Human Factors of Advanced Reactors (NRC JCN Y-6529)
BNL Tech Report No. BNL-91017-2010

Human-system Interfaces to Automatic Systems: Review Guidance and Technical Basis

Prepared for

Division of Risk Analysis
Office of Nuclear Regulatory Research
U.S. Nuclear Regulatory Commission
Washington, DC 20555-0001

Prepared by

John M. O'Hara and James C. Higgins
Brookhaven National Laboratory
Energy Sciences and Technology Department
Upton, NY 11973-5000

January 31, 2010

ABSTRACT

Automation is ubiquitous in modern complex systems, and commercial nuclear- power plants are no exception. Beyond controlling the plant's functions and systems, automation is applied to a wide range of other functions, including monitoring and detection, situation assessment, response planning, response implementation, and interface management. Automation has become a "team player" supporting personnel in nearly all aspects of operating the plant. In light of its increasing use and importance in new- and future-plants, guidance is needed to enable the NRC's staff to conduct safety reviews of the human factors engineering (HFE) aspects of modern automation. The objective of our research that we describe in this report was to develop guidance for reviewing the operator's interface with automation. We first characterized the important HFE aspects of automation, based on how it is implemented in current systems. This description had six dimensions: Levels of automation, functions of automation, processes of automation, modes of automation, flexibility of allocation, and reliability of automation. Next, we reviewed literature on the effects of all of these aspects of automation on human performance, and on the design of human-system interfaces (HSIs). Then, we used this technical basis established from the literature to develop guidance for reviewing designs. It consists of the following seven topics: Automation displays, interaction and control, automation modes, automation levels, adaptive automation, error tolerance and failure management, and, HSI integration. In addition, we offer our insights into the automation-design process, operator training, and operations.

ACKNOWLEDGMENTS

This research is sponsored by the U.S. Nuclear Regulatory Commission. The views presented represent those of the authors alone and not necessarily those of the NRC. The authors wish to thank Stephen Fleger, the NRC Project Manager, and former Project Managers, Mike Boggie and Niav Hughes for their guidance and input during this research project. We are grateful to Val Barnes for her insights and helpful comments on the report. We also thank Avril Woodhead for her technical editing of this report and Maryann Julian for preparing the manuscript.

CONTENTS

ABSTRACT ..... **iii**
ACKNOWLEDGMENTS ..... **v**
ABBREVIATIONS ..... **xi**

Part 1: Technical Basis and Guidance Development

1 INTRODUCTION **1**
1.1 Background 1
1.2 Changes in Plant Automation 1
1.3 Research Objectives 3
1.4 Organization of this Document 3

2 METHODOLOGY **5**

3 CHARACTERIZATION OF AUTOMATION **9**
3.1 Levels of Automation 9
3.2 Functions of Automation 17
3.3 Processes of Automation 25
3.4 Modes of Automation 25
3.5 Flexibility of Allocation 25
3.6 Reliability of Automation 27
3.7 Conclusions 27

4 AUTOMATION AND HUMAN PERFORMANCE **29**
4.1 Automation's Reliability, Operator Trust, and the Use of Automation 29
4.2 High-levels of Automation and Operator Performance 37
4.3 Intermediate- and Low-levels of Automation and Operator's Performance 46
4.4 Varying Levels of Automation, Adaptive Automation, and Operator Performance 49
4.5 Conclusions and Research Needs 52

5 DESIGNING AUTOMATION AND HSIs TO SUPPORT HUMAN-AUTOMATION INTERACTION 57

5.1 General Principles for Supporting Human-Automation Interaction 57

5.2 HSI Approaches for Supporting Human-automation Interaction 64
5.2.1 HSI Requirements Analysis 65
5.2.2 Detailed HSI Design 74

5.3 Conclusions and Research Needs 79

6 REVIEW GUIDANCE DEVELOPMENT 83

7 REFERENCES 87

Part 2: Guidelines for the Review of HSIs to Automatic Systems

8 HSI DESIGN REVIEW GUIDELINES 105

8.1 Automation Displays 109
8.1.1 General Display Considerations 109
8.1.2 Automation Representation 109
8.1.3 Automation's Dynamic Status 110

8.2 Interaction and Control 111

8.3 Automation Modes 113

8.4 Automation Levels 113
8.4.1 Shared Control 113
8.4.2 Operation by Consent 114
8.4.3 Operation by Exception 114

8.5 Adaptive Automation 114

8.6 Error Tolerance and Failure Management 115

8.7 HSI Integration 116

9 DESIGN PROCESS IMPLICATIONS 117

9.1 High-level Goals of Automation Design 117

9.2 Automation Design Characteristics 117

9.3 HSI Design 118

9.4 Test and Evaluation 119

10 TRAINING AND OPERATIONS IMPLICATIONS 121

TABLES

Table 3-1 Sheridan's Levels of Automation 10
Table 3-2 Billings' Levels of Automation 10
Table 3-3 Levels of Automation for NPP Applications 11
Table 3-4 Endsley and Kaber's Levels of Automation 18
Table 3-5 Levels of Automation of Procedure Functions 23
Table 3-6 Niwa et al.'s Levels of Procedure Automation 24
Table 4-1 Usage Decisions Based on Aid Performance 36
Table 4-2 Characteristics of Automation Design and Impacts on Human Performance 37
Table 4-3 Expected versus Actual Effects of Automation 38
Table 5-1 General Principles for Supporting Teamwork with Machine Agents 63
Table 5-2 General Abstraction-Aggregation Matrix 67
Table 5-3 Automatic Event-Detection Decision Matrix 70
Table 5-4 General HSI Requirements for Levels of Automation 74
Table 8-1 Levels of Automation for NPP Applications 106

FIGURES

Figure 1-1 Overview of an automatic system 2
Figure 2-1 Major steps in developing HFE guidance for the NRC 5
Figure 2-2 Technical-basis sources for developing guidance 6
Figure 3-1 Characterizing systems based on levels of function automation 18
Figure 3-2 Generic primary tasks that plant personnel undertake 20
Figure 3-3 Framework for characterizing automation 28
Figure 4-1 Case study of the relationship of automation and human performance 31
Figure 4-2 Calibration of trust and reliability 32
Figure 4-3 Simplified relationship between workload and performance 44
Figure 5-1 Top-down systems analysis 65
Figure 5-2 Defining HSIs for automation 66
Figure 5-3 Simple emergent feature 77
Figure 5-4 Visualization of control functions 78
Figure 6-1 Development of review guidance 83
Figure 6-2 Organizational structure of HSI review guidance 84
Figure 6-3 Format of an HFE design review guideline 85
Figure 8-1 Overview of an automation system 105
Figure 8-2 Generic primary tasks performed by plant personnel 107

ABBREVIATIONS

Abbreviation	Definition
AA	adaptive automation
ABWR	Advanced Boiling Water Reactor
ADS	automatic depressurization system
AECB	Atomic Energy Control Board
AFW	auxiliary feedwater
AGCAS	automatic ground collision avoidance system
ANS	American Nuclear Society
ANSI	American National Standards Institute
AP1000	Advanced Plant 1000
APWR	Advanced Pressurized Water Reactor
ARI	alternate rod insertion
AUD	automation usage decision
BNL	Brookhaven National Laboratory
BWR	boiling water reactor
CANDU	Canada Deuterium Uranium (reactor)
CBP	computer-based procedure
CFIT	controlled flight into terrain
CFR	U.S. Code of Federal Regulations
COSS	Computerized Operator Support Systems
CSEL	Cognitive Systems Engineering Laboratory
CSERIAC	Crew System Ergonomics Information Analysis Center
DCD	design control document
DWC	drywall cooling system
ECCS	emergency core cooling system
EID	ecological interface design
EOP	emergency operating procedures
EOSS	Emergency Operator Support System
EPR	Economic Pressurized (Water) Reacter
EPRI	Electric Power Research Institute
ESBWR	Economic Simplified Boiling Water Reactor
ESF	engineered safety features
ESFAS	engineered safety feature automation system
FAA	Federal Aviation Administration
FITNESS	Functional Integrated Treatments For Novative Novative Ecological Ecological Support Support System
FMS	flight management system
FWC	feedwater control system
GDCS	gravity drive cooling system
GE	General Electric
GEH	General Electric-Hitachi
GPS	global positioning system

Abbreviation	Definition
H/A	human/automation
HEP	human error probability
HFE	human factors engineering
HMI	human machine interface
HPCI	high pressure coolant injection
HSI	human-system interface
I&C	instrumentation and control
IAEA	International Atomic Energy Agency
ICS	isolation condenser system
IEC	International Electrotechnical Commission
IEEE	Institute of Electrical and Electronics Engineers
IFM	intelligent fault management
ISO	International Standards Organization
LD&IS	leak detection and isolation system
LOA	level of automation
LOCA	loss of coolant accident
LOOP	loss of offsite power
MCOSS	Mitsubishi Computerized Operator Support System
MCR	main control room
MEMS	micro electro-mechanical sensors
MFW	main feedwater system
MIL-STD	military standard
NAS	National Academy of Science
NASA	National Aeronautics and Space Administration
N-DCIS	non safety distribution control and instrumentation system
NP	Nuclear Power
NPP	Nuclear Power Plants
NRC	Nuclear Regulatory Commission
OER	operating experience review
PAS	plant automation system
PCC	passive containment cooling
PGCS	power generation control subsystem
PRA	probabilistic risk assessment
PSMS	protection and safety monitoring system
PWR	pressurized water reactor
RC&IS	rod control & information system
RCS	reactor coolant system
RCSL	reactor control, surveillance, and limitation
RHR	residual heat removal
RPS	reactor protection system
RPS/RTS	reactor protection system/reactor trip system
RPV	reactor pressure vessel
SA	safety assessnment

Abbreviation	Definition
SB&PC	steam bypass and pressure control
SG	steam generator
SGWLC	steam generator water level control
SLC	standby liquid control
SRO	Senior Reactor Operator
SW	Service Water
UAV	unmanned aerial vehicles
VDU	video display unit

Part 1:
Technical Basis and Guidance Development

1 INTRODUCTION

1.1 Background

A new generation of commercial nuclear power plants (NPPs) is emerging from technological developments in many engineering disciplines, such as reactor physics, instrumentation and controls, and human-system interfaces. The U.S. Nuclear Regulatory Commission (NRC) reviews the human factors engineering (HFE) aspects of NPPs to ensure that their design uses state-of-the-art HFE principles. These reviews help protect public health and safety by ensuring that operator's performance and reliability are supported appropriately. The main guidance supporting these safety reviews appears in Chapter 18 of the Standard Review Plan, NUREG-0800, (NRC, 2007), the Human Factors Engineering Program Review Model, NUREG-0711, Rev 2, (O'Hara et al., 2004), and the Human-System Interface Design Review Guidelines, NUREG-0700, Rev. 2 (O'Hara et al., 2002).

To ensure that its review guidance is up-to-date, the NRC conducts research to identify potential human-performance issues associated with new and advanced NPP designs, to prioritize them, and to develop the technical bases needed to address those of particular importance (O'Hara et al., 2008a; O'Hara et al., 2008b). The sixty-four identified issues were prioritized based on evaluations from independent subject-matter-experts (SMEs) representing vendors, utilities, research organizations, and regulators. Two of the top-priority issues were related to automation: "Levels of Automation, and, "Interfaces to Automation." In the next section, we give a brief overview of automation.

1.2 Changes in Plant Automation

Sheridan (2002) defined automation as: (a) The mechanization and integration of the sensing of environmental variables (by artificial sensors); (b) data processing and decision making (by computers); and, (c) mechanical action (by motors or devices that apply forces in the environment) or information action by communication of processed information to people (p. 9). At the simplest level, an automation system is designed to accomplish a goal that might be predetermined by designers or set by operators based on their current needs. The automatic system processes inputs from the plant and operators to meet the goal (see Figure 1-1). Since automation can be applied to may aspects of the plant's operations, from analyzing procedure steps to controlling plant systems, the specific processes used to accomplish automation's goal vary, depending on the application of the automation.

Modern automation relies on digital instrumentation and control (I&C) systems that possess considerably more power and functionality than their analog predecessors. The I&C system, working with plant personnel, is the plant's "central nervous system". It senses basic parameters, monitors performance, integrates information, and makes needed adjustments to plant operations. Digital I&C systems enable the precise monitoring of the plant's performance, thus providing better data to control systems. In turn, improved controls support better performance and offer a means to operate closer to performance margins. The I&C system also monitors the various barriers that prevent the release of radioactive material to the public. It responds to failures and off-normal events, thus satisfying the goals of efficiently generating power and assuring safety. Digital systems enable plant personnel to more effectively monitor the health of the plant, identify opportunities to improve the performance of equipment and systems, and to anticipate, understand, and respond to potential issues and problems in meeting both the production and safety goals. Thus, digital I&C systems directly affect the

performance of the entire plant and, consequently, the economics, safety, and security of future reactor designs.

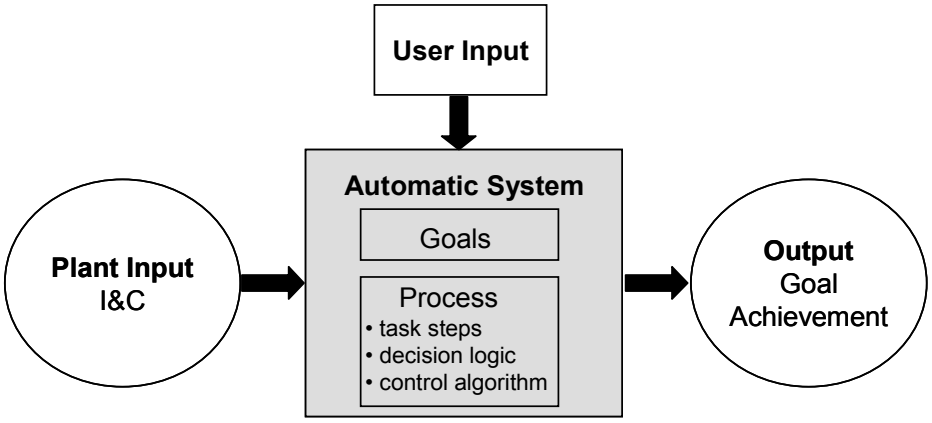


Figure 1-1 Overview of an automatic system

There is increased use of automation in the design-certification submittals for new plants compared with currently operating ones. For example, GE-Hitachi (2008a) stated that "The control systems for the ESBWR have a high level of automation. All systems are automated unless regulation or HFE analysis results dictate otherwise" (p.16). Similarly, commenting on the concept of operation for the U.S. Evolutionary Power Reactor (EPR), AREVA (2007a) stated that "The U.S. EPR design goal is to design the plant and the HSI so that three licensed operators (one of which holds a senior reactor operator (SRO) license) can safely monitor and control the plant under operating conditions, including normal operation, startup, shutdown, abnormal operation, and accident conditions. Because of the levels of automation inherent in the I&C architecture, only one licensed operator will be required to be at the controls during normal, at power operations "(p.4-1). Further, "…the initial MCR staffing level is established based on experience with previous four loop PWR plants and takes into account the increased levels of automation…" (p. 5-29). Looking to future Generation IV NPP operations, two to four operators may manage up to a dozen modular plants (Uhrig, Gao, & Tsoukalas, 2004).

Increased use of automation is not limited to operations; maintenance and testing functions also will become increasingly automated, encompassing fault detection and diagnosis, reconfiguration of systems, and the generation of work orders for required manual interventions. Engineering- and administrative-functions also may become increasingly automated. Indeed, the scope of automation in NPPs has expanded considerably since digital I&C systems were first introduced in the 1960s (Kawai, Takizawa, & Watanabe, 1999). Thus, the "Levels of Automation" in new and future plants was identified as one of the top-priority issues.

Personnel accomplish monitoring of, supervision of, and interaction with automation using the human-system interface; i.e., displays, alarms, and controls. The proper design of the HSIs is vital to the success of personnel in fulfilling these automation-related tasks. Accordingly, "Interfaces to Automation" also was identified as one of the top-priority issues.

1.3 Research Objectives

In light of the increasing use and importance of automation in new- and future-plants, the NRC's staff needs guidance to enable them to conduct safety reviews of applications employing modern approaches to automation. Our objective in this research was to develop guidelines for reviewing HSIs for monitoring and control of automation.

1.4 Organization of this Document

We divided this report into two parts. Part 1, Section 2 details the methodology we used to develop the HFE review guidance. Section 3 addresses the characterization of automation; i.e., defines its key dimensions. In Section 4, we discuss research related to the effects of automation on individual- and team-performance, and in Section 5 we review the design of the HSI to support human-automation interaction. The literature discussed in Sections 4 and 5 constituted the technical basis upon which we developed this guidance. These sections also cover the needs for future research. We discuss the guidance development in Section 6. The references to cited works are contained in Section 7.

Part 2, Section 8 has our guidance for the safety review of the HSIs to automatic systems. We discuss the implications for the process used to design the HSIs to automatic system in Section 9. Finally, Section 10 discusses the implications of our findings for training and operations.

2 METHODOLOGY

Figure 2-1 is an overview of the methodology we earlier used to develop guidance to resolve HFE issues (O'Hara et al., 2008a). This process was steered by our overarching objective of establishing the validity of the guidelines. Validity is defined along two dimensions: Internal- and external-validity. The former is the degree to which the individual guidelines are linked to a clear, well-founded, and traceable technical basis. The latter is the extent to which independent peer reviews support the guidelines. . Peer review is a good method of screening the conformance of guidelines to generally accepted HFE practices and to industry-specific considerations, i.e., for ensuring that the guidelines are appropriate, based on practical operational experience in actual systems.

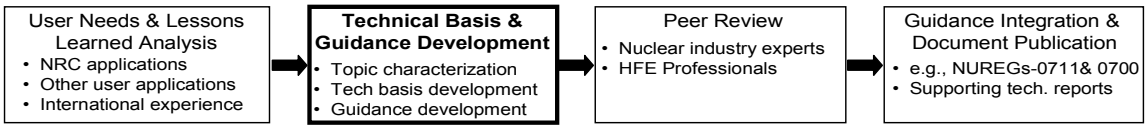


Figure 2-1 Major steps in developing HFE guidance for the NRC

Of the four steps illustrated, this document addresses the second one, viz., technical basis and guidance development. We completed the first step of the methodology in earlier research (O'Hara et al., 2008a, & 2008b); the last two steps will be conducted in the future. The present (second) one, technical basis and guidance development involves three steps: Topic characterization, technical-basis development, and guidance development and documentation.

Topic Characterization

A topic is an HFE issue or group of them for which design-review guidance is being developed. The first step in doing so for any topic is to establish a characterization for that topic that will identify those areas where review guidance is needed. Accordingly, we review existing systems and identify the characteristics and functions that can define the topic. Characterization is important because it affords a structure for developing and organizing the guidance. Also, it gives the reviewer a framework for requesting information from applicants and licensees. Section 3 discusses the characterization of automation.

Technical-basis Development

The next step is to analyze information about the topic to obtain the technical basis upon which guidance can be developed and justified. Figure 2-2 illustrates, in order of preference, the use of several sources of information for elaborating guidance. . Proceeding down the flow chart, the sources of the technical basis change in three ways. First, those near the top are already in the HFE guidance format, or close to it. Toward the bottom, individual research studies must be synthesized and guidelines abstracted. Second, the information at the top already possesses a degree of validity (as discussed earlier), while towards the bottom the validity of the data must be established completely during guidance development. Third, employing the information generally becomes more costly toward the bottom of the flow chart. Preferentially, sources higher in the figure should be used.

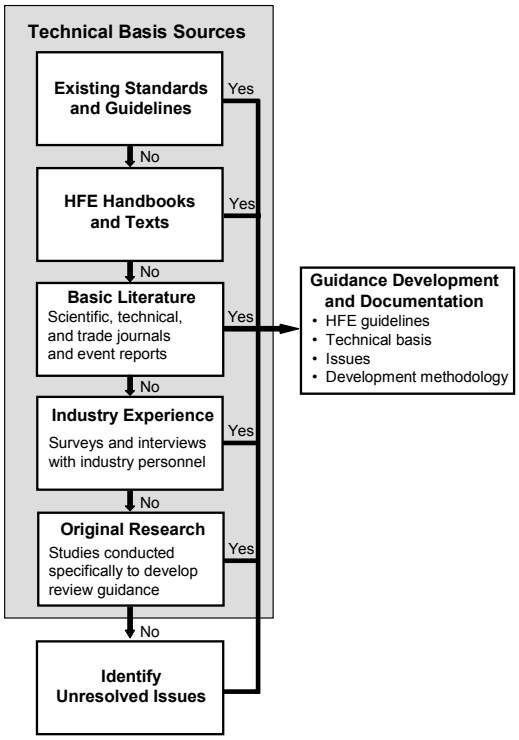


Figure 2-2 Technical-basis sources for developing guidance

Existing HFE standards and guidance documents are considered first, examples of which are the standards set by the U.S. military and standards organizations, such as the American National Standards Institute (ANSI). The authors of such documents established HFE guidelines from available research, operational experience, and their own knowledge/expertise. In addition, many existing standards and guidance documents have been peer-reviewed, thus conferring external-validity. Since the information already is in guideline form, it is generally easier to use than information from other sources. However, the design of user interfaces for automatic systems largely was overlooked in many of the more widely used HFE standards and guidelines. For example, we noted that the topic receives only limited attention in the following key sources of HFE guidance:

- Department of Defense Design Criteria Standard: Human Engineering, MIL-STD 1472 (DOD, 1999)
- Ergonomic Design of Control Centres, ISO 11064 (ISO, 2000)
- Nuclear power plants – Control rooms – Design, IEC 60964 (IEC, 2009)

In MIL-STD 1472 F, automation is treated simply as a general principle:

> 4.12 Automation. Functions shall be automated only to attain greater overall effectiveness, efficiency, reliability, simplicity, economy, and system safety rather than relying on human performance alone. Irrespective of the level of automation, system and task design shall ensure that the human operator is in command, involved in ongoing operations, and appropriately informed to maintain awareness of the situation and other status of automated functions. When used, automated functions shall be predictable, offer the operator an appropriate range of options, monitor operator actions to minimize, resist, and tolerate errors, and be capable of being overridden by the operator in an emergency. (DOD, 1999, p. 7)

Other documents have guidance on limited aspects of automation applicable to particular systems. NUREG-0700, for example, covers automation of alarms, computerized operator support systems (COSS), and computer-based procedures (CBPs).

One exception is the *Human Factors Design Guide* (FAA, 1996) that offers guidance for the design of systems developed by, and for the FAA. Its overall scope is similar to NUREG-0700; in fact, NUREG-0700 is one of technical bases upon which the Federal Aviation Administration (FAA) guidance document was developed. Section 5 of the FAA's document addressed automation; however, the original section focused on automation in the context of maintenance tasks. In 2002, the guidance was updated significantly, and its scope expanded beyond maintenance to automation in general (Ahlstrom, Longo & Truitt, 2002). It encompasses many of the aspects of automation that we discuss this report, including users' acceptance and trust, its modes, levels of adaptive automation, and automation of different functions (such as information acquisition, decision aids, and controls). We note that the chapter also includes many general HSI guidelines and not specifically related to automation.[1] Importantly, the guidance is not restricted to HSI design and covers topics such as design, evaluation, and training.

While standards and guideline documents are a valuable starting place, there may be many aspects of a topic that extend beyond the technology and human performance considerations discussed in these documents. Thus, we utilized additional sources of information. We sought handbooks offering sound analyses and syntheses of existing literature. An excellent example of this type of source is a chapter entitled "Human Factors and Ergonomics in Automation Design" (Lee, 2006) in the *Handbook of Human Factors and Ergonomics* (Salvendy, 2006). Such documents are invaluable in that they constitute a review of research and operational literature by knowledgeable experts. However, the information usually is not expressed in guidance form. Hence, while guidance must be developed from these documents, the establishment of technical basis usually is expedited by information provided in handbooks.

These sources often are insufficient to support our development of guidance on topics reflecting the new technology. Therefore, we then reviewed the basic literature, consisting of papers from research journals and technical conferences. This literature provides a theoretical basis for understanding human performance concerns related to complex human-machine systems, along with a general theory for human-machine interaction vital to user interface design, human error, and usability. Empirical studies of human-machine interaction reported in the literature address a broad range of technologies and user tasks. However, more effort is needed to extend such information into guidance on design review.

When basing guidance on basic literature, engineering judgment is required to generalize from the unique aspects of individual experiments and studies to actual workplace applications. This is because individual experiments have unique constraints that limit their generalizability (such as their unique participants, types of tasks performed, and types of equipment used). For example, most laboratory experiments do not involve tasks as complex as NPP operations, nor under the same performance-shaping factors (such as rotating shifts, stress, and fatigue) that

[1] One problem associated with personnel interaction with automation is the generally poor design of the HSIs. Thus, several papers that offer guidance for human-automation interaction consist mainly of general HSI guidance, such as that found in NUREG-0700. An example is the guidance for personnel interaction with flight management systems (Kaber, Riley & Tan, 2002). We omitted such papers in our review.

exist in some nuclear-industry work environments. While information from research is a valuable part of developing guidance, the results must be interpreted in the context of real-world tasks and systems. Their elucidation involves judgments based on professional- and operational-experience. Some of these same issues of generalization also exist for event reports from nuclear power plants.

Industrial experience that encompasses reports and surveys of plant personnel, including designers, and regulators, is a valuable source of data. Operational experience also can be gathered from interviews, knowledge-elicitation sessions, and walk-through exercises using the actual HSI or a high-fidelity training simulator. Industry's practices cover design approaches that have evolved through experience; they are incorporated into the technical bases as practical examples of design- and evaluation-strategies. While this information can be more difficult and costly to obtain than basic literature, it may be more directly applicable to the NPP domain than basic literature. Like using basic literature, the information must be analyzed critically and synthesized to develop guidance.

Finally, we use original research information for establishing our technical basis. Such research has the advantage of focusing on the specific issues that need to be considered in developing guidance. Because of the time and resources required to conduct original research, it is only undertaken to obtain important information that cannot otherwise be acquired.

During our review, whenever we found topics lacking an adequate technical basis on which to develop review guidance, we identified unresolved issues that could be addressed in future research.

A great deal of information exists about the HFE aspects of complex system automation. The information we used in this report primarily came from the first three sources described in this section. We review and evaluate this data in Sections 4 and 5 of this report. These sections also discuss future research needs.

Guidance Development

Once the steps outlined above are completed, review guidelines are developed using the characterization and technical basis. The guidance is documented in the standard HFE review guidance format used in NUREG-0711 and NUREG-0700. Section 6 describes guidance development in more detail; the actual review criteria are contained in Part 2 of this report (Sections 8, 9, and 10).

3 CHARACTERIZATION OF AUTOMATION

As noted in Section 2, characterization of the HFE aspects of automation is important because it provides a structure for developing and organizing the guidance. It also affords reviewers a framework for requesting information about automation from applicants and licensees.

To develop a topic characterization, we identified the characteristics and functions along which automation can be defined. To do this we reviewed the following:

- Existing automation systems for several new plant designs submitted to the NRC for design certification, including the ABWR (GE, 1997), ESBWR (GEH, 2008c), and US-APWR (Mitsubishi, 2008), and EPR (AREVA, 2007b)
- Descriptions of automation systems, within and outside the nuclear industry, in the various research papers discussed in this section, and in Sections 4 and 5.

Many of these sources identify important characteristics of automation from which we subjectively identified six dimensions characterizing NPP automation:

- Levels of Automation (Section 3.1)
- Functions of Automation (Section 3.2)
- Processes of Automation (Section 3.3)
- Modes of Automation (Section 3.4)
- Flexibility of Allocation (Section 3.5)
- Reliability of Automation (Section 3.6)

3.1 Levels of Automation

In older systems, the allocation of responsibilities for function performance was straightforward: Functions were either automated (i.e., performed essentially without human involvement), or manual (i.e., performed by plant personnel without automation). However, as computers became more involved in process control, the nature of automation changed. Recent approaches to automation involve the cooperation and sharing of responsibilities between automatic systems and plant personnel. In this section, we discuss the changing concept of levels of automation within the continuum of fully manual- to fully automated-operation. Increasingly, designers use intermediate levels of automation resulting in a gradation from manual to automatic wherein the relative responsibilities of human and automation in performing tasks varies. This concept often is referred to as “levels of automation.”

This concept has been around for some time. In 1992, Sheridan defined three global levels of automation: Manual control (all control is accomplished by humans); supervisory control (some or all of the control loop is closed by the computer, but the human supervisor can assert control); and, fully automatic control (all control is automatic and the human cannot vary the process except, perhaps, to terminate it). As technology has evolved, Sheridan (2002) offered more fine grained distinctions between these levels of automation (see Table 3-1).

Table 3-1 Sheridan's Levels of Automation

Level	Description
1	the computer offers no assistance; the human must do it all
2	the computer suggests alternative ways to do the task
3	the computer selects one way to do the task and (see Level 4)
4	executes that suggestion if the human approves, or (see Level 5)
5	allows humans a restricted time to veto before automatic execution, or (see Level 6)
6	executes automatically, then necessarily informs the human, or (see Level 7)
7	executes automatically, then informs the human only if asked
8	the computer selects the method, executes the task, and ignores the human

Billings proposed one of the best-known frameworks for levels of automation (1991, 1997a) based on his work in the aviation industry. Table 3-2 illustrates how Billings (1997a) characterized the division of responsibilities for functions and tasks across humans and automation.

Table 3-2 Billings' Levels of Automation

Level	Role of Automation	Role of Humans
Autonomous Operations	Fully autonomous operation. Human not usually informed. System may or may not be capable of being disabled.	Human generally has no role in operation, and monitoring is limited.
Operation by Exception	Essentially autonomous operation unless specific situation or circumstances are encountered.	Human must approve of critical decisions and may intervene.
Operation by Consent	Full automatic control under close monitoring and supervision.	Human monitors closely, approves actions, and may intervene.
Operation by Delegation	Automatic control when directed by human to do so.	Human provides supervisory commands that automation follows.
Shared Control	Automatic control of some functions task.	Humans control some functions/tasks.
Assisted Manual Control	Primarily manual control with some automation support.	Human manually controls with assistance from partial automation.
Direct Manual Control	No automation is used.	Human manually controls all functions and tasks.

While levels of automation in the commercial nuclear industry have not been discussed explicitly, the concept applies nevertheless. We sought to fit the standard NPP automation functions used in new NPPs to a levels-of-control framework. Considering the diverse applications of automation used in the nuclear industry and discussed below, Billings' automation categorization scheme seemed most appropriate with some modification. Table 3-3 shows the levels of NPP automation and gives examples for each.

We found examples of NPP automation at every level; none were identified that did not fit into the modified scheme. However, these systems often are complex and thus, a system (or portions of it) may sometimes be characterized at one level and at other times at another. Table 3-3 discusses examples of NPP automation applications for these levels.

Table 3-3 Levels of Automation for NPP Applications

Level	Automation Functions	Human Functions	NPP Example
1. Manual Operation	No automation	Operators manually perform all functions and tasks	Demineralized water system
2. Shared Operation	Automatic performance of some functions/tasks	Manual performance of some functions/task	Suppression pool cooling mode of RHR
3. Operation by Consent	Automatic performance when directed by operators to do so, under close monitoring and supervision	Operators monitor closely, approve actions, and may intervene with supervisory commands that automation follows	ABWR startup
4. Operation by Exception	Essentially autonomous operation unless specific situations or circumstances are encountered	Operators must approve of critical decisions and may intervene	ADS/SRVs system
5. Autonomous Operation	Fully autonomous operation. System or function not normally able to be disabled, but may be manually started	Operators monitor performance and perform backup if necessary, feasible, and permitted	RPS

Level 1 - Manual Operation

This level involves no automation. New reactors are expected to have some manual systems, such as demineralized water systems similar to current plants.

Level 2 - Shared Operation

This level involves the automatic operation of some functions or tasks, while others are performed manually. Examples of nuclear plant automation at this level include the following:

- *Service Water (SW) System* - Mostly operator controlled, but pump starts automatically on trip of running pump.
- *Suppression Pool Cooling Mode of RHR* – The operator lines up and starts RHR, then the system controls temperature automatically.

Level 3 - Operation by Consent/Delegation

This level is one of automatic control when directed by operators to do so, under close monitoring and supervision. Examples of this LOA are

- ABWR startup process (GE, 1997)
- ESBWR startup process as described in the DCD (GEH, 2008c)

- US-APWR Pressurizer (Pzr) pressure control and SGWLC, and EPR RCS pressure control (Mitsubishi, 2008)
- EPR RCS pressure control (AREVA, 2007b)

Each is described below along with some additional examples.

ABWR Power Control

The ABWR "Power Generation Control Subsystem (PGCS) is a top level controller that monitors the overall plant conditions, issues control commands to non-safety-related systems, and adjusts setpoints of lower level controllers to support automation of the normal plant startup, shutdown, and power range operations"(GE, 1997). In the automatic mode, the PGCS issues command signals to the turbine master-controller that automatically operates the turbine, feedwater, and related auxiliary systems. The PGCS executes the command signals for startup. The operator interfaces with the PGCS through "breakpoint" controls. The process sequence is divided into discrete chunks, each of which is automated. After a chunk is completed, a breakpoint is reached, and the operator must intervene to transition to the next chunk. Having satisfied all the prerequisites for a predetermined breakpoint in a control sequence, then a permissive is given and, after verification by the operator, the operator initiates the prescribed sequence. The PGCS then initiates demand signals to the various system controllers to carry out the predefined control functions.

Some aspects of the ABWR startup are not automated, e.g., change of the status of the reactor mode switch. The PGCS provides the operator with guidance messages to initiate the startup operations, and then automation continues, reflecting the shared control. Thus, the ABWR startup process incorporates two LOAs: Shared control (Level 2); and, operation by consent (Level 3).

ESBWR Power Control

The ESBWR Plant Automation System (PAS) has the capability for supervisory control of the entire plant by sending setpoint commands to independent automatic-control systems as dictated by changing load demands and plant conditions.

As stated in GEH (2008c), the "PAS provides supervisory control of reactor power during reactor startup, power generation and reactor shutdown by appropriate commands to change rod positions. PAS also controls the pressure setpoint or turbine bypass valve position during reactor heatup and depressurization (e.g., to control the reactor cooldown rate). PAS issues supervisory setpoints commands to sub-loops of various secondary plant systems."

The PAS has redundant process controllers. "The automation process is divided into phases corresponding to plant start-up, shutdown, and normal power generation. Each phase is then divided into several break-points or logical steps in plant operation. The automation proceeds under PAS control until the end of a break-point division is reached, at which time the operator must confirm that conditions are acceptable before automation sequence can continue. PAS controls the overall plant startup, power operation, and shutdown functions under operator break-point control" (GEH 2008c).

The "PAS receives input from the Neutron Monitoring System, the N-DCIS, the Steam Bypass and Pressure Control system, and the operator's control console. The output demand signals

from PAS are sent to the Rod Control System to position the control rods, and to the Steam Bypass and Pressure Control system for automatic load following operations" (GEH 2008c).

The PAS performs its functions via interfacing with the operator's control console. From this console the operator uses the PAS to issue supervisory control commands for non-safety-related systems, and to adjust the setpoints of lower level controllers that support automation of startup, power-range operations, and shut down.

The PAS presents the operator with a series of breakpoint controls on the main control console VDUs for the prescribed plant-operation sequence. When all the prerequisites are satisfied for a particular breakpoint in a control sequence, the operator receives a request to proceed. When permission is granted, the next control sequence is executed. The PAS then sends demand signals to various system controllers to carry out the predefined control functions.

Automatic prompts requiring manual actions are sent to the operator for those non-automated operations that are needed during startup or shutdown (such as changing the Reactor Mode Switch). Automated operations continue after completion of the prompted actions. Thus, the ESBWR startup process incorporates two LOAs: Shared control (Level 2); and operation by consent (Level 3).

If any system or component displays an abnormal condition while executing of the prescribed operational sequences, the PAS automatically switches into the manual mode, so that the operator can manipulate control rods and manage the plant by the normal controls. A failure of the PAS does not prevent manual control of the reactor, nor its safe shutdown.

US-APWR Pressurizer (Pzr) Pressure Control

The operator can select the Pzr pressure control to be either automatic or manual. During normal operation from zero to 100% power, typically the Pzr pressure control is automatic. However, the operator may deselect automatic at any point to control manually. Automatic control consists of cycling the proportional and backup heaters on and off to increase or decrease pressure. In addition, the spray valve is opened to affect a faster pressure decrease. The automated system can handle all normal transients including a full-load (100%) rejection without reaching the safety-trip setpoints.

US-APWR Steam Generator Water Level Control

The US-APWR steam generator water level control (SGWLC) system is considered Level 3 automation with various possibilities for automatic- and manual-operation. When the plant is in normal power operation, it would more closely fit as a Level 4 automation with all the SGWLC-related components under automation, unless some notable failure or disturbance occurs. There are three modes for the automation of SBWLC, here for convenience termed A, B, and C.

- *Mode A:* During normal power operation, a 3-element feedwater control regulates the flow of MFW into the SGs via the MFW line with the MFW regulation valve by continuously comparing the SG water level signal, the fixed level reference, the MFW flow signal, and the steam-flow signal.
- *Mode B:* During low-power operation, a 3-element feedwater control regulates the flow of MFW into the SGs, bypassing the MFW regulation valve, and uses the MFW bypass regulation valve by continuously comparing the MFW flow signal, the SG water-level

signal, the fixed level reference, and the reactor coolant ΔT. A separate measurement of low-range feedwater flow is used in the low-power SG water-level control mode. Thus, the signals are not the same as those for Mode A.

- *Mode C:* During hot standby operation (zero power), a single-element feedwater control regulates the flow of MFW into the SGs, using the SG water-filling control valve. The SG water-level signal is compared directly to the fixed level reference.

The transition between Modes A and B (either way) is accomplished either automatically or manually; transitions to or from Mode C are manual.

EPR RCS Pressure Control

During normal power operations, RCS pressure control in the EPR might be considered as either Level 3 or possibly Level 4. Pressure is controlled automatically by actuating the Pzr heaters to raise pressure, and by turning off the heaters or actuating the Pzr spray to lower pressure. The RCS pressure has an automatically generated, temperature-dependent, pressure setpoint when automatic EPR heat-up, or cool-down is selected (During Modes 2 or 3). The control maintains pressure within an allowable band; exceeding it actuates the pressure control. If the band is surpassed further (past a locking setpoint), then automated heat up or cool down is interrupted and an alarm provided. A manual mode allows operators to determine the pressure setpoint and to manually actuate the pressure-control devices.

Other Examples of Level 3 Automation

- SGWLC in current US NPPs
- Manual start and then automatic operation of ECCS in both current and new reactors

<u>Level 4 - Operation by Exception</u>

This level essentially is autonomous operation, unless there are specific situations or circumstances. Such a special situation may be if the automation required human action, or if the operator decides to manually override. Examples include current BWR HPCI and ADS systems, and the AP1000 PCC System (Westinghouse, 2008).

Current BWR HPCI

The High Pressure Coolant Injection (HPCI) System in current US BWRs essentially is automatic, although operators may intervene and use the HPCI for a normal shutdown. They also may stop the HPCI after an auto-actuation.

Current BWR ADS

Current BWRs have an Automatic Depressurization System (ADS) that depressurizes the reactor allowing the injection of water with low-pressure injection pumps. The ADS opens a fixed number (e.g., 5) of the Safety Relief Valves (SRVs), which varies by plant. The ADS is actuated automatically upon receiving four signals: Coincident high drywell pressure and triple-low reactor water level (indicating a LOCA); a confirmatory low reactor water level; a running low pressure injection pump; and the time-out of a 120 sec timer that starts when the other signals have been received.

The operator can manually reset the 120 sec. timer to delay or override ADS actuation, and also can manually actuate the ADS sequence or open individual SRVs.

AP1000 Passive Containment Cooling (PCC)

The AP1000 PCC System automatically actuates on a high-2 containment pressure signal (signifying a LOCA) by opening the isolation valves of the passive containment cooling-water storage tank. This starts the gravity-driven delivery of the water from the tank to the top external surface of the steel-containment shell where it forms a wet film over the dome and side walls of the containment. Manual actuation also is possible. Further, should the system be actuated inadvertently, operators can manually close the tank's isolation valves and stop the operation of the PCC. Once actuated, the PCC system operates passively for three days without the operator action; thereafter the PCC's water-storage tank must be refilled manually.

Level 5 - Autonomous Operation

This level of operation is fully autonomous; the automatic systems or functions cannot be disabled. In current and new reactor designs most NPP safety systems are fully automated, for example the RPS, ESFAS, and EDGs on a LOOP. We discuss two examples from new reactor below: The ESBWR ADS System, and the US-APWR PSMS.

ESBWR ADS

The Automatic Depressurization System (ADS) function depressurizes the reactor to allow the Gravity-Driven Cooling System (GDCS) to inject flow to replenish core coolant during a LOCA. The ADS also maintains the reactor in a depressurized state for the continued operation of GDCS after an accident.

The ADS actuates the Safety Relief Valves (SRVs) and Depressurization Valves (DPVs) in groups at staggered times controlled by delay timers as the reactor undergoes a relatively slow depressurization. Staggering minimizes the swell in reactor level during the depressurization, thereby enhancing the passive re-supply of coolant by the GDCS.

The ADS automatically actuates when a low RPV water-level signal has persisted for a preset time. The requirement for persistence of this signal ensures that momentary perturbations system do not actuate the ADS when it is not required. A two-out-of-four logic ensures that a single failure does not spuriously actuate system, while ensuring that a single failure cannot prevent initiation. Operators in the control room also can manually initiate the ADS. Unlike current older BWR plants, ESBWR operators cannot override ADS actuation.

US-APWR PSMS

The US-APWR has a Protection and Safety Monitoring System (PSMS) important to safety that consists of a reactor trip, engineered safety features (ESF) actuation, safe shutdown, post-accident monitoring, and interlocks. The PSMS has four trains that can be started up either automatically or manually. Thereafter, the system's operation proceeds to completion and cannot be overridden. In addition, the system- level actuation signals cannot be manually reset until plant conditions have been returned to specified safe conditions.

Summary of Levels of Automation in New Reactors

We summarize below the systems in new reactor designs for selected automation levels.

ESBWR

- Level 1 Direct Manual Control: Water systems, such as demineralized water
- Level 2 Shared Control: Rod Control & Information System (RC&IS); Drywell Cooling System (DWC); RWCU/SDC
- Level 3 Operation by Consent/Delegation: Plant Automation System (PAS), Steam Bypass & Pressure Control System (SB&PC), Feedwater Control System (FWC)
- Level 4 Operation by Exception: SLC
- Level 5 Autonomous Operation: ADS, RPS, ESFAS, EDGs, Leak Detection & Isolation System (LD&IS), Alternate Rod Insertion (ARI), Isolation Condenser System (ICS), Gravity Drive Cooling System (GDCS)

AP1000

- Level 1 Direct Manual Control: Water systems, such as demineralized water
- Level 2 Shared Control: Spent Fuel Pool Cooling
- Level 3 Operation by Consent/Delegation: Reactor Power Control System
- Level 4 Operation by Exception: Passive Containment Cooling (PCC), Normal Primary Pressure Control, Normal Pressurizer Water level Control, Feedwater Control System
- Level 5 Autonomous Operation: Reactor trip, ESF, ADS

EPR

- Level 1 Direct Manual Control: Water systems, such as demineralized water
- Level 2 Shared Control: Fuel Pool Cooling and Purification System
- Level 3 Operation by Consent/Delegation: Rx Pressure Control; Pressurizer Level Control; Steam Generator Water Level Control (SGWLC); Reactor Control, Surveillance, and Limitation System (RCSL)
- Level 4 Operation by Exception: At times SGWLC - main steam pressure control on load reject
- Level 5 Autonomous Operation: RPS and ESFAS

US-APWR

- Level 1 Direct Manual Control: Water systems, such as demineralized water
- Level 2 Shared Control: Essential Service Water
- Level 3 Operation by Consent/Delegation: Pressurizer Pressure Control, Pressurizer Level Control, Steam Generator Water Level Control (SGWLC)
- Level 4 Operation by Exception: At times SGWLC

- Level 5 Autonomous Operation: Protection and Safety Monitoring System or PSMS (consisting of RPS/RTS and ESFAS)

3.2 Functions of Automation

The first thing that came to our minds in considering automation is automating a control function. The frameworks of Sheridan and Billings discussed above mainly focused on control functions. However, the scope of modern automation extends well beyond this. Computer-based systems offer the opportunity to expand the application of automation to the full range of supervisory control activities. This scope reflects the definition of automation we gave earlier.

Consistent with this definition, Parasuraman, Sheridan, and Wickens (2000) identified four general functions within the context of automation:

- The *information acquisition* function refers to sensing data. A low level of automation of this class of function might consist simply of sampling particular sensors at an appropriate rate.
- The *information analysis* function determines the meaning and importance of the data acquired from sensors, and may involve validating, averaging, or estimating it.
- The *decision and action selection* function involves formulating options based on current conditions and deciding upon an appropriate action to take.
- The *action implementation* function involves executing the *a*ctions selected.

Assuming that a system can automate one or more of the general functions, we can describe an automated system by a profile portraying the degree to which each function is automated (see Figure 3-1). In the examples above, System A offers limited automation support for most cognitive functions. On the other hand, System B provides considerable support on all functions. System C affords high automation for information-related functions, but much less for decision- making and action-implementation functions. System D is a fully automated system. The processes (Figure 1-1) used to accomplish the goal of automation relates to the functions it supports. Thus, if the goal is to control a system, then a control-algorithm or control-logic is used; when the function is to support decision-making, then some form of decision-logic is employed.

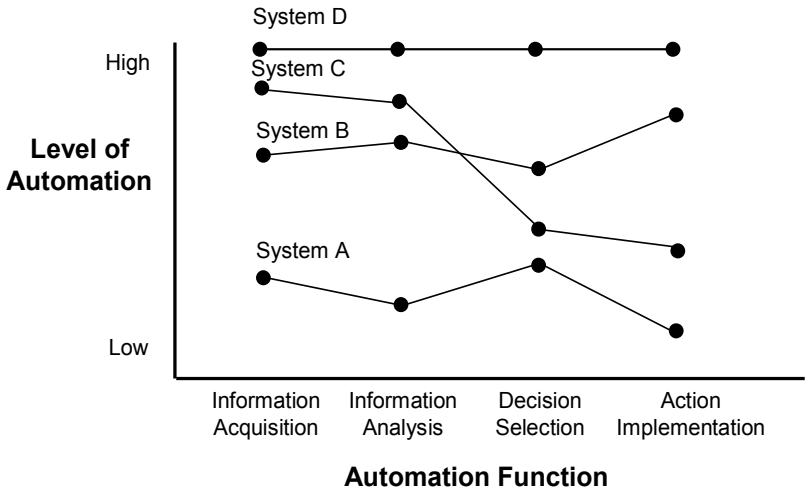


Figure 3-1 Characterizing systems based on levels of function automation (Adapted from Parasuraman et al., 2000)

Endsley and Kaber (Endsley & Kaber, 1999; Kaber & Endsley, 2004) combined the concepts of "levels of automation" and "automation of different cognitive functions" that are similar to the model proposed by Parasuraman et al. (2000). Their framework identifies ten levels of automation, distinguishing between them by the roles of humans and automation in monitoring system status, generating strategies, selecting options, and implementing options. Table 3-4 describes each level and delineates the relative roles for humans and automation.

Table 3-4 Endsley and Kaber's Levels of Automation

Level	Description	Agent Responsible*			
		Mon	Gen	Sel	Imp
1 - Manual	The human performs all tasks.	H	H	H	H
2 - Action Support	Automation assists the operator in performing the selected action, although some human control actions are required.	H/A	H	H	H/A
3- Batch Processing	Although humans generate and select the options to be performed, they are completed automatically.	H/A	H	H	A
4 - Shared Control	Both the human and the automation generate decision options. The human still retains full control in selecting which option to implement; however, carrying out the actions is shared.	H/A	H/A	H	H/A
5 -Decision Support	The automation generates a list of decision options from, which humans select, or they may generate their own options. Once the human has selected an option, it is implemented automatically.	H/A	H/A	H	A

Level	Description	Agent Responsible*			
		Mon	Gen	Sel	Imp
6 - Blended Decision Making	The automation generates a list of decision options, selects one, and carries it out with human consent. The human may approve of the automation's option or select one from among those generated by the automation or the operator. The automation l then completes the human-selected action.	H/A	H/A	H/A	A
7 - Rigid System	Automation presents a limited set of actions from which the human selects one; humans cannot generate other options. Automation implements the selected actions.	H/A	A	H	A
8 - Automated Decision Making	The system selects and implements the best option from a list of alternatives it generated (augmented by alternatives suggested by the human).	H/A	H/A	A	A
9 - Supervisory Control	The system generates options, selects one to implement and carries out that action. The human monitors the system and intervenes if necessary. Intervention requires that the human select a different option from those generated by automation or by the human).	H/A	A	A	A
10 - Full Automation	The system carries out all actions. The human is out of the control loop and cannot intervene.	A	A	A	A

Note: *Abbreviations: Human (H), Automation (A), Monitoring (Mon), Generating (Gen), Selecting (Sel), Implementing (Imp)
Adapted from Endsley and Kaber, 1999.

Thus, in addition to the concept of LOA, we must consider the functions to which automation is applied. The models of Parasuraman and Endsley and their colleagues accomplish this in slightly different ways.

To address the fact that automation can be applied to different cognitive functions, we chose to use the classification applied in many project on developing HFE guidance for the NRC (O'Hara et. al, 2008a). Operators undertake two types of tasks: Primary tasks and secondary tasks. The former includes monitoring plant parameters, following procedures, responding to alarms, and operating equipment (e.g., starting pumps and aligning valves). In the context of automation, the secondary tasks of interest are "interface management tasks." Primary tasks have several common elements: Monitoring and detection, assessing situations, planning responses, and implementing them. In Figure 3-2, we illustrate the relationship between these tasks, and describe them briefly below. Breakdowns in any of these generic primary tasks can entail a human error.

Monitoring and detection refer to the activities involved in extracting information from the environment. Monitoring is checking the state of the plant to determine whether it is operating correctly, including verifying parameters indicated on the control panels, keeping track of the data displayed on a computer screen, obtaining verbal reports from other personnel, and sending operators to areas of the plant to observe equipment. *Situation assessment* is evaluating current conditions to confirm that they are acceptable or to determine the underlying causes of any abnormalities. *Response planning* refers to deciding upon a course of action to resolve the current situation. In an NPP, procedures usually aid response planning; when they are judged appropriate to the current situation, the need to generate a response plan in real-

time largely may be eliminated. However, even with good procedures, some aspects of response planning will be undertaken. *Response implementation* is performing the actions specified by response planning. They include selecting a control, providing input to the control, and monitoring the responses of the system and process.

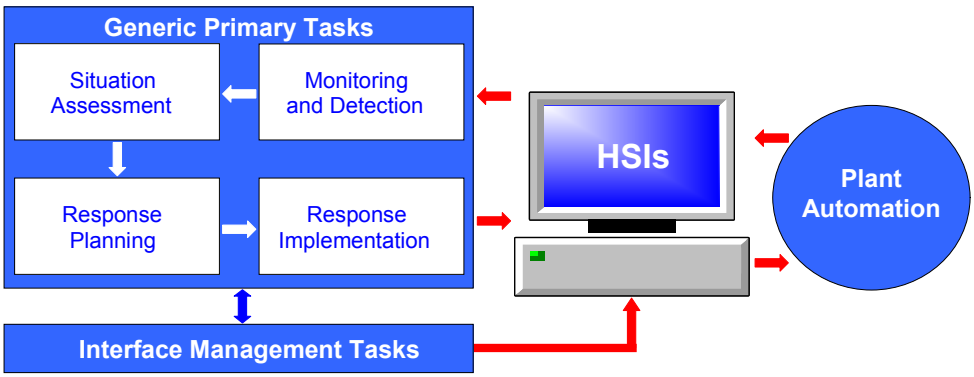


Figure 3-2 Generic primary tasks that plant personnel undertake

To understand human performance, it is also important to consider the secondary tasks, or so-called *interface management tasks,* upon which rests the success of the primary tasks. In a computer-based control room, secondary tasks include navigating through or accessing information at workstations, and arranging various pieces of information on the screen. In part, these tasks are necessitated because operators view only a small amount of information at any one time through the workstation displays. Therefore, they must undertake interface management tasks to retrieve and arrange the information. These tasks are called secondary because they are not directly associated with monitoring and controlling the plant. The distinction between primary- and secondary-tasks is important because of their interactions. For example, secondary tasks create workload and may divert attention away from primary tasks (O'Hara & Brown, 2002). The frameworks of Parasuraman and Endsley did not encompass these important secondary tasks. However, since automation can participate in performing these tasks, we included interface management in our characterization.

Below, we give examples of applying automation to the generic cognitive tasks (both primary and secondary) discussed above.

Monitoring and Detection

In NPPs and most other complex human-machine systems, the multitude of individual parameters involved in monitoring and detection easily can overwhelm operators. Therefore, an alarm system generally is provided to support these activities.

The alarm system is one primary means whereby abnormalities and failures come to the attention of the personnel. An alarm system essentially is an automated monitoring and detection system that alerts operators via visual and/or auditory displays to specific conditions/events, such as when parameters deviate from specified limits or setpoints (O'Hara et al., 1994; O'Hara & Brown, 1999). Alarm systems accomplish their function via sensing, processing, and HSI elements.

Situation Assessment

While alarm systems automatically support monitoring and detection, operators must assess the situation to make sense of the alarms and understand events in the plant. However, support can be provided here by installing disturbance analysis systems that evaluate the pattern of the alarms and identify the associated event (Progner & Meizer, 1978).

In fact, a variety of "computerized operator support systems" (COSS) assist personnel in assessing situations. The following are some of the nuclear plant applications (Garland & Poehlman, 1998; IAEA, 1993, 1995b; O'Hara, 1998):

- Fault/disturbance detection and diagnosis
- Safety-function monitoring (e.g., severity of challenges to critical safety function)
- Plant- performance monitoring (e.g., efficiency of main pumps, turbine, and generator)
- Core monitoring
- Maintenance monitoring and prediction aids
- Boiler-tube failure inspection and prediction
- Turbine-generator on-line diagnostics
- Plant thermal-performance monitoring
- Feedwater heater and condenser analysis

COSSs depend on a wide range of underlying technologies, such as artificial intelligence, expert systems, neural networks, and fuzzy logic (O'Hara, Stubler & Higgins, 1996). For example, expert systems, based on artificial neural network technology, were formulated for the following NPP applications: Diagnosing faults, analyzing core vibrations, monitoring loose parts monitoring, modeling thermodynamics, estimating thermal margins, and identifying transients (Uhrig, 1994).

Fault diagnosis is the principal application area for many of these systems; it requires a monitoring capability as input. The literature discusses various computer-based aids that analyze plant conditions and offer recommendations to plant personnel (e.g., for improving the plant's performance, diagnosing failures, and identifying success paths). Many of these are research prototype systems.

Some other examples of COSSs in the nuclear industry include the following:

- *Emergency-response projection code* - Software for projecting the doses received by areas surrounding a nuclear generating station after the airborne release of radioactive materials following a nuclear accident (AECB, 1994).
- *Fuel-loading expert system* - A computer-assisted system for fuel reloading while at power designed for CANDU NPPs (Gertman et al., 1994).
- *Mitsubishi Computerized Operator Support System (MCOSS)* – The Japan Atomic Power Company's Tsuruga Nuclear Power Plant (Unit 2) uses this system. It aids the operator's decision-making by detecting abnormal operating conditions before they become serious and advises the operator of appropriate actions. Should its early-warning capability fail to prevent a plant trip, the MCOSS assists the operator in reaching safe shutdown (O'Hara, Stubler & Higgins, 1996).

While the first-generation COSSs have been around for some time, the digital I&C infrastructure in new plants will provide a basis for developing second-generation systems. Accordingly, we

anticipate an increase in their use and scope in the control room. In addition, because effective testing and maintenance are the major drivers for the safety, reliability, and economics of nuclear power, we believe that there also will be an increase in the application of COSS technology to maintenance decision-making, and planning. Computerized systems to support maintenance will support 'just-in-time' maintenance, so minimizing the time spent on maintenance, and will evaluate its impact on production, risk, and personnel exposure.

Plant information can feed predictive models and fast-time simulations to provide personnel with much better decision support than previously was possible.

Response Planning

Automation has been applied to response planning in the form of computer-based procedure systems (CBPs). One such usage is emergency operating procedures (EOPs), developed to assist operators in responding to events by identifying the tasks needed to assure safety goals. EOPs relieve operators of the burden of formulating response plans in real time. Instead, plant staff analyze in advance the actions necessary to maintain and restore critical safety functions, which then are developed into a set of detailed procedures.

CBPs also automatically support many aspects of procedure use and management. Like other forms of automation, they can undertake many tasks that formerly the crew members did, including

- retrieving data and assessing its quality
- resolving step logic
- keeping track of location in the procedure
- keeping track of steps of continuous applicability
- assessing cautions, safety-function status trees, and fold-out page criteria

Some CBPs encompass fairly extensive functionality. For example, Ito, Hanada, Yoshida, & Sugino (2006) described Mitsubishi's Emergency Operator Support System (EOSS), a system whose functions extend far beyond procedure management. It monitors critical safety functions, diagnoses abnormal conditions, and identifies appropriate procedures. The system also checks automatic actions, such as reactor trip and safety injection, presenting their status to the operator. In trying to identify possible operator errors, it monitors personnel as well.

O'Hara et al. (2000) developed an overall framework to characterize the level of automation of CBPs for cognitive- and procedure-functions (Table 3-5). This type of characterization is similar to the generic framework suggested by Parasuraman (Figure 3-1); however, it is much more detailed and the functionally is tailored to procedures.

In the rows, we identify the four general cognitive functions (described above) and give the specific procedure-related functions constituting them. In the columns, four levels of automation are identified; they are those originally reported in O'Hara et al. (2000), rather than the more detailed levels Section 3.1:

- *Manual* - The function is performed by the operators with no assistance from the CBP.
- *Advisory* - The CBP provides advice only. For example, it may advise the operator to start Pump A, but does not start it.

- *Shared* - The CBP and the operators both perform the function. For example, a CBP system may perform process monitoring but may not cover all information about the system, such as a valve's position, because it lacks the instrumentation. When this type of information must be monitored, the operator does it.
- *Automatic* - The CBP performs the function automatically without the operator's direct intervention; operators may or may not be notified of the actions taken.

Table 3-5 Levels of Automation of Procedure Functions

Procedure Functions	Level of Automation			
	Manual	**Advisory**	**Shared**	**Automatic**
Monitoring and Detection				
Process parameter values				
Operator actions				
Situation Assessment				
Procedure entry conditions				
Resolution of procedure step logic				
Step status (incomplete or completed)				
Procedure history				
Context sensitive step presentation				
Assessment of continuous, time, and parameter steps				
Assessment of cautions				
High-level goal attainment and procedure exit conditions				
Response Planning				
Selection of next step or procedure				
Procedure modification based on current situation				
Response Implementation				
Transition from one step to the next				
Transition to other parts of procedure or to other procedures				
Control of plant equipment				

Source is O'Hara et al. (2000)

A given CBP system may not offer an entire function. For example, a particular CBP may not address the control of equipment in any capacity; then, operators would control it from other HSIs.

Consistent with this approach, Niwa, Terabe, and Washio (1999) proposed levels of automation for CBP functionality (Table 3-6). At the higher levels of automation, more functions are automated and the system evolves towards full autonomy.

Table 3-6 Niwa et al.'s Levels of Procedure Automation

Level	Description
0	Procedures as documents. On this level, procedures exist as printed procedures or checklists. This is the traditional form that generally is being used.
1	Procedures as computerized documents. Here, procedures are transferred to an electronic format and presented on VDUs, with manual scrolling. The transfer does not change the format of the procedures. The only advantage is that procedures may be read done by scrolling forwards or backwards on the display.
2	Procedures as computer displays. On this level, the formatting of the procedures is altered to take advantage of the facilities offered by computer controlled displays and computer graphics. Beyond this level, we talk about computerized procedures.
3	Computerized procedures with progress monitoring. The difference from the previous level is that there is limited monitoring of progress through the procedure, which is used to implement functions such as automatic scrolling, thereby reducing the operator's tasks.
4	Automated procedures: Management by delegation. On this level, well-defined subsets or parts of the procedure may be performed automatically on the operator's orders. Computerization thereby is extended from formatting and displaying the procedure to its execution; i.e., it includes various levels of automation.
5	Automated procedures: Management by consent. The next logical step is that the procedure system, rather than the operators, monitors the process, identifies an appropriate procedure, and executes it. However, its execution must, have the operator's previous consent.
6	Automated procedures: Management by exception. Going further, the procedure system identifies problems in the process and follows this by automatic execution without needing action by, or approval from operators.
7	Autonomous execution when required. This level may entail two different conditions. In one the results of executing the procedure are announced to operators; in the other, they are not announced. The latter basically corresponds to the level of full automation, and, in a sense, the procedure in its conventional form is no longer necessary. The procedure and its execution are fully computerized.

Note: Source is Niwa et al. (1999)

Response Implementation

A typical control is executing an automatic response. Once the operator knows what action to take, such as to start a system, the operator pushes a button or moves a switch to initiate the action. As noted in O'Hara et al. (2008b), digital computer-based control systems provide the capability to implement much more advanced control algorithms than used in plants to date. Current plants rely primarily on single-input, single-output classical control schemes to automate individual control loops. Some plants have applied multi-variable control schemes, and others incorporate a modest level of integration of control loops. However, more advanced control methods and algorithms can assure optimum performance; they include matrix techniques, nonlinear control methods, fuzzy logic, neural networks, adaptive control (a control that modifies its behavior based on plant dynamics), expert systems, state-based control schemes, and schemes that combine multiple control methods in a multi-mode or hierarchical system (see Wood et al., 2003 for a survey of these methods). Installing these advanced techniques may assure more integrated control of plant systems and processes (versus separate, non-interacting control loops), and greater complexity.

Interface Management Tasks

As noted above, secondary task performance must be considered. The time and effort spent managing HSIs can be considerable, disrupting the operators' primary tasks of monitoring and controlling the plant (O'Hara & Brown, 2002). Thus, aspects of interface management are candidates for automation (Roberts & Parush, 2007). A very simple example is automating the alarm reset (Yenn et al., 2006). Another instance is the automatic identification of a display appropriate to the ongoing situation, e.g., identifying an emergency procedure display upon detecting any of the procedure's entry conditions. Here, the HSI would notify the operator of the availability of the display, such as via a blinking icon at the bottom of the screen, rather than disrupting the operator's ongoing activity by obtrusively showing the display. As display identifying, navigating, and retrieving the display might require considerable effort, this type of automation may reduce the interface management workload and the possibility of the operator erroneously retrieving the wrong display.

3.3 Processes of Automation

Automation uses input from the plant (and perhaps the operator) and processes the information to accomplish a goal. These processes are an important aspect of automation in that they are the means by which automation performs its tasks. Automation processes can include control algorithms, decision logic (such as the use of Boolean logic), and virtually any other type of information processing routine suited to its tasks.

3.4 Modes of Automation

Automated systems can have different modes of operation. Modes define sets of mutually exclusive behaviors that describe the relationship between input to the automation and the response to it (Jamieson & Vicente, 2005). A system can have multiple modes, but only one mode is active at a time. Accordingly, modes do not imply differing levels of automation; rather, they perform the same function in different ways. Modes are beneficial in enabling a system to do different tasks, or to accomplish the same task through using different strategies under changing conditions.

A simple example of modes is a GPS device. When a user inputs a destination, the device automatically plans the best route. Users can select the driving- or the pedestrian-mode. In a city with many one-way streets, the suggested route can be completely different depending on the mode selected. In driving mode, the one-way streets constrain the route selected; in the pedestrian mode, their presence has no impact on the route suggested. Thus, the task is the same, but its solution depends on the chosen mode.

The Reactor Mode switch in a BWR similarly changes various automatic features.

3.5 Flexibility of Allocation

A system can be designed such that the human or machine responsible for performing a task always is the same, so-called static allocation. Alternatively, a task can be performed either by automatic systems or by personnel based on situational considerations, such as the overall workload of personnel. For example, automation may assume control over lower priority tasks when the operator's workload increases to a level where it would be difficult to perform all their current work. This approach ensures that operators focus their attention on high priority tasks

by maintaining their workload within acceptable levels. In the simple example of alarm reset we give above, under conditions of a major plant disturbance when workload is very high and many alarms are coming in, operators can reallocate the alarm-reset task from manual to automatic. Automation is said to be adaptive when the performance of tasks can be interchanged flexibly between humans and machines.

Pirus (2004a and 2004b) described Électricité de France's approach to the next generation of NPP operations that employs adaptive automation (AA). Pirus notes that fixed levels of automation might be problematic for operators; therefore, they are given control over the levels of automation used. The operational concepts and HSIs are being tested using the FITNESS (Functional Integrated Treatments for Novative Ecological Support System) simulator. For example, in real time, operators can select the degree to which operational procedures are automated. The procedural steps can be handled manually or automatically.

A key consideration for adaptive automatic systems is who decides when the responsibility for a task changes from human to machine or vice versa, and on what basis. Some authors distinguish between *adaptable* automation and *adaptive* automation (Lee, 2006; Miller & Parasuraman, 2007). In the former, the operator selects the allocation, e.g., the operator of FITNESS selects the degree of automation of the procedures sequences. In the latter, adaptive automation, the automation automatically adjusts based on some "triggering" condition, that can be based on operator factors (Prinzel, 2003), such as

- psycho-physiological measures
- dynamic workload assessment
- task-performance measures

Triggering conditions also can be set on the presence of critical events or reaching a setpoint(s) of measured parameter(s) (DeVisser et al., 2008). In actuality, triggering can be performed by the operator, triggering conditions, or some combination of the two. Therefore, we prefer to simply use the term adaptive automation, and specify the triggering conditions.

Inagaki (2006) provides a good example. When automation detects a situation where an operator should take an action, it provides an alert. The automation then monitors the situation and should the operator fail to take action, the automation assumes control and does it. This is only done in critical situations. The concept is illustrated by the automatic ground collision avoidance system (AGCAS) used in some combat aircraft. It is designed to prevent controlled flight into terrain (CFIT) accidents. Aircraft typically provide a ground-proximity warning, altering the pilots to take evasive action. However, sometimes they do not hear the alarm or react sufficiently quickly, typically leading to CFIT. The automatic AGCAS monitors the pilot's response to the alarm and sensing no response, takes over and automatically makes the proper maneuver. After the threat is avoided, control is returned to the pilot. Inagaki refers to this as "situation adaptive autonomy."

Situation-adaptive autonomy reflects the trading of authority over a system's performance between human and machine agents (Inagaki, 2006). While personnel typically are in charge of automation, a flexible approach under extreme or critical situations may be the best solution to achieve overall mission success.

3.6 Reliability of Automation

The final dimension of automation in the characterization is reliability that is less than perfect in all engineered systems. Automatic systems might fail entirely or in part, and thus, compromise their ability to achieve their intended function. When an automatic system has a simple, well-defined task to accomplish, its reliability is easy to quantify, e.g., expressed as the probability that the system will correctly perform its function.

When its functions and tasks are complex, as for many COSSs, defining measures of reliability is more involved. Overall reliability may be expressed in terms of the probability the system will correctly perform its function. However, it may be important to distinguish different aspects of a system's functions. Thus, for an alarm system, reliability can be expressed in terms of misses (not alarming when the alarm conditions exist) and false positives (alarming when the alarm condition does not exist). Further, automation's reliability may differ in different contexts of usage or modes of operation.

3.7 Conclusions

We discussed a characterization of automation based on how automation is implemented in current systems. It describes automation along six dimensions:

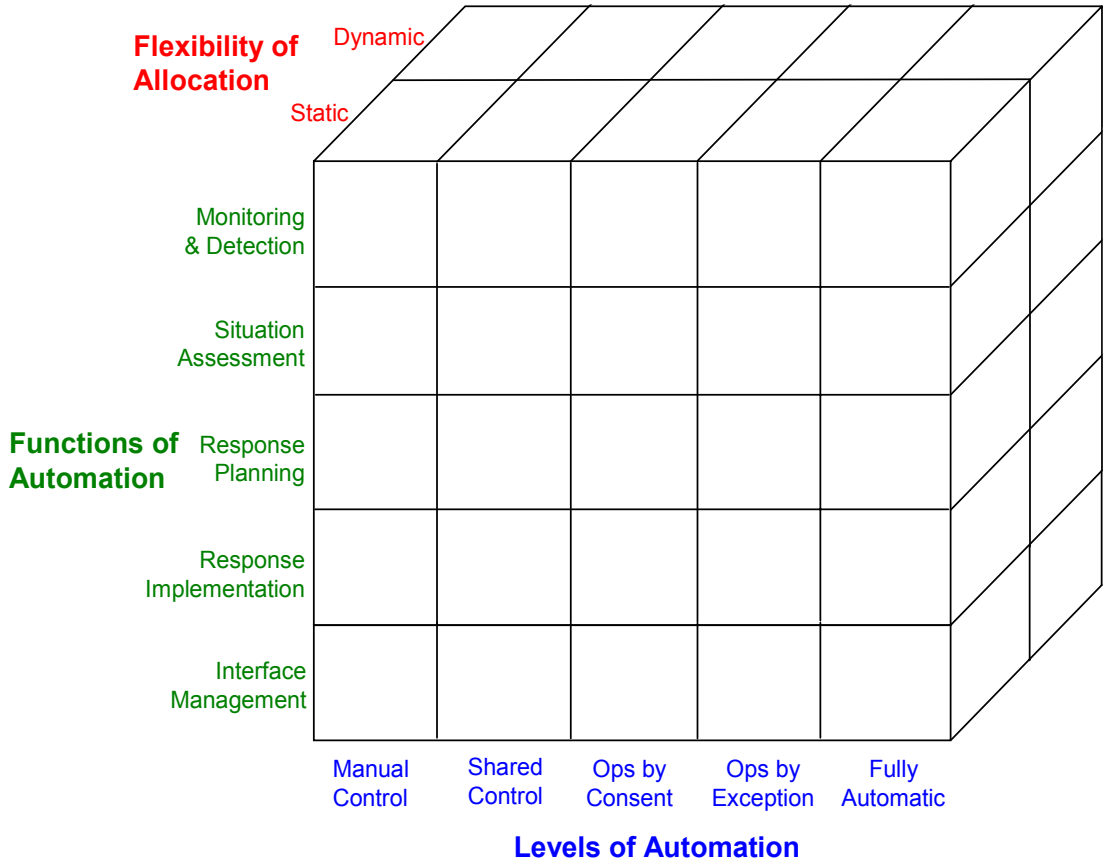
- Level of Automation
- Functions of Automation
- Processes of Automation
- Modes of Automation
- Flexibility of Allocation
- Reliability of Automation

Figure 3-3 illustrates three of the six dimensions, along which all automatic systems can be characterized. This is a generic characterization of automation, defining the design envelope wherein any specific application of automation can be designed. When considering applying the generic characterization to a specific application, we suggest considering the following two points:

- A specific application of automation is likely to reflect a subset of these dimensional combinations, i.e., those that are derived for a sound design process, and fully in accord with the specific aspect of operations being addressed.
- When applying dimensional characterizations to a specific application, they need to be interpreted with respect its functionality. That is, the generic characterization does not reflect the more fine-grained analysis that can be made after accounting for the specific functions of the automatic system being addressed. The CBP characterization table (Table 3-5) illustrates such a fine-grained level of specificity.

Modern approaches to automation emphasize the value of multi-agent teams monitoring and controlling complex systems (Christoffersen & Woods, 2002; Hollnagel & Woods, 2005; Malin et al., 1991a, 1991b, 1992; Woods & Hollnagel, 2006). The teams consist of human, software, and hardware elements working together, sharing responsibilities, and shifting responsibilities to support the plant's overall production and safety missions. In this context, the term "agents" often generically refers to who/what is performing an activity; i.e., agents are entities that do things. An agent will monitor the plant to detect conditions indicating that a function must be

performed. An agent will assess the situation and plan a response. Having established the response plan, it must be implemented by sending control signals to actuators. The agent will continue monitoring the activity to determine that the function is being accomplished, and to plan again if it is not. Finally, the agent must decide when the function is completed satisfactorily. Human or machine agents can perform any one or all of these activities. Uhrig et al. (2004) suggest that for Generation IV plant designs, "multi-agent" systems will be the first line of defense against degraded conditions, assuring continuous surveillance and predictive diagnosis.



(Note the dimensions of Processes, Modes, and Reliability are not shown)

Figure 3-3 Framework for characterizing automation

4 AUTOMATION AND HUMAN PERFORMANCE

In this section, we examine the effect of automaton's design on human performance. In Section 5 we will address how to design automation to support and optimize such interaction.

To the extent possible, we will link information about the automation's effects on human performance to the dimensions of the characterization presented in Section 3. Since the literature does not conform neatly to our characterization, we have interpreted the findings according to our dimensions. For example, the dimensions of levels of automation and automation functions often are confounded in the literature, that is, to increase the levels of automation, studies often added more functions.

This section has two main themes. First, that there are well-known human performance issues associated with automation that is poorly designed, especially upon the failure of automation. We summarize these well-documented issues here. Second, there are newer approaches to automation that can minimize these problems. Our discussion is divided into the following topics:

- Automation's Reliability, Operator Trust, and the Use of Automation (Section 4.1)
- High-Levels of Automation and Operator Performance (Section 4.2)
- Intermediate- and Low-Levels of Automation and Operator Performance (Section 4.3)
- Varying Levels of Automation, Adaptive Automation, and Operator Performance (Section 4.4)

The conclusions derived from the studies in each area are summarized in Section 4.5 with recommendations for additional research.

To make the discussion more realistic, we use a case study wherein many issues associated with human interaction with automation came into play. Figure 4-1 summarizes the 1995 crash of a Boeing 757 in Cali, Columbia. We refer to this summary, and its lessons learned, in the following discussions.

4.1 Automation's Reliability, Operator Trust, and the Use of Automation

While some automation is initiated and proceeds with little or no human intervention, e.g., reactor scram, the use of many automated systems is at the operator's discretion. Operators rely, more or less, on those systems and determine the contexts in which they are useful. Parasuraman and Riley (1997) evaluated numerous studies to examine how operators appropriately and inappropriately use or do not use automation, and to identify the factors underlying their decisions.

Trust is a key factor governing how operators use automation. Trust was defined as "…the attitude that an agent will help achieve an individual's goals in a situation characterized by uncertainty and variability" (Lee & See, 2004).[2] With training and experience, operators develop a level of trust that an automated system will function appropriately; if this level is below some threshold, they are unlikely to use the system. The automaton's reliability is an important consideration in the development of trust; operators tend to trust a reliable system. When an

[2] Jian, Bisantz, and Drury (2000) give measures of trust, viz, their "System Trust Scale" that was validated by a factor analysis study (Spain, Bustamante & Bliss, 2008).

automated system falls below some level of reliability, for example, generates many false alarms or provides inaccurate guidance, operators consider it untrustworthy and will not rely on it. We note that trust is based on the *perception* of a system's reliability that may not correlate perfectly with its actual reliability (Merritt & Ilgen, 2008).

Workload is another important consideration (Parasuraman & Riley, 1997). As discussed earlier, automated systems were developed to lower workload; however, operators often find their workload is not really lowered, but rather is changed and focused on other tasks, such as configuring the automated system to do what is needed, or monitoring it to ensure it is functioning properly. If the time required for interacting with automation is too high, operators will not use it. Operators make tradeoffs between the benefits gained by automation, such as a reduced workload on one task, and the effort required to use it, such as the increased workload in setting it up and monitoring it.

Other factors identified as impacting trust were self confidence in one's own skills, task complexity, and fatigue. Further, for an automated system with the same reliability, there are individual differences in trust (Meyer et al., 2003). Thus, several factors affect people's decision to use automation.

Parasuraman and Riley (1997) identified two inappropriate uses of automation: Misuse and disuse. *Misuse* is the overreliance on automation, where operators may continue to use it, even when it does not function properly. Overreliance on automation was one of the root causes of the Cali accident (see Figure 4-1); the pilots failed to abandon the automation until it was too late.

One of the consequences identified with misuse is an error of commission, i.e., following the automation's guidance without checking it or recognizing its limitations. Another consequence is an error of omission characterized by a failure to monitor the automation appropriately. This finding was supported in a recent study of the automation-monitoring strategies of pilots of commercial aircraft (Sarter, Mumaw, & Wickens, 2007) who monitor basic flight parameters much more than indications of the automation's configuration. They fail to verify manual-mode selections or automatic-mode changes. In fact, the pilots typically did not assess mode annunciations in sufficient depth to understand the implications on the aircraft's behavior.

Among the many factors influencing an operator's automation monitoring behavior are the following:

- Automation's reliability (operators are less likely to monitor automation they consider reliable)
- Operator's workload (operators are less likely to monitor automation when they are busy with other tasks)
- HSI design (operators are less likely to monitor automation when the HSI does not offer an easy means to do so)

Parasuraman and Riley (1997) suggest that monitoring is improved when the behavior of automation can be easily determined in the HSIs, especially those that minimize attentional demands (such as integrated displays and emergent features). They noted that there is evidence to indicate that automation failures were better detected with these types of displays.

The Crash of a Boeing 757 in Cali, Columbia

The 1995 crash of an American Airline Boeing 757 in Cali, Columbia, is an interesting case study in the human-performance impacts of poorly designed automation and the importance of a well-designed HSI (Endsley & Strauch, 1997; Strauch, 1997). The flight left Miami for Cali, with a plan was to proceed past the Cali airport, reverse course, and then come in to land from the opposite direction. While the pilots were preparing for their approach, air-traffic control gave them the option to take a direct approach to the airport. The pilots accepted; however, they made several mistakes in attempting to reprogram the flight management system (FMS), resulting in the crash 33 miles from the airport.

The FMS is an automated navigation- and flight-control system. Its reliability and accuracy are so good that pilots can use it throughout an entire flight except during takeoff and landing. The pilots had several years of experience with the FMS. When the new approach was agreed to, the pilot had to reprogram the FMS to fly directly to Cali. In putting that command into the FMS, the intermediate waypoints between their current location and Cali were deleted, including the Tulua beacon, the first airport-approach waypoint. The pilots were unaware that the information was lost. They recognized that something was wrong when their attempts to review the new approach failed, but did not know its cause. Rather than abandoning the FMS and manually flying to Cali, they continued trying to resolve the problem even though time was very limited.

The pilots attempted to find Tulua in the FMS database. This was unsuccessful, so they entered the final waypoint into the FMS, a beacon named “Roxo” located at the runway. On the navigation chart, “R” is used to designate Roxo. One pilot searched the FMS database to retrieve all beacons beginning with “R.” However, in that database “R” referred to another beacon named “Romeo” which was located near Bogota, in the opposite direction from Cali. The pilot selected “R” and commanded the FMS to fly there. The plane automatically proceeded to bank left to turn around. In reprogramming the FMS, the pilots changed its mode. When pilots program their own flight plan and do not use one generated by the FMS, it no longer automatically avoids any terrain. This new mode of operations was not clearly indicated in the display.

The pilots would have realized that the plane was no longer going to Cali, if they had monitored the automation on their CRTs that displays the predicted lateral flight path, but they did not. Further, the FMS did not display vertical information; it was on another display. It took about a minute for the pilots to realize the plane was turning around, at which time the captain directed the first officer to turn to the right and fly back to Cali. However, it was too late. The ground-proximity warning sounded and the plane crashed into the mountains.

The accident analysis provided many insights into the relationship between personnel and automation:

- *Overreliance on automation* - The pilots’ failure to abandon the automation until it was too late was likely due to great reliance on, and trust in the FMS and because after years of using FMS, the pilots were not as familiar with a manual approach. In addition, once they thought the FMS was reset, they failed to monitor it properly.
- *Loss of situation awareness* - The reliance on automation and failure to monitor it led to a loss of situation awareness about the plane’s position and, perhaps more importantly, its altitude. The pilots seemed unaware of the change in the FMS’s mode and its implication, i.e., that avoiding terrain is not automatic when following pilot-generated flight plans. When the time came to take over, their loss of SA led to a fatal action.
- *Complexity* - The FMS is a complex system with great functionality. The pilots apparently had insufficient knowledge of details of how it works.
- *HSIs to automation* - The FMS HSI was poorly designed, making it difficult for the pilots to reprogram their approach; it did not provide them with critical information about changes in modes of operation and vertical position relative to terrain.
- *Poor integration of the FMS and related reference information* - The FMS design was at variance with supporting documentation (navigation charts), making it easy to make an error once the database was accessed.

Figure 4-1 Case study of the relationship of automation and human performance

The second type of inappropriate use of automation is *disuse;* that is, the situation where operators do not fully and appropriately use of automation. Operators may not use automation even though it is reliable. Again trust, workload, and HSIs are significant factors. Operators may not use reliable automation when

- their trust is low
- the workload required to use automation is considered too high
- HSIs do not provide sufficient information to track what the automation is doing

Lee and See (2004) examined two aspects of trust, calibration and resolution, in detail. Calibration signifies how well trust correlates with the system's actual capabilities. When trust is well-calibrated, the operator's trust is proportional to the reliability of the automation. When calibration is poor, either trust exceeds the automation's capabilities (misuse), or trust is less than automation's capabilities (misuse). We illustrate this relationship in Figure 4-2.

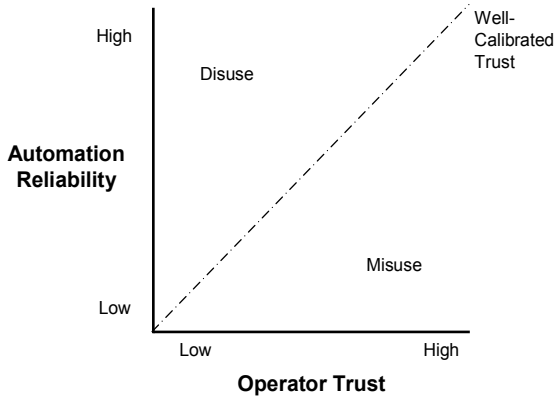


Figure 4-2 Calibration of trust and reliability

Resolution refers to how the operator's level of trust correlates with the different capabilities of automation or to different situations is which automation is used. The automation's reliability may differ across different contexts of use. For example, an alarm system may have one false alarm level during full power operations, but display much higher level during shutdown conditions. The same is true of decision aids and other types of automation; their reliability and performance differ in different situations. When resolution is good, trust is well calibrated for the different capabilities and uses of automation. When resolution is poor, the level of trust does not discriminate the different capabilities and uses of automation.

Like Parasuraman and Riley (1997), Lee found that the content and format of the HSI design affects impact on operator trust (discussed in Section 5). In addition, to make automation trustworthy, Lee recommended that training address

- the purpose of automation, its design bases, and range of applications in a way that relates to user goals
- automation's expected reliability, the mechanisms governing its behavior, and its intended use
- the promotion of appropriate trust and how situations interact with the characteristics of the automation to affect its capability

Once training is completed, the appropriateness of an operator's trust should be evaluated to assess its calibration and resolution, and also later after accruing experience with the system.

Thus, an automated system's reliability impacts trust and ultimately its use by operators. Since no system is perfectly reliable, the question is how reliable automation must be to be trusted? We summarize below several studies that addressed this question.

Skitka, Mosierer and Burdick (1999) compared simulated flight performance with and without an automated decision-aid that monitored specific gauges and recommended actions to be taken when the gauge's readings entered the red zone. The participants, all students, were told the gauges were always 100% accurate, but that the automation did make mistakes. When working properly, the automation increased task accuracy and reduced errors. When the automation failed to monitor properly, operators' errors rose relative to the no automation condition; i.e., errors of omission (missing an event that was not detected by the aid) and of commission (doing what the aid said even when it contradicted their training and the information in the gauges) were higher. The authors suggested that in trying to reduce cognitive effort, operators tend to accept what the decision aids tell them.

Metzger and Parasuraman (2005) examined decision aid reliability and its relationship to using automation. The participants were professional controllers. The aid supported the detection of air traffic conflicts. The aid was either completely reliable or was subject to failures. The researchers assessed task performance and workload. They found that when the aid was very reliable, task performance improved, and workload was lowered. However, when the automation was less reliable, conflicts were missed and manual detection was better. The authors suggested applying automation of lower reliability to support less important tasks, thereby keeping operators more accessible to address the more important tasks.

Ross et al. (2008) examined the relationship between automation reliability, operator trust, reliance (use of automation in place of manual performance), and performance. Student participants performed a simulated unmanned-ground-vehicle task to identify the locations of terrorists, civilians, and improvised explosive devices. They were told that using the aid was optional, but not told about its reliability, the levels of which ranged from 75% to 99%, calculated as a function of misses and false alarms. Some participants performed the task with no aid. Even though the participants did not know the system's reliability, the results showed that participants' reliance on automation was a function of its reliability. As reliability increased, perceived trust was greater and task performance better.

In a study by Rice et al. (2008), student participants performed a simulated security screening task with the support of a decision aid for detecting weapons that was 95%, 80%, or 65% reliable. The aid never missed a target, but could produce false alarms. The participants made target-detection decisions in both time-pressured- and non-time-pressured-scenarios. The former were intended to increase reliance on automation. Overall detection performance was best when the reliability was 95% and worst when it was 65%. A higher level of automation dependence (agreement with the recommendations of the decision aid) was registered in the time-pressure scenarios despite the occurrence of false alarms. The authors concluded that using time-pressure scenarios encouraged automation use.

In a security-screening task, Madhavan and Wiergmann (2005) assessed the effects on students of the type of advisor (human vs. automation), pedigree (expert vs. novice), and reliability (70% vs. 90%) on identifying targets. When the advisor was 90% reliable, there was

no significant difference in identification between the types of advisors. Participants agreed more with the automated novice than the human novice. This bias towards automation fell when the automated aids made errors. Authors suggest that different factors influence the use of advice when it comes from a human vs. automation. When a human is viewed as an expert, participants demonstrated greater acceptance of the advice and were more accepting of errors.

According to Rovira, McGarry, and Parasuraman (2007) the reliability of automation differentially affected the acquisition of information and decision-making functions.[3] Student participants identified targets as part of a simulated command- and control-operation. They had to identifying the most dangerous target, decide upon an engagement strategy (identify which "friendly" resources should be used to attack the enemy). The task was performed manually or with an automated aid that supported the gathering of information, or three levels of decision functions. The aid was either unreliable (60% correct) or reliable (80% correct). The dependent measures were accuracy and speed of identifying the most dangerous target and the correct engagement strategy. Their results revealed that reliable automation improved performance compared with manual performance. If the 80% reliable automation aid failed, the participant's performance was worse with decision support than with information-acquisition support. Performance was poor when the aid was only 60% reliable, regardless of the type. The authors concluded that should decision-support automation not be highly reliable, designers should provide users with information automation only because it is easier to compensate for loss of that function in comparison with decision functions.

Operator trust in automation is higher when performance is better with it than without it (Madhaven et al., 2006). When automation fails, trust declines, there is a corresponding increase in the operator's perception of the accuracy of their own performance. While an increased error rate in an automatic system greatly degrades trust in the system, an increased error rate during manual control has a small effect on one's trust in it (Ezer, Fisk & Rogers, 2005). Madhaven et al. (2006) found that diagnostic aids were especially sensitive to reduced trust when they made misdiagnoses in tasks that operators view as easy. These authors recommend giving operators clear, specific information about the limits of automation, such as why something might go wrong. That information will support proper calibration and resolution of trust. This finding is consistent with those of Rovira et al.'s (2007) study that we reported above.

We discuss studies that examined the effect on subsequent complacency of experiencing automation failure during training. Complacency is the uncritical overreliance on automation based on miscalibrated trust, i.e., the belief that automation is better than it is. In the first two studies (Manzey, Bahner & Hueper, 2006; Bahner, Hueper, & Manzey, 2008), two groups of engineering students performed a simulated maintenance task on a spacecraft life-support system. An imperfect decision-aid supported participants in detecting (alarming), diagnosing, and handling system faults. The first group was instructed that the automation can make mistakes; however, during training, no mistakes were made. The second group also was told the automation can make mistakes; during training, the automation made an incorrect diagnosis in one of twelve situations. Upon its failure, participants had to continue in manual mode. The results demonstrated complacency and errors of commission (taking erroneous action based on incorrect data from the automation). When training included the aid's diagnostic failure, the students' complacency was significantly lower in subsequent trials compared with people whose

[3] The term "function" used here includes information acquisition, information analysis, decision and action selection, and action implementation (Parasuraman, Sheridan & Wickens, 2000). See also, Section 3.2 of this report.

training did not include the automaton's failure. Reduced complacency was evidenced by an increase in the participants' cross-checking the decisions of the aid. However, the reduced complacency applied only to the aid's diagnostic function. Thus, participants did not increase their checking behavior when the aid was not in an alarm-state, even though its detecting function might have failed. Apparently, the benefit of the training was limited to the specific failure the participants experienced.

To verify these findings, Bahner, Elepfandt, and Manzey (2008) conducted a complementary study using the same simulated task. This time, the second group of participants experienced automation failure in the alarming function during training, and like the earlier study, training reduced complacency of the aid's alarm function. However, there was no effect on complacency about its decision-making function. Together these studies demonstrate the potential benefits of training on specific automation failures; further, the benefit appears limited to the specific automation functions that failed in training. They also demonstrate that simply informing users about an automation aid's reliability is not enough to reduce complacency; experience of automation failures during training was the key to doing so.

We next discuss the evaluation by Goh, Wiergmann and Madhavan (2005) on the effects of reliability of an aid (70% vs. 90%) and the type of cue (direct vs. indirect) on the competence of students in identifying targets in a security luggage screening task. The direct cue was a green circle around a suspect target in the security display; the indirect one was a green border around the display suspected to contain a target. Their study also examined the participants' performance after an automation failure. Target identification was better with the direct cue than the indirect cue. Performance was better with the aid that was 90% reliable compared with the one that was 70% reliable. However, performance with the 70% reliable aid was not significantly better than that of a control group lacking an aid. The authors concluded that the 70% reliable aid did not sufficiently support performance, and participants did not rely on it. When the automation failed, participant performance in the high-reliability, direct-cue condition performed best. Seemingly, the presence of the aid served as a training tool.

Thus, we consider that these studies demonstrate clearly that reliability of an automated system impacts trust and the operator's use of it. However, there are no data on the minimum thresholds for reliability of different types of automation, e.g., information vs. decision automation.

In addressing the question of how trust can be better calibrated. Beck, Dzindolet, and Pierce (2007)predicated that misuse and disuse occur because (1) operators cannot determine whether performance would be better with or without automation (appraisal errors), or, (2) operators are aware of the information an aid provides, but fail to use it to support decision making (intention errors). College students participated in a target-detection task. Independent variables were (1) aid performance – superior or inferior, (2) feedback – present or absent, and, (3) scenario training - present or absent. The dependent variable was the participant's automation usage decision (AUD), given the choice as to whether to rely on their own performance or that of a decision aid. The feedback provided was how many detection errors were made by participants and the aid before the participants made the decision to use the aid or not. Table 4-1shows the optimal relationship between aid performance and the AUD demonstrated in this study; disuse was more frequent than use.

The authors also found that a combination of improved feedback about automation and training in its usage was more effective in mitigating disuse than either in isolation.

Table 4-1 Usage Decisions Based on Aid Performance

Automation Usage Decision	Superior Aid	Inferior Aid
Don't use aid	Disuse	Correct Usage
Use aid	Correct Usage	Misuse

Adapted from Beck, Dzindolet, and Pierce (2007)

Wang, Jamieson, and Hollands (2008b) studied students undertaking a target identification task; targets identified as hostile were to be shot and friendly targets were not shot. This task was performed in one of three conditions: No aid, 67% reliable aid, or 80% reliable aid. The aid classified targets as friends or unknown. Its classification of friendly targets always was correct, but it was fallible when classifying targets as unknown. Reliability was quantified as the percent of hostile targets classified as unknown. One group received information about the aid's reliability (the informed group) while the other did not (uninformed group). The informed group was given specific information as to the aid's reliability in its classification of targets as unknown, while the uninformed group only knew the reliability was not 100%. Measures were obtained of performance (false alarms – shooting targets that are friendly; misses – failing to shoot hostiles), trust, reliance, and belief in the aid's reliability (for the uninformed group). Seemingly informing participants of the aid's reliability helped in establishing proper reliance.

McGuirl and Sarter (2006) obtained similar results in examining the effect of providing confidence information about an aids task performance on the operator's use of information. Instructor pilots undertook simulated flights during which icing was encountered. The decision aid supported the detection and management of the icing conditions. One group of pilots received only overall confidence information (system is 70% accurate), while a second group saw a confidence trend display of continuously updated confidence information over time. The latter experienced fewer icing-induced stalls and were more likely to modify their approach to the icing conditions when it was not effective. The authors concluded that providing more precise information about the decision aid's confidence improved the pilots trust and consequently, their use of the automated system. The authors were concerned that the continuously updated confidence information they received might constitute an information overload. After examining its impact on other flying tasks, they uncovered no negative effects.

Lacson, Wiegmann and Madhavan (2005) demonstrated the effect of the mode of presentation of reliability information to operators on their automation-utilization strategies. Students performed a signal detection task with the support of one decision aid. Three approaches were used to communicate the aid's reliability: Positive framing (the aid is 80% reliable), negative framing (the aid is 20% inaccurate), and neutral (the aid is 80% reliable and 20% inaccurate). Performance was better in the group receiving neutral information than in of two other groups suggesting that the more complete is the information given may be the best approach for improving the use of automation utilization.

Our general conclusion from these studies is that providing information about an aid's reliability can support appropriate trust calibration and its usage.

Another type of information that can be provided to operators is about the processes automation uses to accomplish its functions, such as control algorithms, and decision logic. Oduor and Wiebe (2008) gave information about the way a decision aid arrives at its decisions and recommendations to students performing a simulated ask involving adjusting a city's resources and tax rates. Information about its algorithms was given either as a graphic display, a textual display, or sometimes, none was given. Also, the reliability of the decision aid was varied from

low to high. A between-subject design was used. The perceived reliability of the decision aid was greatest for textual information, followed by graphic information and lowest in the no algorithm condition. The results for measures of "understandability" followed a similar pattern. Overall, perceived reliability was low in the low reliability condition as compared with the high reliability condition. The authors concluded that presenting an automated aids algorithm supported appropriate calibration of trust and a better understanding of automation.

4.2 High-levels of Automation and Operator Performance

This section focuses on the consequences on human performance of high-levels of automation when that automation is poorly designed. By "high-levels" of automation, we mean systems that essentially are fully automated and, once operating, require minimal human involvement other than monitoring; i.e., Level 5, Autonomous Operation (Table 3-3).

Billings (1977a) summarized the design characteristics of automation that were associated with problems in human performance problems, as shown in Table 4-2. The impact of such automation is well known and well-documented for decades. Therefore, we summarize them briefly summarize, and give references to sources that more fully discuss them. After discussing impacts on performance, the main characteristics of automation that engender the issues are briefly reviewed.

Table 4-2 Characteristics of Automation Design and Impacts on Human Performance

Design Characteristic	Human Performance Impact
Automation complexity	The details of automation functions may appear quite simple because only a partial- or metaphorical-explanation is provided, and the true complexity of the operation is hidden from the operators making it difficult for them to understand the automation.
Coupling among machine elements	Internal relationships and interdependencies between automation functions are not made obvious to operators, making it difficult for them to understand the automation.
Machine autonomy	Self-initiated automation activity requires the operator to determine if its behavior is appropriate or represents a failure.
Opacity	The automation does not communicate what it is doing nor why, or communicates poorly or ambiguously (inadequate feedback).
Peripheralization	Automation tends to distance operators from the details of an operation; if the automation is reliable, over time operators will become less concerned with and aware of the details of the operation.
Brittleness	The automation performs well while it is within the envelope of its design but behaves unpredictably otherwise.
Clumsiness	The operator has little to do when things are going well, but much interaction with the automation is necessary when the workload is high.
Surprises	The machine behaves in an unexpected, apparently erroneous manner.

Note: Source is Billings (1997a)

Thurman et al., (1977) described the effects of automation design on human performance, noting the differences between the designer's expectation and the experience of operators (Thurman et al., 1977). These differences are summarized in Table 4-3. The expected benefits reflect the so-called "substitution myth," i.e., that automation simply replaces human action with automated action (Hollnagel, 1999; Thurman et al., 1977). This belief is erroneous because changes in automation place new responsibilities for personnel, and if they are not addressed adequately in the design, it will be difficult for personnel to perform their new role.

Table 4-3 Expected versus Actual Effects of Automation

Expected Effect	Actual Effect
Better performance is achieved by substituting machine activity for human activity.	Work practices are transformed, and the roles of personnel change.
Personnel workload is lowered because work is offloaded to the machine.	Automation creates new kinds of cognitive work for personnel.
Personnel can focus exclusively on higher-level considerations.	Automation creates more threads to track, making it harder for personnel to remain aware of, and integrate all the activities and changes around them.
Less operator knowledge is required.	New knowledge and skills are required for understanding, monitoring, and interacting with the automation, and for backing it up when it fails.
Errors are reduced.	Some errors are reduced, but automation creates the potential for new types.

Adapted from Thurman et al. (1977)

Thus, automation is not simply removing human responsibility for performing a function, but has more complex effects than first thought.

Many early studies focused on using automation in aviation (Aviation Week, 1995 a & b). In the late 1990s, a comprehensive study was conducted of flight decks with varying levels of automation (Lyall & Funk, 1998; Funk & Lyall, 2000), by collecting published data, accident/incident reports, and interviewing automation experts and pilots. Table 4-4 summarizes the top issues that we organized into the following categories: Miscalibrated trust; difficulty understanding automation; impaired monitoring and situation awareness; high workload created by interacting with automation; and, skill loss.

Table 4-4 Top Human Factors Issues in Flight Deck Automation

Category	Issue Summary
Miscalibrated Trust	Pilots may become complacent because they are overconfident in, and uncritical of automation, and fail to exercise appropriate vigilance, sometimes even abdicating responsibility to it. This can lead to unsafe conditions.
Difficulty Understanding Automation	Pilots may not understand the structure and function of automation nor their interaction well enough to safely perform their duties.
	Automation may be too complex, consisting of many interrelated components and operating in many different modes. Hence, pilots find automation difficult to understand and use safely.
	Automation may perform in ways that are unintended, unexpected, and perhaps inexplicable to pilots, possibly creating confusion, increasing the pilot's workload in compensating, and sometimes leading to unsafe conditions.
	Pilots may use automation in situations where it should not be used.
	Training philosophy, objectives, methods, materials, or equipment may be inadequate to properly train pilots to safely and effectively automate aircraft operation.

Category	Issue Summary
Impaired Monitoring and Situation Awareness	Reliance on automation may reduce pilots' awareness of the present and projected state of the aircraft and its environment, possibly entailing erroneous decisions and actions.
	The behavior of automation devices (what they are doing now and what they will do in the future based upon pilot input or other factors) may be unapparent to pilots, possibly lowering their awareness of the behavior and goals of automation.
	It may be difficult to detect, diagnose, and evaluate the consequences of automation failures (errors and malfunctions) especially when the behavior seems 'reasonable', so possibly resulting in faulty or prolonged decision-making.
	Automation may change modes without the pilot's commands to do so, possibly behaving surprisingly. .
	Pilots inadvertently may select the wrong automation mode or fail to engage the selected one, possibly causing the automation to react in ways different to those intended or expected.
	Displays (including aural warnings and other auditory displays), display formats, and display elements may not be designed for detectability, discriminability, and interpretability, causing important information to be missed or misinterpreted.
	Important information that automation could display is not, thereby limiting the pilot's ability to make safe decisions and actions.
	Pilots may be unable to distinguish what mode or state the automation is in, how it is configured, what it is doing, and how it will behave. This lack of situation awareness may generate errors.
High Workload	The attentional demands of pilot-automation interaction may interfere significantly with the performance of safety-critical tasks (e.g., "head-down time", and distractions.).
Skill Loss	Pilots may lose the psychomotor- and cognitive-skills required for flying manually, or for flying non-automated aircraft, due to extensive use of automation.

Parasuraman, Sheridan, and Wickens (2000) identified four major issues from research on the effects of automation functions on various aspects of human performance:

- *Complacency* – if automation is highly reliable, then operators may not monitor it adequately and will be less likely to detect its failure. Complacency is worsened when operators have other competing tasks.
- *Situation awareness* – automation of decision-making functions can reduce situation awareness. Humans tend to be less aware of system changes initiated by another agent (automated or human) than when they make the changes themselves.
- *Cognitive workload* – while well-designed information automation can reduce cognitive workload, it sometimes increases it, such as when systems are poorly designed.
- *Skills degradation* – when automation consistently performs a function, the manual skills to do so diminish.

In a recent review of the literature on automation, Lee (2006) expanded the list of human-performance issues into the following categories:

- *Out-of-the-loop unfamiliarity* – loss of situation awareness about the behavior of automation and the status of the system being controlled in part due to a failure to properly monitor the automation. Lee notes that this sometimes reflects an optimal response to automation; i.e., an operator's cost-benefit analysis may engender an overreliance on automation because in a multi-tasking situation it not worth the effort to continuously monitor reliable automation.
- *Behavioral adaptation* – operators change their behavior in unsafe ways because automation offers a safety net.
- *Automation-induced errors* - this issue includes mode errors and configuration errors; the latter are errors made in the complex configuration of an automated system.

Thus, these general studies identified a common set of human-performance issues that we organized into the following seven topics that we summarize briefly below:

- Change in the Overall Role of Personnel
- Understanding Automation
- Monitoring, Vigilance, and Complacency
- Out-of-the-loop Unfamiliarity and Situation Awareness
- Workload
- Skill Loss
- New Types of Human Error

1. Change in the Overall Role of Personnel

Automation does not simply substitute a machine agent for a human agent; it changes the human agent's role. With an increase in the level of automation in a system, the operator's role changes from that of a direct manual controller to a supervisory controller and system monitor. With high levels of automation, the role of monitoring is not one that personnel are well suited to do (Endsley, 1996). Our interviews with people at non-nuclear plants that had distributed control systems indicated that operators often experienced boredom during stable operations (O'Hara et al., 1996). One plant addressed this problem by installing a computer-based training system in the control room (CR), and encouraged operators to use it when the plant was in steady-state operation.

Engineers typically view this type of role change as positive from a reliability standpoint because a human operator often is considered one of the system's more unpredictable and unreliable components. Generally, it is presumed that automation will enhance overall system reliability by removing or reducing the need for human action. However, the potential benefits of automation may not be realized if there is a failure to address the role of personnel in plant control and safety functions under a new automation scheme (Edwards, 1977; IAEA, 1991).

The personnel role relates to the operator's authority and responsibility for each plant function and system. We consider that it should be defined as the total integration across a plant's functions and systems of the operator's responsibility, and not at the individual system level, in isolation from other systems. Since the operator's role is defined in terms of plant functions and systems and the operator's responsibility in each, the notion of "change" in an operator's role can result from changes to either plant functions and systems, allocation of function, or both.

As noted earlier, Parasuraman and Riley (1997) discussed the "abuse of automation;" that is, the implementation of automation without considering the consequences of automation on

personnel. The decision to automate functions should consider whether a function should be automated in the context of the operator's ability to perform as part of the overall plant. Wiener and Curry (1980) cautioned that while "…any task can be automated; the question is whether it should be." Similarly, Billings (1991) emphasized that questions should be posed about the impact of automation before considering any new element of automation in the cockpit. Further, it was argued that allocating a 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 serves the system's overall productivity and safety (Price, 1982, 1985). Similar concerns about automation and personnel performance were raised in the nuclear industry (IAEA, 1991).

Thus, automation changes the role of plant personnel and we believe its consequences should be included in the decision to automate.

2. Understanding Automation

One automation issue we listed in Table 4-2 was "Automation may be too complex in that it may consist of many interrelated components and may operate under many different modes. This makes automation difficult for pilots to understand and use safely." Clearly automation's complexity and the difficulty pilots had understanding it played a role in the Cali accident (see Figure 4-1).

A poor understanding of automation can degrade an operator's management of automation problems. For example, Nikolic and Sarter (2007) examined operators' strategies for diagnosing and recovering from degradations in automation. Pilots generally did not diagnose the cause of the declines, instead opting to manage the effects. The authors believed one reason why pilots did not attempt to diagnose them was their poor mental model of the automation. Pilots were observed to engage in ineffective, generic recovery-strategies, such as resetting the automation that led to delayed responses. Pilots also tended to leave the automation at high levels rather than lower ones that are more responsive to pilot's commands. Lack of feedback from the HSI (not providing information about its settings or not doing so in a salient way) was seen as a contributing factor. The displays did not support visualization of the impact of automation and its current settings on the aircraft's performance.

While automation can make things easier for personnel, for example, automating an error-prone task, its very presence of automation increases a system's overall complexity. As more automation is introduced, personnel are required to understand how it works and its limitations. The complexity of an automatic system may lead to failure to develop an appropriate mental model (understanding) of its behavior, i.e., how and why it does what it does (Wilhelmsen, 1992). A good mental model, the basis for understanding, is built up through training and experience. However, this does not mean personnel must know the intricate details of automation's operations, only that they need to understand it well enough to be an effective supervisor, understand the conditions wherein it may be unreliable and in what ways, and the need to back automation during failure. They must generally understand how the system processes information, so they can determine whether the result is relevant to the task, and whether the automated system is operating properly.

Our earlier interviews with personnel revealed that operators sometimes switch control systems from automatic to manual mode if they do not understand what the system is doing and, thus, think it may be malfunctioning (O'Hara, et al., 1996). For example, we found that introducing increased automation into a Canadian nuclear-power plant had mixed effects on personnel.

Control actions, such as changes in reactor power, were easier to perform because the increased automation simplified many procedural steps. However, operators found that it was more difficult to understand how the automation works. One instructor stated that due to its higher complexity, operators must learn much more than they had to before its introduction to assure a comparable level of understanding of the plant control response. This may cause problems if operators feel that they understand a plant system well enough to correct an abnormality, but in actuality, if they do not, their actions may worsen the initial problem. This insight led to a change in operating practices, so now operators are encouraged to shut down the plant rather than staying on-line and trying to diagnose problems with the automation.

The lack of a proper mental model of how an automated system works can entail human actions that produce unexpected consequences. An example is a digital system that is used for controlling a batch reaction in a chemical plant (Kletz, 1993). When daylight savings ended, the clocks had to be set back by one hour. In resetting the clock of the digital control system the operator mistakenly set it at 2:00 am instead of 3:00 am, and consequently, the digital-control system shut down the plant for one hour until the clock registered 3:00 am again. This event occurred because the application engineer did not fully understand (1) the requirements of the control-system's design, and, (2) the operator's needs in the task environment. Therefore, the operator was inadequately instructed.

Another example occurred at a non-power reactor. A trainee simultaneously depressed a PULSE mode button and an UP button for rod withdrawal, thereby driving a control rod out of the core, a movement that was inconsistent with the rod- withdrawal interlock for that mode of operation. The withdrawal continued even after release of the UP button. This continued withdrawal was inconsistent with the design intent of the control system or the operator (NRC, 1993).

In summary, we consider that effective monitoring and supervision of automation requires plant personnel to have a sufficient level of understanding about how it works to evaluate its performance and assume manual control when necessary.

As plants become more automated, operators will be required to understand how automation functions to become effective supervisory controllers. The Electric Power Research Institute (EPRI) emphasized this point in considering digital upgrades: "It is important for the operators to understand how the system operates, how it reacts to off-normal situations, and how it behaves when failures occur, because this impacts the ability of the operators to take appropriate actions in these situations" (EPRI, 1993, p. 5-9).

3. Monitoring, Vigilance, and Complacency

Endsley (1996) found an increase in catastrophic failures accompanies increases in automation. Parasuraman et al. (2000) noted that when automation is highly reliable, operators may not monitor it adequately and will be less likely to detect its failure; the consequences of such failure have resulted in many serious events. In addition to the Cali accident described in Figure 4-1, other notable examples include

- The shooting of a Korean airliner over the USSR in 1983. Purportedly, the navigation system was programmed incorrectly, and the crew did not monitor the automation; thus, they did not recognize the navigation error that sent them over Soviet airspace (Endsley, 1996).

- The Royal Majesty cruise ship went aground when the electronic chart-display lost the GPS signal and navigated instead by dead reckoning. The crew did not notice that the GPS was lost and, under dead reckoning, the navigation error accumulated to the point that the ship ran aground (Lee, 2006).

4. Out-of-the-loop Unfamiliarity and Situation Awareness

Many issues associated with human interaction with automated systems have been attributed to poor situation awareness (Kibble, 1988). Wickens and Hollands (2000) referred to this as "out-of-the-loop unfamiliarity." Maintaining situation awareness can be difficult when the operator is largely removed from directly performing an activity (Wickens & Kessel, 1981; Ephrath & Young, 1981; Furukawa, Inagaki & Niwa, 2000). Discussing 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." In the Cali accident we described above, the pilots' reliance on automation caused a loss of awareness that the aircraft was navigating to an unexpected location.

Automation affects another aspect of situation awareness in masking of a degraded condition by compensating for it (Bainbridge, 1987; Jamieson & Vicente, 2005; Norman, 1990). Operators may not become aware of the degradation until it exceeds the capabilities of the automatic control system, and they need to take control. For example, if automation is maintaining level in a tank that has a leak, as long as automation can pump water in at a rate that maintains the proper level, operators may be unaware of the a problem. When the level no longer is maintained, operators need quickly to determine whether the failure is in the automation or the system being controlled (Jamieson & Vicente, 2005). An actual event illustrating this problem is an incident in 1985 when a China Airlines 747 suffered a slow loss of power from its outer right engine (Norman, 1990). This would cause the plane to yaw to the right, but the autopilot compensated, until it finally reached the limit of its compensatory abilities and could no longer keep the plane stable. At that point, the crew did not have enough time to determine the cause of the problem and to take action: the plane rolled, and went into a vertical dive of 31,500 feet before it could be recovered.

A similar incident occurred at the Indian Point 2 NPP (NRC, 1980) that flooded the reactor containment with about 100K gallons of river water, placing potential thermal stress to the reactor vessel. In this event, atmospheric fan-cooler units in the containment were cooled by river water through piping that was leaking into containment. Any such leakage is directed to a containment sump that periodically is automatically pumped out of containment to waste processing. This automatic pump-out arrangement masked the leaks in the failed piping. Then, when it, in turn, failed, the operators did not recognize the situation promptly, in part due to stuck indicator lights leaving operators without water-level instrumentation.

We earlier discussed an example of this phenomenon related to a power plant's new digital control system (O'Hara et al., 1996). When a signal was received from the load dispatcher requesting a change in a plant's electrical-power output, the plant's load-response system automatically changed power production by controlling the turbine-steam valve. However, the valve had degraded and was not functioning properly. With a conventional analog control system, a faulty would prevent the unit responding properly to these signals (e.g., the load dispatcher would request a 0.5 percent increase but the unit might respond with only a 0.2 percent increase). However, the new control system compensates for the valve's lower

performance by continual adjustment until the desired power change is met. This compensation effectively hid the degraded performance of the valve from personnel.

Good communication between the automatic system and personnel is vital to the success of human responsibility in monitoring the performance of automation.

5. Workload

Parasuraman, Sheridan, and Wickens (2000) stated that automation's effect on workload was mixed and complex. Automation was associated with lower overall workload (underload), an increase in cognitive workload, and difficulties in workload transition (i.e., going from a monitoring period of low activity to a highly active but more uncertain time at the beginning of a process disturbance).

Research indicates that process disturbances can generate a high cognitive workload (Huey & Wickens, 1993). For example, the automation of aircraft landings can effectively reduce overall workload during this task. However, when landing under complicated, abnormal circumstances, automation makes the task more complex because of the amount of pilot interaction needed to adjust the automaton compared to when it was performed entirely under manual control (Wiener, 1989). Workload also can rise when the HSIs to automation are poorly designed. Another source of difficulty for personnel is the workload associated with transitions from monitoring automated systems to assuming manual control during a fault in the former (Huey & Wickens, 1993). The difficulties the pilots had attempting to reprogram the FMS in the Cali accident illustrates this type of workload.

We conclude that if workload is too low, vigilance suffers and the ability of personnel to develop accurate situation assessment diminishes. As the demands of performing the task rise, a greater workload is experienced. Ultimately, if workload is high enough, the ability to perform the task is reduced. Figure 4-3 illustrates this effect.

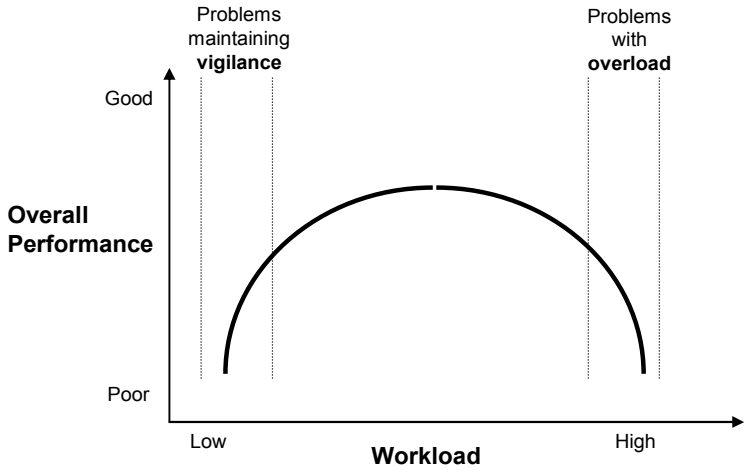


Figure 4-3 Simplified relationship between workload and performance

6. Skill Loss

One of the top automation issues in Table 4-2 is "Pilots may lose psychomotor and cognitive skills required for flying manually, or for flying non-automated aircraft, due to extensive use of

automation." Automation was associated with the potential erosion of operator's skills (due to lack of task performance) to perform during an automated system failure. For example, studies of the ability of process-control operators to produce a step change in a process revealed that experienced operators tend to make a minimum of actions and the process output moves smoothly and quickly to the new level; inexperienced operators cause the output to oscillate around the target value (Bainbridge, 1987). Bainbridge states that because these types of physical skills, particularly refinements of gain and timing, tend to deteriorate when not used, operators may lose these them when processes are automated, and when assuming manual control, may be more likely to put the system into oscillation that would require their further action to correct. When a manual takeover is needed, something likely is wrong, so that unusual actions may be needed to control it. Bainbridge argues that automated control systems l tend to diminish the operator's skill levels while creating the potential for situations wherein higher skill levels are required. In addition, due to the stability (lack of drift and oscillation) of automatic control systems, operators sometimes manipulated the plant closer to operating limits. If the digital system fails, the operator may have difficulty regaining control of the plant and then maintaining it within the limits.

7. New Types of Human Error

The types of human-performance problems we discussed above have been reflected in the emergence of new types of human errors and new ways errors manifest themselves (Wiener & Curry, 1980; Wiener, 1989; Woods, Johannesen, Cook, & Sarter, 1994). Wiener and Curry (1980) grouped these problems into six categories:

- Failures of automatic equipment, such as autopilot
- Automation-induced errors compounded by the crew's error, such as an error following the crew's attempt to recover from the failure of an automated system
- Crew error in setting up automated systems, such as keying in the wrong information and data
- Action taken by the crew in response to a false alarm
- Failure of the crew to pay attention to an automatic alarm
- Failure to properly monitor the automated system

Lee (2006) identified four types of errors associated with automation:

- *Mode errors* - taking an action when the automation is in the wrong mode
- *Configuration errors* - errors made in the complex configuration of an automated system
- *Errors of commission* - concurring incorrectly with an incorrect automation decision
- *Errors of omission* - failing to detect events not detected by the automation

All four types of errors occurred in the Cali accident described in Figure 4-1. Automation-induced errors might be exacerbated because automation can undermine effective error-detecting and correcting strategies typical of teamwork (a loss of defense- in- depth).

Sarter and Woods (1995) examined the relationship between the pilot and automated systems in the Airbus A-320 aircraft. They observed a trend toward errors of omission in which pilots were likely to fail to observe and mitigate undesired actions by automated systems. These

errors have played an important role in aviation accidents, and illustrate the need for improved communication between autonomous systems and their human supervisors to better coordinate their activities.

Mode errors are an increasing phenomenon associated with automated systems (Woods et al., 1994). Automated systems often have a variety of modes in which the inputs used and output provided differ (Sarter & Woods, 1992). Operator inputs might have different effects, depending upon the characteristics of each operating mode. For example, accidents involving aircraft with automated flight-management systems were traced to a lack of pilot awareness of the operating mode of the automated system, and incorrect understanding of how control actions provided by the pilot or automated system affect the aircraft. An important contributor here was the dearth of information about the activities of the automated system (NAS, 1995; Sarter & Woods, 1992; Aviation Week, 1995 a & b). This statement especially is true if the changes in mode are themselves automatic. Operators are more likely to lose track of modes when uncommanded changes occur (Jamieson & Vicente, 2005). When automation has modes, the operator must know

- what the current mode is
- how the automation's behavior changes in each mode
- how the automation's mode impacts the systems being monitored and/or controlled
- how the operator's responsibilities change for each mode.

Breakdowns in mode awareness lead to errors.

Thus, there are many aspects of automation's impact on human performance and they often interact. A "vicious cycle" can be created when one negative outcome leads to a response and subsequently, additional negative outcomes occur (Lee, 2008). For example, in highly autonomous operations, operators may not use their manual skills often and their skills decline. Since self confidence in one's own skills is a determining factor in using automation, this skill decrement can cause operators to rely on automation even more.

4.3 Intermediate- and Low-levels of Automation and Operator's Performance

While the previous section focused on highly automated systems, this section addresses the effects of automation at levels below full automation. The differential effects of automating different cognitive functions have been recognized for some time. For example, when reasoning and decision-making processes are automated, operators are more prone to experience out-of-the-loop unfamiliarity with the ongoing situation (Wickens & Hollands, 2000).

Insights into introducing automation into different functions are gained from studies on using computerized operator support systems (COSSs). We identified numerous human-performance issues that limit the effectiveness of current COSSs. They include poor integration with operators' task performance, complexity of COSS information-processing, lack of transparency of the COSS decision process, and inadequate explanatory information to address personnel's needs for verification. Other drawbacks are the lack of communication pathways that permit people to query the system or obtain a level of confidence in the conclusions it has drawn (O'Hara et al., 1996).

The predominant role of COSSs has been as decision aids, in which the most significant factors diminishing their value are intelligibility and communication (IAEA, 1995a; Malin et al., 1991a & 1991b; Land et al., 1995; Rook & McDonnell, 1993). It is essential to operator acceptance and

their usage that the reasoning process is fully understood by the plant personnel. Also, operators must be able to communicate with the COSSs, e.g., the degree to which explanations of results are provided, and to which operators can query the system when they do not comprehend its results.

Malin et al. (1992) detailed case studies of the design of 15 intelligent systems intended for a variety of aerospace projects; most were real-time fault-management systems. They deemed as problematic the interfaces between the human operator and the intelligent systems. Some specific concerns Malin et al. identified were similar to the concerns identified above: Providing visibility into the system's reasoning, understanding its reasoning, the system's ability to respond to the context in which a question is asked, and its ability to distinguish hypotheses from facts. Additional problematic areas were determining the credibility and validity of information, handling interruptions and changes in planned activity sequences, distinguishing between modes of operation, gaining control over the system's actions, and identifying its errors. The systems also had many problems associated with the general design of the HFE. Operators often did not get the information they needed, or it presented in confusing formats that were unsuited to their task requirements. Other times, excessive detail was provided. This made it difficult for operators to "…visualize the intelligent system's situation assessment and recommendations in relation to the flow of events in the monitored process."

Other studies identified the importance of visibility of the reasoning process. Thus, Rook and McDonnell (1993) experimentally manipulated the interface to an expert system that was designed to support fault diagnosis during simulated space-station problem-solving situations. One version of the HSI clearly depicted the reasoning; in the other, little information about the reasoning process was available. The results demonstrated that the former led to more effective use of the aid.

Similar findings were obtained by Roth, Hanson, Hopkins, Mancuso, and Zacharias (2004) in evaluating the extent to which operators of unmanned aerial vehicles (UAVs) understood the plans developed by automated controllers. Humans and automatic agents cooperated as a team in planning and executing missions. The authors' findings supported the need to communicate more effectively the rationale behind the automation's plan elements, and to provide "levers" enabling the operators to modify the plan. Without such information, operators could not properly assess the plan's appropriateness, and assess whether changes to it were needed.

Working in the nuclear industry, Dien and Montmayeul (1995) surveyed operating experience with COSSs placed into existing control rooms. They concluded that while much effort went into their design, feedback from the survey suggested that few improvements in operations had resulted using them. COSSs often offer guidance for situations that operators already are equipped to handle. That is, they are designed for situations that previously were analyzed, and designers are familiar with. Such aids add little value for operators, except perhaps, to confirm their decisions. Further, the systems were unable to effectively manage unforeseen circumstances and, therefore, did not provide appropriate guidance to operators during them. Another problem was that aids were "acontextual", i.e., their guidance had little reference to the current situation. Also, guidance was given without appropriately communicating what led to its issuance, what parameters were analyzed, and what sequence of reasoning was followed. When the reasoning process was provided, it often conflicted with that of the operators, i.e., seemingly, it was based on the designer's theoretical understanding and not on the operator's practical experience.

Consistent with these studies, Roth, Bennet, and Woods (1987) concluded that the interface of the COSS must support cooperative dialogue so the operator can better understand and utilize the system. In general, they found that these aids tend to be technology-driven, and do not address the operator's needs; the systems are developed by finding an application for a given technology, rather than being designed to meet users' needs. Proper design requires an adequate analysis of user's requirements to identify information needs. The system should accurately provide the needed information, and minimize or eliminate extraneous material. Roth et al. (1987) stated that COSSs should support the operator's cognitive processes and reinforce their existing approach to operations that was formulated through training and experience. Operators should be clearly informed of the limitations of COSSs (Bernard, 1989b & 1989b; Terry, 1989).

Dien and Montmayeul (1995) also found that poor integration with the existing HSI systems also is problematic, e.g., differences between systems in dialog principles (such as command vs. direct manipulation interfaces) and coding (such as the meaning of color usage). Researchers demonstrated that poor integration of an automatic aid into an existing HSI restricted the usefulness of a new system called the "Process Operations and Management System" that was installed in a conventional British Nuclear Fuels plant to provide an on-line early warning and diagnosis of faults (Reed, Hogg, & Hallbert, 1995). This problem led operators to abandon the system.

Automated aids also affect team performance. Our group (Roth and O'Hara, 2002) observed the introduction of a computer-based emergency operating procedures (EOPs) system as part of one utility's digital I&C upgrade of a nuclear power plant. This system automated the functions of information acquisition and analysis and gave some support to decision-making. The crews handled disturbances on a training simulator. Following each scenario, our interviews focused on the impact of the procedures on operations.

Before this upgrade, the usage of EOPs involved the entire control-room crew of three operators. The supervisor read the procedure and decided at each step how to proceed. The board operators retrieved the needed data for each step and told the supervisor about it. At the supervisor's instruction, they took any required actions. This work demanded team communication and coordination. The computer-based EOP automated many of the tasks that the crew performed with paper procedures, including

- retrieving data and assessing its quality
- resolving step logic
- tracking the location in the procedure
- tracking the steps to assure continuous applicability
- assessing cautions, safety-function status trees, and fold-out page criteria.

Thus, the system automated many of the crew's information acquisition, analysis, and decision-making activities.

By introducing the new system, the procedure management workload was reduced to the point that procedure use became a one-person activity. The board operators were far less engaged in this, except to take occasional control actions at the request of the supervisor. Consequently, the operators felt they were out-of-the-loop, had lost situation awareness of EOP activities, and were unsure what to do. Our main point was that the introduction of the automation impacted teamwork, a finding that was unanticipated by the designers and plant staff. This was not a negative finding *per se*. The situation was addressed by the plant's operations and training staff

who redefined the roles and responsibilities of the individual crew members, and took steps to foster teamwork. First, operators were to manage alarms and check key parameters on their side of the plant (reactor and balance-of-plant). Then, specific stop points were added into the procedure where the supervisor updated the operators on the procedure's status and the crew shared their assessments and informed the supervisor of key findings. Because the shift supervisor and the crew worked more independently than before, and attended to separate sources of information, the stop points gave them the opportunity to keep each other informed and to ensure a common understanding of the event. EOP training reinforced this new approach to emergency management.

Other studies recorded similar effects of automation on the interactions of human operators (Kaber et al., 2001). Wright and Kaber (2005) found that while the automation of information acquisition and analysis and functions were beneficial to teamwork, the automation of decision-making functions was not always so.

4.4 Varying Levels of Automation, Adaptive Automation, and Operator Performance

The studies we discussed above examined the consequences on human performance of automation at a single level, either high levels as in fully automatic systems, or low- to intermediate-levels, as in COSSs and decision-aids. In this section we detail studies that compared the differential effects of different levels of automation on human performance. Sometimes individual participants were exposed to a single level of automation only (levels of automation is a between-subjects variable), and sometimes they were exposed to multiple levels of automation (levels of automation is a within-subjects variable). The latter is analogous to adaptive automation, wherein the levels of automation can be varied for, or by the operator (usually as a function of a triggering condition). We first discuss automation as a between-subjects variable, followed by studies where automation is varied within-subjects.

Lorenz et al. (2001) examined the effect of level of automation on out-of-the-loop problems; students undertook environmental control tasks with the support of an intelligent fault management (IFM) system. The IFM had three levels of automation (LOAs). In the lowest, it guided operators on how to find faults. In the medium LOA, the system made a fault diagnosis and recommended actions to take. At the highest level, the IFM made a diagnosis, recommended actions, and automatically implemented them unless the operator disagreed and overrode the action within 45 seconds. The IFM failed (provided no support to the operator) in 10 percent of the trials during which the participant's fault detection and management performance was evaluated. The results showed degraded performance in the medium and high LOAs, but more consistent performance when the IFM having a low LOA failed. This failure was due, in part, to changes in information- sampling strategies with changing LOA. Thus, this study found that higher LOAs were associated with more of the types of issues discussed in Section 4.2 (high LOAs). Recovery from automation failure was better at the lower LOAs. This finding generally consistent is with Parasuraman et al.'s finding that recovery from automation failure is superior when intermediate levels of automation are used rather than high automation (Parasuraman, Sheridan & Wickens, 2000).

Manzey, Reichenbach and Onnasch (2008) investigated the effects on fault identification and management performance of four different levels of automation. In the first level, there was no automation, and the entire task was handled manually. In the second level, the automaton offered a diagnosis of system faults. The third level afforded diagnosis along with recommended actions that the operator had to perform manually. In the fourth, the diagnosis and actions were

automatically performed upon gaining the operator's approval. Student participants simulated controlling a spacecraft life-support system in which malfunctions occurred. Measures were collected of primary- and secondary-task performance, and automation bias (commission errors - doing what automation suggests even when it is wrong). The authors also examined "return-to-manual control" (skills deficit) after the automation failed. They found that any automation improved primary- and secondary-task performance compared with manual operation, and the higher the LOA, the better the performance. In using the two lower levels of automation, differences were observed in undertaking the secondary tasks, but not primary ones. A cost was incurred however; automation bias was observed in approximately 50% of the possible opportunities, and was about equal for all automation functions. The authors indicated that these errors were due to less attentive cross-checking of information with automation. Thus, we consider that a partial explanation of the improved performance at higher levels of automation may be that participants unquestioningly accepted the automation's actions. In addition, there was some evidence of loss of control skills at the highest LOA, the only one for which automation control was available. The authors concluded that medium LOAs are preferred if manual skills must be maintained. This may partially explain the strong preference experienced pilots have for management-by-consent approach (our Level 3), where automation cannot act unless and until explicit pilot consent is received (Olson & Sarta, 2001).

Willems and Heiney (2002) examined the effects of three levels of automated decision aids, viz., no aids, limited automation, and full automation on the behavior of air traffic controllers using human-in-the-loop simulations. These behaviors were visual scanning, situation awareness (SA), and workload. The effects of the aids were examined under low- and high-traffic conditions. The relationship between LOA and SA was found to be complex. Generally, SA was lower with limited automation than with no automation or full automation. However, under high-traffic loads, SA was worse with full automation. An increase in automation was associated with an increased workload. The results also showed that operators spent much time transitioning between the aid's display and the primary-information display, during such time no information is processed. The authors suggested that better integrating these two displays might alleviate this problem. The suggestion of better integration is consistent with other findings (Lee & Seong, 2006). The authors also recommended that in implementing automation, designers should ensure that it is compatible with any existing work habits (consistent with the findings of COSSs we discussed in Section 4.3).

Many of the problems with automation are caused by a mismatch in expectations between designers and operators. One example we consider is the issue of "meta-control" Lee (2008). From a designer's standpoint, designing automatic systems is easy (if you use comparison "easier", you must say easier than what) to the extent that a function can be completely analyzed and the response is well-defined. However, when the work domain is be expected to have unanticipated variability, designing an automated system becomes much more difficult. In such situations, operators may be in the best position to determine the extent to which automation should be used because they must tradeoff the value of having top-down control provided via automation by designers, and the bottom-up control by operators in judging how it should be used. We believe that adaptive automation (AA) is one potential solution to this problem.

AA is also seen as a potential solution to other automation issues. Endsley (1996) suggests that people are not well suited to a monitoring role, especially monitoring automation. Automation impacts SA in three ways: Changes in vigilance and complacency; passive rather than an active role; and, changes in the quality of feedback to human operator. In addition, automation's complexity challenges SA, even when personnel attempt to monitor it. Automation

also impacts workload, but the effect is complex. It may reduce workload at certain times and increase it at other times. Using AA may help to reduce these issues because it attempts to optimize the dynamic allocation of tasks by creating a mechanism for determining, in real-time, when tasks need to be automated or manually controlled.

We note that the potential of AA as a partial solution to automation-induced human performance issues received some empirical support. Ryser (2003) found a positive effect of varying LOA in a study examining the relationship between degree of automation, strategies applied by operators, and mental representation of the system. The participants were trainee operators who performed simulated tasks on methanol-synthesis operations in a chemical plant. Some participants were trained primarily under manual-control conditions, a second group under high-automation conditions, while a third group experienced varying levels of automation in different trials. The results showed that participants from the third group developed a better understanding of the role of automation than those from the other two groups. Ryser concluded that it was important to provide new staff with varying LOAs as part of their training.

In a study by Kaber and Endsley (2003), student participants performed a dual-task scenario (dynamic target tracking and elimination task and a secondary monitoring task) under conditions of low, intermediate, and high-levels of automation that were allocated dynamically. In this study, the AA was varied according to a predefined schedule. The dynamic allocation was compared to fully manual and fully automatic operations by measuring task performance, SA, and workload. The LOA was the primary determinant of primary task performance and SA. Low levels of automation evoked superior performance, while intermediate levels facilitated higher SA. AA was the determining factor in workload and secondary-task performance. In general, the results support intermediate LOAs and AA.

McGarry, Rovire, and Parasuraman (2005) adaptively varied information and decision automation across segments of a simulated battlefield engagement. The participant's task was to identify the most dangerous enemy unit and to decide which friendly unit should engage them. The variations in automation (80% reliable) were based on a predefined schedule, and some segments required participants completing manual tasks. These authors found that the accuracy of the participants' decisions improved in segments with decision automation when they were preceded with segments with information automation. Exposing users to periods of information automation minimized some problems associated with imperfect decision automation by keeping operators in the loop (making the decisions during information automation trials.)

One concern with AA is the potential disruption in performance due to the shift between automation levels. This issue was examined by DiNocera, Camilli and Terenzi (2007). Students played the video game Tetris under three levels of difficulty in either manual or automatic mode. The automation gave a projection of the falling block on the lowest level. In some trials the automation level shifted, while in others it did not. The shift followed a predefined schedule rather than a particular triggering mechanism. The player's performances and workloads were impacted by either shift, not just from automation to manual as is commonly thought. A shift in either direction disrupted the ongoing cognitive activity involved in mental rotation; the switch also was affected by task load. Better performance ensued when shifting from manual to automatic in the high-difficulty task, while the reverse was true for the low difficulty task (the intermediate difficulty task did not significantly differ from the other two). However, since the shift was based on a schedule rather than some triggering criteria, the shifts might not have occurred at an optimum time, and this may have disrupted performance.

We note that a limitation of the AA studies outlined above is the absence of triggering mechanisms (see Section 3.4 for our discussion of the role of triggering mechanisms in AA). That is, automation varied based on a schedule and not on specific criteria. We expect the advantage of varying automation is to support the operator's management of workload. Thus, one possible triggering mechanism is to base automation shifts on workload criteria. Two studies described below examine the use of workload as an AA trigger. However, we note that little research seems to address other possible triggering criteria, such as task performance.

The effects of AA were assessed on the performance by students of an unmanned aircraft task using workload as a triggering mechanism (Cosenzo, Parasuraman & Pillalamarri, 2008). The findings from these simulations pointed to an improvement in performance with automation along with a decline in workload, suggesting that workload is a good triggering mechanism since it gives participants automated support when it is needed.

In another study, student participants took part in a simulated air traffic control task in which AA was used (Kaber et al., 2005). Automation was applied to information acquisition, information analysis, decision making, and action implementation. The automation was varied using workload as a trigger; that is, the automation changed, based on each participant's workload measured on a secondary task. When performance was below a predefined threshold (indicating a high workload), automation was introduced. In the reverse situation (indicating a low workload), the automation was stopped and the participants performed the task manually. The participants' performance was better when AA was applied to acquiring information and implementing actions; switching its control to higher-level cognitive functions (information analysis and decision making) was disruptive. The finding of potentially disruptive impacts of an automation shifts is consistent with the findings reported by DiNocera et al. (2007).

One additional consideration is identifying the appropriate level of analysis for LOA and AA (Miller, 2005). Operators rarely want to delegate whole tasks or functions to automation; more typically, they want to delegate some portion of them, e.g., the information-gathering portions of a task. Operators would prefer to have delegation options and HSIs are needed to support this type of approach.

4.5 Conclusions and Research Needs

We consider that research on trust and automation use has shown the following:

- The operator's use of automation is influenced by trust, workload, HSI design, and other factors.
- The automation's reliability impacts the operator's trust. In general, the better the automation's reliability, the more operators trust it.
- The operator's trust in automation is based on their perception of its reliability and capability that may or may not be consistent with reality. This relationship is called trust calibration. When the operator's perceptions accurately match the automation's reliability and capabilities, trust is "well-calibrated" and operators use it appropriately. Miscalibrated trust leads to either an overreliance on automation (misuse) or its underutilization (disuse).
- Misuse (overreliance) on automation is associated with a failure to properly monitor it. This can engender large errors in system performance, e.g., the system deviates

considerably from the desired performance before it is recognized, if it is recognized at all.

- Disuse (underutilization) of automation can lead operators to turn off automation or to ignore its potential benefits.
- There is no precise answer on how reliable automation must be; however, different levels of reliability may be necessary for different automation functions, e.g., operators may be more tolerant of automation errors in information acquisition than they are in decision making. Additional research is needed on methods of quantifying reliability, and the appropriate thresholds of acceptability.
- Training is important to ensure proper trust calibration. Operators need to understand properly the limitations of automation, and they should be given clear, specific information about these limitations, such as how automation might go wrong, the reasons why something might do so, and what to do when it does. That will help support proper calibration and resolution of trust. Simulator training specifically should provide experience with automation reliability and failures.
- HSIs are important to proper trust calibration and should provide a variety of types of information to improve trust and resolution calibration, including its reliability in varying contexts of use and automation's processes (e.g., the algorithms used).
- Trust should be measured and the operators' trust calibration and resolution assessed in the context of using automation.

Research on levels of automation and adaptive automation show the following:

- When poorly designed, high levels of automation were associated with numerous interrelated human performance problems, including
    - change in the overall role of personnel
    - understanding automation
    - monitoring, vigilance, and complacency
    - out-of-the-loop phenomena and situation awareness
    - workload
    - skill loss
    - new types of human error (e.g., mode errors)
- The design characteristics of the automation that exacerbate the problems listed immediately above include
    - automation's complexity
    - inadequate visibility into how automation is working
    - inadequate feedback about the automation's activities
    - lack of facilities for operators to communicate with automation
    - inadequate explanation of its reasoning processes
    - workload associated with configuring and interacting with automation
    - poor HSI design for interaction with automation
    - poor integration of the automation's HSI design with that of the other HSIs
- The impact of automation on team performance has to be better understood. While lower levels of automation were beneficial to teamwork, the automation of decision-making sometimes had a negative impact.

- For automation to be effective in supporting operations, it must meet an operational need and be well-integrated into ongoing work practices and other HSIs.
- Automation can mask failures and degraded conditions in other plant systems when it compensates for them. This can lead to a loss in situation awareness and may be problematic when the situation reaches a point where the automation can no longer compensate and personnel have to take over.
- To help minimize the workload associated with automation, better integration is needed of information about the automation and information about the operators' other activities. This would help minimize the transitions between displays.
- The information on levels of automation shows the following:
    - automating lower cognitive functions (monitoring/detection and response implementation) is effective in lowering workload without negatively impacting situation assessment
    - automating the higher cognitive functions (situation assessment and response planning) can improve overall performance, but should be done cautiously due to its potential to lower situation awareness and heighten the difficulty in recovering from automation failures
- Adaptive automation (AA) has a positive effect on the operators understanding of automation, situation awareness, and ability to recover when the automation fails.
- AA was demonstrated to help support task performance and manage workload, especially for lower-level cognitive functions (information acquisition- and action implementation-functions). The application of AA to higher-level cognitive functions (information analysis and decision making) is more complicated, and performance may be disrupted.
- There can be a cognitive cost to switching between LOAs in adaptive automation that can impede ongoing task performance. Additional research is needed on how to implement shifts smoothly. Research on the triggering mechanisms for AA is sparse. What has been done suggests that workload measures may offer effective switching triggers. Additional research is needed on appropriate triggering mechanisms.
- HSIs for automation should be well integrated into the operator's normal monitoring HSIs and be consistent with the overall design implementation of other HSIs.

We reviewed a wide range of studies in this section, e.g., from interviews with professional operators to laboratory studies using simulations with students. We suggest considering the following general limitations of the research:

- Most studies involved automating aspects of fairly simple operations that can be learned by participants with a few hours of training. Therefore, the studies do not reflect the complexity that exists in integrating automation into complex system operations with highly trained operators, such as those in nuclear power plants.
- One lesson learned from studying the introduction of automation into actual systems is the importance of meeting a real operational need and of integrating the operators' use and interaction with the automation into ongoing work practices. For most laboratory simulations we discussed in this section, it is unclear whether the automation resulted from an analysis of an operational task to ensure that the automation met an operational need. Further, it was not certain whether the automation was installed as a result of a

design process that identified information needs from analyses of functions and tasks, and the application of HSI design guidance to ensure that the HSI reflected state-of-the-art HFE principles. Thus, the findings from these experiments may well differ from those expected from a fully designed automated system in an actual complex system.

- Many of the studies were conducted with students and trainees; not many were made with professional operators. Studies are needed establishing the value of generalizing and projecting the results from students to professional operators.

We list next what we deem as the general needs for research related to automation and human performance.

- Additional research is needed to address all of the research limitations noted above, and to increase confidence in the generalization of the results to actual complex systems operated by highly trained, skilled, and experienced professionals with a deep knowledge of the systems they are in charge of.
- Levels and functions often are confounded in the literature. Studies more specifically isolating the effects of each are required, so we can better understand the independent effects on the operator's performance of these two independent dimensions.
- Automation's process can range from simple to complex. Research is needed to understand the complexity of the processes on operator trust and usage.
- More research is required to identify the appropriate triggering mechanisms for automation changes, and how they should be implemented to minimize any disruptions to the operator's performance when the change occurs.

Throughout these studies, we emphasized the importance of HSI design. In the following section, Section 5, we discuss HSI design for automation.

5 DESIGNING AUTOMATION AND HSIs TO SUPPORT HUMAN-AUTOMATION INTERACTION

In the previous section, we examined the effect of automation's design on human performance. In this Section 5, we address how to design automation to support human-automation interaction, emphasizing the HSIs through with that interaction occurs. Many studies discussed in the preceding section focuses on its critical importance for this interaction. For example, Liu, Nakata and Furuta (2004) stated

> In fact, incidents and accidents have actually been caused because operators either did not understand the goals or working states of the automation or had a misperception of their own tasks since they could not construct an up-to-date mental model of the current system state in time. Therefore, it is very difficult for operators to adapt to manual control if the automatic systems fail. This ''out-of-the-loop'' problem has often been attributed to inadequate design of the human-machine interface. Designing an effective user interface for an automatic system is very challenging due to complexity of the controller algorithm, the amount of information that is potentially relevant and the complex interaction of the underlying process. However, only by visualizing the working of automatic systems in an interface can an operator track what an automatic system is doing, why and how it is doing it, and what it will do next (pp. 87-88).

This section encompasses three subsections. The first addresses general principles for designing human-automation interactions. They mainly are directed to the relationship between personnel and the automation and generally reflect the need to make automation an interactive team player. Section 5.2 discusses approaches to HSI design including HSI requirements analysis and its detailed implementation. We note in advance that, despite the wide acknowledgement of the importance of the HSIs in human-automation interaction, far less research has been devoted to detailed HSI design than to the design of automation itself, such as levels of automation. Finally, we present our conclusions in Section 5.3.

5.1 General Principles for Supporting Human-Automation Interaction

In Section 4, we discussed several challenges to personnel performance stemming from poorly designed automation, and newer approaches to automation designed, in part, to partially mitigate those effects. Here, we describe the general principles offered in the literature to improve human interaction with automation; i.e., how to make automation a better team player.

From his extensive study of automation in aviation systems, Billings (1991, 1997a, 1997b) identified general principles for supporting personnel interaction with automated systems:

- Humans are responsible for outcomes in human-machine systems; thus, humans must be in command.
- Humans must be actively involved in the processes undertaken by these systems, and where appropriate, be given options on decisions and actions. Humans are needed for their flexibility, creativity, and knowledge. They are able to cope with incomplete knowledge and uncertainty.
- Humans must be adequately informed of human-machine system processes, so they can track what automation is doing.
- Humans must be able to monitor the machine components of the system.
- The activities of the machines must be predictable.

- The machines must be able to monitor the performance of the humans, to alert them to potential errors.
- Each intelligent agent in a human-machine system must know the intent of the other agents.

Billings' principles describe a human-machine system in which humans are in charge and work is accomplished interactively with machine agents. Each agent involved in the process is aware of and monitors the performance of other agents. Billings' view is essentially that automation is one of the team, a fellow crewmember.

Many authors used human teamwork as a model to identify the general characteristics of desired human-automation interaction (Klein et al., 2004 & 2005; Lee & See, 2004; Parasuraman & Riley, 1997; Woods & Hollnagel, 2006). In fact, in their study of human trust in automation, Lee & See noted that "…many studies show that humans respond socially to technology, and reactions to computers can be similar to reaction to human collaborators" (Lee & See, 2004, p. 51). Thus, designing automation to have the characteristics of a good, trusted team member is viewed as a pathway to overcoming the negative effects on human performance of poorly designed automation.

In commercial nuclear power plants, the coordinated activity of multi-person teams accomplishes operations. In today's plants, several reasons dictate the need for teams, including the distribution of workload, and the physical layout of the control room where tasks are completed via dozens of control boards. NPP teams coordinate in sharing information and perform their tasks to maintain safe operation, and to restore the plant to a safe state should there be a process disturbance. Important HFE aspects of teamwork include having common, coordinated goals, maintaining shared situation-awareness, engaging in open communication, and cooperative planning. We showed that successful teams monitor each other's activities, back each other up, actively identify errors, and question improper procedures (O'Hara & Roth, 2005).

In human teams, there must be shared situation awareness (SA) to support the coordination of the team's goal-directed activity. An important aspect of shared SA is the extent to which team members have a common understanding of what is needed to support team performance, and knowledge of the responsibilities of each individual member, the status of their activities, and an expectation of the actions they will take in the future. Multi-agent teams are not the exception, and a shared SA still is needed (Kaber, Riley, Tan & Endsley, 2001). Inherent in designing automation are assumptions about the roles and responsibilities of the human operators with whom it will interact. Likewise, operators need to clearly understand the automation's role, be able to anticipate its contributions, and what it will do in the future.

Supporting team SA is the degree to which operators perform their tasks together in an "open" work environment (Hutchins 1990). Typically, they are aware of others' actions and infer their intentions, often without explicit communication. By contrast, automated systems tend to be "opaque" (Billings, 1997a) and lack the means of taking into account the operator's actions.

Within the concept of open work environment, Hutchins (1990) identified the characteristics that contribute to team performance:

- *Openness of Tools* - This refers to the degree to which an observer can infer useful information about the problem at hand by observing another person's use of a tool. For

example, when an operator aligns a piping system by manipulating pump- and valve-icons on a graphical mimic display, such information is more likely to be useful to an observer than if the same task were performed via text commands on a keyboard.

- *Openness of Interaction* - This refers to the degree to which the interactions between team members provide an opportunity for others with information to contribute. Openness of interaction depends on the nature of communication (e.g., discussing actions or decisions in the presence of others) and the style of interaction (e.g., the degree to which unsolicited input is accepted). It also is influenced by characteristics of the work environment (e.g., openness of tools, horizon of observation) that allow other team members to see/hear the interaction.
- *Horizon of Observation* - This refers to the activities of each member that can be seen or heard by the other team members, and largely is determined by the arrangement of the work environment (e.g., proximity of team members), the openness of interaction, and the use of tools. By making portions of a job more observable, other team members can monitor for errors of intent and execution, and situations in which additional assistance may be helpful.

While an open work environment supports teamwork for human crews, an HSI design that supports such an environment with machine agents also will support multi-agent crews.

While designing automation to be a team player may be appealing from a design perspective, it is challenging. An example comes from a study of extended teamwork that included nuclear-plant operators and automatic agents (Skjerve, Nihlwing & Nystad, 2008). The operators found it "highly" useful when an automatic agent provided suggestions for handling a disturbance. However, in those situations where the operator's workload was high, operators did not like the fact that the agent continued giving suggestions, and did not adjust its behavior in response to the current situation. The authors quoted one operator as stating

> When the turbine operator looks at me, in a situation where I am busy, the turbine operator immediately observes that I have a lot to do, and he will start to take it easier…such as, delay the performance of certain tasks until I tell him to perform them… And I can say to him: OK, now you can start to open this valve to 10% - slowly. And he will be careful. He might start opening the valve 1% and see what happens, and if things are OK, he will open it to 2% and so on. The (automation) agent will open the valve to 10% immediately (p. 23).

Nevertheless, the potential benefits of making automation a better team player are widely acknowledged.

Within a teamwork model of automation, the first aspect to address is the issue of operator trust in automation. Parasuraman and Riley (1997) offered some general guidance: Fostering an understanding of automation; minimizing overreliance on automation; and, establishing confidence in automation. We summarized each.

Fostering an understanding of automation - When operators understand the purpose and the functioning of the automation, they can use it more effectively. Therefore, the conditions for using the automation, and conditions under which it should not be used, should be explicitly included in procedures and operator training. The decision to use automation should not be influenced by the effort involved in managing it; automation should not be difficult or time-consuming to engage.

Minimizing over-reliance on automation - Operators may rely on automation too much unless they encounter factors favoring overreliance. For example, when monitoring the performance of automation, common behavioral biases make operators unlikely to detect an automated process going wrong, especially when they are busy. One way to counter this tendency is to reduce workload especially that involved in monitoring. Feedback about the automation's states, actions, and intentions can be presented such that they direct the operators' attention appropriately without imposing an undue burden. In making decisions under uncertainty, operators may overvalue the data provided by the automation and fail to seek out independent information; again, training can help operators to recognize and counter decision biases that may lead to overreliance.

Establishing confidence in automation - Operators will not use automation if they lack confidence in it. Ensuring sufficient reliability is the automatic system will promote confidence.

Also, using a human teamwork model, Klein et al. (2004 & 2005) proposed six requirements for automation to be a team player:

- Basic compact
- Predictability
- Goal negotiation
- Coordination phases
- Attention management
- Controlling costs of coordination activity

Basic compact refers to engaging in a joint activity where the activities and status are communicated to operators and other agents; i.e., maintaining common ground. This includes having the automated agent alert personnel if it can no longer performing any of its functions.

Predictability refers to the predictability of the actions of human and machine agents. To participate in joint activity, automation should be predictable; and, therefore, must signal its status and "intentions," including its goals, state of knowledge, and impending actions. To the extent possible, automation should be able to interpret the status and intentions of human operators. Klein noted the basic asymmetry between humans and machine agents in their abilities to interpret the activities of other agents. Thus, people can infer the goals of other operators by observing their actions, and can detect whether another operator is having difficulty by observing their behavior. Developing corresponding capabilities for machine agents is problematic; one approach may be inferring the operator's intent from the manipulations made on plant systems and equipment, such as starting and stopping pumps. Another approach is using machine sensing of physiological indicators to infer the operator's cognitive state of operators. However, broad application of such technology may be years away. The authors cautioned that such machine-initiated adaptability to the inferred state of the human participants in the activity could make automation less predictable or cause the human agents to alter their behavior.

Goal negotiation requires that automation convey its goals to the operator and allow operators easily to revise them.

Coordination phases refer to the collaboration between operators and automation and involve handoffs from one to the other. As the automation becomes more capable, it is necessary to exchange more information to maintain common ground.

Attention management suggests that automation must strike a balance between working silently (leading to the well-documented automation-related problems), or burdening operators by requiring them to frequently pay attention to it.

Controlling costs of coordination activity refers to the fact that time and effort is necessary to maintain common ground among operators and automation. The design should account for coordination activities, aiming to adequately support collaborative activity while controlling its costs (e.g., fewer interruptions of ongoing tasks).

Woods and colleagues identified some of the generic characteristics that support teamwork involving machine agents (Christoffersen & Woods, 2002;, Dekker & Woods, 2002; Ranson & Woods, 1996b; Woods, 2005; Woods & Hollnagel, 2006; Woods & Sarter, 2000). We list them next, with examples of each.

Coordination - the ability to coordinate and synchronize activity across agents, e.g.,

- share frame of reference or common ground
- synchronize activities
- ensure the predictability of all agents

Resilience - the ability to anticipate and adapt to potential for surprise and error, e.g.,

- availability of failure-sensitive strategies
- explore outside current boundaries, set, focus, or priority
- overcome automation's brittleness
- revise focus

Observability - feedback giving insight into a process, e.g.,

- highlight current changes and events
- show how and why the automation arrived at its current state
- provide a historical context
- indicate data sources, processing, synthesis, and effects
- delineate the relations between the current process state, the control means, and the target state
- show what the automation will do next and why, including conditional logic to support attention direction, predictions, planning, and coordination
- signal when the automation is progressing towards its limits and having trouble
- support the anticipation of failure, and show the reasons for automation failures that have occurred or are about to occur
- disambiguate automation effects and process effects, showing how automation contributes to process evolution
- reveal contributions of multiple players and illustrate side effects of each agent's actions

Directability - ability to direct/re-direct resources, activities, and priorities as situations change and escalate, e.g.,

- assign specific sub-activities to the automation (or permit the automation to do entire tasks)
- specify the strategies to be used (or permit the automation to suggest or select one)
- take detailed control over an activity (or make only high level inputs as needed)

*Directing Attentio*n - ability to reorient focus in a changing world

- track the focus of attention of other agents
- judge the interruptability of others

Shifting Perspectives - contrasting points of view, e.g.:

- suggest other possibilities as activity progresses
- point out alternatives as activities approach completion

We note some common themes emerging from these efforts to describe teamwork involving automation. Taken together with the conclusions derived from the studies reviewed in Section 4; we derived several general principles for human-automation interaction. They are summarized in Table 5-1.

In Section 5.2, we look more closely at specific HSI characteristics to support these general principles. In addition to HSI design, it is important to support and reinforce human interaction with automation through tests/evaluations, procedures, and training.

Table 5-1 General Principles for Supporting Teamwork with Machine Agents

Principle	Definition
Define the purpose of automation	Automation should have a clear purpose, meet an operational need, be well integrated into overall work practices, and be sufficiently flexible to handle anticipated situational variations and adapt to changing personnel needs.
Establish locus of authority	In general, personnel should be in charge of the automation, be able to redirect, be able to stop it, and assume control, if necessary. This does not preclude the automation from initiating actions. Some actions are allocated to automation because they cannot be reliably performed by personnel within time- or performance-requirements. There may be situations where automation initiates a critical action because personnel have failed to do so. Such automatically initiated actions, e.g., SCRAM and ECCS, are needed to support the safety of personnel and equipment.
Optimize the performance of human-machine team	The allocation of responsibilities between humans and machine agents should seek to optimize overall integrated team-performance. This may involve defining various levels of automation, each with clear-cut, specific responsibilities for all agents and each with a clear rationale. It also may involve flexible allocations that change in response to situational demands. Personnel's interactions with automation should support their development of a good understanding of the automation, and the maintenance of their personal skills needed to perform tasks if automation fails. This optimization may involve exposing personnel to various levels of levels of automation. The HSIs should support a clear mutual understanding of the roles and responsibilities for both human and machine agents.
Understand the automation	Personnel should clearly understand the automation's abilities, limitations, and goals, and be able to predict its actions within its various contexts. Minimizing automation's complexity will support this objective. While operators' understanding largely will come from training and experience, the HSI should support that understanding by reinforcing the operator's appropriate mental model through the information provided in automation displays. That is, the HSI should accurately representation of how the automation functions overall, and how it interacts with the plant functions, systems, and components.
Trust the automation	Personnel should have a well-calibrated trust in automation that involves knowing the situations when the automation can be relied on, which require increased oversight by personnel, and which are not appropriate for automation. The HSIs should support the calibration of trust, such as providing information about the automation's reliability in its various contexts of use and specific functions.
Maintain situation awareness	The HSIs to automation should provide sufficient information for personnel to monitor and maintain awareness of automation's goals, current status, progress, processes (logic/algorithms, reasoning bases), difficulties, and the responsibilities of all agents. Special attention should be given to changing LOAs and for AA where the roles and responsibilities of all agents may alter. HSIs should support differing levels of need for information, from determining the overall status at a glance to more detailed data in support of greater interaction with automation.
Support interaction and control	Personnel interaction with automation should support the human's supervisory role: • HSIs should support personnel interaction with automation at a level commensurate with the automation's characterization, e.g., level, function, flexibility, and its reliability. • Communication functions should enable personnel to access additional information about its processes beyond that provided in monitoring displays. Automation should communicate with personnel when necessary, such as when it encounters an obstacle to meeting a goal, or when information is needed from personnel (e.g., information not accessible to automation). Communications from automation should be graded for importance, so as not to be overly intrusive. • Personnel should be able to redirect automation to achieve operational goals. Then they should be able to override automation and assume manual control of all or

Principle	Definition
	part of the system.
Minimize workload from secondary tasks	A minimal workload should be entailed in dealing with the automation's configuration, and in monitoring, communicating, changing allocations, and directing it.
Manage failures	Automatic systems should support error tolerance and manage failures: • Personnel should monitor the activities of automation to detect automation errors, and be adequately informed and knowledgeable to assume control if automation fails. • Automation displays should support operators in the determining the locus of failures as being either the automation, or the systems with which the automation interfaces. • To the extent possible, automation should monitor personnel activities to minimize human error by informing personnel of potential error-likely situations. • Automation should degrade safely and straightforwardly when situations change sufficiently to render its performance unreliable, and should communicate this to personnel in a timely way to enable them to become more engaged in the responsibilities of the automation.

5.2 HSI Approaches for Supporting Human-automation Interaction

The main approaches to providing HSIs supporting the monitoring and understanding of automation that we identified in the literature are functional methodologies based on ecological-interface design (EID) principles.[4] Some specific recommendations made include the following ones:

- *Information requirements analysis* - Identifying the information operators need to interact with automation using (1) work-domain analysis using an abstraction hierarchy to identify the information needed to interact with automation and ecological interface design principles to increase the operator's understanding of automation and current situation awareness (Duez & Jamieson, 2006; Linegang et al., 2006); and, (2) functional modeling using a means-end hierarchical structure (Liu, Nakata & Furuta, 2004; Piccini, 2002; Pirus 2004a & 2004b; Riera, 2001). This research is discussed in Section 5.2.1.
- *Detailed HSI design* – Presenting information about automation using ecological HSI designs, integrated displays, emergent features, and mixed modal feedback (Guerlain et al., 2002; Parasuraman et al., 1997, 2000). This research is discussed in Section 5.2.2.

These recommendations basically stem from applying work-domain analysis to identify information requirements and the principles of EID to designing information displays to offer the required information (Vicente, 1999; Burns & Hajdukiewicz, 2004). We briefly explain this basic approach below. Vicente and Rasmussen (1992) promoted this methodology for the nuclear industry.

[4] EID refers to an approach to display design that focuses on presenting information at various "levels of abstraction" (from lower-level parameter information about a component to high-level plant functions such as critical safety function status). EID principles seek to display this information to making maximum use of graphical features to present information. See O'Hara et al. (2000) for more information.

The application of this approach to HSI design will be discussed next. HSI design results from two activities. First, the requirements for the HSI must be identified, i.e., the information, controls, and functionality necessary to allow personnel to carry out their role, as identified in function and task analysis. Second, the designer must decide how those identified requirements will be presented in the HSI.

5.2.1 HSI Requirements Analysis

This section is divided into two subsections. The first covers the methodology for determining HSI requirements. The second subsection discusses the general categories of HSI requirements, e.g., information about automation's goals, which are discussed in the literature on automation.

HSI Requirements Analysis Methodology

NUREG-0711 takes a systems-engineering approach (DoD, 1996; IEEE, 1998) to this HSI requirements analysis, a key aspect of which is a top-down functional decomposition (see Figure 5-1). Top-down refers to an evaluation that starts at the "top" with high-level plant mission goals that successively are broken down into the functions necessary to achieve them. Functions are allocated to human and system resources (automation) and are divided into tasks. Personnel tasks are analyzed to specify the alarms, information, decision support, and controls needed to allow plant personnel to accomplish their functions. Tasks are arranged into specific jobs assigned to individual crewmembers. The detailed design of the HSI, procedures, and training to support job task performance is the "bottom" of the top-down process. HSI information requirements supporting detailed HSI design are derived from this process.

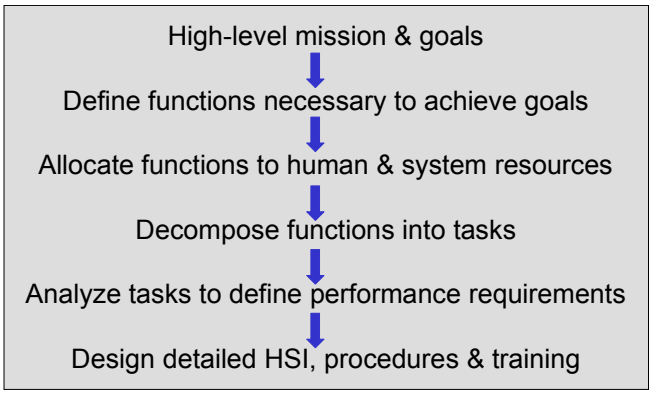


Figure 5-1 Top-down systems analysis

As applied to the design of HSIs for automation, the process must account for the complexity of automation systems, and the dimensions of the characterization used (see Figure 5-2). Interestingly, we note that current design methods may not be fully adequate to encompass the diversity of automation implementation options available. For example, the characterization of automation we gave in Section 3, reflects how automation is implemented in current systems. However, the part of the functional decomposition process that allocates functions to human and automatic systems does not sufficiently discriminate to account for the characterization dimensions available to designers. Lacking such methods, the technical bases used to indentify the appropriate type of automation to use are based on operating experience and subjective approaches to design.

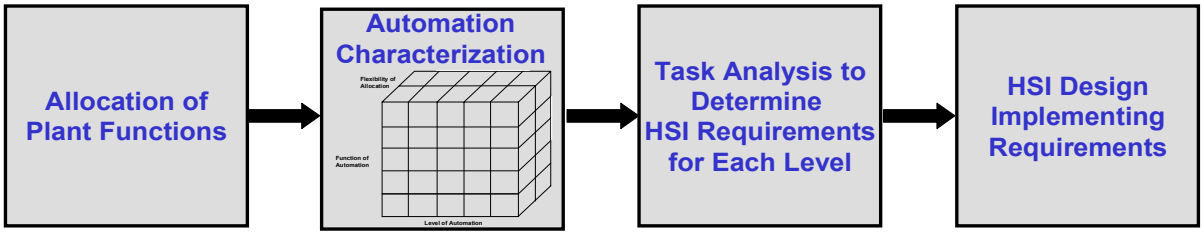


Figure 5-2 Defining HSIs for automation

Within the context of systems engineering, work-domain analysis and EID provide one means of employing a functional decomposition approach consistent with NUREG-0711 criteria. Then, information about a system varies along two dimensions: Abstraction, and aggregation (Rasmussen, 1986). Abstraction reflects the conceptualization of system's means-ends relationships along a hierarchy consisting of various levels. Rasmussen's approach employs five levels:

- *Functional purpose* – the purpose for which a system is designed
- *Abstract function* – the causal structure and design basis of a system
- *Generalized function* – the basic functions a system or process is designed to achieve
- *Physical function* – the characteristics of the components within a function in a system or process, and their interconnections
- *Physical form* – the appearance and spatial location of those components.

These levels encompass the physical components in the system and their overall functional purpose. Since monitoring and situation assessment requires information at various levels, the abstraction hierarchy affords a framework within which to describe those needs and consider HSI design.

Aggregation reflects the degree of integration, from part to whole, that operators need to support situation assessment. The part-whole dimension also consists of levels ranging from the individual component to the entire plant. These two dimensions form a matrix describing the information needs of plant personnel, called the abstraction-aggregation matrix, as illustrated in Table 5-2.

Table 5-2 General Abstraction-Aggregation Matrix

Level of Abstraction	Level of Aggregation			
	Whole System	Subsystem	Functional Unit	Component
Functional Purpose				
Abstract Function				
Generalized Function				
Physical Function				
Physical Form				

Note: Adapted from Rasmussen (1986)

During situation assessment, operators shift their monitoring strategy between levels of abstraction and aggregation[5] enabling them to conceptualize the situation assessment in different ways. Lower levels of abstraction support knowing what to do; higher levels support an understanding of why it is necessary. Rasmussen (1986) suggested that HSIs often fail to provide information to meet these needs, instead providing one level of abstraction, reflecting a 'one sensor – one indicator' approach. Consistent with the monitoring studies we briefly discussed above, this complicates both monitoring and situation assessment because the data available often do not match the information needed. Rasmussen stated that

> In the design of human-machine interfaces for supervisory control, e.g., industrial process control consoles, the emphasis has traditionally been on the presentation of measured data representing the physical state of the system and its processes. In complex systems, this information has been supplemented by information about the underlying functional structure by graphical means such as mimic diagrams, etc. This information is intended to serve the controller's identification of the actual state of processes bottom-up through the hierarchy. Information representing the intentions behind the system design, in terms of the purpose of functions and equipment and of constraints upon the acceptable operation, for instance, as derived from safety considerations, has only been very sparsely represented. This means that the interface system gives little or no support in the top-down derivation of the proper or acceptable states of processes. This kind of information was supposed to be immediately available to operators from their basic training. However, as systems become complex and potentially risky... this can no longer be assumed. During such situations, information about the purpose of interlocks, properties of equipment if used for untraditional purposes, etc., may be vital for ad hoc improvisations. Consequently, it becomes increasingly important to include in the support for decision making the information needed for top-down consideration of reasons. This means that the properties of the system to be controlled should be represented in terms of a consistent means-end hierarchy, systematically mapping the purpose/function/equipment relationships. (1986, pp. 130-131)

Rasmussen indicated that this situation places the burden on operators to find the needed information to support their current activities. The NRC's research on information system design (O'Hara et al., 2000) and interface management (O'Hara & Brown, 2002) supports this view.

[5] The two dimensions tend to be coupled; that is, people tends to think at lower levels of abstraction in dealing with components, and to think functionally when working at the plant level (O'Hara, et al., 2000).

Plant behavior is governed by a set of known relationships defined by the physical nature of plant equipment, the physical laws governing the process, and the purposes for which the system was designed. By analyzing requirements according to the abstraction-aggregation matrix, designers can represent these relationships in the HSI. This is the rationale behind the recommendations of automation researchers who support using work-domain analyses and abstraction hierarchies (Duez & Jamieson, 2006; Linegang et al., 2006; Liu, Nakata & Furuta, 2004; Piccini, 2002; Pirus 2004a & 2004b; Riera, 2001).

An illustration of an abstraction hierarchy approach is the HSI design for FITNESS (Pirus, 2004a & 2004b), i.e., Functional Integrated Treatments for Novative Ecological Support System, that is EdF's approach to the next generation of NPP operations that employs adaptive automation (AA). Its development reflects an abstraction hierarchy for operator interaction with automation that builds upon a generalization of the functional representation of the plant, and enables the complexity of the process to be controlled in various areas:

- The propagation of functional failures from low levels to high levels clearly is represented, so allowing reliable synthesized information to be generated on the availability of the key functions.
- The scheme of the operations for the main functions during plant startups and shutdowns is explicit (the initiation of a function starts at the lowest level and goes up the hierarchy to the highest functional level), with the possibility of carrying out tasks in parallel on sub-functions of the same level that are not directly linked.

The display and information system was designed to cohere with operating objectives, while the relationships and interactions between plant functions are clarified. This functional approach is formulated via a formal hierarchy of displays, information, and alarms. From the unique global-plant overview display, the operator goes down to the function level to be managed, and then to the component level, which represents elementary operating functions.

The displays are organized into three levels. The first one is the general monitoring display for the whole plant that gives operators a comprehensive view of the working of the plant and the current alarms. It acts as a gateway to the other displays. Level 2 contains displays for supervising the main operating functions of a functional set. The operator uses them to monitor and control the main- and basic-functions of the plant and the automation, and to guide troubleshooting and diagnosis during an anomaly. Level 3 contains displays detailing the sub-functions required to perform the main function, including the equipment supporting each.

The level 2 and 3 displays are split up into three sub-groups: Process functioning displays; process operating displays; and, basic-sequence operating displays. Process functioning displays synthesize the status of the main functions of the functional set to which they are linked. They support the operator's understanding of process situations and diagnose deviations. Process operating displays serve to monitor or carry out operating tasks. The third subgroup is the basic sequence-operating displays, supporting the use of procedures.

To identify the HSI requirements for any specific implementation of automation, a precise analysis must be made for that particular automation. However, some more general categories of automation were suggested; we consider them next.

General Categories of HSI Requirements

NUREG-0711 gives one general source of information about what information is needed (O'Hara et al., 2004). While the document addresses plant functions in general, the type of information given also is applicable to automation. Its Section 4.4, guideline 4, states that the description of a function should include

- purpose of the function
- conditions that indicate the function is needed
- parameters that indicate the function is available
- parameters that indicate the function is operating
- parameters that indicate the function is achieving its purpose
- parameters that indicate operation of the function can or should be terminated

This information should be available to operators monitoring automatic functions.

Duez and Jamieson (2006) suggested presenting information at different levels of abstraction to include

- data about the automation's purpose, i.e., the function for which it was designed
- data about the automation's process, i.e., how it meets its purpose, e.g., the algorithms used
- data about the automation's performance, i.e., the results of the automation process

Similarly, Lee and See (2004) suggested HSIs should provide information that

- supports appropriate trust in the automation, such as automation's reliability
- supports the operator's evaluation of the automation's capabilities under different situations in which those abilities vary
- shows the automation's past performance for the current use
- provides specific details about how the automation is functioning, e.g., the process and algorithms of the automation by clearly and comprehensively revealing intermediate results to operators

In exploring Lee and See's first point, our review of operator trust and their use of automation (Section 4.1) showed that the HSIs should provide information about its expected reliability in varying contexts of use. That is, if automation's reliability differs between one situation and another, then that information should be communicated to the operator who relies on the automation. How this reliability information is presented to operators should consider the complexity of the task. When the purpose of the automation is to take an action, such as to actuate a system, its reliability quantification may be plain, such as the probability of performing the action. In other circumstances, it may be more complex. For example, in the simple case of an event-detection system, showing the results of the system from a decision matrix containing four cells (see Table 5-3). Reliability information presented to operators must reflect the tradeoffs in the system's decision-making logic. Furthermore, since the reliability of the system may vary in different modes, at different levels of automation, or in different situational factors, this complexity needs to be reflected in the information offered to operators.

Table 5-3 Automatic Event-Detection Decision Matrix

	System Detects	**System Does Not Detect**
Event Occurs	Correct Detection	Miss
No Event Occurs	False Detection	Correct Non Detection

Other authors identified the high-level information requirements of operators interacting with automation; thus, Jamieson and Vicente (2005) proposed a set of high-level design principles for HSIs to automation whose main function is control.

- The HSI should accurately represent both the plant and the automation, so aiding operators to visualize the relationship between the actions of automation and aspects of the plant being controlled. They distinguished four system elements: The automation; the controlled components; the process; and, the HSI. Since failures in each of these elements qualitatively are different events, they require different actions by the operator actions. This will help operators when automation masks a process failure.
- All signals in the control feedback loop should be available to the HSI.
- Analytical redundancy should be used to provide information about whether automation is working as expected. Analytical redundancy is recommended in NUREG-0700 (Guideline 1.1-21, Analytical Redundancy), and to support determining the quality of data. In the present context, it is used to compare the demand signal to a controlled component to the actual value of the parameter. A model of how the components should respond can suffice to see if the control is meeting expectations.
- The HSI needs to address mode transitions, especially uncommanded ones. Information is needed about the state conditions or changes leading to changes in the uncommanded mode.

In addition, Jamieson and Vicente (2005) recommend reducing the structural complexity of the controller as much as possible, e.g., reduce the number of modes; consistent with their recommendation to simplify automation algorithms discussed earlier.

Another view of the high-level information requirements for automation comes for the work of Skjerve and colleagues at the Halden Reactor Project. They examined how nuclear-plant operators handle two types of automation malfunctions while using two types of HSIs (Skjerve, Strand & Saarni, 2002; Skjerve & Skranning, 2004a, 2004b). “Component” malfunctions were failures of the automatic system to do what it was supposed to. “Strategy” malfunctions were situations where the automated system did what it was designed to do but masked a problem in the plant by compensating for it. The two types of displays differed in the amount of information given about the automation. In one type of HSI, information about the automation had to be inferred from information provided about the process. In the second, the “experimental” HSI, information about the automation was given explicitly, as vocal notifications. The results showed the latter better supported the operators’ recognition of malfunctions, and the voice

feedback was effective. This is consistent with Parasurman's recommendation of employing multimodal feedback to supply information about automation (Parasuraman et al., 1997, 2000). In addition, the operators stated that their workload was reduced due to the immediate access to data about the automation, and to the voice messages. Thus, increasing the observability of automation improved performance. The group formulated guidance for designing of HSIs for automatic systems based on these studies and studies of teams of human and machine agents (Skjerve, Nihlwing & Nystad, 2008):

- The activity of key automatic agents should be represented as graphical feedback in an overview display. It should show the progress of key events in the accomplishment of the agent's task.
- Information about machine agents should be integrated naturally into the representation of the process components on the overview display.
- Key agents should inform the operators of their start-up, shut-down, and when deviations occur.
- Machine agents should give verbal feedback with graphical feedback. Operators like verbal feedback because they did not have to search for it. Messages should be specific, short, and concise, and delivered formally. There should be a way to repeat the message.

Kaber et al. (2001) addressed high-level requirements of HSIs for AA. Since AA can impose additional workload on operators, they suggest that its success predominantly will depend on the HSIs. These authors suggest that HSIs for adaptive automation should do the following:

- Support operators' awareness of their responsibilities, as well as those of the automation.
- Support quick, easy, and unambiguous shift of AA allocations.
- Provide personnel with information on how well automation has assumed its new tasks when transitioning to higher levels of automation.
- Provide personnel with information about the current status of the tasks automation has been performing so operators are fully aware of what needs to be done during any transition to lower LOAs.
- Alert personnel to the need to switch LOAs and supply the information that will be required to make that shift smoothly.

The studies discussed above, all pertain to the display of information about automation's goals, capabilities, processes and results. Another important requirement we identified in the previous section is explanatory information. That is, operators need to be able to query automaton about the basis for its actions, whether they are control actions or decision making. In fact, automated systems should afford a roadmap for tracking, interpreting, and verifying their recommendations (Mosier et al., 2007). After reviewing earlier research on intelligent-agent communications facilities, Haynes et al. (2009) identified a framework of four classes of communications:

- *Ontological explanations* – information pertaining to "what" questions, e.g., what does this mean, what event led to this state, and what are the consequences of an event.
- *Mechanistic explanations* – information describing the mechanics of an agent's behavior, how the different components interact

- *Operational explanations* - information that describes the steps to be performed to interact with the agent
- *Design-rationale explanations* – information pertaining to "why" questions.

Using this framework, Haynes and colleagues undertook a study to further examine expert user's requests for explanations. Twelve participants (experts in different areas) interacted with an expert system providing tactical air-combat information. The users' requests for explanations were recorded and classified according to the above framework. The relative percentage was as follows: Ontological explanations – 58%; mechanistic explanations – 19%; operational explanations – 12%; and, design-rationale explanation – 11%. They proposed generic designs for structuring communications to support these communications. Their work suggests that in designing communication interfaces to automaton, attention should be paid given to the types of explanations provided, emphasizing the provision of ontological information at a minimum.

We consider that several common types of information emerge from these studies, and summarized them as follows:

- Automation's purpose and current goal
- Automation's reliability in accomplishing its goal (considering the complexity of the task and reflecting the decision tradeoffs)
- Automation's structure (how it achieves its goal) and its interaction with plant systems and functions, including inputs, current modes, and current LOA
- The roles and responsibilities of all agents involved in meeting the current goal
- The current progress of automation's processes (e.g., control algorithms, decision logic) in accomplishing its goal
- Explanations of the automation's process
- Difficulties or challenges to accomplishing the current goal, including automation failure

Operators also should have access to information about the situational context within which automation is functioning, including

- the conditions indicating the automation is needed
- the conditions that are appropriate for automation's use
- the conditions for terminating automation

These HSI requirements apply to automation in general, but they do not address HSI requirements that may be pertain of specific levels of automation, except perhaps full automation. We can derive some general HSI requirements for the other aspects of automation (shared operations, operation by consent, operation by exception, and adaptive automation) when we consider the general roles of humans and machine agents at each level from a general-task analytic perspective.

In *Shared Operations*, operators and automation cooperate on different aspects of a task. Thus, operators will need the information necessary to coordinate the shared activity, especially for tasks that might be inter-dependent, and require input from both agents.

In *Operation by Consent*, automation is completing task segments independently under operator's supervision. At specific points in the task, automatic activities are suspended and operators must assess the situation to determine if automation can proceed to the next segment. To do this, operators need information on the status of all tasks performed by automation, e.g., all tasks accomplished thus far, and the remaining ones. Operators then can evaluate the current status of automation to assure all conditions are met for authorizing the automation to proceed. However, at each decision point, operators should be given information on any valid options, and the implications of each. For example, operators may decide that conditions are not acceptable and automation should repeat the task or return to an early point in the task sequence. Alternatively, operators may determine that automaton should be suspended or stopped and perhaps restarted later. Thus, information should be available for making these decisions, and their implications.

In *Operation by Exception* automation performs the task independently unless an exception condition is encountered. At that point, automation stops until the operator assesses the condition and provides direction. Thus, the HSI should identify the exception the automation encountered and provide the operator with the information needed to evaluate the exception. Then, as with operation by consent, the HSI should identify the valid options and their implications for the particular exception.

Adaptive Automation involves changing levels of automation and the relative roles and responsibilities of both the operators and machine agents; the shifts are based on a triggering condition. That trigger may be the operator's judgment, i.e., operators determine that their workload has increased and delegate increased responsibilities to automaton. In this case, the HSI should incorporate controls for operators to shift responsibilities to automation or away from it. Alternatively, the triggering condition for the shift may be based on predefined operator conditions (such as a measure of workload) or system condition (such as exceeding a critical parameter). Then, the triggering condition should be identified and, where possible, operators should be given advanced notification of an impending shift so they can adjust their behavior accordingly, or to prevent it. Operators also should also be informed when the shift has been made and the responsibilities changed. While providing information about the roles and responsibilities of all agents was identified in the situations above, it is especially important in adaptive automation because of the dynamic shifts that occur.

Table 5-4 summarizes these high-level HSI requirements for shared operations, operation by consent, operation by exception, and adaptive automation.

Table 5-4 General HSI Requirements for Levels of Automation

Level	Automation Functions	Human Functions	HSI Requirements
Shared Operation	Automatic performance of some functions or tasks	Manual performance of some functions/task	• information need for task coordination • see requirements for autonomous operations
Operation by Consent	Automatic performance when directed by operators to do so, under close monitoring and supervision	Operators monitor closely, approves actions, and may intervene to provide supervisory commands that automation follows	• provide information on task status • provide information needed to authorize task continuation • identify valid options • see requirements for autonomous operations
Operation by Exception	Essentially autonomous operation unless specific situation or circumstances are encountered	Operators must approve of critical decisions and may intervene	• provide information on reason for exception • identify valid options • see requirements for autonomous operations
Adaptive Automation	Flexible task assignment	Flexible task assignment	• operator control of automation shifts • identification of triggering conditions • notification of impending shifts • shift conformation

In summary, the general approach to HSI requirements analysis recommended in the literature is functional decomposition, such as an abstraction hierarchy, an approach that is consistent with the guidance for functional analysis in NUREG-0711. In addition, general categories of HSI requirements we identified generally are consistent with the principles for supporting teamwork with machine agents, set out in Table 5-1. For any automation design, analyses should be carried out, and the detailed requirements within each of these general categories identified.

5.2.2 Detailed HSI Design

Identifying HSI requirements for automation is the first step towards an HSI design. The next step is to develop a detailed HSI design that satisfies the identified requirements. In this section, we address two aspects of HSI design: Design of displays, and of controls.

Display Design

Automation researchers recommended following EID principles for the detailed design of the HSIs for automation, including integrated displays, emergent features, and placing data in a meaningful context (Duez & Jamieson, 2006; Guerlain et al., 2002; Parasuraman et al., 1997, 2000). In this section, we examine these design principles. We note that very few specific recommendations about detailed display design for automation have been published. Thus, our discussion mainly is focused on EID principles in general.

The EID approach to interface design has its roots in Gibson's theory of visual perception (Gibson, 1979). His central concept is that human behavior cannot be understood as an entity independent from the environment in which it occurs. Thus, knowledge of the context or domain within which behavior occurs is essential to understanding human performance. Gibson's concepts have influenced the EID approach to HSI development. Several authors described the basis for using ecological perception theory as an approach to interface design (e.g., Flach, 1990; Vicente & Rasmussen, 1990, 1992). Direct perception is one of Gibson's ideas that is important to displaying information about a complex system (Flach, 1989; Flach & Hancock, 1992). *Direct perception* means that the information presented in the display has immediate meaning within the context of the operator's current information needs. There is little need for the operator to analyze and interpret direct-perception displays. In the natural world, direct perception is possible because our visual systems automatically detect various invariant features of the environment. In the context of HSI design, direct perception is achieved in several ways. The first is *representational aiding* (Bennett, 1992; Woods & Roth, 1988).

Representational aiding means mapping the relationships between the display, the operator, and the system. Within an EID approach, the goal of display design is "...to map the domain semantics (low-level data, high-level constraints, and relevant performance goals) into the appearance and dynamic behavior of a graphic display so that this information is readily available (easily extracted or decoded by the user)" (Bennett et al., 1993, p. 73). This involves the two types of maps (Bennett et al., 1997):

- *Correspondence map* between the properties and characteristics of the system to be represented, and the features in the representation (how well the display represents meaningful information about the system)
- *Coherence map* between the features in the representation and the mental model of the operator (how comprehensible the displayed representation is to the operator)

When effectively accomplished, these mapping techniques ensure that the information representations trigger the appropriate understanding of the situation. The critical cues necessary to support this mapping should be determined, and the displays should make these cues salient. Effective representational aids support rapid situation assessment since they minimize the need for operators to mentally process data to obtain the needed data. We detail several examples below.

A common EID strategy to support direct perception is to map low-level perceptual processes to plant information. Bennett and Flach (1992) defined three potential relationships between data that can be represented in displays: Separable; integral; and configural. *Separable* relationships are those that can be shown by individual data points, and are characterized by a lack of interaction among the data's dimensions; i.e., each dimension retains its unique perceptual identity. *Integral* relationships are defined by a strong interaction among data dimensions, such that the unique identities of individual dimensions are lost. In this relationship, a change in one dimension necessarily produces a change in a second one. Bennett and Flach used the example of color perception that is a function of the dimensions of hue and brightness. In color perception, the perception of each individual dimension is lost in the integration. *Configural* relationships refer to an intermediate level of interaction between dimensions, wherein each maintains its unique identity, but new *emergent features* are created from the interaction between the dimensions (we describe emergent features further below).

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

Separable displays are representations where each process parameter is presented individually, and the representation itself does not show relationships between the parameters. The key aspect of separable displays is not that individual parameters are presented, but that no interaction or relationship between them is perceived. While there may be a relationship between the parameters, the separable displays do not show it.

Integral displays merge the information in such a way that the individual parameters used to generate the display are not represented in them. An example is a display that provides information on a system's status by the appearance of an icon. The appearance of the icon may change based on the computation of lower-level parameters, but these parameters are not presented. When decisions are based on integrated information, the concept of integral display suggests that information processing is supported by integrating information into a single object (Kahneman & Triesman, 1984). Integral displays are thought to support direct perception by capitalizing on the abilities of humans to recognize patterns, and thereby reduce demand on working memory associated with simultaneously considering many individual variables.

Configural displays combine the other two types. Information about the basic parameters is available; however, information on their relationships becomes evident as features emerge from the representation. NUREG-0700 defines an "emergent feature" as a high-level, global, perceptual feature produced by the interactions among the individual parts or graphical elements of a display (e.g., lines, contours, and shapes). Configural displays often use simple graphic forms, such as a polygon. Information that could be presented by separate display formats is integrated into a single format in which each of the separate pieces of information is represented, for example, by the distance of a polygon's vertex from its center. In addition, the geometric shape of the polygon provides a high-level summary (the emergent feature) (Buttigieg et al., 1988; Sanderson et al., 1989). Such displays are thought to enhance parallel processing, enabling operators to better understand the relationships between display elements, and ultimately leading to a rapid, accurate awareness of the situation (Bennett and Flach, 1992; Flach & Bennett, 1992). Extracting information for high-level task requirements is supported by the emergent features produced by a configural display.

Emergent features can be formed by purely separable displays; i.e., where no specific graphic is incorporated into the display (Wickens & Carswell, 1995). A systematic pattern formed by a series of bars on a bar chart (see Figure 5-3) or the parallel appearance of a set of analog meters may constitute an emergent feature. In Figure 5-3, operators looking at the series of bar charts on the left must compare the parameter value of each bar to a referent value indication normal to determine its status. Operators looking at the bar charts on the right can immediately see that all values are normal by observing the straight line formed from one to the next (the emergent feature). Detecting a problem is far easier when the emergent feature of a straight line is broken. The emergent feature is effective if it conveys high-level information and provides status-at-a-glance functionality, without requiring operators to analyze the individual parameters.

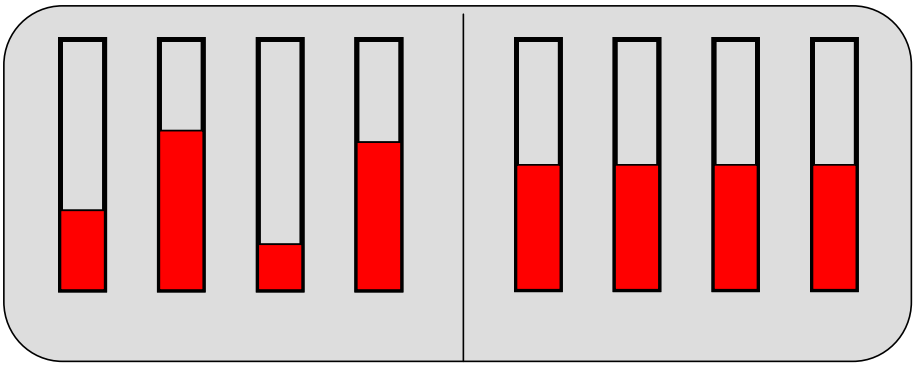


Figure 5-3 Simple emergent feature

The degree to which the individual and emergent features perceptually are salient to the observer is important in allocating attention to the elements of the display. The design goal is to map meaningful aspects of the operator's task-information requirements to the visual characteristics of the display. Significant aspects of domain structure and behavior must be mapped to the characteristics of the representation so that the domain's semantics are visible directly to the operator (Woods & Roth, 1988).

The value of each type of display – separable, integral, and configural – may depend on the task requirements (Bennett & Flach, 1992). That is, if operators carry out their tasks based only on individual parameters, then separable displays may be preferable. If they depend on the integration of individual parameters, integral displays may be optimum. When performance is based on a combination of the two, configural displays may be best.

Liu, Nakata, and Furuta (2004) discuss display design for automatic control functions that reflect representation aiding. As we discussed above, the first step is determining what information about the automatic system is needed for operators to properly monitor and understand it. In an earlier paper, these authors proposed employing functional modeling using a means-end hierarchical structure (Liu, Nakata & Furuta, 2002). At the top of the hierarchy are the system's goals, while its lower end describes the sub-functions used to accomplish them. Each function can be described by a functional primitive. Liu et al. proposed a set of functional primitives to model a system: Generate, store, transport, transform, balance, barrier, and sink. They extended these basic concepts to control- and automation-systems (Liu, Nakata & Furuta, 2004). A set of control primitives were identified, including control, generate, transform, set, select, limit, calculate, and delay. Each of these primitives can be further divided into sub-items. For example, "control" can be "rate control," "closed-loop control," and so forth; each has a unique mathematical expression.

The authors noted that a good HSIs display helps operators to develop an accurate understanding of how automation works. Control algorithms enable the control system to meet its goals that constitute the internal constraints on the system. When functioning properly, the relationships between the variables conform to the algorithms. However, when there is a failure or degraded conditions exist, one or more of the constraints are broken so comprising its function. The role of the HSI is to make these constraints visible to the operator (a central tenet of EID). Liu offers a simple example using a water-level controller with the function "control x at x_{set}" where x is the water level, and x_{set} is the setpoint. The mathematical expression of this

control function is "x = x_{set}." One method of allowing operators to visualize that relationship is to depict graphically the level and its setpoint value, as in the control function displayed in Figure 5-4. It shows a tank level with the current level and setpoint level. The colored regions of the scale correspond to normal operating range and to alarms for low and high levels. In Display A, the actual and controlled levels are the same (no automation fault). In Display B, a fault exists. The level setpoint is 36 meters, but the actual level in the tank is 23.[6] The right side of Figure 5-4 illustrates the same concept for a rate controller. The deviation of the actual rate from the set rate indicates a disturbance in the either the control system or the equipment being controlled. These are simple examples; many alternative designs will work just as well. Liu proposed establishing a library of graphical representation of the functional primitives for constructing displays, so enabling operators to monitor and understand automated controls and to ensure consistency in the HSI design.

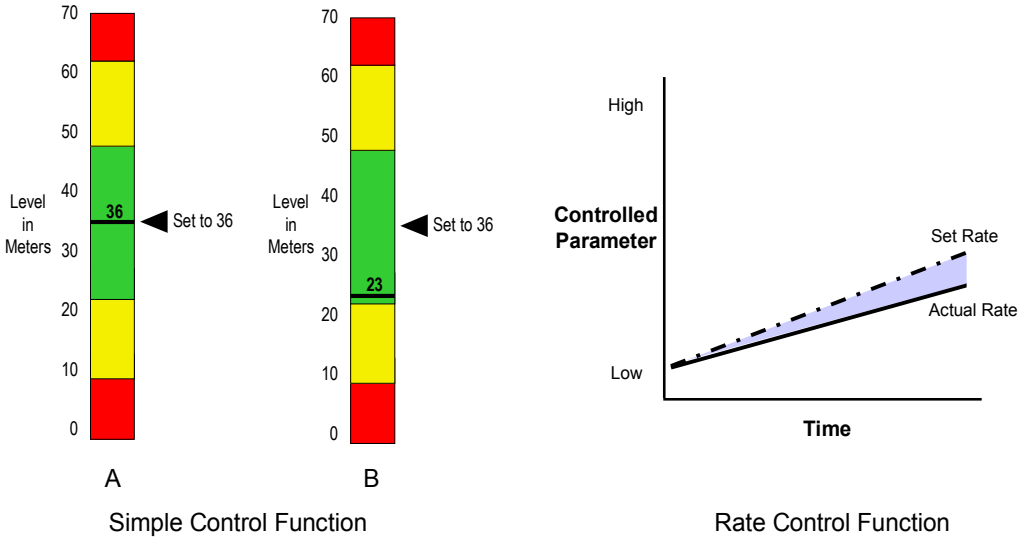


Figure 5-4 Visualization of control functions

Thus, EID principles are aimed at supporting operator monitoring and situation assessment (at significantly less workload) by capitalizing on human perceptual capabilities. Accordingly, when HSIs designed using EID principles are organized into an abstraction hierarchy, the HSI conveys the functional and mean-end relationships inherent in the automation system, and in its functional relationship to the aspects of the plant automation is acting on. This arrangement should support the operators' need for information at various levels, viz., high-level for overall status monitoring, and lower levels for more detailed interactions.

Control Design

Another aspect of HSI design for automation relates to interaction with, and controlling automation. Operators may fail to use reliable automation because of the work required to do

[6] Fault detection is more complex since automation can compensate for system faults. Thus, in Display A it is possible that the automation is compensating for a failure in the controlled system. In Display B, failure can be in the automation itself or the controlled system. An operator needs additional information to resolve these issues.

so; this is especially important with adaptive automation where their interaction may be more frequent.

Parasuraman and colleagues examined the issue of minimizing workload for AA. They proposed installing a "delegation interface" for interacting with automation levels (Miller & Parasuraman, 2003, 2007; Miller et al., 2005). Delegation is the process of assigning specific roles and responsibilities for a subtask of a parent task for which the delegating agent retains authority and responsibility. Communication about intent to subordinates frequently is expressed in terms of goals, methods, constraints, and resource utilization. As supervisory controllers, operators select tasks for automation to perform and set procedures for how to accomplish them. The underlying concept is that the operator can delegate tasks to the automation to ensure a flexible approach to completing that task that enables operators easily to vary the level of automation. The approach is modeled on work delegation in human teams.

The interface is called "Playbook" and is built on a metaphor of a sports team's use of a playbook of specific plays that all team members understand. A hierarchal task model at its center reflects the levels of automation provided in the system. Groups of tasks are organized into plays, and the relevant task parameters are identified, such as times and locations. The parameters can be identified beforehand, or specified when the particular play is called by operators using a short command. The predefined plays establish for all team members a common view of what each agent will do. The more the operator specifies in real time, the more effort is involved in communicating with the automation but the more exactly will the automation will do what the operator wants. The less that is specified in advance, the less effort is required on the operator's part; however, the automation will operate more independently and the less predictable the outcome will be.

Playbook has a planning module that develops a specific plan based on the current situation. The planner has access to knowledge about information, such as resources available (e.g., fuel) and can adjust the tasks accordingly. It alerts the operator if there are constraints that would compromise success. There are control algorithms for executing actions specified in the plan. Finally, if necessary, an event-handling module makes fine adjustments during the execution of the plans.

There is some support for the effectiveness of a Playbook approach. Parasuraman, Galster, Squire, Furukawa, and Miller (2005) compared the effect of Playbook on human supervision of unmanned vehicle tasks with a restricted interface with only one level of control. Success rate and time to completion was better with Playbook, although the benefits fell as the number of vehicles simultaneously controlled was increased. The HSIs enabled operators to identify goals and provide instructions to automation agents. Further, operators could adapt and respond to the automation's ineffective behavior.

The lessons-learned from these studies is that providing operators with "set plays," i.e., predetermined definitions of a set of roles and responsibilities of human and machine agents, can reduce the operator's workload from interacting with the automation.

5.3 Conclusions and Research Needs

Based on our characterization of automation, our review of the effects of automation design on human performance, and our considerations for making automation a team player, we developed nine general principles for supporting teamwork with machine agents (described in Table 5-1):

- Define the purpose of automation
- Establish locus of authority
- Optimize performance of human-machine team
- Understand the automation
- Trust the automation
- Maintain situation awareness
- Support interaction and control
- Minimize workload from secondary tasks
- Manage failures

The general principles for supporting the teamwork with machine agents are addressed through the design of the automation and the HSI, along with procedures, and operator training.

The design of HSIs for automation should involve an analysis of HSI requirements and a detailed HSI design. The literature points to work-domain analyses and EID as the main approaches to these two activities. The methods for HSI design generally are consistent with the staff's guidance for reviewing the design process (NUREG-0711), and for implementing HSI design (NUREG-0700).

The recommendations about the operator's high-level information needs in the publications on automation mostly are consistent with the HSI implementations, listed above, of the general principles for supporting teamwork with machine agents' needs. The general categories of information include the following:

- The automation's purpose and current goal
- The automation's reliability for accomplishing its goal (taking into consideration the tasks' complexity and reflecting the decision tradeoffs)
- The automation's structure (how it achieves its goal) and its interaction with plant systems and functions, including inputs, current modes, current LOA
- The roles and responsibilities of all agents involved in the current goal
- The current progress of automation's processes (control algorithms, decision logic) in accomplishing its goal
- The explanations of automation's process
- The difficulties or challenges to meeting the current goal, including failure of the automation

Operators also should have access to information about the situational context within which automation is functioning, including

- the conditions that indicate the automation is needed
- the conditions are appropriate for the automation's use
- the conditions for terminating automation

Information should be presented hierarchically to operators to support high-level status monitoring and detailed interaction, while simultaneously controlling the operator's workload, for example

- a hierarchy of displays at various "levels of abstraction" from high-level summary information to very detailed information
- top-level overview displays that afford broad overviews suitable for monitoring the plant
- detailed displays showing progressively more detailed information suitable for situation assessment should something be abnormal
- navigation aids to enable users to quickly and easily move from higher-level displays to lower-level displays in the hierarchy

The detailed design of the HSIs to automation should ensure status-at-a-glance functionality, i.e., the displays are readily and reliably interpreted with little cognitive workload. One way of accomplishing this is to employ EID principles to ensure accurate representational mapping, maximum use of integral- and configural-displays, and application of graphical features, such as emergent features, that that require little interpretation.

Multimodal displays, i.e., displays employing more than one information-processing channel, should be considered as a way to support situation awareness and minimize workload. Some success was found with verbal notifications.

Within the context of adaptive automation, the HSI should provide the operator with “set plays,” i.e., predetermined definitions of a set of roles and responsibilities of human and machine agents. This would heighten the operator’s understanding of automation and minimize the workload due to the changes in the automation’s configuration.

Operators must be able to query automation about the basis for its actions, whether they are control actions or decision making. The HSI should support the tracking, interpreting, and verifying of automation’s recommendations. When designing communication interfaces to automation, attention should be paid to the types of explanations provided, emphasizing the provision of ontological information at a minimum; i.e., information pertaining to “what” questions such as, what does this mean, what event led to this state, and what are its consequences.

In this section, we examined HSI design for automatic systems and determined that considerably less research has been conducted here than for other aspects of human-automation interaction, such as level of automation. Further, the work that was done focused predominantly on very general characteristics of HSI design, rather than specific approaches. More research is needed on HSI design approaches to human-automation interactions.

We offer one final conclusion about the design process. The technology of automation engendered a great deal of flexibility that affords operators many different types of involvement and interactions. Our characterization of automation revealed numerous dimensions, including LOA, functions, flexibility (adaptive automation), and modes that can be combined to design a particular automation application. How designers decide upon what combinations are appropriate is unclear. For example, current function-allocation methods do not address such decisions. Thus, additional research is needed on the “front-end” of an automation specification, that is, selecting what types of automation and what level of operator involvement to include.

6 REVIEW GUIDANCE DEVELOPMENT

We developed design review guidance from the findings and source materials discussed in Sections 3, 4, and 5 (see Figure 6-1). The methodology was conservative, in the sense that guidelines were formulated only for those aspects of display design that, in our interpretation, are supported directly by the literature or are derived from good HFE practices.

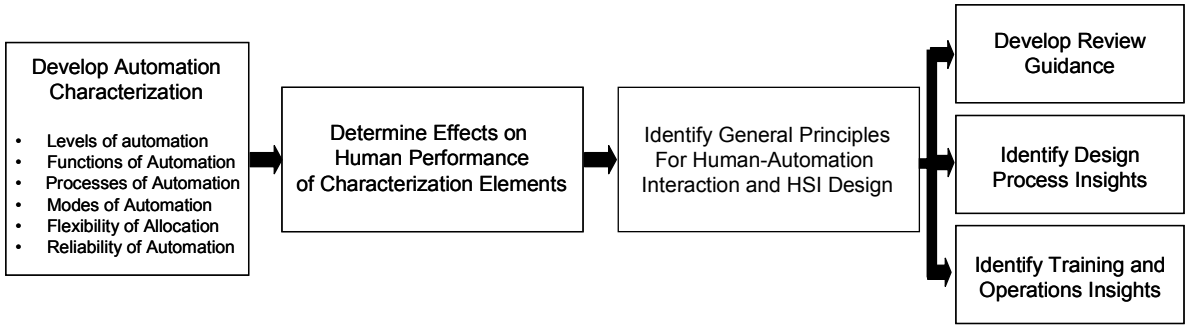


Figure 6-1 Development of review guidance

In characterizing automation, each dimension is addressed in the guidance except "functions of automation." This was not done because NUREG-0700 already has considerable guidance for most functions, and our review did not give us a basis for developing additional guides. The functions identified, and pertinent sections of NUREG-0700 include

- monitoring and detection (see NUREG-0700, Section 4 for review guidance for alarm systems)
- situation assessment (see NUREG-0700, Section 9 for review guidance for COSSs)
- response planning (see NUREG-0700, Section 8 for review guidance for CBPs)
- response implementation (see NUREG-0700, Section 7 for review guidance for soft controls)
- interface management

Presently, NUREG-0700 does not have guidance on automating interface management functions; however, the literature we reviewed did not give us a basis to develop new guidance. Thus, interface management automation continues to be a subject for research.

Our guidelines are organized into subsections, as shown in Figure 6-2.

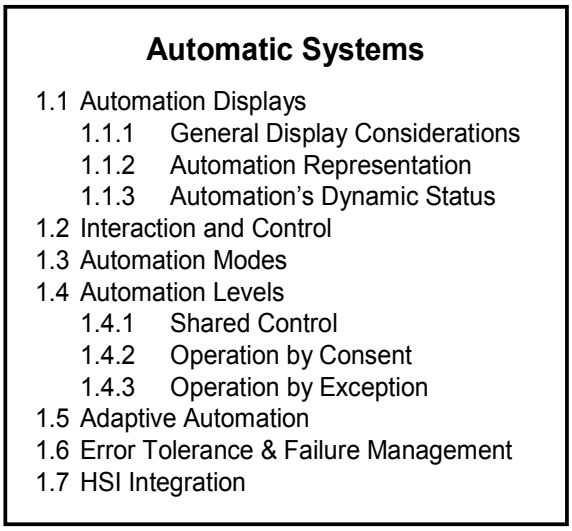


Figure 6-2 Organizational structure of HSI review guidance

We documented the review guidance in the standard format of NUREG-0700 (an example is presented in Figure 6-3):

- *Guideline Number* – Within sections/subsections, individual guidelines are numbered consecutively from 1 to n. Each guideline has a unique number that indicates its section/subsection location, followed by a dash, and then its serial number.
- *Guideline Title* – Each guideline has a unique, descriptive title.
- *Review Criterion* – Each guideline contains a statement of an HSI characteristic with which the reviewer may judge the HSI's acceptability. The criterion is not a requirement, and discrepant characteristics may be judged acceptable as per the procedures in the review process (see NUREG-0711, Section 11.4.2.3.2, HFE Design Verification Review Criteria, Criterion 2).
- *Additional Information* – For many guidelines, additional information is provided that may address clarifications, examples, exceptions, and details about measurements, figures, or tables. This information is intended to assist the reviewer in the interpreting or applying the guideline.
- *Source* - The source document(s) on which the guideline is based is shown in superscript. This typically is the number of the NUREG/CR or technical report. In the example in Figure 6-3, the number "91017" is used, but will be replaced with the number of this document when completed.

The review guidelines are contained in Part 2 of this report.

8.1.2-1 Overall Representation of an Automation System

The HSI should accurately represent automation and its plant interfaces.

Additional Information: Providing a representation of the automation and the aspects of the plant with which it interfaces helps operators to link the actions of automation to its goals for the plant itself. For example, if automation is maintaining a level in a tank that has a leak, so long as automation can pump water in, the level is achieved and operators may not know there is a problem. When the level can no longer be maintained, operators need to quickly determine whether the failure is in the automation or the controlled system. Offering an overall representation of both automation and its plant interfaces helps operators assess this situation.[91017]

Figure 6-3 Format of an HFE design review guideline

In addition, the technical basis provided insights into the process of automaton design, operator training, and operations that appear in Part 2 of this report. This information can be incorporated into NUREG-0700, Appendix B, Design Process Guidelines.[7] Appendix B contains design process and related considerations specific to HSI technology. Currently, Appendix B of NUREG-0700 has review guidance about the design of

- Information systems (Section B1)
- User interface interaction and management (Section B2)
- Computer-based procedure systems (Section B3)

[7] Note that this differs from the more general review guidance on the HFE programmatic-design process in NUREG-0711. NUREG-0711 does not cover design considerations for specific HSI technologies.

7 REFERENCES

AECB. (1994). *Errors in Software for Emergency Offsite Dose Estimation* (Significant Event Report 9492). Ottawa, Canada: Atomic Energy Control Board.

Ahlstrom, V., Longo, K., & Trui, T. (2002). *Human Factors Design Guideline Update (Report Number DOT/FAA/CT-96/01): A Revision to Chapter 5 – Automation Guidelines* (DOT/FAA/CT-02/11). Washington, DC: Federal Aviation Administration.

AREVA (2007a). *U.S.EPR Human Factors Engineering Program Topical Report* (ANP-10279, Rev. 0). Lynchburg, VA: AREVA NP Inc.

AREVA (2007b).*U.S. EPR Final Safety Analysis Report* (Rev 0). Lynchburg, VA: AREVA NP Inc.

Aviation Week (1995a). *Automated Cockpits Special Report, Part 1*. *142* (5), 52-65.

Aviation Week (1995b). *Automated Cockpits Special Report, Part 2*. *142* (6), 48-57.

Bahner, E., Elepfandt, M. & Manzey, D. (2008). Misuse of Diagnostic Aids in Process Control: The Effects of Automation Misses on Complacency and Automation Bias. In *Proceedings of the Human Factors and Ergonomics Society 52nd Annual Meeting*. Santa Monica, CA: Human Factors and Ergonomics Society.

Bahner, E., Huper, A. & Manzey, D (2008). Misuse of Automated Decision Aids: Complacency, Automation Bias and the Impact of Training Experience. *Int. J. Human-Computer Studies*, *66*, 688–699

Bainbridge, L. (1987). Ironies of Automation. In J. Rasmussen, K. Duncan, and J. Leplat (Eds.), *New Technology and Human Error* (pp. 271-283). New York: Wiley.

Beck, H., Dzindolet, M. & Pierce, L. (2007). Automation Usage Decisions: Controlling Intent and Appraisal Errors in a Target Detection Task. *Human Factors,* Vol. 49 (3), 429-437.

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

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

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

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

Bernard, J. & Washio, T. (1989a). *Expert Systems Applications Within the Nuclear Industry*. LaGrange Park, Illinois, American Nuclear Society.

Bernard, J., & Washio, T. (1989b). The Utilization of Expert Systems Within the Nuclear Industry. *1989 American Control Conference*, American Automatic Control Council.

Billings, C. (1991). *Human-centered Aircraft Automation: A Concept and Guidelines* (NASA Tech. Memo No. 103885). Washington, DC: NASA.

Billings, C. (1997a). *Aviation Automation: The Search for a Human-centered Approach*. Mahwah, NJ: Lawrence Erlbaum Associates, Inc.

Billings, C. (1997b). Some Questions about Advanced Automation. In M. Mouloua & J. Koonce (Eds.), *Human-automation Interaction: Research and Practice* (pp. 314-320). Mahwah, NJ: Lawrence Erlbaum Associates.

Burns, C., & Hajdukiewicz, J. (2004). *Ecological Interface Design*. Boca Raton, FL: CRC Press, Taylor & Francis.

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

Christoffersen, K., & Woods, D. (2002). How to Make Automated Systems Team Players. *Advances in Human Performance and Cognitive Engineering Research* (Vol. 2, pp. 1-12): Elsevier.

Cosenzo, K., Parasuraman, R., & Pillalamarri, K. (2008). The Effect of Task-Based Automation for the Control of Unmanned Systems on Operator Performance. In *Proceedings of the Human Factors and Ergonomics Society 52nd Annual Meeting*. Santa Monica, CA: Human Factors and Ergonomics Society.

Dekker, S., & Woods, D. (2002). MABA-MABA or abracadabra? Progress on human-automation co-ordination. *Cognition, Technology & Work*, *4*(4), 240 - 244.

De Visser, E., LeGoullon, M., Freedy, A., Freedy, E., Weltman, G., & Parasuraman. R. (2008). Designing an Adaptive Automation System for Human Supervision of Unmanned Vehicles: A Bridge from Theory to Practice. In *Proceedings of the Human Factors and Ergonomics Society 52nd Annual Meeting*. Santa Monica, CA: Human Factors and Ergonomics Society.

Di Noccera, F., Camilli, M., & Terenzi, M. (2007). Psychophysiological Correlates of Shifting Between Levels of Automation. In *Proceedings of the Human Factors and Ergonomics Society 51st Annual Meeting.* Santa Monica, CA: Human Factors and Ergonomics Society.

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

DoD (1999). *Department of Defense Design Criteria Standard: Human Engineering* (MIL-STD-1472F). Washington, DC: U.S. Department of Defense.

DoD (1996). *Human Engineering Requirements for Military Systems* (Mil-HDBK-46855). Washington, DC: U.S. Department of Defense.

Duez, P., & Jamieson, G. (2006). Toward Designing for Trust in Database Automation. *Proceedings of the 5th American Nuclear Society International Topical Meeting on Nuclear Plant Instrumentation, Controls, and Human Machine Interface Technology*. LaGrange Park, Illinois: American Nuclear Society.

Edwards, E. (1977). Automation in Civil Transport Aircraft. *Applied Ergonomics*, 8, 194-198.

Electric Power Research Institute (1993). *Guideline on Licensing Digital Upgrades* (EPRI TR-102348). Palo Alto, CA: Electric Power Research Institute.

Endsley, M. (1996). Automation and situation awareness. In R. Parasuraman and M. Mouloua (Eds.) *Automation and human performance: Theory and applications* (pp. 163-181). Mahwah, NJ: Lawrence Erlbaum

Endsley, M., & Kaber, D. (1999). Level of Automation Effects on Performance, Situation Awareness and Workload in a Dynamic Control Task. *Ergonomics*, 42(3), 462-492.

Endsley, M., & Strauch, B. (1997). Automation and situation awareness: The accident at Cali, Columbia. In R. Jensen & L. Rakovan (Eds.), *Proceedings of the Ninth International Symposium on Aviation Psychology* (pp. 877-881). Columbus, OH: Ohio State University.

Ephrath, A., & Young, L. (1981). Monitoring vs. Man-In-The-Loop Detection of Aircraft Control Failures. In *Human Detection and Diagnosis of System Failures*, Plenum Press: New York.

Ezer, N., Fisk, A., & Rogers W. (2005). The Effect of Perceived Consequence on Automation Reliance in a Human-automation Collaborative System. *Proceedings of the Human Factors and Ergonomics Society 49th Annual Meeting.* Santa Monica, CA: Human Factors and Ergonomics Society.

FAA (1996). *Human Factors Design Guide for the Acquisition of Commercial-off-the-Shelf Subsystems, Non-Development Items, and Developmental Systems* (DOT/FAA/CT-96/01). Washington, DC: Federal Aviation Administration.

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

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

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

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

Funk, K., & Lyall, B. (2000). *A Comparative Analysis of Flightdecks with Varying Levels of Automation.* Washington, DC: Federal Aviation Administration.

Furukawa, H., Inagaki, T., & Niwa, Y. (2000). Operator's situation awareness under different levels of automation; Evaluations through probabilistic human cognitive simulations. *IEEE Explore*, 1319-1324.

Garland, W. & Poehlman W. (1998). *Impact of Operator Aids on Human Factors and Organizational Structure*. Ottawa, Canada: Atomic Energy Control Board.

GE (1997). *ABWR Design Control Document* (Rev 4). San Jose, CA: GE Nuclear Energy.

GE-Hitachi (2008a). *ESBWR Human Factors Engineering Allocation of Function Implementation Plan* (NEDO-33220, Rev. 2). Wilmington, NC: GE Hitachi Nuclear Energy.

GE-Hitachi (2008b). *ESBWR Human Factors Engineering Human-System Interface Design Implementation Plan* (NEDO-33268, Rev. 3). Wilmington, NC: GE Hitachi Nuclear Energy.

GE-Hitiachi (2008c). *ESBWR Design Control Document* (Rev 5*)*. Wilmington, NC: GE Hitachi Nuclear Energy.

Gertman, D., Ostrum, L., Wilhelmsen, C., & Romero, H. (1994). *Methodologies for Assessing the Risk Impact of New Technologies,* (Tech. Report EGG-2740). Idaho Falls, ID: Idaho National Engineering Laboratory.

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

Goh, J., Weigmann, D., & Madhavan, P. (2005). Effects of Automation Failure in a Luggage Screening Task: A Comparison between Direct and Indirect Cueing. In *Proceedings of the Human Factors and Ergonomics Society 49th Annual Meeting.* Santa Monica, CA: Human Factors and Ergonomics Society.

Guerlain, S., Jamieson, G., Bullermer, P., & Blair, R. (2002). The MPC Elucidator: A Case Study in the Design for Human-Automation Interaction. *IEEE Transactions on Systems, Man and Cybernetics, Part A, Systems and Humans*, 32, 25-40.

Haynes, S., Cohen, M., & Ritter, F. (2009). Designs for explaining intelligent agents. *Int. J. Human-Computer Studies*, 67, 90–110.

Hollnagel, E. (1999). From Function Allocation to Function Congruence. In S. Dekker & E. Hollnagel (Eds.). *Coping with Computers in the Cockpit*. Aldershot, UK: Ashgate.

Hollnagel, E., & Woods, D. (2005). *Joint Cognitive Systems: Foundations of Cognitive Systems Engineering*. Boca Raton, FL: Taylor & Francis.

Huey, B., & Wickens, C. (1993). *Workload Transition: Implications for Individual and Team Performance*. Washington, D.C.: National Academy Press.

Hutchins, E. (1990). The Technology of Team Navigation. In J. Galegher, R. Kraut, & C. Egido (Eds.), *Intellectual Teamwork: Social and Technical Bases of Cooperative Work*. Hillsdale, NJ: Erlbaum.

IAEA (1991). *Safety Implications of Computerized Process Control in Nuclear Power Plants* (IAEA-TECDOC-581). Vienna: International Atomic Energy Agency.

IAEA (1993). *The Potential of Knowledge Based Systems in Nuclear Installations* (IAEA-TECDOC-700). Vienna: International Atomic Energy Agency.

IAEA (1995a). *Computerization of Operation and Maintenance for Nuclear Power Plants*. (IAEA-TECDOC-808). Vienna: International Atomic Energy Agency.

IAEA (1995b). *Control Room Systems Design for Nuclear Power Plants* (IAEA-TECDOC-812). Vienna: International Atomic Energy Agency.

IEC (2009). *Nuclear power plants – Control rooms – Design* (IEC 60964). Geneva, Switzerland: International Electrotechnical Commission.

IEEE (1998). *Standard for Application and Management of the Systems Engineering Process* (IEEE Standard 1220-1998). New York: Institute of Electrical and Electronics Engineers, Inc.

Inagaki, T. (2006). Design of human–machine interactions in light of domain–dependence of human–centered automation. *Cognition, Technology & Work, 8* (3),161-167.

ISO (2000). *Ergonomic Design of Control Centres* (ISO 11064). Geneva, Switzerland: International Standards Organization.

Ito, K., Hanada S., Yoshida, Y., & Sugino, K. (2006). Development of Emergency Operator Support System for Next Japanese PWR Plants. In *Proceedings of the 5th American Nuclear Society International Topical Meeting on Nuclear Plant Instrumentation, Controls, and Human Machine Interface Technology*. LaGrange Park, Illinois: American Nuclear Society.

Jamieson, G., & Vicente, K. (2005). Designing Effective Human-Automation-Plant Interfaces: A Control-Theoretic Perspective. *Human Factors,* 47 (1), 12-34.

Jian, J., Bisantz, A., & Drury, C. (2000). Foundations for an empirically determined scale of trust in automatic systems. *International Journal of Cognitive Ergonomic*s, *4*, 53-71.

Kaber, D., & Endsley, M. (2004). The Effects of Level of Automation and Adaptive Automation on Human Performance, Situation Awareness and Workload in a Dynamic Control Task. *Theoretical Issues in Ergonomics Science*, *5*(2), 113 - 153.

Kaber, D., Riley, J., & Tan, K. (2002). Improved usability of aviation automation through direct manipulation and graphical user interface design. *Intl. Journal of Aviation Psychology* 12(2), 153-178.

Kaber, D., Riley, J., Tan, K., & Endsley, M. (2001). On the design of adaptive automation for complex systems. *International Journal of Cognitive Ergonomics*, 5(1), 37-57.

Kaber, D., Wright, M., Prinzel III, L., & Clamann, M. (2005). Adaptive Automation of Human-Machine System Information-Processing Information. *Human Factors, 47* (4), 730-741.

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

Kawai, K., Takizawa, Y., & Watanabe, S. (1999). Advanced Automation for Power-Generation Plants - Past, Present and Future. *Control Engineering Practice*, *7*, 1405-1411.

Kibble, M. (1988). Information Transfer from Intelligent EW Displays. *Proceedings of the Human Factors Society - 32nd Annual Meeting*. Santa Monica, CA: Human Factors Society.

Klein, G., Woods, D., Bradshaw, J., Hoffman, R., & Feltovich, P. (2004). Ten Challenges for Making Automation a "Team Player" in Joint Human-agent Activity. *IEEE Intelligent Systems*, *19*(6), 91-95.

Klein, G., Feltovich, P., Bradshaw, J., & Woods, D. (2005). Common Ground and Coordination in Joint Activity. In W. Rouse & K. Boff (Eds.), *Organizational simulation*. New York: Wiley.

Kletz, T. (1993). Computer Control - Living with Human Error. *Reliability Engineering and System Safety*, *39,* 257-261.

Lacson, F., Weigmann, D., & Madhaven, P. (2005). Effects of Attribute and Goal Framing on Automation Reliance and Compliance. In *Proceedings of the Human Factors and Ergonomics Society 49th Annual Meeting.* Santa Monica, CA: Human Factors and Ergonomics Society.

Land, S., Malin, J., Thronesberry, C., & Schreckenghost, D. (1995). *Making Intelligent Systems Team Players: A Guide to Developing Intelligent Monitoring Systems* (NASA Technical Memorandum 104807). Houston, Texas: National Aeronautics and Space Administration.

Lee, J. (2008). Review of a Pivotal Human Factors Article: Humans and Automation: Use, Misuse, Disuse, Abuse. *Human Factors, 50* (3), 404-410.

Lee, J. (2006). Human Factors and Ergonomics in Automation Design. In G. Salvendy (Ed.), *Handbook of Human Factors and Ergonomics* (3rd Ed.). New York, NY: John Wiley & Sons, Inc.

Lee, J., & See, K. (2004). Trust in Automation: Designing for Appropriate Reliance. *Human Factors,* 46 (1), 50-80.

Lee, S., & Seong, P. (2006). Human-centered HMI Design to Support Cognitive Process of Operation in Nuclear Power Plants. In *Proceedings of the 5th American Nuclear Society International Topical Meeting on Nuclear Plant Instrumentation, Controls, and Human Machine Interface Technology.* LaGrange Park, Illinois: American Nuclear Society.

Linegang, M., Stoner, H., Patterson, M., Seppelt, B., Hoffman, J., & Crittendon, Z. (2006). Human-automation Collaboration in Dynamic Mission Planning: A Challenge Requiring an Ecological Approach. In *Proceedings of the Human Factors and Ergonomics Society 50th Annual Meeting.* Santa Monica, CA: Human Factors and Ergonomics Society.

Liu, Q., Nakata K., & Furuta K. (2002). Display Design of Process Systems Based on Functional Modeling. *Cognition, Technology & Work*, *4*, 48–63.

Liu, Q., Nakata K., & Furuta K. (2004). Making control systems visible. *Cognition, Technology & Work*, *6*, 87–106.

Lorenz, B., Di Nocera, F., Röttger, & Parasuraman, R. (2001). The Effects of Level of Automation on the Out-of-the-Loop Unfamiliarity in a Complex Dynamic Fault-Management Task during Simulated Spaceflight Operations. In *Proceedings of the Human Factors and Ergonomics Society 45th Annual Meeting.* Santa Monica, CA: Human Factors and Ergonomics Society.

Lyall, B., & Funk, K. (1998). Flight Deck Automation Issues. In M. Scerbo & M. Mouloua (Eds.) *Proceedings of the Third Conference on Automation Technology and Human Performance*. (pp. 288-292). Mahwah, NJ: Lawrence Erlbaum Associates.

Madhavan, P., & Weigmann, D. (2005). Effects of Information Source, Pedigree, and Reliability on Operators' Utilization of Diagnostic Advice. In *Proceedings of the Human Factors and Ergonomics Society 49th Annual Meeting.*

Madhaven, P., Wiegmann, D., & Lacson, F. (2006). Automation Failures on Tasks Easily Performed by Operators Undermine Trust in Automated Aids. *Human Factors, 48* (2), 241-256.

Malin, J. (2000) Preparing for the Unexpected: Making Remote Autonomous Agents Capable of Interdependent Teamwork. *Proceedings of the Human Factors Society – 44th Annual Meeting*. Santa Monica, CA: Human Factors Society.

Malin, J. & Schreckenghost, D. (1992). *Making Intelligent Systems Team Players: Overview for Desigers*. (NASA Technical Memorandum 104751). Houston, Texas: National Aeronautics and Space Administration.

Malin, J., Schreckenghost, D., Woods, D., Potter, S., Johannesen, L., Holloway, M., & Forbus, K., (1991a). *Making Intelligent Systems Team Players: Case Studies and Design Issues. Volume 1: Human-Computer Interaction Design*. (NASA Technical Memorandum 104738). Houston, Texas: National Aeronautics and Space Administration.

Malin, J., Schreckenghost, D., Woods, D., Potter, S., Johannesen, L., & Holloway, M. (1991b). *Making Intelligent Systems Team Players: Case Studies and Design Issues. Volume 2: Fault Management System Cases* (NASA Technical Memorandum 104738). Houston, Texas: National Aeronautics and Space Administration.

Manzey, D., Bahner, J., & Hueper, A. (2006). Misuse of Automated Aids in Process Control: Complacency, Automation Bias and Possible Training Interventions. In *Proceedings of the Human Factors and Ergonomics Society 50th Annual Meeting.* Santa Monica, CA: Human Factors and Ergonomics Society.

Manzey, D., Reichenbach, J., & Onnasch, L. (2008). Performance Consequences of Automated Aids in Supervisory Control: The Impact of Function Allocation. In *Proceedings of the Human Factors and Ergonomics Society 52nd Annual Meeting*. Santa Monica, CA: Human Factors and Ergonomics Society.

McGarry, K., Rovira, E., & Parasuraman, R., (2005). Adaptive Change in the Type of Automation Support Reduces the Cost of Imperfect Decision Aids in a Simulated Battlefield

Engagement Task. In *Proceedings of the Human Factors and Ergonomics Society 49th Annual Meeting.* Santa Monica, CA: Human Factors and Ergonomics Society.

McGuirl J., & Sarter, N. (2006). Supporting Trust Calibration and the Effective Use of Decision Aids by Presenting Dynamic System Confidence Information. *Human Factors*, *48* (4), 656–665.

Merritt, S., & Ilgen, D. (2008). Not All Trust is Created Equal: Dispositional and History-Based Trust in Human Automation Interactions. *Human Factors, 50* (2), 194-210.

Metzger, U., & Parasuraman, R. (2005). Automation in Future Air Traffic Management: Effects of Decision Aid Reliability on Controller Performance and Mental Workload. *Human Factors, 47* (1), 35-49.

Meyer, J., Feinshreiber, L., & Parmet, Y. (2003). Levels of automation in a simulated failure detection task. *Systems, Man and Cybernetics, IEEE International Conference*, *3*, pp. 2101-2106.

Miller, C. (2005). Levels of Automation in the Brave New World: Adaptive Autonomy, Virtual Presence and Swarms—Oh My! In *Proceedings of the Human Factors and Ergonomics Society 49th Annual Meeting.* Santa Monica, CA: Human Factors and Ergonomics Society.

Miller, C., Funk, H., Wu, P., Goldman, R., Meisner, J., & Chapman, M. (2005). The Playbook™ Approach to Adaptive Automation. In *Proceedings of the Human Factors and Ergonomics Society 49th Annual Meeting.* Santa Monica, CA: Human Factors and Ergonomics Society.

Miller, C., & Parasuraman, R. (2007). Designing for Flexible Interaction Between Human and Automation: Delegation Interfaces for Supervisory Control. *Human Factors,* 49 (1), 57-75.

Miller, C. & Parasuraman, R. (2003). Beyond levels of Automation: An Architecture for More Flexible Human-Automation Collaboration. In *Proceedings of the Human Factors and Ergonomics Society 47th Annual Meeting.* Santa Monica, CA: Human Factors and Ergonomics Society.

Mitsubishi, (2008). *Design Control Document for the US-APWR* (Rev 1).

Mosier, K., Sethi, N., McCauley, S., Khoo, L., & Orasanu, J. (2007). What You Don't Know Can Hurt You: Factors Impacting Diagnosis in the Automated Cockpit. *Human Factors, 49* (2), 300-310.

NAS (1995). *Digital Instrumentation and Control Systems in Nuclear Power Plants: Safety and Reliability Issues*. Washington, D. C.: National Academy Press.

Nikolic, M., & Sarter, N. (2007). Flight Deck Disturbance Management: A Simulator Study of Diagnosis and Recovery from Breakdowns in Pilot-Automation Coordination. *Human Factors, 49* (4), 553-563.

Niwa, Y. Terabe, M., & Washio T. (1999). Autonomous Recovery Execution in Nuclear Power Plant by the Agent. *Cognition, Technology & Work*, *1*, 197-210.

Norman, D. (1990). The 'Problem' of Automation: Inappropriate Feedback and Interaction, not 'Over-automation.'. *Philosophical Transactions of the Royal Society of London, B*, *327*, 585–593.

NRC (2007). *Standard Review Plan* (NUREG-0800); Chapter 18, *Human Factors Engineering*. Washington, D.C.: U.S. Nuclear Regulatory Commission.

NRC (1993). *NRC Information Notice 93-57: Software Problems Involving Digital Control Console Systems at Non-power Reactors*. Washington, D.C.: Nuclear Regulatory Commission.

NRC (1980). *Containment Cooler Leaks and Reactor Cavity Flooding at Indian Point Unit 2, Oct. 24, 1980* (Information Notice No. 80-37). Washington, D.C.: Nuclear Regulatory Commission.

Oduor, K., & Wiebe E. (2008). The Effects of Automated Decision Algorithm Modality and Transparency on Reported Trust and Task Performance. In *Proceedings of the Human Factors and Ergonomics Society 52nd Annual Meeting*. Santa Monica, CA: Human Factors and Ergonomics Society.

O'Hara, J. (1998). *The Development of HFE Design Review Guidance for Hybrid Human-System Interfaces* (BNL Letter Report J6012-T6-12/98). Upton, New York: Brookhaven National Laboratory.

O'Hara, J., & Brown, W. (1999). Alarm Systems. In J. Webster (Ed.) *Encyclopedia of Electrical and Electronics Engineering*. New York: John Wiley & Sons.(pp. 392-402).

O'Hara, J. & Brown, W. (2002). *The Effects of Interface Management Tasks on Crew Performance and Safety in Complex, Computer-based Systems*. (NUREG/CR-6690). Washington, D.C.: U.S. Nuclear Regulatory Commission.

O'Hara, J., Brown, W., Higgins, J., & Stubler, W. (1994). *Human Factors Engineering Guidelines for the Review of Advanced Alarm Systems* (NUREG/CR-6105). Washington, D.C.: U.S. Nuclear Regulatory Commission.

O'Hara, J., Brown, W., Lewis, P., & Persensky, J. (2002). *Human-system Interface Design Review Guidelines* (NUREG-0700, Rev 2). Washington, D.C.: U.S. Nuclear Regulatory Commission.

O'Hara, J., Higgins, J., Brown, W., & Fink, R. (2008b). *Human Factors Considerations with Respect to Emerging Technology in Nuclear Power Plants: Detailed Analysis* (BNL Technical Report No: 79947-2008). Upton, NY: Brookhaven National Laboratory.

O'Hara, J., Higgins, J., Brown, W. & Fink, R., Persensky, J., Lewis, P., Kramer, J., Szabo, A., & Boggi, M. (NRC) (2008a). *Human Factors Considerations with Respect to Emerging Technology in Nuclear Power Plants* (NUREG/CR-6947). Washington, D.C.: U. S. Nuclear Regulatory Commission.

O'Hara, J., Higgins, J., & Kramer, J. (2000). *Advanced Information Systems: Technical Basis and Human Factors Review Guidance* (NUREG/CR-6633). Washington, D.C.: U.S. Nuclear Regulatory Commission.

O'Hara, J., Higgins, J., Stubler, W., & Kramer, J. (2000). *Computer-based Procedure Systems: Technical Basis and Human Factors Review Guidance* (NUREG/CR-6634). Washington, D.C.: U.S. Nuclear Regulatory Commission.

O'Hara, J., Higgins, J., Persensky, J., Lewis, P., & Bongarra, J. (2004). *Human Factors Engineering Program Review Model* (NUREG-0711, Rev. 2). Washington, D.C.: U.S. Nuclear Regulatory Commission.

O'Hara, J., & Roth, E. (2005). Operational Concepts, Teamwork, and Technology in Commercial Nuclear Power Stations. In C. Bowers, E. Salas, & F. Jentsch (Eds.) *Creating High-Tech Teams: Practical Guidance on Work Performance and Technology*. Washington, DC: American Psychological Association.

O'Hara, J., Stubler, W., & Higgins, J. (1996). *Hybrid Human-system Interfaces: Human Factors Considerations* (BNL Report J6012-T1-4/96). Upton, New York: Brookhaven National Laboratory.

Olson, W., & Sarter, N. (2001). Management by consent in human-machine systems: When and why it breaks down. *Human Factors*, *43*, 255-266.

Parasuraman, R. (2000). Designing automation for human use: empirical studies and quantitative models. *Ergonomics* 43 (7), 931-951.

Parasuraman, R., Galster, S., Squire, P., Furukawa, H., & Miller, C. (2005). A Flexible Delegation-type Interface Enhances System Performance in Human Supervision of Multiple Robots: Empirical Studies with RoboFlag. *IEEE Transactions on Systems, Man, and Cybernetics—Part A: Systems and Humans,* 35 (4) x-y.

Parasuraman, R., & Riley, V. (1997). Humans and Automation: Use, Misuse, Disuse, Abuse. *Human Factors*, *39* (2), 230-253.

Parasuraman, R., Sheridan, T. B., & Wickens, C. D. (2000). A Model for Types and Levels of Human Interaction with Automation. *IEEE Transactions on Systems, Man, and Cybernetics*, *30*(3), 286-297.

Piccini, M. (2002). Human Factors in the Design of Supervisory Control Systems and Human–Machine Interfaces for Highly Automated Complex Systems. *Cognition, Technology & Work*, *4*, 256–271.

Pirus, D. (2004a). How a Functional Approach Allow to Set an On-Line Flexible Level of Automation for NPP's Computerized Operation. In the *Proceedings of the ANS International Meeting on Instrumentation, Control, and Human Machine Interface Technology*. La Grange Park, Illinois: American Nuclear Society.

Pirus, D. (2004b). Functional HSI For Computerised Operation. In the *Proceedings of the ANS International Meeting on Instrumentation, Control, and Human Machine Interface Technology*. La Grange Park, Illinois: American Nuclear Society, Inc.

Price, H. (1982). *The Allocation of Functions in Man-Machine Systems: A Perspective and Literature Review* (NUREG/CR-2623). Washington, D.C.: Nuclear Regulatory Commission.

Price, H. (1985). The Allocation of Functions in Systems. *Human Factors*, 27 (1), 33-45.

Prinzel III, L. (2003). *Team-Centered Perspective for Adaptive Automation Design* (NASA/TM-2003-212154). Hanover, MD: NASA Center for AeroSpace Information.

Progner, B., & Meizer, C. (1978). On Line Power Plant Alarm and Disturbance Analysis System (EPRI Report NP-615). Palo Alto, CA: Electric Power Research Institute.

Ranson, D., & Woods, D. (1996b). Animating Computer Agents. In *Proceedings of the 3rd Symposium on Human Interaction with Complex Systems*. NY: IEEE.

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

Reed, J., Hogg, D., & Hallbert, B. (1995). An Evaluation of an On-Line expert System in Nuclear Process Control. *Proceedings of the Topical Meeting on Computer-Based Human Support Systems: Technology, Methods, and Future*. La Grange Park, Illinois.

Rice, S., Hughes, J., McCarley, J., & Keller, D. (2008). Automation Dependency and Performance Gains Under Time Pressure. In *Proceedings of the Human Factors and Ergonomics Society 52nd Annual Meeting*. Santa Monica, CA: Human Factors and Ergonomics Society.

Riera B. (2001). Specifications, Design and Evaluation of an Advanced Human-Adapted Supervisory System. *Cognition, Technology & Work*, *3*, 53–65.

Roberts, S., & Parush, A. (2007). A Dynamic Model Balancing User Control and Workload In Automatic and Adaptive Systems. In *Proceedings of the Human Factors and Ergonomics Society 51st Annual Meeting.* Santa Monica, CA: Human Factors and Ergonomics Society.

Rook, F., & McDonnell, M. (1993). Human Cognition and the Expert System Interface: Mental Models and Inference Explanations. *IEEE Transactions on Systems, Man, and Cybernetics. 23* (6), 1649-1661.

Ross, J., Szalma, J., Hancock, P., Barnett, J., & Taylor, G. (2008). The Effect of Automation Reliability on User Automation Trust and Reliance in a Search-And- Rescue Scenario. In *Proceedings of the Human Factors and Ergonomics Society 52nd Annual Meeting*. Santa Monica, CA: Human Factors and Ergonomics Society.

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

Roth, E., Hanson, M., Hopkins, C., Mancuso, V., & Zacharias, G. (2004). Human in the Loop Evaluation of a Mixed-initiative System for Planning and Control of Multiple UAV Teams. In *Proceedings of the Human Factors and Ergonomics Society 48th Annual Meeting.* Santa Monica, CA: Human Factors and Ergonomics Society.

Roth, E. & O'Hara, J. (2002). *Integrating digital and conventional human system interface technology: Lessons learned from a control room modernization program*. (NUREG/CR-6749). Washington, D.C.: U.S. Nuclear Regulatory Commission.

Rovira, E., McGarry, K., & Parasuraman, R. (2007). Effect of Imperfect Automation on Decision Making in a Simulated Command and Control Task. *Human Factors,* 49 (1), 77-87.

Ryser, C. (2003). Degree of Automation: Influence on Control Strategies and Mental Representations. Paper presented at the *8th Spymposium on Automated Systems Based on Human Skill and Knowledge, IFAC,* Göteberg, Sweden.

Salvendy, G. (2006). *Handbook of Human Factors and Ergonimics (3rd Ed.)*. New York, NY: John Wiley and Sons.

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

Sarter, N., Mumaw, R., & Wickens, C. (2007). Pilot's Monitoring Strategies and Performance on Automated Flight Decks: An Empirical Study Combining Behavioral and Eye-Tracking Data. *Human Factors, 49* (3), 347-357.

Sarter, N., & Woods, D. (1995). From Tool to Agent: The Evolution of (cockpit) Automation and its Impact on Human-machine Coordination. In *Proceedings of the Human Factors and Ergonomics Society 39th Annual Meeting*. Santa Monica, CA: Human Factors and Ergonomics Society.

Sarter, N., & Woods, D. (1992). Pilot Interaction with Cockpit Automation I: Operational Experiences with the Flight Management System. *International Journal of Aviation Psychology* 2(4), 303-321.

Sexton, G. (1988). Cockpit-Crew Systems Design and Integration. *Human Factors in Aviation*. New York, NY: Academic Press.

Sheridan, T. (2002). *Humans and Automation: System Design and Research Issues*. New York: Wiley & Sons.

Sheridan, T. (1992). *Telerobotics, Automation, and Human Supervisory Control*. Cambridge, Massachusetts: The MIT Press.

Skitka, I. Mosier, K., & Burdick, M. (1999). Does automation bias decision-making? *Int. J. Human-Computer Studies, 51*, 991-1006.

Skjerve, A., Nihlwing, C., & Nystad, E. (2008). *Lessons Learned from the Extended Teamwork Study* (HWR-867). Halden, Norway: OECD Halden Reactor Project, Institute for Energy Technology.

Skjerve, A., & Skraaning, G. (2004a). The quality of human-automation co-operation in human-system interface for nuclear power plants. *International Journal of Human-Computer Studies*, 61, 649-677

Skjerve, A., & Skraaning, G. (2004b). *The Quality of Human-Automation Co-operation as Assessed by Nuclear Power Plant Operators When Working with Two Human-Machine Interfaces that Presents Information on the Automatic System's Activity Differently* (HWR-). Halden, Norway: OECD Halden Reactor Project, Institute for Energy Technology.

Skjerve, A., Strand, S., & Saarni, R. (2002). Human-centered automation–Experimental Studies of Two Human-machine Interface Designs. In *Proceedings of the 2000 IEEE Conference on Human Factors and Power Plants*. NY, NY: IEEE

Spain, R., Bustamante, E., & Bliss, J. (2008). Toward an Empirically Developed Scale for System Trust: Take Two. In *Proceedings of the Human Factors and Ergonomics Society 52nd Annual Meeting*. Santa Monica, CA: Human Factors and Ergonomics Society.

Strauch, B. (1997). Automation and Decision-Making – Lessons From the Cali Accident. In *Proceedings of the Human Factors and Ergonomics Society 41st Annual Meeting*, pp 195-199.

Stubler, W., Higgins, J., & O'Hara, J. (1996). *Evaluation of the Potential Safety Significance of Hybrid Human-System Interface Topics* (BNL Letter Report J6012-T2-6/96). Upton, New York: Brookhaven National Laboratory.

Terry, P. (1989). A Layman's Guide to Expert Systems. *Power Engineering*, September, 52-55.

Thurman, D., Brann, D., & Mitchell, C. (1977). An Architecture to Support Incremental Automation of Complex Systems. In *Proceedings of the 1997 IEEE International Conference on Systems, Man, and Cybernetics*, Orlando, FL.

Uhrig, R. (1994). Artificial Neural Networks in Nuclear Power Plants. *Nuclear News 37* (9), 38-40.

Uhrig, R., Gao, R., & Tsoukalas, L. (2004). Use of Multi-agents to Improve Efficiency and Safety of Nuclear Power Plants. In *Proceedings from the Fourth American Nuclear Society Meeting on Nuclear Plant Instrumentation, Controls and Human-Machine Interface Technologies.* LaGrange Park, Illinois: American Nuclear Society.

Vicente, K. (1999). *Cognitive Work Analysis: Towards safe, productive, and healthy computer based work.* Mahweh, NJ: Lawrence Erlbaum & Associates.

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

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

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

Wang, L., Jamieson, G., & Hollands, J. (2008b). Improving Reliability Awareness to Support Appropriate Trust and Reliance on Individual Combat Identification Systems. In *Proceedings of the Human Factors and Ergonomics Society 52nd Annual Meeting*. Santa Monica, CA: Human Factors and Ergonomics Society.

Westinghouse (2008). *AP1000 Design Control Document* (APP-GW-GL-700). Pittsburgh, PA: Westinghouse Electric Company LLC.

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

Wickens, C., & Hollands J. (2000). *Engineering Psychology and Human Performance* (3rd ed). Upper Saddle River, NJ: Prentice-Hall Inc.

Wickens, C., & Kessel, C. (1981). The Detection of Dynamic System Failures. *Human Detection and Diagnosis of System Failures*. New York, NY: Plenum Press.

Wiener, E. (1989). *Human Factors of Advanced Technology ("Glass Cockpit") Transport Aircraft* (NASA Report 177528). Moffett Field, CA.: National Aeronautics and Space Administration.

Wiener, E., & Curry, R. (1980). Flight-deck Automation: Promises and Problems. *Ergonomics*, *23*(10), 995-1011.

Wilhelmsen, C. (1992). Reviewing the Impact of Advanced Control Room Technology. In *1992 IEEE Conference on Human Factors and Power Plants*. New York: IEEE.

Willems, B., & Heiney M. (2002). *Decision Support Automation Research in the En Route Air Traffic Control Environment* (DOT/FAA/CT-TN02/10). Washington, DC.: Federal Aviation Administration.

Wood, R., Antonescu, C., Arndt, S., Britton, C., Brown-VanHoozer, S. Calvert, J. Damiano, B., Easter, J., Freer, M. , Mullens, J., Neal, J., Protopopescu,V., Shaffer, R., Schryver, J., Smith, C. Tucker, R., Uhrig, R., Upadhyaya, B., Wetherington, G., Wilson, T., White, J., & Whitus, B. (2003). *Emerging Technologies in Instrumentation and Controls* (NUREG/CR-6812). Washington, D.C.: U.S. Nuclear Regulatory Commission.

Woods, D. (2005). Generic Support Requirements for Cognitive Work: Laws that Govern Cognitive Work in Action. In *Proceedings of the Human Factors and Ergonomics Society 49th Annual Meeting.* Santa Monica, CA: Human Factors and Ergonomics Society.

Woods, D., & Hollnagel, E. (2006). *Joint Cognitive Systems*. Boca Raton, FL: CRC Press, Taylor & Francis.

Woods, D., Johannesen, L., Cook, R., & Sarter, N. (1994). *Behind Human Error: Cognitive Systems, Computers, and Hindsight* (CSERIAC SOAR 94-01). Wright Patterson Air Force Base, Ohio: Crew Systems Ergonomics Information Analysis Center.

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

Woods, D. ,& Sarter, N. (2000). Learning from Automation Surprises and going sour accidents. In N. Sarter & R. Amalberti, (Eds.). *Cognitive Engineering in the Aviation Domain*. Hillside, NJ: Lawrence Erlbaum.

Wright, M., & Kaber, D. (2005) Effects of Automation of Information-Processing Functions on Teamwork. *Human Factors,* 47 (1), 50-66.

Yenn, T., Hwang, S., Huang, F., Yu, Y., Hsu, C., & Huang, H. (2006). A Study of Reset Mode in Advanced Alarm System Simulator. In *Proceedings of the 5th American Nuclear Society International Topical Meeting on Nuclear Plant Instrumentation, Controls, and Human Machine Interface Technology.* LaGrange Park, Illinois: American Nuclear Society.

Part 2:

Guidelines for the Review of HSIs to Automatic Systems

8 HSI DESIGN REVIEW GUIDELINES

Automatic Systems

Sheridan (2002, p. 9) defined of automation as (a) the mechanization and integration of the sensing of environmental variables (by artificial sensors); (b) data processing and decision making (by computers); and, (c) mechanical action (by motors or devices that apply forces in the environment) or information action by communication of processed information to people. At the simplest level, an automation system is designed to accomplish a goal that can be predetermined by designers or set by operators, based on their current needs. The automatic system processes inputs from the plant and operators inputs to meet the goal (Figure 8-1). Since automation is applicable many aspects of the plant's operations, from analyzing procedural steps to controlling the plant's systems, the specific processes used to accomplish automation's goal vary depending on its particular usage.

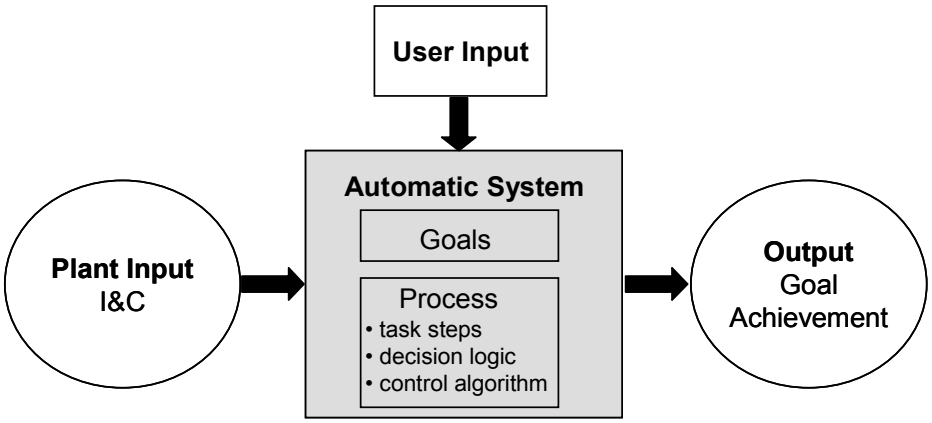


Figure 8-1 Overview of an automation system

Six dimensions characterize NPP automation:

- Levels of Automation
- Functions of Automation
- Process of Automation
- Modes of Automation
- Flexibility of Allocation
- Reliability of Automation

Levels of Automation

In older systems, the allocation of responsibilities to perform functions was fairly straightforward: Functions were either automated (i.e., performed essentially without human involvement), or manual (i.e., completed by plant personnel without automation). However, as computers have become more involved in process control, the nature of automation has changed. More recent approaches involve cooperation and sharing of responsibilities between automatic systems and plant personnel. In this section, we discuss this changing concept of automation. Increasingly, intermediate levels of automation are being implemented, such that there is a continuum from manual operation to automatic operation, wherein the relative responsibilities of humans and automation in carrying out tasks varies. This often is referred to as "levels of automation."

Table 8-1 illustrates the levels of automation for NPP applications and identifies the general responsibilities of both automation and personnel. Since NPP systems often are complex, sometimes they are characterized at one level, and, at other times another level is appropriate.

Table 8-1 Levels of Automation for NPP Applications

Level	Automation Functions	Human Functions
1. Manual Operation	No automation	Operators manually perform all functions and tasks
2. Shared Operation	Automatic performance of some functions or tasks	Manual performance of some functions/tasks
3. Operation by Consent	Automatic performance when directed by operators to do so, under close monitoring and supervision	Operators monitor closely, approve actions, and may intervene to provide supervisory commands that automation follows
4. Operation by Exception	Essentially autonomous operation unless specific situations or circumstances are encountered	Operators must approve of critical decisions and may intervene
5. Autonomous Operation	Fully autonomous operation. System or function cannot normally be disabled, but may be started manually	Operators monitor performance and perform backup if necessary, feasible, and permitted

Functions of Automation

The first thing to come to mind in considering automation, is automating a control function. The Sheridan and Billings frameworks discussed in Part 1 mainly focused on control functions. However, the scope of modern automation extends well beyond them, and includes both primary- and interface management-tasks (see Figure 8-2). Each is described below:

- *Monitoring and detection* refer to the activities involved in extracting information from the environment. Monitoring is checking the state of the plant to determine whether it is operating correctly, including checking parameters indicated on the control panels, monitoring those displayed on a computer screen, obtaining verbal reports from other personnel, and sending operators to areas of the plant to check on equipment. An alarm system is an example of automation applied to monitoring and detection (NUREG-0700, Section 4 has review guidance for alarm systems).
- *Situation assessment* is evaluating current conditions to assure their acceptability or determining the underlying causes of any abnormalities. An example of automation applied to situation assessment is a computerized operator-support system (NUREG-0700, Section 9 has for review guidance for COSSs).
- *Response planning* refers to deciding upon a course of action to address the current situation. In an NPP, procedures usually aid response planning. When operators judge available procedures as appropriate to the current situation, the need to generate a response plan in real-time largely may be eliminated. However, even with good procedures, some aspects of response planning will be undertaken. An example of automation applied to response planning is a computer-based procedure (CBP) system (NUREG-0700, Section 8 gives review guidance for CBPs).

- *Response implementation* is undertaking the actions specified by response planning. They include selecting a control, providing control input, and monitoring the responses of the system and process. An example of automation applied to implementing a response is an automatic safety system, such as soft controls (NUREG-0700, Section 7 contains for review guidance for soft controls).
- *Interface management* encompasses activities such as navigating or accessing information at workstations and arranging various pieces of information on the screen. An example of applying automation to interface management is the automatic identification of a display appropriate to the ongoing situation, e.g., the identification of an emergency-procedure display upon detecting any of the procedures entry conditions. In this context, the HSI would notify the operator of the availability of the display, such as by a blinking icon at the bottom of the screen, rather than disrupting the operator's ongoing activity by obtrusively showing the display.

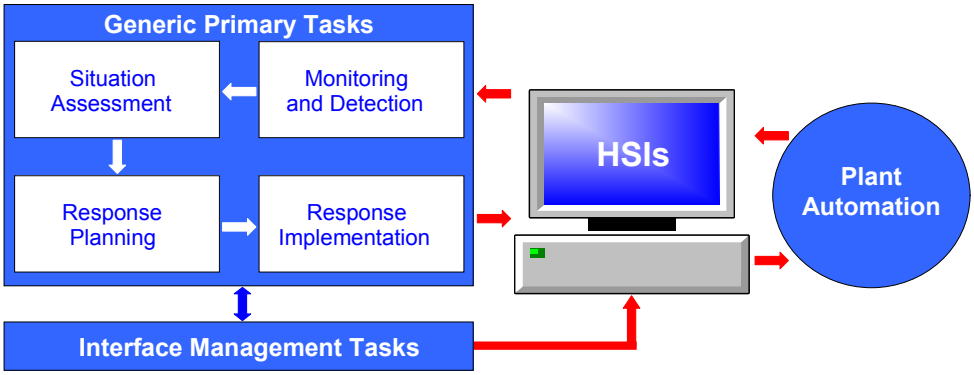


Figure 8-2 Generic primary tasks performed by plant personnel

Processes of Automation

As noted in the introduction, automation uses input from the plant (and perhaps the operator) and processes the information to accomplish a goal. These processes are an important aspect of automation in that they are the means by which automation performs its tasks. Automation processes can include control algorithms, decision logic (such as the use of Boolean logic), and virtually any other type of information processing routine suited to its tasks.

Modes of Automation

Automated systems may have different modes of operation. Modes define sets of mutually exclusive behaviors that describe the relationship between input to the automation and the response to it (Jamieson & Vicente, 2005). A system can have multiple modes, but only one is active at a time. Modes do not imply differing levels of automation; rather, they involve performing the same function in different ways. Modes are beneficial in providing the capacity for a system to do different tasks, or to accomplish the same task using different strategies under changing conditions.

A GPS device is a simple example of modes. After the user specifies a destination, the GPS device automatically plans the best route. Users can select the driving mode, or the pedestrian mode. In a city environment where there are many one-way streets, the route suggested by each mode may be completely different. In driving mode, the one-way streets constrain the

route selected; in pedestrian mode, one-way streets have no impact on the route selected. Thus, the task is the same, but the solution depends on the mode selected.

The Reactor Mode switch in a BWR similarly changes various automatic features.

Flexibility of Allocation

A system can be designed such that the human or machine agent responsible for performing a task always is the same, the so-called static allocation. Alternatively, a task can be performed either by automatic systems or by personnel based on situational considerations, such as the operator's overall workload. For example, automation may assume control over lower priority tasks when the operator's workload increases to a level where all the current work becomes difficult to complete. This approach ensures that operators can focus their attention on high-priority tasks because their workload levels remain within acceptable limits. A simple example is alarm reset above, during a major plant disturbance when workload is very high and many alarms are coming in, operators can reallocate the alarm- reset task from manual to automatic. When tasks can be flexibly performed by human or machine agents, the automation is said to be adaptive.

A key consideration for adaptive automatic systems is the "triggering" condition; i.e., the condition that causes the adaptive automation shift. The triggering conditions include

- operator's judgment, that is, the operator decides a shift is necessary
- operator factors, such as psycho-physiological measures, dynamic workload assessment, and task-performance measures
- critical events or setpoint(s) based on measured parameter(s)

Reliability of Automation

The final dimension of automation is reliability. All engineered systems have less than perfect reliability. Automatic systems can fail in whole or in part and thus compromise their ability to achieve their intended function. When an automatic system has a simple, well-defined task to accomplish, its reliability is easy to quantify, e.g., as the probability the system will correctly perform its function.

When its functions and tasks are complex, as is the case for many COSSs, defining the measures of reliability is more involved. Overall reliability may be expressed in terms of the probability the system will perform its function correctly. However, it may be important to distinguish different aspects of a system's functions. Thus, for an alarm system for example, reliability can be expressed in terms of misses (not alarming when alarm conditions exist) and false positives (alarming when an alarm condition does not exist). Further, automation's reliability may differ across different contexts of use, or modes of operation.

The guidelines for reviewing the HSIs to automation follow; it is divided into the following topics:

- Automation Displays
- Interaction and Control
- Automation Modes
- Automation Levels

- Adaptive Automation
- Error Tolerance and Failure Management
- HSI Integration

8.1 Automation Displays

The following three sections address the display of general information about automation: General display considerations; automation representation; and, and automation's dynamic status.

8.1.1 General Display Considerations

8.1.1-1 Hierarchal Access to Information

Information should be presented hierarchally, enabling operators to determine the overall status of automation from top-level displays, and to access more detailed information on lower level displays.

Additional Information: Information hierarchies are a means whereby operators can monitor automation's status at a glance, and also obtain progressively more detailed information to support their situation assessment of automation and troubleshooting. The displays should contain navigation aids to enable users to quickly and easily move from higher-level displays to lower-level displays in the hierarchy (see NUREG-0700, Section 2.5.1, Display Selection and Navigation).[91017]

8.1.1-2 Use of Graphical Features for Status-at-a-glance Functionality

The detailed design of the HSIs to automation should ensure status-at-a-glance functionality.

Additional Information: Display features supporting status-at-a-glance functionality enable operators to assess automation's performance with a minimal workload. This functionality is supported by display considerations, such as representational mapping, maximum use of integral- and configural-displays, and inclusion of graphical features, such as emergent features, that require little interpretation (see NUREG-0700, Section 1.1, General Display Guidelines, for explanations of these concepts.[91017]

8.1.2 Automation Representation

8.1.2-1 Overall Representation of an Automation System

The HSI should accurately represent automation and its plant interfaces.

Additional Information: Providing a representation of the automation and the aspects of the plant with which it interfaces helps operators to link the actions of automation to its goals for the plant itself. For example, if automation is maintaining a level in a tank that has a leak, so long as automation can pump water in, the level is achieved and operators may not know there is a problem. When the level can no longer be maintained, operators need to quickly determine whether the failure is in the automation or the controlled system. Offering an overall representation of both automation and its plant interfaces helps operators assess this situation.[91017]

8.1.2-2 Current Goals

The HSIs should provide information on automation's current goals.

Additional Information: Knowledge of automation's current goals helps operators to appropriately use the automation.[91017]

8.1.2-3 Current Processes

The HSIs should offer information on the current process being used, e.g., control algorithms, and reasoning processes.

Additional Information: This information provides the operator with information about how automation is accomplishing its goals.[91017]

8.1.2-4 Inputs to Processes
The HSIs should provide information on the inputs used by automation's processes.[91017]

8.1.2-5 Current Responsibilities of Each Agent
The HSIs should identify the roles and responsibilities of human and automation agents.
Additional Information: Within a human-automation team, an agent is the one responsible for performing some portion of the task. A clear delineation of the responsibilities of the human and automation agent especially is important when varying levels of automation are used, and when it is adaptive because of the changing nature of roles and responsibilities.[91017]

8.1.2-6 Indicate Automation's Reliability
The HSI should provide information about automation's reliability in the current situation.
Additional Information: The intent of this guideline is give operators knowledge about how well automation is likely to do. Expectedly, information about reliability will be developed as part of the design process, and can be communicated to operators in the HSI. Operators should have a well-calibrated trust in automation that involves knowing in which situations automation can be relied upon, which situations require increased oversight by personnel, and which situations are inappropriate for automation. The availability of information about reliability helps support the calibration of trust, and the appropriate use of automation.[91017]

8.1.3 Automation's Dynamic Status

8.1.3-1 Goal Accomplishment
The HSIs should provide information on the degree to which automation's goals have been accomplished. The final attainment of a goal should be clearly displayed.
Additional Information: The way in which the displays show information on goal attainment should support the rapid assessment of automation's progress toward this end. For example, if the automation changes some measured value over time (rate change), then displaying progress via a trend graph that reveals the goal state or objective will facilitate personnel's assessment of progress towards the goals.[91017]

8.1.3-2 Current Progress
The HSIs should provide information on the progress of its current processes.
Additional Information: In addition to progress of processes, analytical redundancy can be employed to offer information about whether automation is working as expected. In the present context, analytical redundancy could compare the demand signal to a controlled component to the parameter's actual value. A model of how the components should respond show whether the control is meeting expectations.[91017]

8.1.3-3 Quality of Inputs
The HSIs should provide information on the data quality of inputs used by automation's processes.
Additional Information: Operators should be able to assess the overall quality of the data the automation is using .[91017]

8.1.3-4 Support Prediction
The HSI should support the prediction of future status of automation and the aspects of the plant being controlled.
Additional Information: An important aspect of situation awareness is in anticipating future states. This can be supported by HSI tools that will help operators gain an understanding of where automation is heading.[91017]

8.1.3-5 Notification of Significant Status Changes

The HSIs should notify operators to important status changes of automation.

Additional Information: The display of automation alerts should be commensurate with the need for the operator's attention. For example, if the operator's attention is not needed immediately, then a nonintrusive message is appropriate. Some success was found with automation-generated verbal notifications .[91017]

8.1.3-6 Notification of the Need for Automation

When automation's use is based on predefined conditions and operator actuation, the HSI should provide notification when those conditions exist.

Additional Information: An example is alerting the operator to conditions in which a particular computerized procedure should be used. [91017]

8.1.3-7 Notification of the Failure of Automation Initiation

When automation is automatically actuated, operators also should be alerted to the failure of automation to start.

Additional Information: An example is an alarm indicating failure of an auxiliary feedwater (AFW) pump to start within a preset time period after receiving an AFW initiation signal.[91017]

8.1.3-8 Status of Preconditions

The HSI should provide information on the status of any initial conditions that must be met before automation should begin.

Additional Information: This information helps operators determine when it is acceptable to start automation, or to understand why automation has not started when it should have.[91017]

8.1.3-9 Cautions and Warnings

The HSI should provide any applicable cautions and warnings related to automation's use in the current situation.

Additional Information: This knowledge will help ensure that the operator is aware of such concerns.[91017]

8.1.3-10 Terminating Conditions

The HSI should provide information on the conditions for terminating automation.

Additional Information: This information supports the operator's awareness of when automation is no longer needed.[91017]

8.2 Interaction and Control

8.2-1 Locus of Authority

Operators should be in charge of the automation, be able to redirect it, stop it, and assume control if necessary except in cased where automation is mandatory, based on performance requirements.

Additional Information: While operators are ultimately responsible for safely operating the plant, this does not suggest that automation cannot initiate action. Some actions are allocated to automation because operators cannot carry them out reliably within temporal or performance requirements, e.g., reactor scram, and ECCS actuation. In these situations, the operator's primary role is to backup up the automation if it fails or encounters difficulty. There also may be situations where automation initiates a critical action because operators have failed to do so. While such automatically initiated actions are necessary to support the safety of personnel as well as equipment, operators should have ultimate authority over the human-machine system.[91017]

8.2-2 Operator Control of Interaction Pace

Where automation is not event-driven, the operator should be able to control the pace of the interaction.

Additional Information: Operators may be performing multiple tasks; therefore, they should control the pace of interaction with automation, so they can manage their priorities and workload.[91017]

8.2-3 Support All Operator Interactions

HSIs should support all necessary interactions with automation commensurate with the automation's characterization, e.g., level, function, flexibility, and reliability.

Additional Information: Detailed analyses should be undertaken of personnel's tasks to ensure that all the operator's interactions with automation are identified and supported in the HSI.[91017]

8.2-4 Obvious and Unambiguous Control Options

The HSI should display control options in such a manner that their purpose and means of operation are obvious and unambiguous.

Additional Information: As far as is feasible, automated control systems should prevent input errors by the operators. [91017]

8.2-5 Feedback for Operator Inputs

Automated systems should provide clear feedback about the receipt of operator's inputs.

Additional Information: Automated control systems should prevent, as far as is feasible, input errors by the operators. Controls and displays of the automated system should be designed to lower the likelihood of the occurrence of incorrect inputs from the operator, and increase the likelihood of detecting them. [91017]

8.2-6 Support for Operator Queries

The HSI should enable operators to query automation about the basis for its actions and recommendations to support the tracking, interpreting, and verifying of automation's recommendations.

Additional Information: If operators cannot understand the basis underlying the automation's actions or recommendations, they will not use it. Being able to query automation gives operators the opportunity to better understand automation's behavior. Attention should be paid to the types of explanations provided, with an emphasis on providing ontological information at a minimum; i.e., information pertaining to "what" questions, e.g., what does this mean, what event led to this state, and what are the consequences of an event.[91017]

8.2-7 Provide Operator Control of Level of Detail

When automation explanations are lengthy, the HSI should support operators in adjusting the level of detail.

Additional Information: In these situations, the initial automation explanations to the user should be brief. Operators can request more detail, including access to process information or an explanation for the rules, knowledge-basis, and solutions used by an automated decision aid.[91017]

8.2-8 Automation Communications with Operators

The HSI should support communications from the automation when necessary, such as when an obstacle to completing a goal is encountered or when information is needed from operators (e.g., data that the automation cannot access through the I&C system.)

Additional Information: Operators should be alerted to any condition requiring their attention. The HSI should warn personnel to plant conditions or situations that lie outside the range within which the automation can perform reliably. For example, an automated process may operate reliably provided the measured values used as its inputs are within specified ranges (e.g., within a range set based on the required accuracy of the associated instruments, or within which a calculated value or control algorithm remains valid).[91017]

8.2-9 Unobtrusive Communication

Communications from automation should not be intrusive and should not disrupt the operator's ongoing tasks unless necessary.

Additional Information: Except for high-priority messages that are important to situation awareness, or that require operator intervention, operators should be permitted to determine when to address communications from automation. [91017]

8.3 Automation Modes

The guidance in this section addresses automation having multiple modes.

8.3-1 Indicate Automation's Mode
The HSI should indicate the current mode using highly salient design features.
Additional Information: Conspicuous indication of the current mode will help prevent operators from making mode errors, i.e., taking an inappropriate action, or failing to take a needed one due to thinking the system is in one mode when it is in another mode.[91017]

8.3-2 Mode Change Controls
The HSI should provide controls to change modes.
Additional Information: Valid options for mode change should have controls that clearly distinguish the modes.[91017]

8.3-3 Implication of Mode Change
The HSI should provide information about how a new mode changes the automation's functioning, impacts plant systems, and operator's responsibilities.
Additional Information: Providing information on the implications of mode changes will help prevent operators from making mode-related errors.[91017]

8.3-4 Alert to Significant Changes
When the mode change potentially has significant consequences, operators should be alerted to those changes, and operator verification required.
Additional Information: Mode changes may have consequences that the operator is not immediately aware of. [91017]

8.3-5 Notification of Automatic Mode Change
If mode change is automatic, operators should be notified before it takes place, and again when it happens.
Additional Information: If the mode change is associated with changes in the operator's tasks, the notification should precede the change well in time to allow the operators to adjust their behavior.[91017]

8.3-6 Conditions Leading to Automatic Mode Change
The HSI should provide easy access to information about the conditions leading to an automatic mode-change.
Additional Information: This data will help operators to understanding the reason for the change.[91017]

8.4 Automation Levels

This section contains review guidance for the unique aspects of the different levels of control. In addition to these guidelines, all other automation guidance is applicable.

8.4.1 Shared Control

8.4.1-1 Information Need for Task Coordination
When operators and automation jointly perform a task, the HSI should provide the information necessary to coordinate the shared activity.

Additional Information: This data may include information, such as notification of the need for operator input, subtask accomplishment, need for hold on a task by one agent if the other agent's subtask must be completed first.[91017]

8.4.2 Operation by Consent

8.4.2-1 Provide Information on Task Status
The HSI should provide the information on the status of all tasks performed by automation, e.g., all tasks accomplished thus far, and those yet to be performed.
Additional Information: Operators should be able to review the current status of automation, including the full set of tasks that automation has performed, and will do so to meet its goal.[91017]

8.4.2-2 Provide Information Needed to Authorize Task Continuation
The HSI should provide the information needed for operators to easily evaluate the status of the current task and determine if all conditions are met for authorizing automation to continue it.[91017]

8.4.2-3 Identify Valid Options
The HSI should identify the valid options at each task hold-point, and the implications of each.
Additional Information: Operators may have several choices once they have evaluated the task's status, e.g., to authorize automation to continue, to return to an earlier task, or to skip a task. [91017]

8.4.3 Operation by Exception

8.4.3-1 Provide information on Reason for Exception
The HSI should identify the exception automation encountered and the information needed by the operator to evaluate the exception condition.
Additional Information: Several reasons may cause the automation to pause, and an operator's decision on how to proceed may differ depending on the exception encountered.[91017]

8.4.3-2 Identify Valid Options
The HSI should identify the valid options after exception is encountered and the implications of each.
Additional Information: Operators may have several choices after encountering an exception, e.g., to input information to the automation, or to bypass the exception and continue.[91017]

8.5 Adaptive Automation

This section contains review guidance for the unique aspects of adaptive automation. In addition to these guidelines, all other automation guidance is applicable.

8.5-1 Predefined Set of Roles and Responsibilities
The HSI should provide operators with "set plays," i.e., predetermined definitions of a set of roles and responsibilities of human and machine agents.
Additional Information: This information will minimize the workload due to changing the with automation configuration, and will support the operator's understanding of automation by limiting the number of available options.[91017]

8.5-2 Operator Control of Automation Shifts
The HSI should provide controls for implementing valid automation shifts.[91017]

8.5-3 Identification of Triggering Conditions

If automation can shift for reasons other than by the operator's request, the triggering conditions and the new level of automation should be identified.

Additional Information: Adaptive shifts can be made based on factors such as measured workload indicators, performance decrements, or other criteria.[91017]

8.5-4 Notification of Impending Shifts

If automation can shift for reasons other than operator's request, the operators should be notified of impending shifts.

Additional Information: Operators should be alerted to impending changes in automation (approach to triggering condition) so they are not surprised and have time to block it, if appropriate.[91017]

8.5-5 Shift Conformation

The HSI should confirm that a change in automation has taken place.

Additional Information: Adaptive shifts should be confirmed positively by the system to prevent operators becoming confused about their current roles and responsibilities.[91017]

8.6 Error Tolerance and Failure Management

8.6-1 Failure Alert

The HSI should indicate when automation fails to accomplish its goal.

Additional Information: Alerts should be graded based on the need for operator's action, e.g., if immediate action is needed, an alarm should be used. Indications are especially important for systems that fail without producing immediately noticeable changes in the plant's behavior. [91017]

8.6-2 Degraded Conditions Alert

The HSI should alert operators to situations in which its performance is degrading.

Additional Information: Automation should degrade smoothly when situations change sufficiently to render its performance unreliable, and should communicate such circumstances to personnel in a timely way to enable them to become more engaged in the responsibilities of the automation. [91017]

8.6-3 Information on Failure Cause

The HSI should support operators in determining the cause(s) of failures as being either the automation, inputs to it (e.g., failed sensor), or the failure of those systems automation interfaces with.

Additional Information: Automation can mask failures and degraded conditions in other plant systems by compensating for them. This can lead to operators losing situation awareness, and might be problematic when the situation reaches a point where the automation can no longer compensate, and personnel have to take over.[91017]

8.6-4 Support Failure Recovery

The HSI should support operators in determining the steps for failure recovery, or suggest back-up actions should recovery not be possible.

Additional Information: When a failure of automation is detected, the HSI should provide displays and information that allow personnel to rapidly determine what actions they must take to respond to the failure. For example, the HSI for an automated process that fails over to manual mode should alerting personnel that manual control now is required, and point to or directly display the actions or procedures necessary to carry out the required manual actions. [91017]

8.6-5 Monitoring of Personnel Actions

To the extent possible, automation should monitor operators' activities and the HSI should alert operators to potential errors of commission (taking an incorrect action) and omission (failing to take a needed action).

Additional Information: For example, automation should check for errors in the operator's inputs, e.g., misplacing a decimal point in keyboard input, and when their actions appear incompatible with the state of the process or the goals currently established by/for the automation. This capability should extend to their actions in setting-up and configuring the automation, since these were found to cause many failures of the automation.[91017]

8.6-6 Operator Requested Status Check

The HSI should give operators the ability to request a system check.

Additional Information: If operators suspect that automation may not be performing as expected, the ability to ask for a status check can help operators resolve the concern. [91017]

8.7 HSI Integration

8.7-1 Procedure Support

The operator's interaction with automation should be guided by procedures including situations where automation degrades or fails.

Additional Information: The availability of procedures helps operators to manage their interactions with automation, especially transitioning to manual operations when automation degrades or fails.[91017]

8.7-2 Access to Supporting Reference Materials

Operators should have easy access to reference materials that support their use of automation.[91017]

8.7-3 Integration into Existing HSIs

The HSIs for automation should be integrated into the operator's main HSIs.

Additional Information: To help minimize attention demand for monitoring automation and the workload associated with interacting with it, information about automation and information about the operators other activities must be well integrated. This will help minimize the transitions between displays.[91017]

8.7-4 Consistency with HSIs

HSIs for automation should be designed following the same design conventions used for the main HSIs.

Additional Information: As detailed in NUREG-0711, all HSIs should be designed to a common set of principles described in a style guide. They should be consistent with NUREG-0700.[91017]

9 DESIGN PROCESS IMPLICATIONS

The information we discuss in this section summarizes the implications of the design process we identified in the literature, stemming mainly from that reviewed in Section 3, 4, and 5. However, some information comes directly from the FAA's automation guidance (Ahlstrom et al., 2002).

9.1 High-level Goals of Automation Design

Define the Purpose of Automation

Automation should have a clear purpose, meet an operational need, be well integrated into overall work practices, and be sufficiently flexible to handle anticipated situational variations and to adapt tractably to changing personnel needs.

Optimize Performance of Human-Machine Team

The allocation of responsibilities between human and machine agents should seek to optimize overall integrated team-performance. This may involve defining various levels of automation each with clear cut, specific responsibilities for all agents and each with a well-defined rationale. It also may involve flexible allocations that change in response to situational demands. Personnel interactions with automation should support all human roles, including developing a good understanding of automation and maintenance of the skills necessary to perform tasks when automation fails. This recommendation may involve exposing personnel to various levels of levels of automation. The HSIs should support a solid understanding of the roles and responsibilities for both humans and machine agents at all times.

Keep Operators Active in Monitoring and Control

Automation should be designed so that users are involved in active monitoring and control, rather than being just passive monitors. Automation failures may be easier to detect when users are actively involved in both activities, than when they are not taking part (Ahlstrom et al., 2002).

Minimize Workload

The workload associated with configuring, monitoring, communicating with, changing allocations, and directing automation should be minimized.

Ensure Safety should Automation Fail

Automated systems should permit manual control and preservation of safe operations should there be a failure of one or more components of the system on which the automation depends.

9.2 Automation Design Characteristics

Complexity

The complexity of automation should be minimized, and the automation's processes (algorithms, reasoning processes) simplified as much as possible.

Number of Modes.

The number of different modes for a given system should be minimized. Multiple modes will provide flexibility but introduce more opportunities for error. Furthermore, automation with multiple modes of operation is difficult to learn and can generate increases in workload. Users must understand and remember how and when to use each mode, and also which mode currently is active (Ahlstrom et al., 2002).

Levels of Automation

Levels of automation should be carefully chosen:

- Automating monitoring/detection and response implementation functions is effective in lowering workload without negatively impacting situation assessment
- Automating situation assessment and response planning can improve overall performance, but should be done with caution because it lowers situation awareness and increases difficulty in recovering from automation failures

Adaptive Automation

Adaptive automation has a positive effect on the operator's understanding of automation, situation awareness, and ability to recover when the automation fails. AA is known to help support task performance and manage workload, especially for lower-level cognitive functions (information acquisition and action implementation functions). The situation is more complex when it is applied to higher-level cognitive functions (information analysis and decision making), and performance may be disrupted.

In adaptive automation, there can be a cognitive cost to switching between LOAs that can disturb ongoing task performance. Thus, the design of the triggering mechanisms must be addressed carefully to minimize this issue and should be easily accomplished with the HSI. Additional research is needed to identify appropriate triggering mechanisms, and how they should be implemented to minimize shift disruptions. Research suggests that workload measures may provide effective switching triggers.

Adaptive automation must be made at least as skilled as a user, if not greater, to promote the user's optimal performance (Ahlstrom et al., 2002).

9.3 HSI Design

An HSI requirements analysis should be performed to define HSI support for operator roles and responsibilities for each applicable level of automation. The design of HSIs for automation should involve an HSI requirements analysis and a detailed HSI design. The literature recommends that approaches to these two activities are work-domain analysis and EID. Both generally are consistent with the NRC staff's guidance for reviewing the design process (NUREG-0711), and HSI design implementation (NUREG-0711).

9.4 Test and Evaluation

Validate System Design

Contextually valid human-in-the-loop experiments and simulations should be conducted to validate and refine the design of the automated system (Ahlstrom et al., 2002).

Evaluate through Simulation

Alternative schemes for allocating functions should be examined in the context of the whole system by employing high-fidelity simulations. Because there may be multiple potential schemes involved in doing so, simulating them in the context of the whole system ensures their proper evaluation. A scheme that seems to be the most appropriate for accomplishing a specific task may not be the best choice in terms of the functioning of the entire automated system (Ahlstrom et al., 2002).

Assess Overall Impact

The overall impact of automation shall be thoroughly examined before its implementation to ensure that changes do not engender additional complexities, loss of situational awareness, or possible errors. Automating some user tasks may result in the user processing less information or processing information at less depth. A diminished understanding and appreciation for the overall situation may result (Ahlstrom et al., 2002).

Determine the Impact of Automation on Team Performance

While lower levels of automation were beneficial to teamwork, the automation of decision-making sometimes has a negative impact. In introducing new automation, designers should consider the possibility of negative effects on team coordination. Automation may lower team interaction and cooperation unless all parties are given information that allows them to be actively involved in the task. Automation can cause physical difficulty in seeing what other team members are doing, reduce the ability to cross monitor actions, change traditional roles and responsibilities, and change the manner in which team members attempt to help each other.

Evaluate Interactions with Other Functions

Possible interactions with other tools, system functions, and user tasks should be assessed when new automation is designed (Ahlstrom et al., 2002).

Test Normal and Failure Modes

Automated systems should be tested under normal modes of operation and under their failure modes automation (Ahlstrom et al., 2002).

Test before Implementation

Automated systems shall be tested in a realistic operational environment with representative users before implementing them to ensure that the operator's performance is not compromised and workload is not increased (Ahlstrom et al., 2002).

10 TRAINING AND OPERATIONS IMPLICATIONS

The information we describe in this section summarizes the design process implications identified in the literature. This information stems mainly from the literature reviewed in Section 3, 4, and 5. However, some information comes directly from the FAA's automation guidance (Ahlstrom et al., 2002).

1. Training should be directed to establishing a clear understanding for operators of automation's capabilities and limitations. They should understand

    - the purpose of automation, design bases, and range of applications in a way that relates to user's goals
    - automation's operational goals
    - how automation works
    - how it interacts with the plant functions, systems, and components
    - automation's expected reliability, the mechanisms governing its behavior, and its intended use
    - how to predict its actions within its various contexts of use

2. Training should result in an accurate mental model of the automation.

3. Training clearly should identify the role of personnel in supervising and interacting withy all levels of automation.

4. Training is important to proper trust calibration. Operators should be given clear, specific information about the limits of automation, such as the reasons why something might go wrong. That information will help support proper calibration and resolution of trust. Operator's trust in automation should be tested and measured to ensure it is appropriate to each context in which automation is used.

5. Training should help operators avoid over-reliance on automation (Ahlstrom et al., 2002). When users rely on automation too much, they become susceptible to automation-induced complacency; under those circumstances, monitoring failures are likely to occur.

6. Training should help operators recognize the inappropriate uses of an automated tool including automation bias (the use of automation in a heuristic manner, as opposed to actively seeking and processing information) (Ahlstrom et al., 2002). There are different categories of inappropriate use, including automation bias, ignoring or turning off the automation, and its improper implementation. Users may rely on automated decision-aids in a heuristic manner (referred to as automation bias). Using heuristics is intended to apply simple decision-making rules to make inferences or to draw conclusions simply and quickly. Heuristics are useful principles with wide applications, but may not be strictly accurate. Usually a heuristic strategy is optimal; however, under certain conditions, heuristics are inappropriate and errors or misuse may occur. Automation bias leads to errors of omission (failure to notice system anomalies when automation fails) and errors of commission (acceptance of automated decisions without cross-checking or in presence of contradictory information). Training will help prevent automation bias and help the user learn to examine multiple sources of information before making a decision. Early training on automation bias

7. may reduce commission errors for users new to automation, but may be less likely to reduce omission errors, or errors made by expert users. Inappropriate use of automation may be influenced by various individual factors, such as self-confidence in completing the task, trust in the automation, differential effects of fatigue, and how all of these factors combined weigh into the decision-making process. Inappropriate use of automation can be due to misuse (automation bias, complacency), disuse (ignoring or turning off automation), or abuse (improper implementation of automation).

8. Training should help operators develop appropriate automation monitoring behavior to minimize errors of commission and omission. Personnel should monitor the activities of automation to detect its errors and to be in an informed and knowledgeable position to assume control if it fails.

9. Training specifically should address available modes, how to track of them, know the impact of the mode differences on behavior, and behave in a manner consistent with the mode and consequence of mode-related errors.

10. Training should help operators to question automation (Ahlstrom et al., 2002). They should recognize and understand the conditions under which automation may be unreliable, and to learn the conditions where it performs well (when or when not to question the automation). Users must learn not to categorically accept the recommendation of a decision aid. Understanding the automation's weaknesses allows them to better judge how much they should trust the automation without becoming overconfident in its performance. This recognition process may impose an additional workload on the user.

11. Training should specifically address failure-recovery transitions (Ahlstrom et al., 2002). Users shall be trained on transitioning from automated to conventional systems. If automation fails, users need to be skilled at recognizing the failure and taking manual control. Simulator training specifically should offer experience with automation reliability and failures. Exposure to failures helps operators to develop well-calibrated trust, and failure-recovery skills.

12. Training should encompass specifically backing-up automation. Users should have training in undertaking any manual tasks replaced by automation, or in operating any backup systems controlled by automation (Ahlstrom et al., 2002). Training should ensure that manual skills are not degraded so that personnel can effectively assume control when needed.

13. Training should cover specifically the impacts of automation on team performance. While lower levels of automation were beneficial to teamwork, automating decision-making sometimes is detrimental.

14. Training and operational practices should address providing intermittent manual control to improve the operator's monitoring and manual-recovery behaviors (Ahlstrom et al., 2002). This reinforcement should help minimize complacency and maintain skills.

15. Where available, training and operational practices should address using adaptive automation to mitigate the loss of skills.