmarks* - running heads on each page to identify guideline content areas; i.e., Section: Information Display; Sub-section: Information Format; Area: Graphics; and Sub-area: Flowcharts.

- *Placemarker* - a book-mark type feature to allow the reviewer to mark one or more guidelines for future access.

- *Evaluation function* - on-screen record of whether the item under evaluation passes, fails, or is not applicable (N/A) to the current guideline.

- *Note taking* - capability for the reviewer to append his/her own comments to individual guidelines.

5.2.4 Hardware Objectives

The first hardware consideration is memory capacity. The total estimated storage requirement for the present version of the interactive document is approximately eight megabytes. Reviewers will also require access to project-related files (e.g., copies of previous review reports, project-related memos, review plans) and other basic applications (e.g., word processing software). Thus, the storage requirements exceed what can be reasonably handled by floppy drives, and the host computer will require a hard disk of at least 20 megabytes.

One of the main purposes of the electronic version of the DRG is to support HSI reviews in NPPs. The host computer should be portable in size and weight. In addition, reviewers may use the DRG throughout a plant; thus alternating current (AC) may not always be available. Under other circumstances, laying a power cord across a work area would create unacceptable personnel hazards. Therefore, the computer needs to be capable of battery operation for the entire work day. However, since computer batteries typically last from two to five hours (depending on model and usage), the computer must be capable of battery replacement.

Finally, the display screen should support viewing of test and graphics material under non-optimal lighting conditions, thus the screen must be self illuminating. A keyboard and some type of direct manipulation device (e.g., mouse, trackball, etc.) will be needed to support the types of usability objectives identified above. The design of the display and input devices should support prolonged reviewer input and meet the human factors guidelines.

These hardware objectives were considered easy to achieve since many laptop computers acceptably meet these objectives.

5.3 Interactive Document Prototype

The design objectives analysis provided a basis for selection of hardware and software for DRG document prototyping and initial development. An Apple MacIntosh™ computer was selected and the guidelines database was implemented in HyperCard™ software.

HyperCard satisfies the functional requirements of the DRG. It has the capability to display text in multiple, scrolling fields that can be simultaneously displayed on the screen. This provides reviewers with a high degree of control over the access, manipulation, and display of information. HyperCard also can implement such features as bookmarks and an embedded notebook. It supports note links, where the reviewer can access notes pertaining to a specific topic or field. Graphics support is included where nontextual, bit-mapped images can be displayed in association with the text. In addition, HyperCard offers a powerful help facility, allowing reviewers to seek context-sensitive help such as clarification on a document navigation problem, or more detailed information pertaining to a specific area or field of the DRG.

Among the program's most positive features are adaptability and extendibility. HyperCard contains its own object-oriented programming language, "HyperTalk™," that permits essentially total control over the look and feel of the interface and the ability to rapidly prototype HSIs. This capability enabled the project staff to easily design interface concepts, present the HSI to potential reviewers, and incorporate reviewer comments into the final design.

The initial DRG software was developed for an Apple Macintosh with the following hardware and software:

- a minimum of 4 megabytes of RAM,
- Macintosh system software 6.0.5 or later (including System 7),
- Hard disk drive with at least 8 megabytes of free space,
- a Superdrive (1.4 megabyte floppy drive),
- a 640 by 480-pixel resolution display, and
- Hypercard Version 2.1.

The prototype interactive document was implemented on a Macintosh laptop computer. For a more detailed description of the prototype, see Appendix A. The prototype was used in the tests and evaluations described in the next section. While a MacIntosh was used for prototype development and testing, the final version of the interactive document will be implemented in a DOS-based system to be compatible with the NRC's general computing environment.

6. GUIDELINE TEST AND EVALUATION

This section describes the DRG test and evaluation (T&E) program. Section 6.1 outlines the general objectives. Three separate evaluations were performed: Test, User Test, and Peer-Review Workshop. The tests are described in Sections 6.2, 6.3, and 6.4, respectively. Section 6.5 summarizes the general conclusions from the overall T&E program. This section provides a summary of the T&E program. The reader is referred to various Brookhaven National Laboratory (BNL) technical reports, where appropriate, for the detailed test descriptions.

6.1 General Objectives

The primary purpose of the T&E program was to assess the DRG in terms of its *technical merit* for achieving the NRC goal to develop a tool for the human factors review of ACR technology. A second purpose was to evaluate the *general usability* of the document implementation as an aid to reviewers for meeting the primary objective. The specific objectives in each category are elaborated below (see O'Hara, 1991a, for more detail).

6.1.1 Technical Merit Objectives

Technical Basis - Validity

- To determine if the technical basis of the guidelines is valid, i.e., based upon empirical research and/or consistent with current human engineering practice.

Guideline Scope

- To determine if the guidelines cover all aspects of advanced controls and displays required for the evaluation of ACRs and/or advanced technology upgrades in existing plants.
- To determine if the review areas have been identified for which available guidance is deficient or missing.

Guideline Content

- To determine if the topical organization is appropriate for conducting a review.
- To determine if the guidelines presented in each section are adequate for the evaluation of HSIs in the areas covered.
- To determine if the information available for each guideline is sufficient to provide a basis for evaluation.
- To determine whether the information is presented at an appropriate level of resolution (e.g., enough detail to support a review but not overly prescriptive).
- To determine if there are any internal conflicts or contradictions in the DRG.

6.1.2 Usability Objectives

Design Objectives

- To determine if the DRG achieves the design objectives as identified in the design objectives analysis (see Section 4.2).

- To determine if the design objectives are appropriate (are any specified design objectives unnecessary or do any require modification).

- To determine if the design objectives are sufficient or whether additional design objectives should be specified.

- Where appropriate, to determine if the design objectives are adequately implemented.

General User Interface Design

- To determine if the interactive document conforms to HFE guidelines for HSI design.

Interactive Document Functionality

- To determine if the HSI supports the primary task-related functions for HSI design review.

- To determine if the document functions (such as table of contents, glossary, index) are necessary and sufficient.

- To determine if the landmark features (such as section headers) and navigation functions (such as the browsing functions and navigation features of the table of contents and index) are necessary and sufficient.

- To determine if the search functions are necessary and sufficient.

- To determine if the evaluation, note-taking, and reporting functions are necessary and sufficient.

Interactive Document Usability

- To determine if the document is easy to use (i.e., is its usage easy to learn, intuitive, and unobtrusive to the primary task of evaluation).

- To qualitatively evaluate the benefits and limitations of conducting evaluations with an interactive, computer-based document when compared with a hard-copy document.

The specific test objectives, methodology, and results of the Development Test, User Test, and Workshop are described in the following sections.

6.2 Development Test

The Development Test provided a preliminary evaluation of the untested prototype DRG (Revision 1) and an opportunity to correct interface problems prior to subsequent testing. The DRG was evaluated by the project staff using a variety of review methodologies in order to assess the DRG implementation objectives, especially the design analysis and general user interface design objectives. The Development Test included a limited field evaluation, also conducted by the project staff. The field test was the first time the DRG was used to assess a NPP HSI, and its purpose was to provide (1) experience in the document's intended use to the project staff, (2) a preliminary and partial assessment of the DRG Technical Content objective, and (3) a pilot test of the procedures and evaluation methods to be used in the User Test. A complete description of the Development Test can be found in O'Hara, 1991b and 1991c.

6.2.1 Objectives

The project-related objectives for the Development Test were:

- Limited Guideline Content Evaluation
- Design Objectives Evaluation
- General User Interface Design Evaluation
- Document Functionality Evaluation
- Usability as a Review Aid Evaluation

Two additional objectives were to:

- Develop recommendations for modifications to the DRG to improve its use as a evaluation tool for the User Test, and

- Provide a pilot test of the test methodology and measures so they could be improved for the User Test.

6.2.2 Methodology

6.2.2.1 Overview

The Development Test consisted of three types of evaluations: a Function Implementation Review, an HFE Review and a Limited Field Test. The Function Implementation Evaluation was designed to evaluate how easily novice users understand the interface and use its functions. For the HFE review, the project staff evaluated the human factors design of the interactive document using the DRG itself. The Field Test was designed so that the Project team could evaluate the DRG technical content and its HSI for conducting an evaluation in a CR environment. The design objectives, general user interface design, document functionality, and usability as a review aid objectives were also assessed following the interface evaluation.

In the next section, the evaluation instruments and measures are discussed; then, each of the development test evaluation methodologies is presented.

6.2.2.2 Evaluation Instruments and Measures

A variety of evaluation and assessment techniques are employed in usability tests (Herring, 1990; Karat, 1988) including task performance assessments, checklists, subjective rating scales, verbal protocol analyses, interviews, and observations by the project team. Based upon a consideration of available methods, the following evaluation instruments and measures were used.

Operations Sequence Accomplishment Checklist (OSAC), Participant Comments, and Test Conductor's Observations

The OSAC was used by the test conductor to record the outcome (successful or not) for each instruction in the Operations Sequence List. It recorded the Test Conductor's Observations (TCO) and Participant Comments (PC), such as problems observed and comments/explanations for each item. These comments were content analyzed to identify areas for potential modification.

User Interface Rating Scale (UIRS)

The UIRS was adapted from the scales developed by Ravden and Johnson (1989) for the evaluation of human-computer interface usability. The UIRS was completed after an interface was used. The development of scale items was based upon the usability and evaluation work of Clegg et al. (1988), Smith and Mosier (1986), Gardner and Christie (1987), and Shneiderman (1987).

The UIRS consists of nine sections based on individual criteria that a well-designed user interface should meet. The interface is evaluated on items pertaining to:

Visual Clarity - Information displayed on the screen should be clear, well-organized, unambiguous, and easy to read.

Consistency - The way the system looks and works should be consistent at all times.

Compatibility - The way the system looks and works should be compatible with user conventions and expectations.

Informative Feedback - Users should be given clear, informative feedback on where they are in the system, what actions they have taken, whether these actions have been successful, and what actions should be taken next.

Explicitness - The way the system works and is structured should be clear to the user.

Appropriate Functionality - The system should meet the needs and requirements of users when carrying out tasks.

Flexibility and Control - The interface should be sufficiently flexible in structure, in the way information is presented and in terms of what the user can do, to suit the needs and requirements of all users, and to allow them to feel in control of the system.

Error Prevention and Correction - The system should be designed to minimize the possibility of user error, with facilities for detecting and handling those that do occur; users should be able to check their input and to correct errors, or potential error situations before the input is processed.

User Guidance and Support - Informative, easy-to-use, and relevant guidance and support should be provided, both on the computer (via an on-line help facility) and in hard-copy document form to help the user understand and use the system.

For these sections, a four-point Likert-scale is employed, with available ratings of "Always," "Most of the Time," "Some of the Time," and "Never." An overall rating of criteria accomplishment is also obtained using a five-point rating of "Very Satisfactory," "Moderately Satisfactory," "Neutral," "Moderately Unsatisfactory," and "Very Unsatisfactory." A tenth section is concerned with usability problems encountered, and employs a three-point Likert-Scale with ratings of "No Problems," "Minor Problems," and "Major Problems."

HSI Review Guideline Ratings

The individual guidelines contained in the DRG were used to evaluate the interactive document. Applicable guidelines were scored in OK/Discrepancy form, along with comments and explanations included in the DRG's Reviewer Comments field. Discrepancies were tabulated, along with their associated comments, and served as input to interface design modifications.

Requirements Analysis Rating Scale (RARS)

The RARS was an evaluation performed by the test participant following use of the interactive document. The scale was specifically tailored to assess how well the interactive document satisfied the design objectives. The scales were divided into four sections: technical content (evaluation of level of detail), capabilities/functions (evaluation of usefulness and ease of use), screen design (evaluation of ease of use and readability), and general usability (evaluation of user satisfaction). The evaluations were made using a four-point scale.

Debriefing Questionnaire (DQ)

The DQ was a structured questionnaire administered to each test participant, addressing the DRG's technical content, usefulness in supporting the review process, usability, and interface design.

Debriefing Interview (DI)

A DI was conducted with each test participant to obtain comments in a less structured, more interactive manner. The DI occurred following all other data collection.

6.2.2.3 Function Implementation Evaluation Methodology

Test Site

The Function Implementation Evaluation portion of the Development Test took place independently at two locations: BNL in Upton, New York, and Carlow International, Inc. (CII) in Falls Church, Virginia.

Test Participants

Participants included one person each from BNL and CII who were not directly involved in the development of the interactive implementation of the DRG. Neither was familiar with the use of HyperCard and one had only a slight familiarity with the Macintosh operating system.

Procedures

In the Function Implementation Evaluation, the participant's interaction with Revision 1 of the DRG was governed by the Operations Sequence List. This task list exercised all functions and operations of the interactive document. A member of the project team served as the test conductor and read individual instructions from the Operations Sequence List. The participant attempted to carry out that operation. The participant was asked to use a talk-through technique, verbalizing his thoughts while carrying out each operation and noting favorable, unexpected, and difficult aspects of the interface design. These comments were recorded. The test conductor made note of similar observations. This procedure continued until all elements of the Operations Sequence List were completed. At the conclusion of the Operations Sequence List exercise, the participants completed the UIRS and RARS, discussed below.

Data Collection

The OSAC, TCO, PC, and DI were used. Due to the participants' limited experience with the DRG, the more detailed rating scales and questionnaires were not used.

6.2.2.4 HFE Evaluation Methodology

Test Site

The formal HFE Review was conducted at BNL in Upton, New York.

Test Participant

The participant was a member of the Project Team. This BNL participant also took part in the Function Implementation Evaluation Test prior to performing the HFE evaluation.

Procedures

In the HFE Review Procedure, Revision 1 of the DRG was evaluated with the guidelines contained in the DRG. The DRG was implemented on a Macintosh II fx computer having eight megabytes RAM and a 80-megabyte hard drive. The computer had a 13-inch, high-resolution, color monitor and an extended keyboard with a mouse.

Comments on favorable, unexpected, and difficult aspects of the interface design were noted. Following the evaluation, the UIRS and RARS were completed by the participant.

Data Collection

The evaluation instruments and measures used were:

- TCO
- PC
- DRG
- UIRS
- RARS
- DQ
- DI

6.2.2.5 Field Test Methodology

Test Site

The Field Test was conducted at the NRC's Technical Training Center in Chattanooga, Tennessee. The SPDS in the BWR simulator (based on the Black Fox CR) served as the CR HSI under review. The SPDS was selected because it utilized a graphic display, CRT-based interface similar to the type of interface for which the DRG was developed.

Test Participants

Participants were two members of the project staff.

Procedures

The participants alternated roles as the User/Reviewer and the test conductor. The Reviewer performed the interface evaluation using the interactive document and talked through the evaluation process for testing purposes. The Reviewer's verbalizations and Test Conductor's notes/comments were recorded. Selected portions of the evaluation were videotaped. Revision 1 of the DRG was implemented on a Macintosh Portable computer with 4 MB RAM and a 40 MB hard drive. The computer had a 13-inch, black-and-white, supertwist LCD screen, and a keyboard with a trackball.

At the conclusion of the evaluation, the participants completed the rating scales and questionnaire.

Data Collection

The evaluation instruments and measures used were:

- TCO
- PC
- UIRS
- RARS
- DQ
- DI

6.2.3 Results

The general findings pertaining to the DRG's technical content and DRG interface design are summarized below (for a detailed discussion, see O'Hara, 1991b). The results represent a compilation of data from several sources: UIRS, RARS, debriefing, PC, and TCO. These results were used to define modifications to the DRG (see Section 6.2.4).

6.2.3.1 Guideline Technical Content

Participant comments on technical content and recommendations for problem resolution are summarized below.

- No contradictions in guideline content were noted during the tests.

- No technical content areas were identified as missing during the tests.

- There were many abstract guidelines that were difficult to apply as review criteria. Further clarification of their content was warranted.

- Apparent duplication or redundancy was found in the guidelines.

- Some of the guidelines required measurements that test participants indicated may not be practical in a field review environment. It was recommended that, where possible, individual guidelines should be based upon simple observation with the specification of detailed measurements reserved for those guidelines where a measurement is essential, and for those cases where, based on observation, whether the guideline is violated or not. Measurement information should not be discarded but should be put in the "Additional Information" section of the guideline.

- Some terms were not used consistently across guidelines, thus, their meanings were unclear.

- Some reorganization of the material within individual sections was recommended.

- Several questionable guidelines (i.e., excessively specific or prescriptive) were encountered. It was recommended that these guidelines be further evaluated to determine their applicability to the NPP domain.

- Poor titles were identified for several guidelines.

6.2.3.2 Guideline Interface Design

Overall Usability

As part of the Function Implementation Evaluation methodology, two participants completed the Operations Sequence List. In neither case were difficulties encountered in properly executing operational functions; i.e., in no case was the user unable to perform an available function. No step required more than a few seconds to determine and complete the required action. Very few errors were observed and when an error was made, such as navigating to the wrong guideline, the error was readily identified and corrected. It should be noted that neither participant was familiar with HyperCard and only one was minimally familiar with a Macintosh operating system. Further, little briefing on the system or the DRG was provided. Thus, these findings indicate that the objective of developing a self-evident interface was largely achieved.

Overall usability of the DRG was evaluated using the UIRS and RARS. On the UIRS, the DRG was evaluated according to visual clarity, consistency, compatibility, informative feedback, explicitness, appropriate functionality, flexibility and control, error prevention and correction, and user guidance/support. While each area contained many questions to be rated, the average rating in each category is given in Table 6.1. The DRG was rated highly (3) on all usability categories except user guidance. Test participants comments indicated that the on-line help was weak and the lack of a hard-copy manual contributed to concerns in this area.

Table 6.1. Average Usability Ratings as a Function of UIRS Category[1]

USABILITY CATEGORY	NO. ITEMS	AVG. RATING[2]
Visual clarity	15	3.6
Consistency	13	3.5
Compatibility	15	3.1
Informative feedback	15	3.3
Explicitness	13	3.5
Appropriate functionality	11	3.1
Flexibility/control	15	3.5
Error prevention/correction	14	3.1
User guidance/support	05	2.6

1 Based on UIRS evaluations (N = 3).
2 Always (4, best rating) - Never (1, worst rating).

General system characteristics were also evaluated on the UIRS as presenting "no," "minor," or "major" usability problems. Only one of the 25 characteristics was rated by one participant as presenting major problems - the use of the trackball for entering evaluation and navigation information. Most other characteristics were rated as presenting "no" problems. Those presenting minor problems are discussed further below.

On the RARS, ten usability characteristics were rated on four-point scales, and the results are presented in Table 6.2. Since most of the ratings are high (≥ 3), the DRG can be said to have achieved the goal of providing an intuitive, user-friendly interface. The only moderate score was on User Satisfaction. Comments indicated that this lower rating was attributed to some difficulty encountered with the abstract nature of the technical content of some of the guidelines (as discussed), thus, making them difficult to use with respect to participant comments noted above.

Table 6.2. Average Ratings as a Function of Usability Characteristics[1]

CHARACTERISTIC	SCALE (4-1)	AVG. RATING
Overall ease of use	Easy-Difficult	3
Ease of learning	Easy-Difficult	4
Efficient use of time	Efficient-Inefficient	3.5
Minimize errors	Good-Bad	4
Ease of remembering	Easy-Difficult	4
Minimize needless inputs	Good-Bad	4
Meaningfulness of feedback	Good-Bad	4
Quality of system help	Good-Bad	3
Satisfaction	Satisfied-Dissatisfied	2.5
Response time	Fast-Slow	3

1 Based on RARS evaluations (N = 3).

General Screen Design and Organization

On the RARS, the four principal DRG screen designs were rated on four-point scales of Ease of Use and Readability. The results of these evaluations are presented in Table 6.3.

Table 6.3. Average Usability Ratings as a Function of UIRS Category[1]

SCREEN	EASE OF USE[2]	READABILITY[3]
Presentation screen	3.5	4
Evaluation Summary Screen	4	4
Context Index Screen	2.5	3
Glossary Screen	4	4

1 Based on RARS evaluations (N = 3).
2 Ease of Use: Very Easy (4) - Very Difficult (1).
3 Readability: Very Easy (4) - Very Difficult (1).

Again, most of the ratings are high (≥ 3), indicating that while improvements can be made, the screen designs are acceptable. The only moderate score was for the ease of use of the context index screen. Comments indicated this was attributed to perception of high information density.

General Functions and Controls

The RARS was used to obtain ratings of the interactive document functionality on four-point scales of Usefulness and Ease of Use. These results have been compiled in Table 6.4, although the data will be discussed here as well as in subsequent sections addressing the specific areas of document functionality (such as Table of Contents).

Table 6.4. Average Usability Ratings as a Function of UIRS Category[1]

FUNCTION	USEFULNESS[2]	EASE OF USE[3]
Table of contents	3.5	3
Glossary function	2.5	3.5
Index function	4	3
Evaluation function	3	2
Reviewer remarks function	4	3
Reporting function	3	1
Search functions	3.5	3
Navigation functions	N/A	3.5
Edit	N/A	4
Input information	N/A	1.5

1 Based on UIRS evaluations (N = 3).
2 Usefulness: Very Useful (4) - Useless (1).
3 Ease of Use: Very Easy (4) - Very Difficult (1).

The general ratings of the usefulness of most system characteristics were high (≥ 3), with the exception of the glossary function. With respect to ease of use of the functions, the ratings were not as high. This indicated that although the functions were generally considered useful, their implementation in the interactive document needed improvement. The input of information was rated low. Comments indicated that this was due to the complete reliance on trackball/mouse input for evaluation and navigation functions. The use of direct manipulation techniques for input of evaluation (such as "pass") and some navigation functions (such as "next" guideline) was found to be cumbersome.

Keyboard command options for all major evaluation and navigation functions were recommended.

Another comment indicated that initial selection of the guidelines appropriate for review is cumbersome. A review planner was recommended for up-front guideline selection.

Table of Contents

As indicated in Table 6.4, the Table of Contents was rated high on both usefulness and ease of use, although some minor difficulties were noted. When the "Table of Contents" button was activated, a message appeared indicating that the mouse button must be held down. However, the message did not appear long enough to be read easily. Further, this requirement was inconsistent with the point and click characteristic of the rest of the interface.

Glossary

As indicated in Table 6.4, the glossary was rated high on ease of use but not on usefulness. This was principally due to its poor correlation with the content of the guideline. It should be noted that while a glossary function was built into the DRG, at the time of the Development Test, little effort was spent developing definitions of words specific to the area of human-computer interface and advanced HSI technology.

Context Index

The context index function was rated high on both usefulness and ease of use.

Evaluation Functions

The evaluation functions were rated high on usefulness but difficulties in ease of use were encountered. Participant comments indicated that this was mainly due to the need to enter evaluations with the mouse/trackball and the use of keyboard inputs to simplify entry of these data was recommended. Also part of the evaluation function was the capability for comments into the interactive document. This is listed separately on Table 6.4. This function was rated high on both usefulness and ease of use. Minor difficulties were noted, including the need for an evaluation option to return to a guideline. A reviewer could specify that a guideline is applicable, but that additional information to evaluate it is required. Such an option should be linked to a reason for returning, e.g., need operator input, measuring instrument, clarification, and documentation.

Report Functions

As indicated in Table 6.4, the reporting functions were rated high on usefulness, but difficulties in ease of use were encountered. Comments indicated that this was mainly due to problems in the reporting process and time required to generate reports.

Location Functions

No specific rating scales were included to evaluate the participant's sense of location in the DRG. However, comments on this topic indicated that the transition from one section of the DRG to the next occurs without any cue and that this was something disorienting.

Navigation Functions

As indicated in Table 6.4, the navigation functions were rated high on ease of use. Recommended improvements included:

- A "next section" button, so the reviewer would not have to go back to the Table of Contents or page through the individual guidelines to switch sections,

- A button for retracing the previous steps through the document, and

- A placemarker so that the reviewer could return to the location where the guidelines were exited.

Search Functions

As indicated in Table 6.4, the search functions were rated high on both usefulness and ease of use. However, the search function was not sufficiently intuitive, i.e., it was not clear exactly how the search function worked. Further, inadvertent clicks in fields invoked a jump to the current search term. This was problematic since there was no means of backtracking to the previous location.

Edit Functions

As indicated in Table 6.4, the edit functions were rated high on ease of use. However, it should be noted that only very minor editing was attempted using the HyperCard text edit capability. More extensive editing would be accomplished with word processing applications rather than from within HyperCard.

Help/Feedback/Guidance

Rating scales for help, feedback, and general user guidance were included in Table 6.1 (see "User guidance/support") and Table 6.2 (see "Meaningfulness of feedback" and "Quality of system help"). While help and feedback were rated high on ease of use, reviewer guidance was found to be lacking. In general, some waiting states were poorly indicated and status messages were not always informative as to what the system was doing.

6.2.4 Development Test Conclusions

While the technical content received only a limited evaluation, one general conclusion to emerge was that the content of many guidelines was sufficiently abstract to make guideline interpretation difficult. This problem is, in part, indicative of generally recognized limitation of guidelines in the area of advanced technology HSI and of human-computer interface guidelines in particular. There are many reasons for this, including limitations in the technical basis for guidance development due to deficiencies in scientific knowledge and industry experience with advanced technology (see Section 2 for more discussion). Inconsistent wording also contributed to participants' difficulty with some guidelines.

General DRG usability was found to be good. On both the UIRS and RARS, most interface characteristics indicative of usability (such as visual clarity, consistency, explicitness, ease of use, ease of learning and remembering, and response time) were rated highly. Some difficulties were encountered, mainly in the areas of input devices, reporting, and help functions. It should be noted that the two participants in the Functional Implementation Evaluation had little difficulty exercising system functions.

Based on these results, modifications addressing the noted concerns were made, including:

- Redesign of the review screen.
- Addition of an evaluation option for returning to the present guideline.
- Improvement of the Table of Contents function to make it easier to use.
- Improvement in location/navigation functions.
- Improvement to search functions.
- Improvement in the reporting function to make it more reliable.
- Improvement of the consistency across screens.
- Provision for input of evaluation and navigation functions via keyboard.

The DRG was also modified to improve its technical content. The guidelines were reviewed to eliminate redundancy, revise technical terminology to ensure better consistency throughout the document, and ensure better consistency between the titles and contents of each section. Several hundred guidelines were eliminated.

The modifications resulted in Revision 2 of the DRG used in the User Test and Workshop evaluations.

6.3 User Test

The User Test was a field test of the DRG in environments of greater fidelity to an ACR and encompassing a greater diversity of ACR technologies than the Development Test. Independent volunteer reviewers conducted evaluations using the DRG. Therefore, the User Test was a simulation of the actual DRG utilization. A complete description of the User Test can be found in O'Hara, 1992a.

6.3.1 Objectives

Both Technical Content and Guideline Implementation objectives were assessed. With respect to Technical Content, the objectives of guideline scope and guideline content were evaluated. Issues related to technical basis and validity were addressed in the Peer-Review Workshop (see Section 6.4) and not in this test. Since the test participants were unfamiliar with the use of the interactive document, the user test was well-suited for evaluation of the Guideline Implementation objectives. Specifically, the objectives of design objectives analysis evaluation, interactive document functionality, and usability as an inspection aid were evaluated.

6.3.2 Methodology

6.3.2.1 Test Participants

The goal of the test was to obtain results from volunteer participants who were experienced human factors professionals. Complete test materials were sent to five experienced individuals who agreed to participate. Problems occurred obtaining access to CR simulators at two facilities within the time available. Thus, the results described below are based on three reviews. The participating organizations were:

- General Physics,
- Science Applications International, Corp. (SAIC), and
- Oak Ridge National Laboratory (ORNL).

6.3.2.2 Test Sites

Participants used the DRG for HSI reviews of:

- An ACR prototype at a national laboratory employing a large overview display and several workstations, each utilizing window displays and keyboard/mouse input devices,

- A commercial fossil power plant having a computerized CR, and

- A highly-automated NPP in Europe employing advanced I&C technology.

6.3.2.3 Procedures

The test procedure can be divided into four components: Familiarization, DRG Utilization, Data Collection, and Debriefing, as described below.

Familiarization

Each participant was contacted by telephone to solicit their assistance in the study. A general overview of the project was provided. In addition, an explanation as to what was expected of participants in terms of DRG utilization and data collection were provided, and they were assured confidentiality. Once participants agreed to take part in the study, they were sent a formal familiarization package and a copy of the guidelines. All received a hardcopy of the DRG (Revision 2), and those with Macintosh capability received an interactive version. Two of the participants used the interactive version of the DRG and one the hardcopy. The familiarization package contained:

- DRG development description,
- DRG technical content description,
- Interactive document functionality description,
- Interactive document functionality familiarization exercise, and
- Interactive document installation instructions.

Guideline Utilization

Following familiarization, the DRG was used to evaluate part of the identified HSI. The participants selected the appropriate sections of the DRG for their evaluation and proceeded with the review.

Data Collection

The principal method of data collection was through the evaluation package. While the package contained several checklists and open-ended questions, only one of the participants filled out the data forms in their entirety. The other two participants preferred to provide their evaluations in narrative form.

Debriefing

All participants were debriefed by telephone following the study.

6.3.3 Results

The test objectives were related to the DRG's technical content (overall scope, organization, and level of detail) and implementation (interactive document functionality and usability for conducting reviews). The results of the user tests were consolidated and organized by these objective areas.

6.3.3.1 Technical Content

The DRG was evaluated as generally comprehensive in scope with most topics addressed; no contradictions or inconsistencies were identified. Some review areas were found incomplete, including large screen displays, group displays, displays with integrated controls, and guidelines for automated systems and function allocation. To some extent, this finding reflects the fact that general HFE guidance is weak in these areas. In addition, the DRG did not include guidance from NUREG-0700, which was intentionally left out. Thus, the DRG was weak in the area of conventional technology and general CR configuration.

Consistent with results of the Development Test, the participants found some guidelines vague and difficult to apply. It was recommended that additional tables, figures, and illustrations be included to facilitate an understanding of abstract guidelines.

6.3.3.2 Guideline Implementation

Review Preparation

With respect to review preparation:

- One reviewer indicated that the task of evaluating an entire CR would require the review of too many displays. A method to sample displays should be developed to enable reviewers to identify a subset of the entire CR display.

- All participants indicated that some form of review planning assistance was needed to facilitate the selection of guidelines relevant to the review.

Guideline Organization

To optimize a reviewer's time spent in a CR and other review activities, it was recommended that the guidelines be organized into five categories based on DRGs that:

- should be addressed only once,
- need many reviews (e.g., on all displays),
- can be reviewed against a documented design specification (rather than the actual CR),
- require an observation of (or interview with) operators based upon performance using the display, and
- are not used for a specific review.

Guideline Functions

The functions evaluated included the table of contents function, context functions, glossary function, navigation functions, search functions, evaluation functions, reviewer comments function, and reporting functions. All functions with the exception of reporting were rated highly on both usefulness and ease of use. The reporting function was problematic because too much time was required. Long response time was also mentioned as an occasional issue for navigation functions.

On a summary of usability testing dimensions, the DRG was rated on a five-point scale from Very Unsatisfactory (1) to Very Satisfactory (5). The results are provided in Table 6.5. Note that the actual ratings come from only one participant. The other two participants were queried in debriefings as to these topic areas. One did not use the interactive document, and could not comment. The other participant's comments regarding usability were generally favorable and consistent with the results in Table 6.5.

Table 6.5. Usability Ratings as a Function[1] of UIRS Category

USABILITY CATEGORY	RATING[2]
Visual clarity	5
Consistency	5
Compatibility	4
Informative feedback	4
Explicitness	4
Appropriate functionality	4
Flexibility/control	3
Error prevention/correction	4
User guidance/support	5

1 Based on UIRS evaluations (N = 1).
2 Always (5, best rating) - Never (1, worst rating).

It was clear from comments received that the participants were not fully aware of all the interactive document's functional capabilities. For example, one participant commented that keyboard entry for evaluation functions would have been useful apparently unaware that the capability to accept single key-stroke evaluation entry was available. (Participants received only a familiarization package since no user's manual was available.)

Screen Design

The main review screen of the interactive document was also evaluated. It was rated highly for readability and ease of use.

6.3.4 User Test Conclusions

The main conclusions of the User Test were that:

1. The technical content of the DRG was generally comprehensive in scope and free of contradictions and inconsistencies. (Some areas of weakness were identified.)

2. Additional support was required for review planning and guideline selection for specific reviews.

3. The interactive DRG's functions and screen designs were rated highly in terms of usefulness, ease of use, and general dimensions of usability evaluation. The major difficulties encountered were related to speed of function execution, especially the reporting function.

6.4 Peer-Review Workshop

The Workshop methods and results are summarized in this section. A complete description can be found in O'Hara, 1992b.

6.4.1 Objective

The purpose of the Workshop was to assess the DRG in terms of its technical merit to achieve the NRC goal of developing a tool to support human factors reviews of ACR technology. The overall objective of the Workshop can be divided into three categories: technical basis/validity, scope, and content. The specific objectives in each category are elaborated below.

- Technical Basis/Validity

  - To determine if the technical basis of the DRG is valid, i.e., based upon empirical research and/or consistent with current human engineering practice.

- Scope

  - Within the current scope of computer-based controls and displays, to determine if the DRG covers all aspects of advanced controls and displays required for the evaluation of ACRs and/or advanced technology upgrades in existing plants.

  - To identify HSI technology areas for which available review guidance is deficient or missing.

- Content

  - To determine if the topical organization is appropriate for conducting HFE reviews.
  - To determine if the guidelines presented in each section are adequate for the evaluation of HSIs in the areas covered.
  - To determine if the information available for each guideline is sufficient to provide a basis for evaluation.

- To determine whether the information is presented at an appropriate level of resolution (e.g., enough detail but not overly prescriptive).
- To determine if there are any internal conflicts or contradictions in the DRG.

6.4.2 Methodology

6.4.2.1 Participants

Thirteen individuals were invited by BNL to participate as subject matter experts (SMEs). The SMEs were selected based upon their expertise with one or more of the following: (1) human factors evaluations of advanced systems, (2) inspections of NPP CRs, (3) NRC regulatory reviews, and (4) advanced NPP CR technology. Several additional observers were present from BNL, the NRC, workshop organizers, and others. Two of the SMEs were unable to attend the workshop but provided comments following the protocol established for all attendees. A list of the organizations represented by these individuals is presented below:

- OECD - Halden Reactor Project,
- Electric Power Research Institute,
- Toshiba Corporation - (ABWR Program),
- Atomic Energy of Canada, Ltd. (AECL),
- Tennessee Valley Authority,
- Electricite de France (EDF),
- Ontario Hydro,
- Westinghouse Electric Corporation,
- General Physics,
- Science Applications International, Corp. (SAIC),
- U.S. Air Force - Wright Patterson Air Force Base (AFB), and
- NASA, Lyndon B. Johnson (LBJ) Space Center.

In the remainder of this section, the term "reviewer" refers to the eventual users of the DRG to conduct NRC HSI safety reviews.

6.4.2.2 Location

The workshop was held at the Sheridan Research Park Conference Center in Mississauga, Ontario (a suburb of Toronto), on June 16-18, 1992.

6.4.2.3 DRG Materials Reviewed

The principal materials subject to peer review were:

- Advanced Human-System Interface Design Review Guideline (Revision 2): Volume 1 - Technical Development (BNL Technical Report L1317-2-5/92).

- Advanced Human-System Interface Design Review Guideline (Revision 2): Volume 2 - HFE Guidelines (BNL Technical Report L1317-2-5/92).

Interactive versions of the DRG were available during the Workshop.

6.4.2.4 Workshop Structure

The workshop included three activities: preparation, conduct, and post-workshop follow-up.

Preparation

All SMEs were sent the DRG materials described above approximately two weeks prior to the workshop. In addition, several SMEs received the interactive, computer-based version of the DRG. They were also sent a list of suggested review topics ranging from high-level questions such as "What are the key human factors issues that may impact safety in an advanced nuclear power plant?," to specific and detailed questions regarding the DRG's breadth, organization, source documents, and utility as a review aid.

Meeting

The workshop was structured in three phases: orientation, working groups, and closing plenary session. In the orientation session, on the first day, an overview of the DRG's basis and technical development was provided. Revision 2 of the DRG was described and a demonstration of the interactive document was given. The orientation phase was concluded with a visit to the control center of the Darlington Nuclear Power Station for the purpose of providing an example of a CR utilizing the types of technology addressed by the DRG.

On the second day of the workshop, the SMEs were divided into three working groups. In addition to SMEs, each working group had a chairperson who acted as a facilitator and secretary to record comments and prepare working group minutes. The working groups were guided by a review agenda.

The closing plenary session was held on the third day. A summary of the results of each working group was presented by the chairpersons. Afterward, the floor was opened to general discussion.

Follow-up

Following the workshop, additional discussions were held with several SMEs to provide further evaluation and clarification. Telephone discussions were held with the two SMEs unable to attend the workshop to obtain their comments.

6.4.3 Results and Discussion

This section is organized by the main objectives of the workshop; i.e., assessment of the DRG with respect to technical basis/validity, scope, and content. In addition, the issue of review procedures is addressed.

6.4.3.1 Technical Basis/Validity

One principal objective of the workshop was to determine if the technical basis of the DRG was valid, i.e., based upon empirical research and/or consistent with current human engineering practice. SME comments supported the technical basis on which the guidelines were developed. The primary source documents were considered appropriate. It was suggested that the list of primary source documents be expanded.

6.4.3.2 Scope

The main objectives of this area were to determine (1) if the DRG covers all aspects of advanced controls and displays required for the evaluation of ACRs and/or advanced technology upgrades in existing plants within its present scope and (2) if the review areas have been identified for which available guidance is deficient or missing.

SME comments on the first point generally addressed issues beyond the scope of the DRG. For example, while the DRG's scope was computer-based interfaces, it was noted that guidance is lacking in the area of the conventional technology. Other scope-expansion comments addressed the need for attention to areas such as function allocation and task analysis which were not addressed in the DRG.

With regard to review areas for which available guidance is deficient or missing, several new topics were identified and confirmatory comments were provided for those topics already defined as weak. Additional areas in need of guidance development identified were:

- Large screen displays,
- Ambient lighting systems,
- Soft controls and integrated controls,
- Use of video,
- Maintenance,
- Display customization (operator capability to format displays),
- Noise, and
- Advanced operator aids other than expert systems.

6.4.3.3 Content

Several objectives relating to content were addressed as identified above. In general, the HFE PRM was considered an appropriate review scheme for advanced reactors. The guidelines were evaluated to be technically valid and appropriate for application in safety reviews. However, several improvements were recommended, which can be divided into two main categories: prioritization and level of resolution.

Prioritization

The SMEs expressed concern that the number of guidelines (approximately 1,900) was large enough to make the DRG's use as a practical review tool somewhat cumbersome. The SMEs recommended the development of further prioritization to identify a smaller set of key guidelines that would principally guide the NRC review.

Level of Resolution

Related to the issue of priority is the issue of level of resolution. Concern was expressed about the differential level of resolution of individual guidelines. Some are relatively general and may be subject to different interpretations by reviewers. Other guidelines were thought to address details of HSI design that may not be of concern to reviewers. Few specific recommendations were made concerning how to address these two issues.

The appropriate level of resolution of HFE guidelines is a difficult issue which depends, in part, on a document's intended use. The DRG must be capable of supporting reviews of diverse HSI designs. Judging the level of resolution that is appropriate for a review document involves balancing the generality required to support breadth of coverage and the specificity to support ease of use and reliability of reviewer judgements. This represents a tradeoff because increasing generality increases breadth of coverage but decreases ease of use. As specificity increases, the guideline becomes easier to use with greater inter-rater reliability, but (1) its breadth of coverage decreases, (2) the guidelines become more prescriptive, and (3) increasingly tend to preclude design options.

Making general guidelines more specific can be inappropriate for a review guidance document that will be used for many different CR designs. Typically, guidelines are worded in general terms when they represent a general principal which is not amenable to more specific definition in the absence of a specific application. For example, the guideline presented below cannot be made more specific if it is to be used by NRC reviewers to evaluate a wide range of CR designs. Instead, the guideline must be interpreted within the context of a specific CR review and the operator tasks that the display is intended to support.

Necessary Data Displayed
All data required for any transaction should be available for display.
COMMENT: Displayed data should be tailored to user needs, providing only necessary and immediately usable data for any transaction; displays should not be overloaded with extraneous data.
SOURCE: ESD-TR-86-278

The presence of guidelines that are too detailed poses a different problem. The implication is that some guidelines are not important enough to impact operator. It is difficult, given the state-of-the-art concerning our understanding of the effects of individual design factors on human performance, to confidently judge that a given guideline will be unimportant in each and every review context. At the Workshop, the guideline below was used as an example of a guideline that was too detailed:

Conventional Use of Mixed Case
Text should be presented using upper and lower case characters.
COMMENT: Reading text is easier and faster when capitalization is used conventionally to start sentences and to indicate proper nouns and acronyms. There are several exceptions, however. An item intended to attract the user's attention, such as a label or title, might be displayed in upper case. Also, upper case should be used when lower case letters will have decreased legibility, e.g., on a display terminal that cannot show true descenders for lower case letters.
SOURCE: DoD-HDBK-761A; NASA USE-1000; and ESD-TR-86-278

In CR designs where little text-based information is presented, this guideline would be inapplicable or of very low priority. However, if the CR design incorporated computer-based EOPs, computer-based alarm response procedures, or some other more "text-intensive" VDU displays, then supporting the readability of text becomes quite important. This is especially true considering research that text readability is diminished when presented on VDUs as compared with conventional paper presentations. This guideline was considered to be important enough to appear in three of the primary sources.

The importance of individual guidelines is a function of the review context. In general, therefore, it may be more appropriate to address guidelines judged to be of lesser importance within the context of prioritization (as discussed above) rather than by eliminating them. Thus, the determination that an individual guideline is important or not should be made by the NRC reviewer based upon the requirements of each individual review.

Additional specific comments were received relative to individual guidelines and organization not individually addressed here. (Each such comment was evaluated as part of the development of the current version of the DRG.)

6.4.3.4 Review Procedure

The SMEs identified the need for a procedure for DRG use. Recommendations included:

- Specification and organization of prerequisite information (like operator task information),
- Algorithm for selection of HSI characteristics to be evaluated (e.g., individual displays to be reviewed),
- Selection of appropriate guidelines for a specific HSI review,
- Required review team skills,
- Use and interpretation of evaluation results, and
- Integration with other aspects of a review.

6.4.4 Workshop Conclusions

The primary purpose of the Workshop was to assess the DRG in terms of its technical merit for achieving the NRC goal of developing a tool to support human factors reviews of ACR technology. The overall objective was divided further into three categories: technical basis/validity, scope, and content. The Workshop successfully provided peer review in each of these areas.

The HFE PRM was considered an appropriate review scheme for advanced reactors. SMEs supported the technical basis on which the guidelines were developed. The primary source documents were considered an appropriate and valid source of guidance. With respect to scope, several areas of weakness were identified. These guidelines were evaluated to be appropriate for application in safety reviews, however, several further developments were recommended before the DRG is put to use in NRC reviews.

6.5 Overall Conclusions from the Test and Evaluation Program

6.5.1 Technical Merit

The T&E program resulted in several general conclusions regarding the technical merit of the DRG.

1. The HFE PRM was found comprehensive and appropriate to the review of advanced HSIs in NPPs, although several aspects of the model not developed in detail would need further specification (see Section 7).

2. The technical basis of the guidelines was evaluated as valid. It was recommended that the number of guidelines be reduced (there were more than 1,900 guidelines in Revision 2) and layered to better identify key guidelines in each section.

3. Review guidance in some areas to advanced HSI was weak or absent.

4. A procedure for DRG use was needed (Revision 2 did not have an explicit procedure).

6.5.2 Modifications to the Guideline

Based on the results of the User Test and Peer-Review Workshop, many modifications were made to Revision 2 of the DRG, which lead to the current version described in detail in Volume 2 of this report. In this section, a brief overview of the major technical modifications is provided. Details on these modifications can be found in the guidelines and interactive document description in this report.

1. The guidelines were reorganized to reflect the comments of T&E participants. Planned redundancy in Revision 2 was eliminated in favor of layering, resulting in an approximately 40 percent reduction in the number of guidelines.

2. Individual guidelines were extensively edited, and terminology was made more consistent.

3. Procedures for the use of the DRG were developed and are described in detail in Volume 2.

4. A Review Planning Utility in the interactive document was developed to support guideline selection for specific reviews. The function selection screen provides entry to the planning utility as described in Section 5.

5. A Guideline Maintenance function was developed to support NRC modification and update of the guidelines as described in Section 5.

6. A detailed glossary was developed.

7. DRG WEAKNESSES AND A METHODOLOGY FOR FURTHER GUIDELINE DEVELOPMENT

In this section, several topics related to further DRG development are discussed:

- DRG weaknesses (Section 7.1), and

- Guidance development methodology and criteria by which new guidelines can be added to the DRG (Section 7.2).

7.1 DRG Weaknesses

This section describes HSI design areas that require additional effort to better support the design reviews. The topics were prioritized based on: (1) significance of the topic to crew performance and safety, (2) anticipated near-term need, and (3) availability of existing criteria if further development was not pursued by the NRC. Since these factors were judgmentally applied, only two priorities were assigned:

- Priority 1 - an important area, needed in the near term, with little interim guidance.
- Priority 2 - remaining topics.

Weaknesses and gaps in the DRG guidance were identified and prioritized based upon multiple sources, including:

- An identification of gaps between identified HSI technology and the guidance available in the DRG,

- The results of the testing program, and

- The results of the peer-review workshop.

A listing of the identified and prioritized weaknesses and gaps is presented in Table 7.1.

Table 7.1. Guideline Priorities

PRIORITY 1	PRIORITY 2
Alarm Systems	Knowledge-Based Systems & Aids
Graphical Presentation of NPP Concepts	Flat Panel Display Characteristics
Computer-Based Procedures	Visual Display Hardware Characteristics
Automation Interface Methodologies	New Input Devices & Soft Controls
Interface Management	Computer-Based Workstation Integration
Large-Screen Displays	Computer-Based CR Layout & Environment
Advanced-Conventional Integration	Test & Maintenance of Digital Systems

Alarm Systems

The human factors issues of NPP alarm systems have been persistent. Recent efforts to improve these systems have incorporated alarm filtering and prioritization techniques and more sophisticated methods of alarm display (see O'Hara, Brown, and Kim, 1991, for a review of human factors issues associated with advanced alarm systems). Review guidance on advanced alarm system characteristics is needed.

Graphical Presentation of NPP Concepts, Status, Information, and Data - Priority 1

A vast number of graphic display techniques for representing plant/system status, information, and numerical data are available. In order to make the most effective use of these screen design techniques, research is needed on the effects that various graphic data display techniques have on operator perception and assimilation of information. Specific areas where further guideline development is needed are:

- Display requirement for crew (as a group) and individual operator situation awareness.
- Displays supporting various levels of abstraction and ecological interface design.
- Display formats (e.g., mimic diagrams, trend displays, flowcharts, simulated meters, surface charts, segmented column histograms).
- Display elements using highlighting, spatial relationships, and animation (see Tullis, 1988, for a detailed discussion).
- The integration of display format and graphic techniques such as displays that integrate multiple formats.
- Integration of controls into displays (such as on-screen or soft controls).
- The dynamic characteristics of displays.
- Integration of workstation displays with large-screen displays.

Also of interest in this area is video and display customization (operator capability to re-format displays).

Computer-Based Procedures - Priority 1

Procedures (especially EOPs) play a very important role in NPP safety. In several ACR designs, procedures are provided in computerized form. In some cases, the computerization is simple and merely represents a VDU version of paper procedures. In other cases, the procedures are fully integrated with the plant data management systems. Guidance for the review of the computerization of procedures and for the integration of procedures with plant data are needed.

Automation Interface Monitoring and Control Methodologies - Priority 1

Advanced reactor designs will likely involve more sophisticated interactions between operators and automated systems than currently exists (see IAEA, 1991). This will include task sharing, task trading, and sequence automation; e.g., at certain points the automated process stops until the operator authorizes the system to proceed. Thus, the operator plays a more active "monitoring" role than is traditionally the case with automated processes. Guidelines for these types of human-system interaction are not available and need to be developed.

Interface Management and Navigational Strategies - Priority 1

Managing the interface of a computer-based workstation can impose significant workload on the operator not related to the primary task of monitoring and supervising the process control system. Typical interface management tasks include:

- Display paging vs. framing,
- User-system dialogue,
- Navigation between displays,
- Display selection,
- Navigation within display hierarchies (such as seeking the next level display),
- Window control/management, and
- Display controls such as pan, zoom, scroll.

These "secondary" tasks will compete for cognitive resources which would be better allocated to the primary task. Further research is needed on the balance between workstation flexibility and the imposition of interface management workload on operators.

Large-Screen Displays - Priority 1

Large-screen displays are a significant design feature in most advanced reactor designs. The DRG provides some guidance for the review of physical aspects of large screen displays. However, these guidelines fail to address the specific NPP usage of such displays as devices to provide critical plant information, to serve as a focal point of crew situation awareness (the group view display concept), to allocate information to large-screen and workstation-based displays, and to control/integrate displays on a large screen and workstations.

Integration of Advanced Technology into Conventional Control Rooms - Priority 1

As plants age and equipment is replaced, the opportunity to replace systems with digital technology increases. As a result, the CR becomes an increasing mix of conventional and advanced technology. The introduction of digital technology into a conventional CR can pose safety issues since the operator's tasks and methods of interacting with the system change and operators will now need to cope with both types of interfaces simultaneously. Guidelines for the review of this integration are needed.

Knowledge-Based Systems and Intelligent Operator Aids - Priority 2

Operators in future CRs will be provided with many different types of intelligent aids. Despite the emergence of many books on the subject, the availability of validated human factors guidelines for these systems is limited, as is industry experience with their use in actual systems.

Flat Panel Display Characteristics - Priority 2

Flat panel displays have been identified as a potential display technology for use in advanced NPP CRs of the future. Among these flat panel displays are light emitting diodes, plasma displays, thin film electroluminescence, electrochromics, electrophoretics, and liquid crystals. According to manufacturer specifications, flat panel technology appears to be compatible with requirements of the human visual system (e.g., in terms of contrast and viewing angles). However, little human factors guidance exists on these technologies, at least within the primary documents surveyed (for example, the "American National Standard for HFE of Visual Display Workstations" (HFS, 1988) does not address flat panel displays, and the measurement of display resolution for color CRTs is not developed).

VDU Hardware Characteristics - Priority 2

Human factors guidelines lacked many of the VDU variables which impact specific aspects of the readability and legibility (see Snyder and Bogle, 1989, for a detailed discussion). Specific areas where additional guidelines are needed include:

- The measurement of raster modulation for color displays,
- Determination of appropriate maximum character and background contrast ratio,
- Determination of polarity recommendations,
- A requirement for luminance uniformity (acceptable variation in luminance),
- Selection and specification of suitable color coding metrics and color spaces,
- Character, line, and word spacing for emissive displays, and
- Flicker sensitivity.

New Input Devices, Soft Switches, and Multifunction Displays/Controls - Priority 2

While many guidelines exist for the more traditional methods of interacting with VDUs (i.e., displacement keyboards), guidance is sparse for some of the more recently developed input approaches, such as membrane keyboards, head movement controllers, glove controllers, and multi degree-of-freedom (>3) handcontrollers. While more guidance was found for other devices (e.g., mice, light pens, touch input devices), it is not as complete as that for displacement keyboards. Since keyboards have been the primary input devices for computers, this is not surprising. However, with the recent advances made in display and computing technology, graphic displays are becoming more accessible. With the benefits associated with graphic (direct manipulation) user interfaces, new methods for interacting with these displays are being explored and human factors guidelines for these new input devices are needed.

Computer-Based Workstation Integration - Priority 2

This topic addresses the integration of alarms, VDUs, indicators, soft controls, and hard controls, into workstation consoles. This topic is not covered in the DRG. The guidance provided in NUREG-

0700 is oriented toward conventional hardware and, therefore, is not completely appropriate to more compact, seated-operator, virtual workstations.

Computer-Based Control Room Layout and Environment - Priority 2

This area addresses the integration of computer-based workstations, supervisor's consoles, and large screen displays into a supportive work environment for crew tasks. Ambient lighting systems and environmental considerations for computer-based CRs need to be reviewed by the NRC. Like workstation integration (discussed above), this topic is not covered in the DRG, and the guidance provided in NUREG-0700 is oriented toward conventional hardware.

Test and Maintenance of Digital Systems - Priority 2

Digital systems offer new opportunities both to eliminate past human errors and create new human errors that are not well understood by the human factors community. This area requires development of review guidance to support staff evaluations of interfaces and procedures for test and maintenance of digital systems.

7.2 Guideline Development Methodology

In the selection of primary source documents to serve as the technical basis for the DRG, a high priority was given to assure the validity of the guidelines (as discussed in Section 4). A similar approach should be followed for further guideline inclusion. However, since the development of further guidance will likely involve (1) documents below the classification of primary and (2) new data collection and research, the concepts will have to be applied differently.

When developing human factors guidelines and acceptance criteria, it is generally most efficient, in terms of resources, to incorporate relevant sections of other acceptable existing guidelines whenever possible. However, due to the high rate of innovation within HSI technologies, newer issues of human performance may not be addressed by existing human factors guidelines. In addition, existing human factors guidelines may not address issues that are specific to NPP operation. Therefore, it is necessary to develop additional guidance and acceptance criteria from a variety of methodological approaches, including:

- Primary and secondary source documents,
- Tertiary source documents,
- Basic literature,
- Industry experience,
- Original research.

The basic methodology is illustrated in Figure 7.1. Once an area needing guidance is identified, the potential source material for guidance development is addressed. In Figure 7.1, the sources are listed in order of decreasing cost-effectiveness. (Note in Figure 7.1 that potential source documents in the first two boxes are contained in the HFE Source Document Database described in Section 4 of this report.) The guidance developer may proceed through the flow chart in the order proposed. However, it should be noted that a set of guidelines for a topic area may require a combination of some or all of these sources (e.g., development of guidance for advanced alarm systems is utilizing all sources).

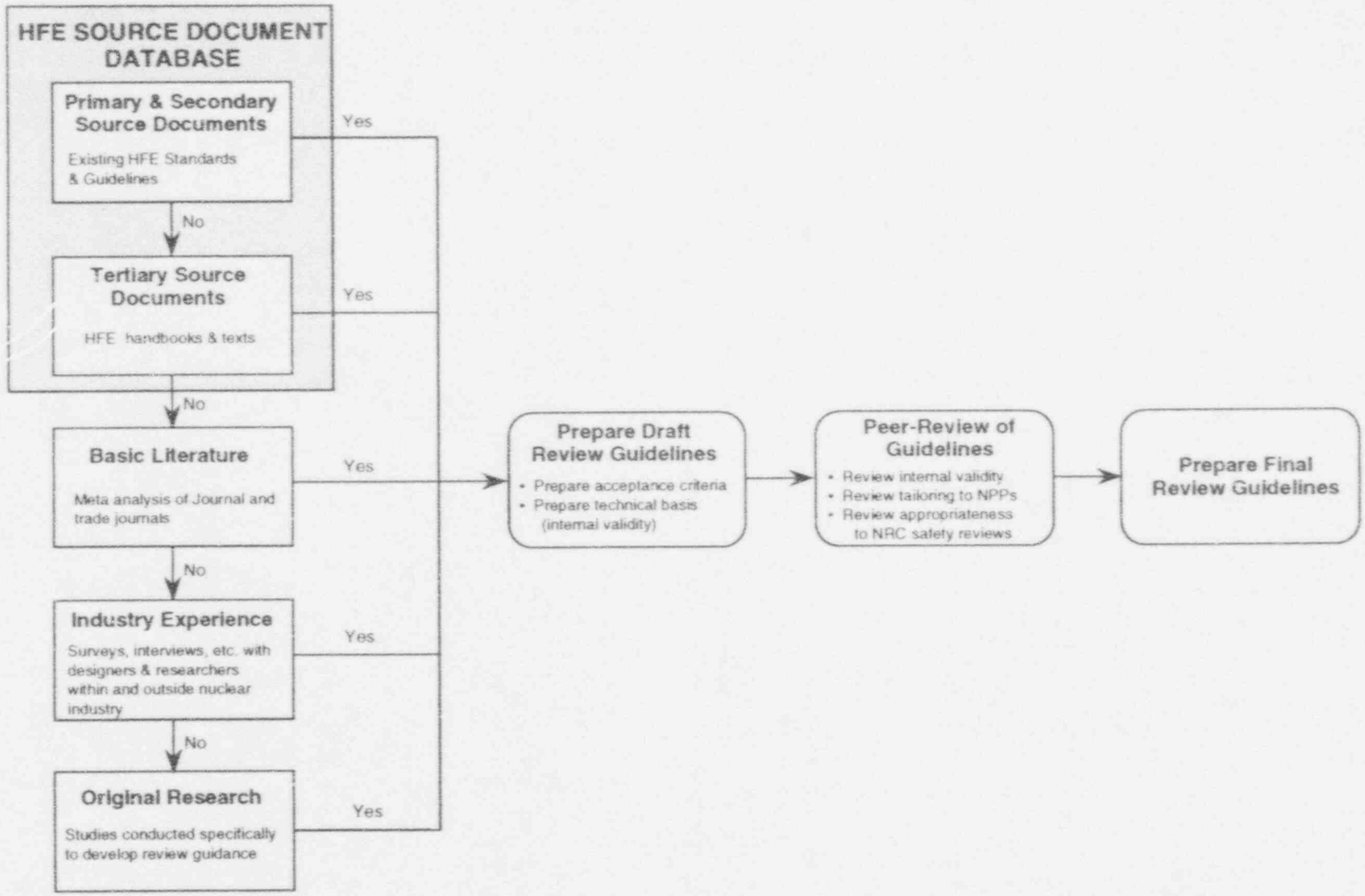

Figure 7.1. Guidelines and acceptance criteria development methodology

The meaning of the terms primary, secondary, and tertiary source documents corresponds to the classification described in Section 4. Primary source documents are guidelines documents with internal and external validity, while secondary source documents possess either internal or external validity. Tertiary documents are typical HFE handbooks and texts, rather than guideline documents, and lack demonstrated internal or external validity. Handbooks and texts, however, represent a compilation of human factors knowledge for specific topics, and guidelines can be derived from these documents with relatively little effort (compared with the final three sources).

In areas of guideline development that cannot be addressed from primary, secondary or tertiary sources, more labor-intensive approaches may be followed. Guideline developers may compile results from basic literature such as articles from refereed technical journals, reports from research organizations, and papers from technical conferences. A meta-analysis of these sources should be performed to provide a technical basis for review guidance.

Industry experience is a valuable source for identifying human performance issues and tested design solutions that are of particular interest to a specific domain (e.g., NPP operation). This information may be obtained from sources such as published case studies and surveys/interviews with knowledgeable domain experts. Although this information may lack a rigorous experimental basis, it does have the benefits of high relevance and high face validity.

The most resource-intensive method is original research which may be appropriate when sufficient guidance does not exist in the sources described above or when additional experimentation is desired to provide supporting evidence. Independent research has the advantage of being focused on specific issues of interest. Interpretation of results for the problem domain (e.g., NPP operation) is more straightforward for this type of research than for general research. Independent research, therefore, has both high relevance and an experimental basis.

Once the source methodology is executed, a draft set of guidelines should be developed, which would be evaluated according to the criteria in Section 4. The guidelines should contain the specific acceptance criteria to be used by the NRC reviewer and the technical basis on which the guideline was formulated. This will provide the basis for evaluating the *internal validity* of the guidelines. The type of technical basis will vary depending on the source material. Evaluation of the guidance and its technical basis should be made by a peer-review panel of subject matter experts. This panel will evaluate:

- Internal validity of the guidance,
- Tailoring of the guideline to NPPs, and
- Appropriateness of the guideline to NRC safety reviews.

Peer review will constitute the *external validation* of the guidelines.

By incorporation of additional guidance in this way, the DRG can maintain the validity of its technical content.

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Appendix A
Prototype Interactive Document Description

Section 5 discussed the development of the prototype interactive Design Review Guideline (DRG). This appendix will briefly describe the prototype's database structure, functions, and interfaces.

A.1 Database Description

As discussed in Section 5, the prototype was developed on an Apple MacIntosh™ and the guidelines are stored in a HyperCard™ (Version 2.1) database file (called a stack). Each guideline is represented as a single record (called a card) and includes 10 fields (called containers).

1. *Section Field* - contains the numeric sequence number and title for the Guideline Section (e.g., Section 1. Information Display).

2. *Sub-Section Field* - contains the numeric sequence number and title for the Guideline Subsection (e.g., 1.1 General Display Guidelines).

3. *Area Field* - contains the numeric sequence number and title for the Guideline Area (e.g., 1.2.7 Flowcharts).

4. *Subarea Field* - a fourth-level field (e.g., 1.2.X.X). The DRG does not contain these currently.

5. *Guideline Name Field* - contains the numeric sequence number and title of the current DRG.

6. *Guideline Field* - contains the text of the current DRG.

7. *Additional Information Field* - provides additional information needed to interpret or apply the current DRG (not all Guidelines contain information in the Comments field).

8. *Source Field* - contains the primary source document from which the guideline was developed.

9. *Comment Field* - initially blank, but provides a place for the reviewer to enter information related to evaluation of the current guideline.

10. *Search Term Field* - stores terms to be searched for; new terms can be added (see Section 5.4).

Each field is limited to 30,000 characters. Thus, for the DRG application, there is no practical limitation on the amount of information or reviewer-specific notes (comments) that can be stored.

A.2 Functions and Human System Interfaces (HSIs)

This section provides a description of how the interactive document's databases are presented to the reviewer and the functions available. For ease of reading, all figures are located at the end of this section. A User's Manual has been developed for reviewers using the interactive DRG.

Figure A.1 provides the overall structure of the DRG software displays. Reference to some individual screens presented as figures in this section are provided. The guidelines are first accessed through a master stack. Upon startup, an opening screen is displayed (see Figure A.2). The master is a reserved stack to "control" the guidelines; reviews cannot be performed using it. It can be modified only through the DRG's maintenance functions. To begin a review, a working copy of the master stack must be created. This is accomplished through the Guideline Maintenance screen (see Figure A.3). When the **Create Working Copy** button is activated, the reviewer is asked to name the working stack, e.g., the name of the review to be performed.

Upon startup of the working copy of the DRG, an opening screen is displayed (see Figure A.2). The reviewer then activates the **Click Here to Proceed**. The Function Selection screen is presented (Figure A.4), giving access to the four main modules necessary to conduct a review: Planning, HSI Review, Report, and Maintenance. System help is available in all modules.

The Planning module is accessed by clicking on the **Planning** button. It allows the reviewer to select which guideline topics will be reviewed. The HSI Review module is accessed by clicking on **HSI Review**. It contains all the functions for reviewing and evaluating an HSI system. The report module is accessed by pressing **Report**, allowing the reviewer to structure and print reports that summarize the results of the review. When one of these buttons is clicked on the Function Selection screen, the DRG displays the main screen for the selected module. In addition to these three modules, a **Clear All Evaluations** button is available on the Function Selection screen that will remove all evaluations from the guidelines and essentially put the *working stack* in an original, untouched condition. The main function modules are briefly described below.

Planning: Selecting the Appropriate Guidelines

Selecting the **Planning** button on the Function Selection Screen presents the Planning Screen (Figure A.5) that shows the hierarchical Table of Contents in the large window. The reviewer can move through the list using the scroll bar on the right of the window. On initial entry to the Planning Module, all sections of the DRG are included in the working stack. Sections can be excluded from review by first clicking on the titles and then clicking on the **Exclude Section** button. The same button toggles between the **Exclude Section** and **Include Section** functions, depending on the status of the selected title. As a planning aid, the **Browse Section** button opens a window listing the titles and text of the individual guidelines in the currently highlighted section(s) (Figure A.6). This window is closed by clicking on it.

The **Include All** button re-includes all excluded items and effectively resets the Table of Contents List. The **Accept and Process** button initially requests a confirmation, then processes the inclusion/exclusion status of all guideline sections. It suppresses navigation in the working copy to excluded guidelines and prohibits using these guidelines during a review. Excluded guidelines can only be accessed via the context index and search functions.

The **Function Selection** button exits the Planning function and returns to the Function Selection Screen (Figure A.4).

HSI Review

Selecting the **HSI Review** button on the Function Selection Screen presents the HSI Review Screen (Figure A.7). The screen is divided into two main sections: the upper section displays the guidelines and related information (described below), and the lower section provides reviewer support functions (described below). Buttons in these sections are described below. Some button functions can also be accomplished by keyboard inputs (e.g., pressing the left arrow key to move to the previous guideline). These are shown in Table A.1.

Table A.1. Keyboard Options for Navigation and Evaluation Functions

FUNCTION	TYPE OF KEYBOARD	
	Function Keys	No Function Keys[1]
OK	F1	Option-1
Discrepancy	F2	Option-2
Return	F3	Option-3
Not Applicable (N/A)	F4	Option-4
Next Guideline	F5	Option-5 or Right Arrow
Previous Guideline	F6	Option-6 or Left Arrow
Top of Section	F7	Option-7 or Up Arrow
Next Section	F8	Option-8 or Down Arrow

1 On keyboards without function keys, the functions can be accomplished using the keystrokes shown in the table. Note that Macintosh keyboards have an "option" key, so, for example, depressing the "option" and "5" keys will display the next guideline. Alternatively, depressing the right arrow key has the same effect.

The upper area contains two zones. The *Guideline zone* (at the left of the screen) displays the hierarchical context, the title, and the text of the guideline. The *Additional Information zone* (at the right of the screen) has a window that provides further information, clarification, or examples related to the guideline. The **Source** button will display the name of the source document.

The reviewer support section (the lower part of the screen) is divided into three zones: navigation, guideline evaluation, and document support. The *navigation zone* contains buttons for moving around within the DRG document. The *guideline evaluation zone* contains the evaluation buttons and the reviewer's comments window. The *document support zone* (located across the bottom of the screen) contains buttons that invoke functions frequently used during a review: **Table of Contents**, **Index**, **Glossary**, and **Search**. Each of the three zones is further described below.

The *navigation zone* contains those functions that are used for moving around the DRG. The **Next GL/Prev GL** (next guideline and previous guideline) buttons cause the next guideline/previous guideline to be displayed. If the **Next GL** button is activated while the last guideline in the section is being displayed, a beep will sound to alert the reviewer and the first guideline in the next section of the document will be displayed. If the **Prev GL** button is activated while the first guideline in the section is being displayed, the last guideline in the previous section will be displayed and a beep will sound. The **Top of Section** button causes the first guideline of the current section to be displayed. The **Next Section** button causes the first guideline of the section following the current section to be displayed. The **Retrace Steps** button retraces the reviewer's path through the guidelines. (Note that this is different from **Prev GL**, which backs through the guidelines in the order in which they appear in the document (e.g., from 5 to 4 to 3, etc.)).

The *evaluation support functions zone* contains the evaluation buttons and reviewer's comments window. The evaluation buttons allow the reviewer to record assessments of whether the system being reviewed conforms to the intent of the guideline (**OK**) or not (**Discrepancy**). Additional evaluation options are whether the guidance is not applicable (**N/A**) to the current system or **Return**. The **Return** button allows the reviewer to record that a guideline was applicable but that insufficient information was available at the time to make an evaluation (for example, operator input was required). When the **Return** button is selected, a window appears that allows the reviewer to indicate the reason for returning to the guideline, by choosing from a pre-defined list. Guidelines classified as Return can be reviewed later by using the **Review Returns** button. The reviewer selects the category of Return items from the same screen used for selecting reasons to classify an item as Return, and this category is displayed under the Evaluation window. All the guidelines classified in the Return category are collected. The **Next** button is used to move through the subset of selected items. The **Next** button appears on the screen (next to the **Review Returns** button) only when Returns are being reviewed. The reviewer can append comments in the Reviewer Comments window. These comments are stored with the guideline and can be printed in an evaluation report summary.

The *document support functions zone* includes Table of Contents, Index, Glossary, and Search functions. The **Table of Contents** button causes a pop-up scrollable window to open on the screen (Figure A.8). Selection of a section displays the first guideline of the selected topic in the guideline area of the HSI Review Screen. The scroll bar at the right of the Table of Contents screen is used to move through the topics list. Clicking on the instruction box returns to the HSI Review screen at the point where the **Table of Contents** button was activated.

Clicking the **Context Index** button displays the Context Index screen (Figure A.9). To the left of an index term is a number that indicates the number of times the term appears. The Index Term list can be moved through using the **Line Up/Line Down**, **Page Up/Page Down** buttons, or by clicking on the **Set Term** button, then entering the desired index term into the dialogue box and clicking **OK**. When a word in the Index Term List is selected, all occurrences of that word in guideline titles or text are displayed in a window, and can be scrolled using the **Line Up/Line Down**, **Page Up/Page Down** buttons. This index is essentially a "Key Word in Context" (KWIC) display: each line in the window displays the selected word in the center along with the surrounding text (before and after the selected word) as it appears in the guideline. Clicking on a line of text causes the associated guideline to be displayed in the guidelines area of the HSI Review screen. The **Return to Guideline** button will return the reviewer to the HSI Review screen at the point where the **Context Index** button was activated.

A generic Human Factors Engineering glossary is accessible by activating the **Glossary** button (Figure A.10). The glossary itself is displayed as an alphabetical list in the Glossary Term scrollable window to the left of the Glossary screen. Clicking the **Enter Term** button presents a dialogue window in which the reviewer can enter the desired term. On clicking the **OK** button, the Glossary Term window displays the desired term and the Definition window displays the term's definition. If a single letter is entered, the Glossary Term window display moves to the first word beginning with that letter. If the desired term is displayed in the Glossary Term window, clicking on the word displays the definition in the Definition window. Definitions can be stored temporarily in the "Definition Holder" by clicking the **Add to Holder** button. The **Save** button will save the current contents of the holder to a file, via a dialogue box in which the reviewer enters a file name for the contents of the Definition Holder and clicks **OK**. The **Print** button will print the contents of the Definition Holder, and the **Clear** button will empty the Definition Holder.

In addition, certain glossary definitions can be accessed without leaving the HSI Review screen. The underlined terms in the DRG section of the HSI Review screen indicate hypertext links to glossary definitions (see Figure A.7). Clicking on any of these terms will cause the glossary definition for that term to be displayed in the Additional Information window on the HSI Review screen.

The **Search** button on the HSI Review screen presents the dialogue box where the reviewer can enter a desired search term and, after pressing the **Return** key or clicking the **OK** button, the guidelines and additional information fields will be searched for the next occurrence of that term. The associated guideline will then be displayed. The term last searched for is displayed to the right of the **Search** button.

At the lower right corner of the HSI Review screen are the **Function Selection**, **Help**, and **Quit** buttons. **Function Selection** returns to the Function Selection Screen. When the **Help** button is activated, the reviewer can point to any field or button and click, and a description of the field or button will be displayed. Pressing the **Quit** button exits the DRG.

Preparing a Report

Pressing the **Report Preparation** button on the Function Selection screen presents the Report Preparation screen (Figure A.11). The screen displays the number of guidelines currently evaluated as "OK," "Discrepancy," "Not Applicable," "Incomplete" (i.e., not yet evaluated), or marked "Return" for later review. The reviewer may choose to include any or all of these evaluation categories in the report by clicking the **Include** or **Omit** check boxes associated with each category. The Report Preparation Screen also indicates the number of guidelines currently included and excluded that were selected in the Planning Module.

Clicking the **Build Report** button generates the specified report. The Report Summary screen is displayed (Figure A.12). The report can include all guidelines or only one, depending on the evaluation categories selected for inclusion. The guidelines in the report appear in the upper window. The list can be navigated using the **Page Up**, **Page Down**, **Top**, and **Bottom** navigation buttons at the lower right of the screen.

The **Export Summary** button will print the report to a text file; a standard dialogue box permits the reviewer to name the export file and select the save location. The **Print Summary** button automatically sends the report to the selected printer, and the **Report Specification** button returns to the Report Preparation Screen to permit modification of selected evaluation categories.

DRG Maintenance

A maintenance module was developed to output structured guidelines or glossary text files. These files can be edited using word processing software, and then read back into HyperCard. A table of contents and context index is generated. Upon request, hypertext links are automatically established between the guidelines text and tables, figures, and glossary items (see Figure A.3).

System Help

On-line help is available from all screens using the **Help** button. When pressed, the help window is displayed and the reviewer is given instructions. While system help is activated, the reviewer can point to anything on the screen and the help window describes the purpose of that section of the screen and indicates how selected functions operate. Help is also available in a User's Manual (both on-line and hardcopy format).

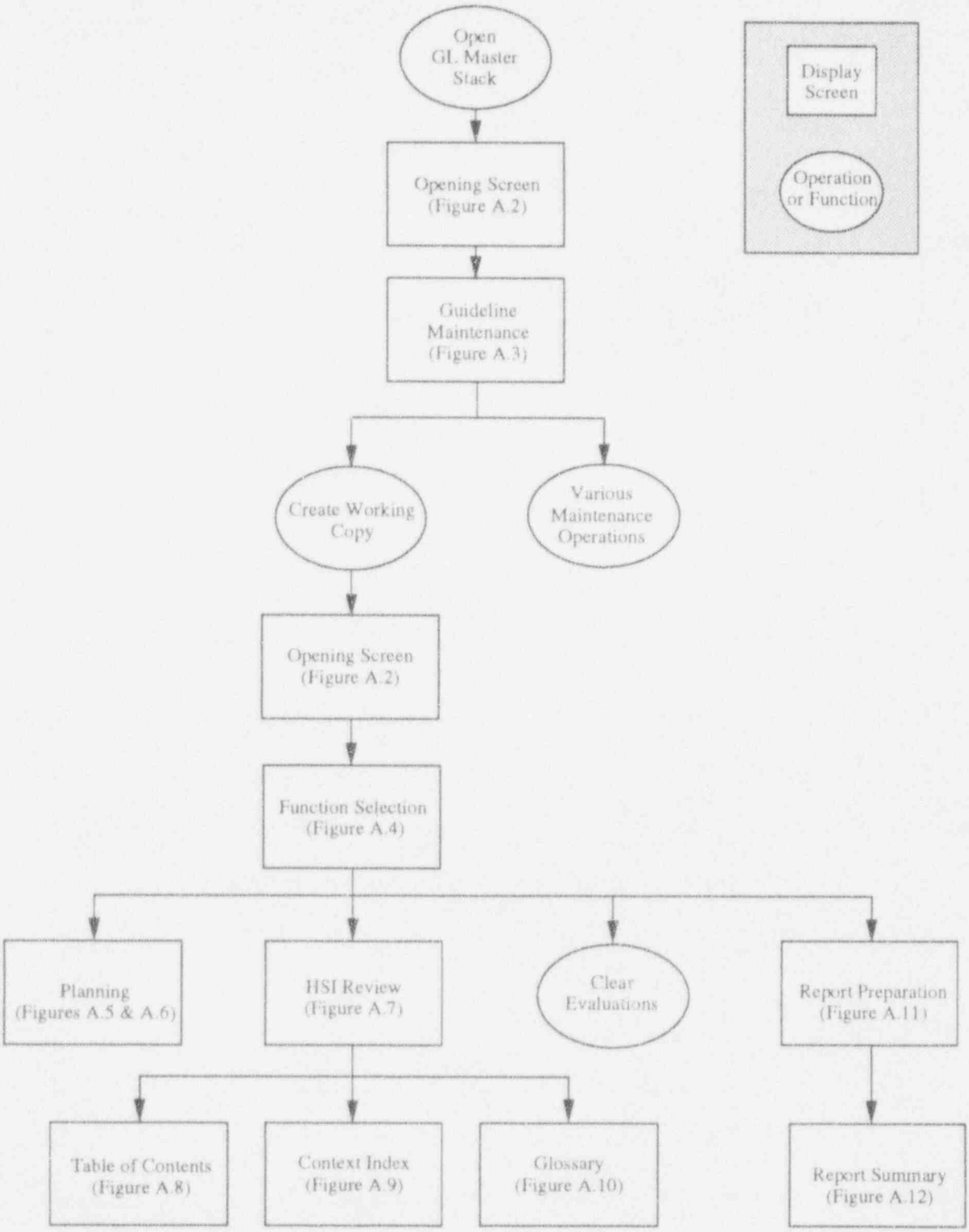

Figure A.1. DRG interactive document display structure

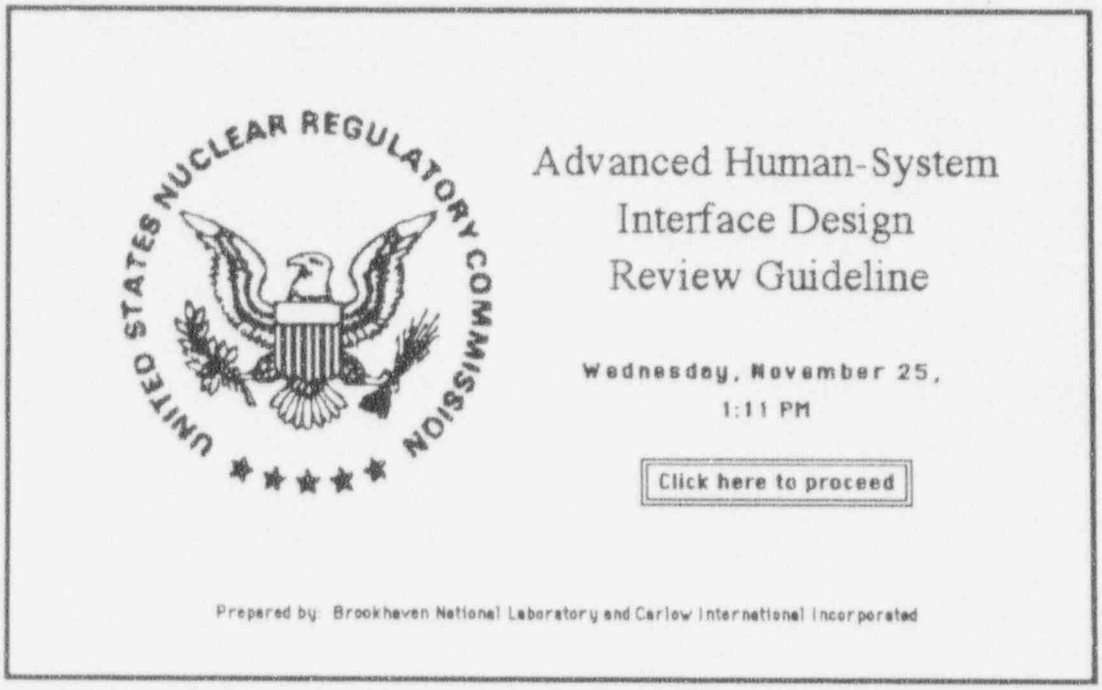

Figure A.2. Opening screen

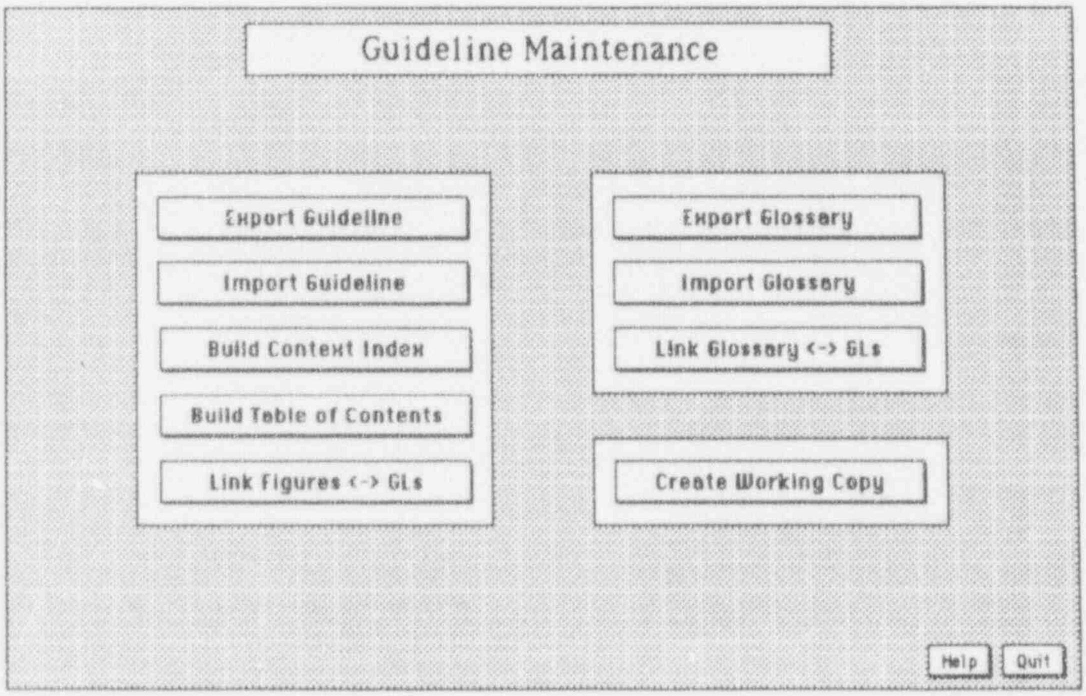

Figure A.3. Guideline maintenance screen

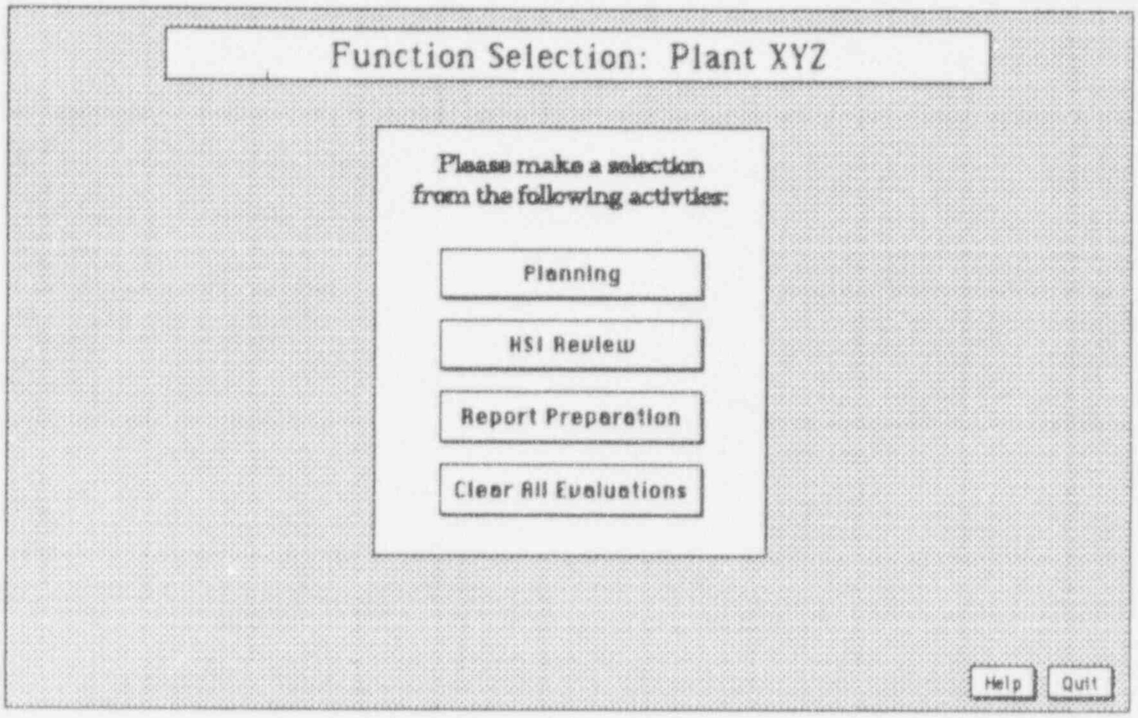

Figure A.4. Function selection screen

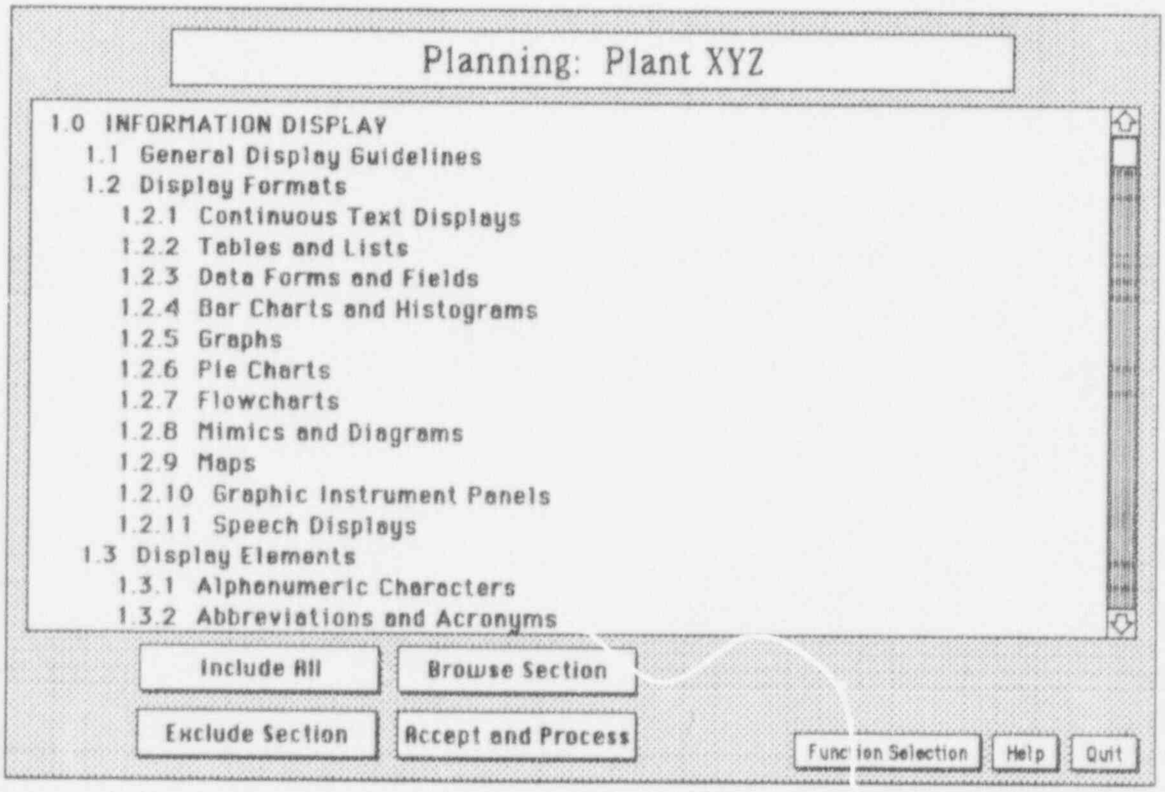

Figure A.5. Planning screen

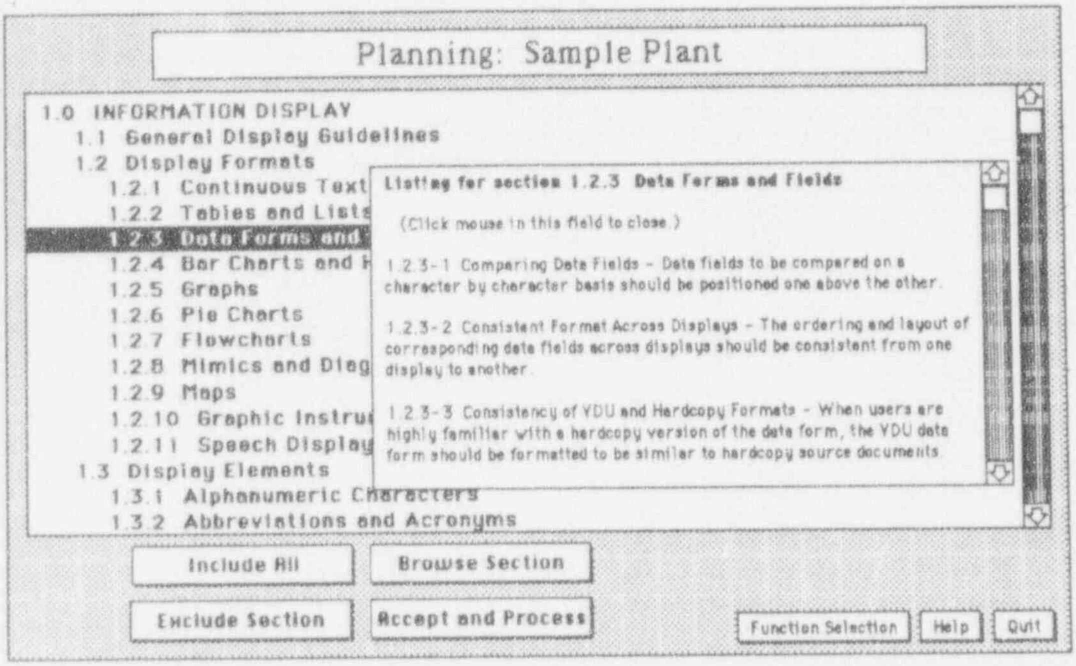

Figure A.6. Planning screen with browse window open

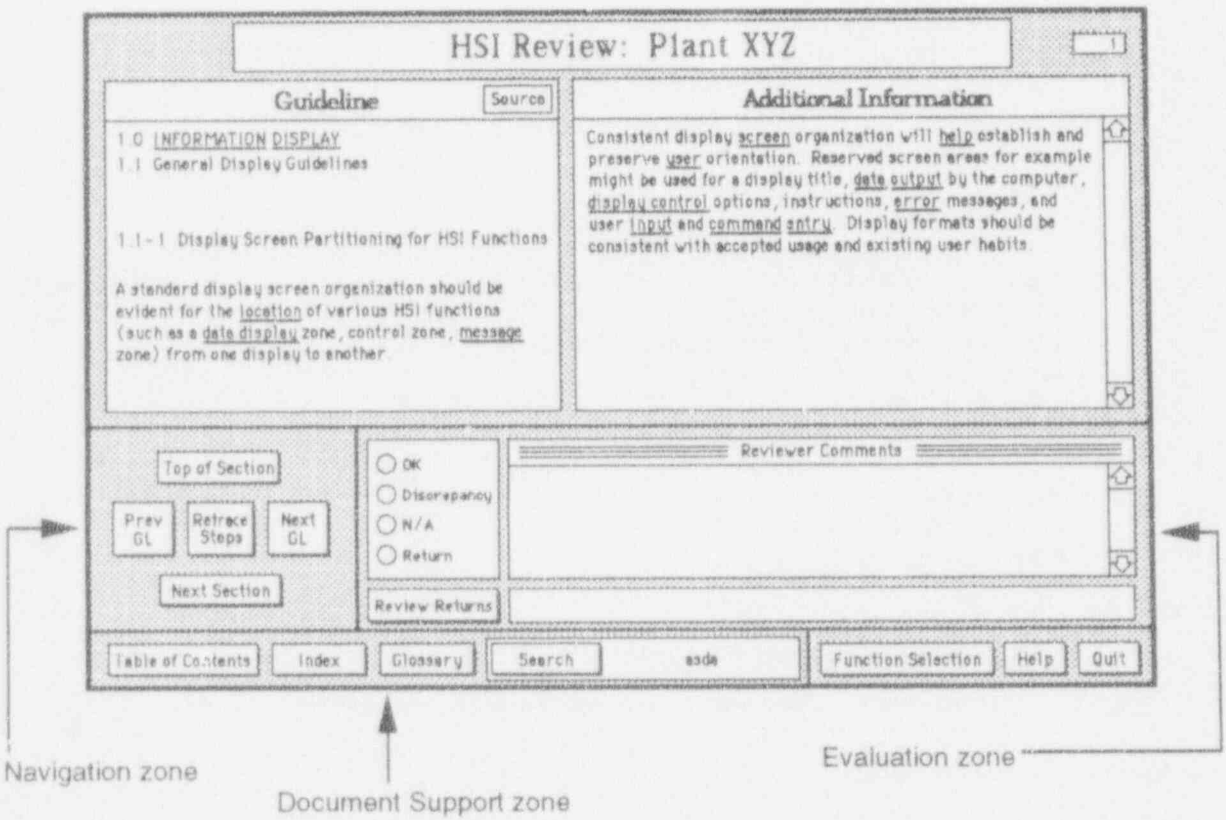

Figure A.7. HSI review screen

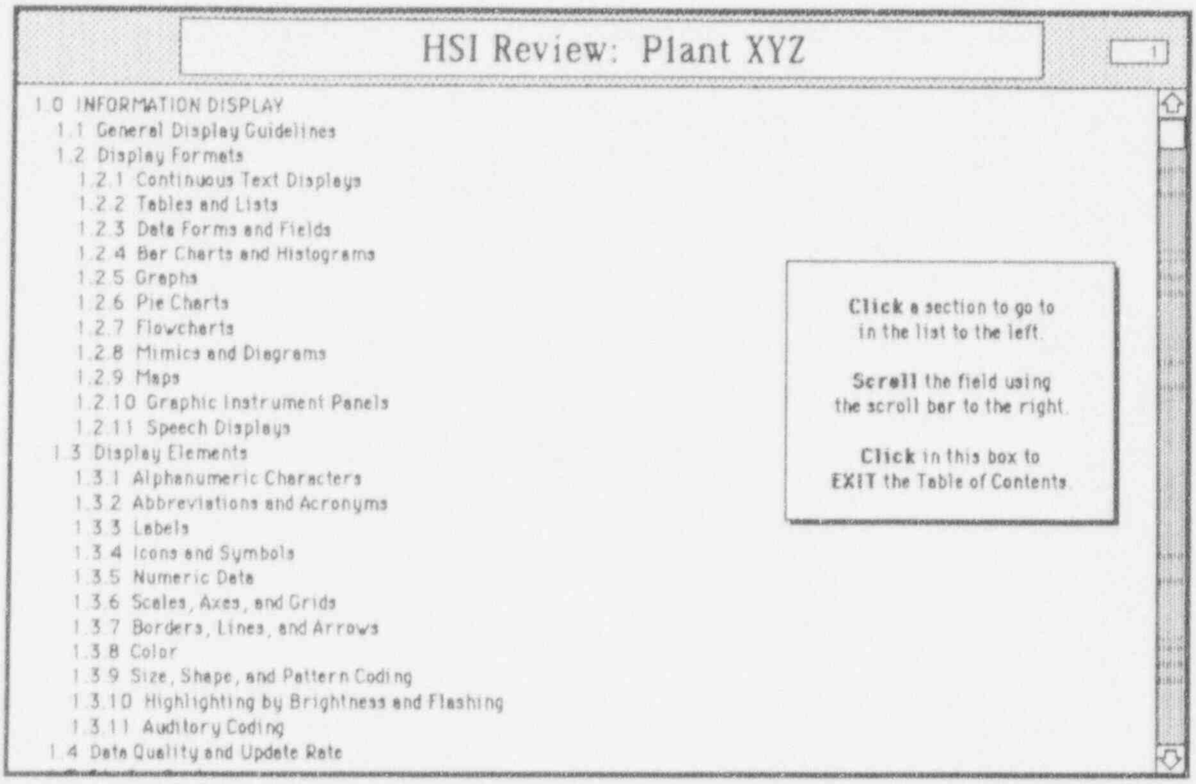

Figure A.8. Table of contents screen

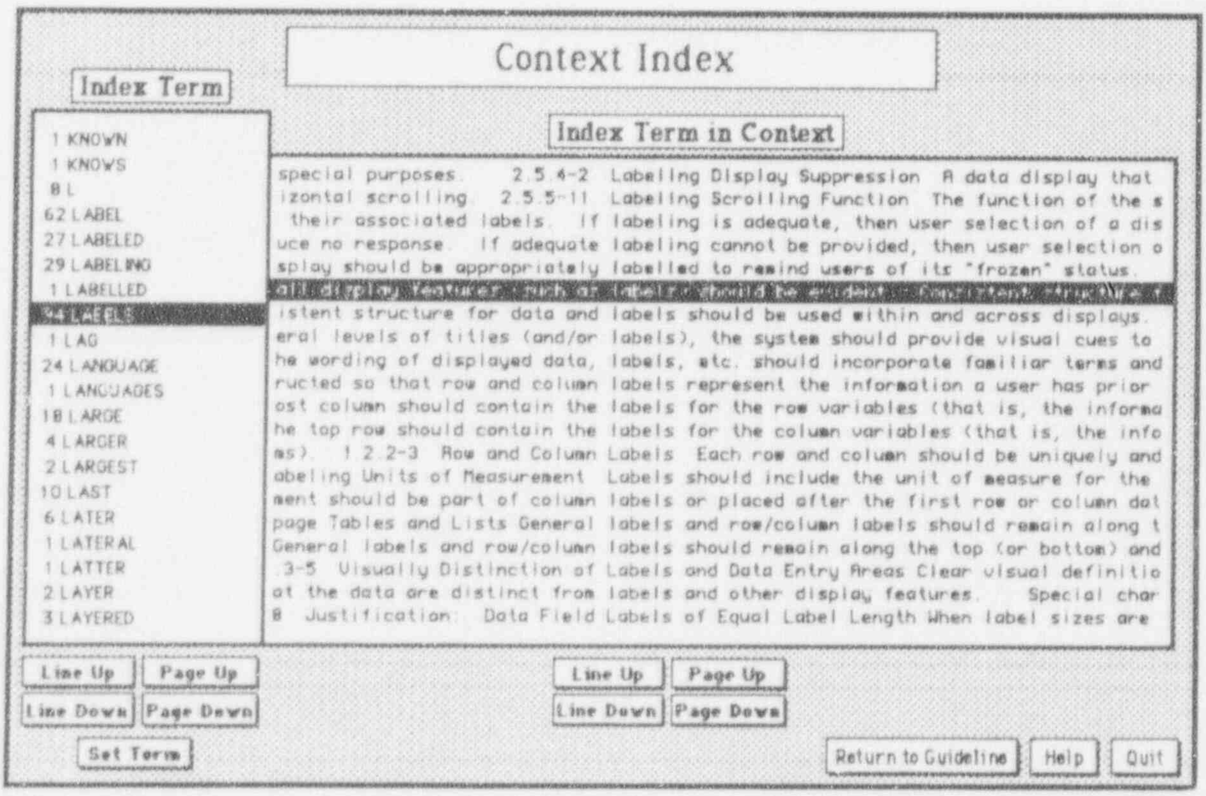

Figure A.9. Context index screen

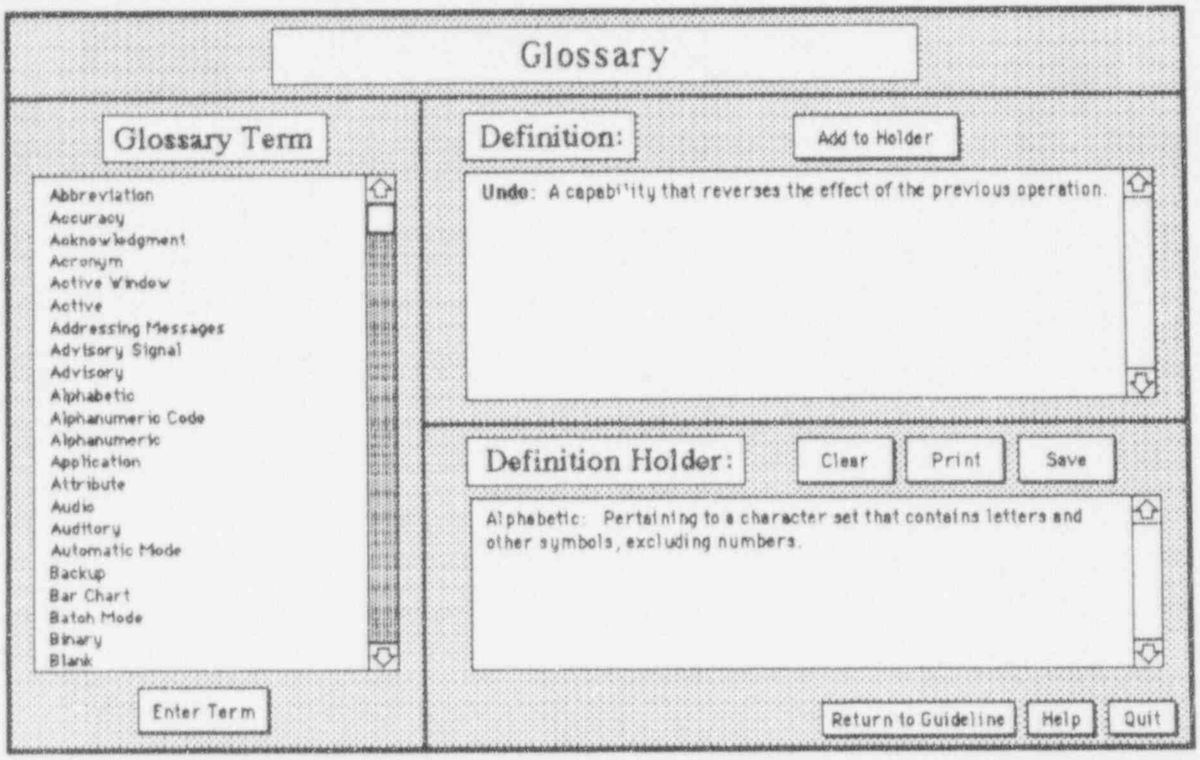

Figure A.10. Glossary screen

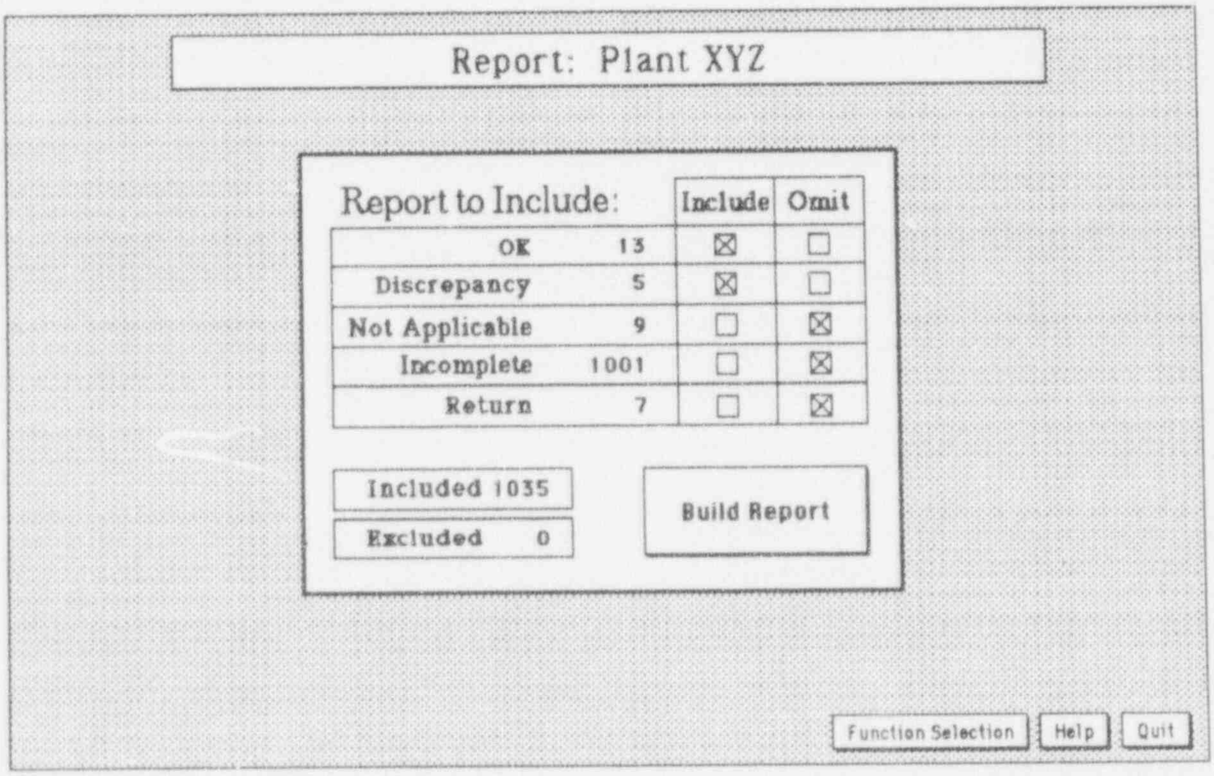

Figure A.11. Report preparation screen

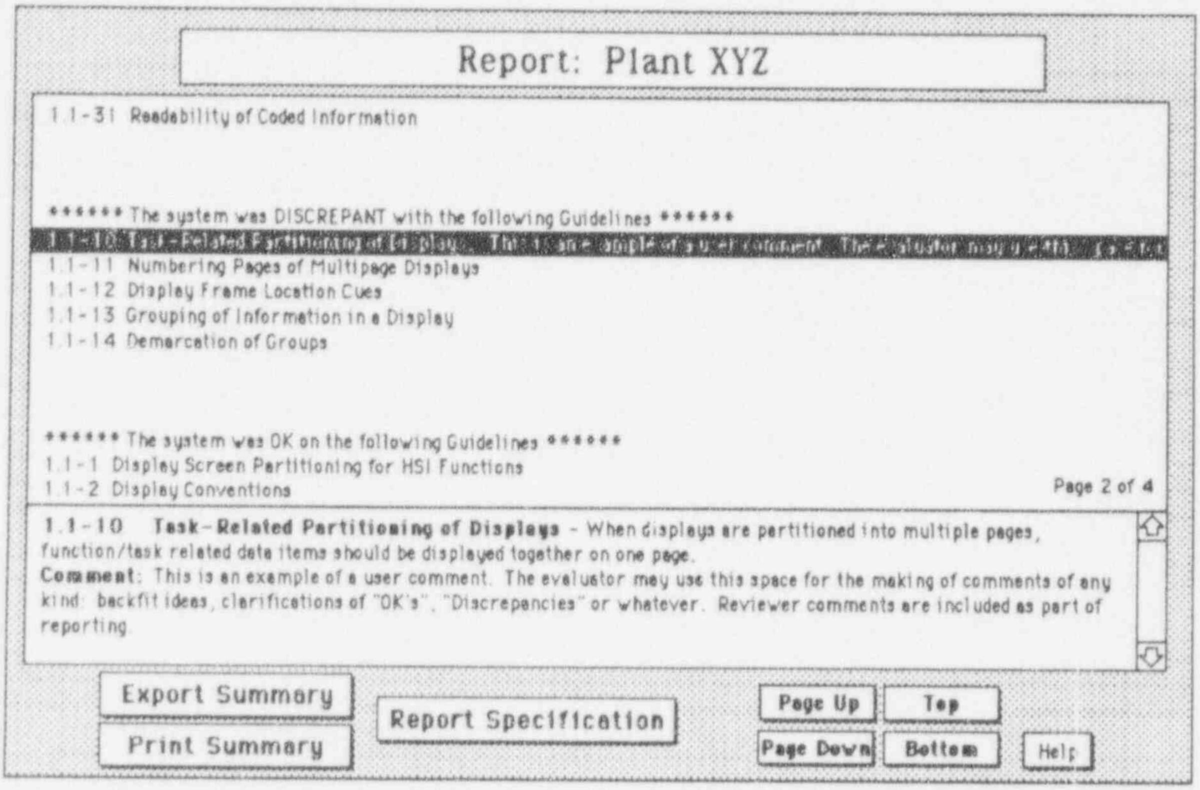

Figure A.12. Report summary screen

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11. ABSTRACT (200 words or less)

Advanced control rooms will use advanced human-system interface (HSI) technologies that may have significant implications for plant safety in that they will affect the operator's overall role in the system, the method of information presentation, and the ways in which operators interact with the system. The U.S. Nuclear Regulatory Commission (NRC) reviews the HSI aspects of control rooms to ensure that they are designed to good human factors engineering principles and that operator performance and reliability are appropriately supported to protect public health and safety. The principal guidance available to the NRC, however, was developed more than ten years ago, well before these technological changes. Accordingly, the human factors guidance needs to be updated to serve as the basis for NRC review of these advanced designs. The purpose of this project was to develop a general approach to advanced HSI review and the human factors guidelines to support NRC safety reviews of advanced systems. This two-volume report provides the results of the project. Volume 1 describes the development of the Advanced HSI Design Review Guideline (DRG) including (1) its theoretical and technical foundation, (2) a general model for the review of advanced HSIs, (3) guideline development in both hard-copy and computer-based versions, and (4) the tests and evaluations performed to develop and validate the DRG. Volume 1 also includes a discussion of the gaps in available guidance and a methodology for addressing them. Volume 2 provides the guideline to be used for advanced HSI review and the procedures for their use.

12. KEY WORDS/DESCRIPTORS (List words or phrases that will assist researchers in locating the report.)

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