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Light Water Reactor Sustainability Program

Control Room Modernization End-State Design Philosophy

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Katya Le Blanc
Jacques Hugo
Zachary Spielman
Casey Kovesdi
Rachael Hill
Johanna Oxstrand
Tyson Hansen
Brandon Rice

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ABSTRACT

The Control Room Modernization (CRM) research effort is a part of the Light-Water Reactor Sustainability (LWRS) Program, which is a research and development program sponsored by Department of Energy (DOE) and performed in close collaboration with industry research and development programs that provides the technical foundations for licensing and managing the long-term, safe, and economical operation of current nuclear power plants. One of the primary missions of the LWRS program is to help the U.S. nuclear industry adopt new technologies and engineering solutions that facilitate the continued safe operation of the plants and extension of the current operating licenses. This report describes the background and technical basis for an end-state vision design philosophy for and advanced hybrid control room.

ACKNOWLEDGEMENTS

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ACRONYMS

ASM	Abnormal Situation Management
CPP	Critical Performance Parameters
DCS	Distributed Control System
EEMUA	Engineering Equipment and Materials User Association
EID	Ecological Interface Design
FOD	Function-Oriented Display
HMI	Human Machine Interface
HPHMI	High Performance Human Machine Interface
HSI	Human-System Interface
IA	Information Architecture
IRD	Information Rich Display
LWR	Light Water Reactor
LWRS	Light Water Reactor Sustainability
NPP	Nuclear Power Plants
OD	Overview Display
P&ID	Piping and Instrumentation Diagram
SCADA	Supervisory Control And Data Acquisition
TBD	Task Based Displays
U.S.	United States
VTT	Technical Research Centre of Finland

Control Room Modernization End-State Design Philosophy

1. INTRODUCTION

This research is a part of the United States (U.S.) Department of Energy-sponsored Light Water Reactor Sustainability (LWRS) Program conducted at Idaho National Laboratory. The LWRS Program is performed in close collaboration with industry research and development programs, and provides the technical foundations for licensing and managing the long-term, safe, and economical operation of current nuclear power plants (NPPs). One of the primary missions of the LWRS Program is to help the U.S. nuclear industry adopt new technologies and engineering solutions that facilitate the continued safe operation of the NPPs and extension of the current operating licenses.

One challenge facing the U.S. nuclear industry is maintaining outdated or obsolete equipment. Many NPPs are choosing to replace worn-out equipment on an as-needed basis. This approach results in a series of like-for-like replacements of obsolete or worn out components on the control boards such as like-for-like annunciator system replacements. There have also been several distributed control system replacements for systems such as turbine control, feedwater, or chemical and volume control. These upgraded components and systems have typically addressed an immediate need to replace equipment that is past its usable life. Such upgrades rarely represent an encompassing or systematic vision for control room modernization and instead address primarily matters of equipment obsolescence. These upgrades may leave control rooms in a hybrid digital and analog state where upgraded systems are not consistently designed and do not add the additional benefit of enhanced support for operators in the control room.

None of the 99 currently operating commercial NPPs in the U.S. has completed a full-scale control room modernization to date. A full-scale modernization might, for example, entail replacing all analog panels with digital workstations. Such modernization has been undertaken successfully in control room upgrades in Europe and Asia, but the U.S. has yet to undertake a control room upgrade of this magnitude. Such technology remains the sole province of new reactors such as the four AP1000 NPPs currently under construction in the U.S. Instead, NPP main control rooms for the existing commercial LWR fleet remain significantly analog, with little evidence of digital modernization.

As noted in EPRI (2005), control room upgrades are scarcely an all-or-nothing undertaking. While it may be viable for one NPP in a regulated market to complete a full-scale digital upgrade, the cost, expertise, and time required for such an upgrade is significant. The downtime required to replace a sizeable portion of an existing main control room well exceeds the outage cycle of an NPP. In a commercial electricity market such as the U.S., it is challenging to justify the lost revenue of taking the plant offline to modernize the control room. Control room modernization, such as the fully digital control rooms found in some chemical and process control facilities, does not significantly decrease the cost of operating the plant, nor does it necessarily increase the safety or reliability of the plant. A commercial NPP's operating license requires a prescribed crew complement, regardless of the underlying technology in the control room. Further, the plant already operates at extremely high safety and reliability margins, and gains through digitization are likely to be minimal. Thus, the modernization of the control room becomes a sunken cost to the private utility, and there is little perceived benefit to the effort and cost required to replace the control room.

Although there are significant challenges in undertaking control room modernization, there are also significant opportunities to enhance the efficiency and reliability by carefully designing the upgraded systems to support operators and to include advanced features such as diagnostic support, advanced human system interface designs, and decision support tools. The purpose of the work described in this report is to provide guidance on how to realize those opportunities by designing control room human system interfaces (HSIs) with these advanced capabilities in mind. Further, this work seeks to ensure that control room modernizations are undertaken with a sound understanding of the impacts to human operators and are designed based on state-of-the art human factors principles.

This research is conducted in close collaboration with a utility partner undergoing a phased modernization approach. The first phase of the project is updating a local control room for the liquid radiological waste system, and additional phases will result in modernizing about 60% of the control main control room equipment. The purpose of this research is to provide an industry wide approach and road map for effective modernization that not only addresses obsolescence, but provides guidance for enhancing the economic viability of the existing LWR fleet by improving efficiency and safety through effective design of the control room, incorporating human factors principles across the entire design. The approach addresses human factors throughout the entire upgrade process by first identifying a realistic and desirable end state concept for the control room layout, then identifying how to ensure consistency throughout the upgrade process with an overarching design philosophy, and finally by providing guidance on how to enhance the effectiveness of upgraded human system interfaces (HSIs) by considering the end state throughout the life of the phased upgrade project and incorporating an integrated approach to HSI design in each system upgrade, regardless of the individual components being upgraded. Previous work has defined an end state vision for the control room layout, which identified which component would be removed in each phase of the upgrade and where new digital displays will be located on the control boards (Boring et al., 2016), this project will define how the information on the digital displays will be presented.

The purpose of this report is to provide an initial description of an overarching design philosophy that can serve as high level guidance for identifying the functional and design characteristics of human system interfaces that are included as part of control room upgrades. This report provides background on existing guidance, industry best practice and focused research where it is available. This report is intended to document the design philosophy to provide a consistent approach to designing HSIs as part of control room modernization. Although there is a great deal of information on the aspects of HSI design presented here, there are also many unanswered questions regarding how to design to best support operators in modernized hybrid control rooms, therefore this document will be updated as new research that addresses these topics emerges.

1.1 Review of Design Concepts

There are several existing approaches and philosophies for design of HSIs that may be applicable to an effective overarching design philosophy for control room modernization. These approaches are briefly summarized in the next section and general principles that can be extracted from the concepts are provided.

1.1.1 Ecological Interface Design (EID)

Ecological interface design (EID) is a work-domain approach to designing complex social-technical system interfaces. The EID approach is centered on two principle activities. The first is to determine the information requirements based on models of the work domain. This is usually accomplished through an abstraction hierarchy which is paired with a part-whole decomposition of the systems. The second activity is to represent that information based on strengths and limitations of human cognitive ability. EID highlights the importance of supporting the propensity for human operators to rely on skill and rule based behavior more than knowledge based behavior (Rasmussen et al., 1994). Thus, displays are designed to facilitate the use of signals and signs and minimize the reliance on symbols. The advantage of the EID approach over traditional approaches (e.g., task analysis) is that it leads to interface designs that can facilitate operator decision making in unanticipated or abnormal events (Lau et al., 2008).

In simulated control room studies, displays designed using the EID approach have been shown to aid operator performance for unanticipated or abnormal events in process control (Vicente, 2002), medicine (Vicente, 2002), and NPP control rooms (Lau et al., 2008). The advantage of EID approach is the flexibility its resilience in abnormal situations however, depending upon the implementation, operators may have to modify their mental model of the nuclear process (e.g., operators may have to think of the plant in terms of energy balance (Braseth et al., 2009). Careful regard of this trade-off is important to the end design state.

1.1.2 Information Rich Display (IRD)

Information Rich Display (IRD) is characterized by several principles that allow large amounts of information to be displayed in ways that facilitate situation awareness. IRD is currently implemented in large screen overview displays, but the principles may be implemented on smaller screen displays as well.

One of the main features of IRD is the use of the “Dull Screen principle” (Braseth et al., 2009). The Dull Screen principle is characterized by conservative use of saturated color, which is reserved for important signals like alarms. The static elements of the display are presented in shades of grey to minimize interference with the important and dynamic elements of the display.

Another important principle in IRD is the use of analog display elements. Careful design of analog displays can reduce the amount of cognitive effort (i.e., memorizing and calculating) that is necessary when compared with simply displaying a digital value. One of the major examples of the use of analog display elements is the use of normalized integrated mini trends. Mini-trend plots are integrated into the configurable displays instead of digital values. On the mini trend plot, the scale is normalized so that the top is the high-high alarm set point and the bottom is the low-low alarm set point. The center (on the y axis) of the plot is the normal operating value. The region between the low and low-low alarm set points is shaded with a low contrast color (the same is true for the high and high-high alarm set points). These plots are grouped so that the set of plots is perceived as a single object and that deviation in a single parameter is easily detected (see Figure 1 for an example).

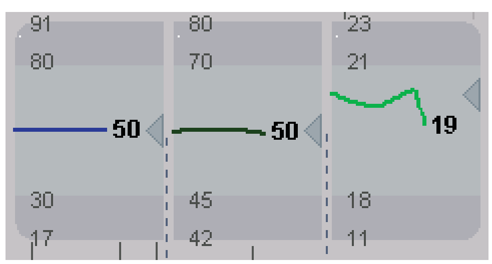


Figure 1: Example of mini trend plots in an IRD

1.1.3 Function-Oriented Displays (FOD)

Function Oriented Display design is based on a functional analysis. As part of this approach, the analyst determines high level goals and then decomposes the plant into functions and sub functions and these are then represented explicitly on the HSI display. A 2005 evaluation of a function oriented display indicate that operators liked the high level overview and felt that the FOD was a good way to organize the process information (Braseth et al., 2009).

1.1.4 Task Based Displays (TBD)

The task-based approach is to design displays that provide operators with all information needed to perform pre-defined tasks as effectively and safely as possible. The display design caters to the task-relevant system information and interdependencies needed to perform effectively within a pre-defined task space. Initial work indicated that procedure based tasks were particularly suited for such an approach. At Halden, work in the HAMMLAB in support of task based displays (TBD) determined 3 types of displays were useful to support the task based display concept. These are the Procedure Selection and Overview Display, the Procedure Performance Display and the Event-dependent Assistance Display (Braseth et al, 2009). Their research results indicated 60% of operator preferred computerized procedures s and a subset indicated that the TBD concept is necessary for operations in a computerized control room.

1.1.5 High Performance HMI

High performance human machine interface (HPHMI) are displays depicting relevant information which in context is made useful to the operator (Hollifield at al., 2008). A HPHMI should be designed to provide process values along with the context of what is expected or desired. This will enable the operator to scan and process multiple values on the display within a few seconds and hence improve the operator's ability to detect abnormalities early.
The use of color according to the HPHMI concept:

- Use a gray background and muted colors minimize screen glare and reflection
- Use the dull screen concept to make abnormal and alarm conditions more salient
- Use bright colors to draw attention to abnormal conditions
- Indicate alarms by a redundantly coded (e.g., shape, color, and text) element indicating the presence and priority of the alarm
- Color alone should not be used as the only discriminator of an important status condition
- Colors used for alarm conditions should not also be used for less important information
- Use brightness coding and words to indicate component state (e.g., use white color and the word "RUNNING" to indicate a pump is operating).

The HPHMI describes the use of a four level graphic hierarchy based on progressive exposure of detail:

Level 1 – Process area overview. The big picture overview.

Level 2 – Process unit display. The primary graphic for detailed surveillance and control manipulations. These displays should have embedded trends with indications of the desirable range.

Level 3 – Process unit detail display. Addresses a single piece of equipment of control scheme. To be used for detailed diagnosis.

Level 4 – Process diagnostic display. Provides details of subsystems, individual sensors, or components.

1.2 General Design Philosophy

The following section summarizes insights from existing design concepts, approaches and philosophies that describe principles to guide all aspects of this design philosophy.

1. *Provide Functional Information.* The approaches listed above generally advocate displaying functional information rather than simply displaying physical information.

2. *Facilitate Skill and Rule Based Behavior and Provide Graphics that Support Knowledge Based Behavior.* One of the principles of EID is to present information in a way that is compatible with the strengths and weaknesses of human information processing. This is typically accomplished in EID by applying Rasmussen's (Rasmussen et al., 1994) Skills, Rules and Knowledge taxonomy. The IRD approach also emphasizes the importance of supporting skill and rule based behavior.

3. *Use Trend Displays where applicable.* Trend displays allow an operator to quickly determine how a parameter is changing over time. When changes over time are important for the operator to control or monitor the plant, displaying parameters in trend plots rather than simply displaying

the current value reduces the amount of cognitive processing an operator must do. Trend plots enable the operator to *see* how the parameters changing over time rather than relying on the operator's limited memory capacity to recall where parameter values were in the past. In addition, applying the principles laid out in IRD mini-trends such as shading of alarm set points on the plot also allows operators to quickly detect how far a parameter is away from set points and limits. Using these principles, operators do not have to remember what the set points are or calculate how far the current value is from those set points, thus freeing up cognitive resources for other important tasks.

4. *Facilitate Perceptual Processing of Information Where Possible.* IRD, EID and HPHMI approaches highlight the need to support perceptual processing of information. IRD's analog normalized mini trends allow operators to visually perceive when a parameter is out of range and how far it is away from alarm and trip set points. The operator does not need remember all these details, he can simply see them on the screen. Similarly, grouping functionally related information and scaling trends to line up during normal operation so deviations can be easily perceived may reduce the operator's workload.
5. *Minimize Use of Saturated Color.* The approaches summarized above tend to emphasize reserving saturated color for highlighting abnormal conditions, while using lower contrast greys and blues for static display elements and dynamic elements that are within normal operating conditions.
6. *Improve Abstraction and Data Aggregation*. A design principle common among the above approaches is avoiding presenting plant parameter and equipment status on a component-by - component and system-by-system level and instead supplying operator information based on the functional response required by plant conditions and operational goals.
7. *Provide Diagnostic Guidance and Planning Support*. Integrating lower level information for purposes of determining the existing plant state and to predict future states is a source of operator workload. To reduce operator effort, displays can offer hypotheses, suggested recovery actions and uncertainty information to aid operator decision making.

2. Technical Basis and Philosophy

The following section presents the technical basis and philosophy for the end state design concept. The philosophy is organized based on several topics that the end-state philosophy needs to address. The majority of the topics are features or aspects of the Human system interface (HSI) design, but higher level topics are addressed as well. The topics include:

1. Ensuring an Effective End-state in a Phased Approach
2. Information Architecture
3. Overviews
    a. Plant Overview
    b. System Overview
4. Controls
5. Navigation
6. Use of Mimics
7. Use of Color
8. Use of Graphics
9. Alarms
10. Integrated Displays

Each topic includes a review of applicable guidance and a review of research that addresses the topic to serve as an initial technical basis. Following the technical basis is a list of high level design principles that serve as the philosophy for that topic.

2.1 Ensuring an Effective End-state in a Phased Approach

One risk in embarking on a phased upgrade rather than a full-scale, all in-one modernization is the phased approach may result in a piecemeal look and feel in the control room even in the presence of an overarching design philosophy. This document is intended to maximize the likelihood that the phased upgrades will result in a consistent design for the HSI features across all systems.

However, a consistent design philosophy is only one consideration is ensuring and effective end-state. Another important consideration is how to maximize the effectiveness of information abstraction and aggregation even when some systems may not yet be upgraded. The authors recommended identifying information that is relevant to high level plant overview and for integrated system overview (see section 2.9 for more detail on integrated displays) and ensuring that process parameters and component status for all relevant equipment be brought into the DCS regardless of whether it will be upgraded into the current or in future phases of the control system upgrade. This ensures that information needed to provide effective plant status and system status is available to the system that is used to present information through the HSI. Initially this may be accomplished by providing information pulled from a plant computer or other system that is used to store and process plant information. As each phase is complete,relevant information will be pulled directly from the DCS as it is made available.

This approach enables the use of effective overview and integrated displays even when information needed is not yet part of an upgraded system and ensures that there will be no need for redesign of individual system displays or a plant overviews when the plant upgrades reach the final end state.

2.2 Information architecture

One aspect of system design that may heavily contribute to HSI design is information architecture. "*Information architecture (IA) focuses on organizing, structuring, and labeling content in an effective and sustainable way. The goal is to help users find information and complete tasks. To do this, you need to understand how the pieces fit together to create the larger picture, how items relate to each other within the system. (www.usability.gov/what-and-why/information-architecture.html)*"

2.2.1 Background and Technical Basis for Information Architecture

In a modern distributed control system (DCS), the information architecture is a direct reflection of the hierarchical structure of sensors, transmitters, device controllers, process controllers, group controllers, and sequence controllers:

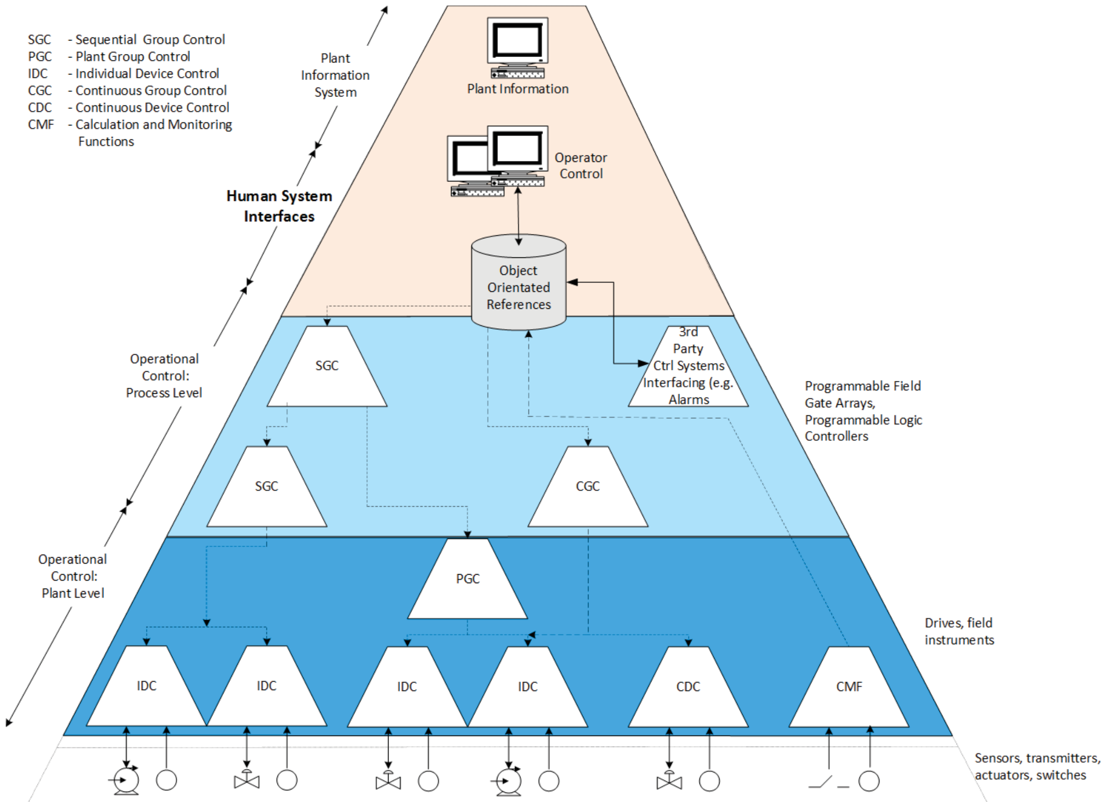


Figure 2: Typical Automation System Hierarchy

This hierarchy can in most cases provide the basis for the structure of the HSI and the plant information interfaces, which then form the top of the hierarchy, as shown in the diagram. This can also serve as the basis for the way information is structured and displayed to operators.

2.2.2 Design Philosophy for Information Architecture

1. Information should be organized hierarchically from high level plant process information at the top level, to lower level component function and status information at the lowest level.
2. Information related to process control logic or diagnostic information related to individual sensors or instrumentation should be available on demand, but should not be presented on the higher level process control displays.

2.3 Overviews

In the literature on overview displays, three terms are often conflated: Large Screen Display, Overview Display, and Group View Display. The ambiguity is also found in NUREG-0700 (see the description of “group view displays” in Section 6, p. 313), but it does make a useful distinction between the two uses of overviews:

1. An overview of an information structure, for example, a navigation scheme for the HSI (also called “display network”, similar to a “site map” on a web site). This is considered essential for user interface management and also useful to show the user’s current location within the information structure.

2. Large screen displays that enable multiple individuals to refer to the same information and allow individuals to move about the control room while still viewing the information.

These terms are ambiguous and it is recommended that the following simple definition be adopted: "*An Overview Display in the control room is a summary of information for sub-processes of the system of interest, presented to the operator in one display*."

2.3.1 Background and Technical Basis for Overview Displays

Overview displays are beneficial when:

1. Information from multiple indicators need to be integrated to understand the state of a complex system
2. Several operators must find and understand the status of a system at the same time
3. An operator needs the information from an overview but is not standing within viewing distance of current board indicators.
4. Operators have to coordinate their actions and/or have to work together

The main functions of overview displays are to:

1. Provide an overview of the state of the plant or process
2. Support situation awareness
3. Provide support for the rapid event diagnosis
4. Support operators' co-operation, collaboration and coordination of activities

For further refinement of the definition provided above, it is recommended that in its implementation, a distinction is made between the physical and functional form of the OD as well as the particular level of information in relation to the overall control room information architecture:

Functional: a general description or outline of something. "General description" means a summary, simplification, or a defined level of abstraction of detail information.

Physical: graphical and textual representation of information about the physical system at a defined level of abstraction.

In addition to form and function, level of information is a useful way to classify ODs.

Level 1: This is the top level of the plant performance information hierarchy. It represents the "span of control" of the whole plant and contains primarily the critical performance parameters (CPPs) for a rapid assessment of overall plant status. This means that it provides information about the entire responsibility of an operator, which in most cases is the same as for the whole process. This type of display is usually a read-only display and offers qualitative information with high information density.

Level 2 overviews represent the performance information (CPPs) of a specific process unit (e.g., a major system section, such as feedwater control). It presents information as well as some interaction support for the main process areas of the system.

Lower levels of information (e.g., levels 3 and 4) typically represent process control and diagnostic detail, and can no longer be regarded as "overviews".
See ANSI/ISA-101.01 (2015) "Human Machine Interfaces for Process Automation Industries", Section 6.3, p. 43-46. See also http://mycontrolroom.com/services/human-machine-interface-hmi-design/

Table 1: Overview Literature References

Source	Comments
NUREG-0700, Section 6, p. 309*ff*	This guideline describes the role of overview displays in coordinating crew interaction. It states that overviews "should be used when crew performance may be enhanced by access to a common view of plant information or a means of sharing information between personnel." It is not specific about the operators' interaction with the display or if it is read-only.
Laarni, J. et al. (2009) *Designing large screen overview displays for nuclear power plant control rooms*. VTT Presentation, SAFIR2010 Interim Seminar	VTT have defined large overview displays as follows: Display quality - Medium and high quality 2-D displays - 3-D displays Display location - Distant-contiguous displays - Desktop-contiguous displays - Peripheral displays Interaction type - Displays aimed only for viewing purposes - Interactive displays - Integrated systems
Lavin, E. (2014) *Design of a Process Overview Display in a Human-Machine Interface*. Master's Thesis, Lund University.	This thesis provides definitions and justification for the typical four levels of the HSI display hierarchy, as proposed in the "High Performance HMI Handbook" and defined in ANSI/ISA-101.01 ("Human Machine Interfaces for Process Automation Systems"). It also discusses situation awareness, workload, salience, complexity and other performance issues not often found in the literature. Several excellent examples of overview displays are shown.
Myers, W.P. & Jamieson, G. (2013) *Operating Experience Review of Large Screen Displays in Nuclear Power Plant Control*. Cognitive Engineering Laboratory, University of Toronto	This is the only review in the literature of large screen displays in nuclear and other industries. Several examples of actual implementation in control rooms and simulators are shown, including a review of basic principles and summary of subject matter expert interviews.

Härefors, E. (2008) *Use of large screen displays in nuclear control room*. Field Study, Uppsala University.	This study includes a review of the nuclear work domain and some basic concepts and definitions, including a discussion of design philosophies, human cognitive abilities and constraints, and implementation considerations. An important reference is made to ecological interface design (Vicente, 1999) and information rich design (Braseth, 2004) and the fact that neither of these concepts can effectively be implemented without work domain analysis.
Hollifield, B., Oliver, D., Nimmo, I. and Habibi, E. (2008) *High Performance HMI Handbook*. PAS	This book is a comprehensive guide to designing a range of human-system interfaces, including large screen overviews. It is not specific to nuclear power plants, but all the principles discussed are applicable to NPP control rooms. Several examples of "high performance HMIs" are shown. Note that this book represents significant consensus on industry best practice, but there is little evidence that the recommendations were based on empirical research or formal experiments.

2.3.2 Design Philosophy for Overview Displays

1. System overviews should provide an abstracted representation of overall system status.
2. System overviews should provide functional information, and provide physical information in the form of simplified process mimics where appropriate (see section 2.5 for more detail)
3. System overviews should contain embedded information such as trends, indications of alarm states, indication of process control parameters
4. System overview should be designed for use by an operator at the boards for a hybrid control room. System overview may also be used to provide shared situation awareness in the control room by way of other operators or supervisors accessing a duplicate display from a workstation. Overviews do not need to be designed to be read from across the control room.
5. System overviews should be designed to be task-based. The number and type of tasks supported will vary by system but will include the following at a minimum. Additional high-consequence or critical tasks will be identified for each system based on frequency of task impact of task to operations, and the potential to increase efficiency and safety by directly supporting those tasks with a tailored task-based display.
    a. System start-up
    b. System shut-down
    c. System steady-state normal operation

2.4 Use of Mimics

The term "mimic" means an imitation of something else. In an industrial environment, a mimic is a visual representation of certain aspects of a plant or system's function, layout, or appearance. In this sense it can be regarded as a "model", that is, a simplified version, of a specific view of the system. NUREG-0700 defines "mimic display" as follows:

"*A mimic is a display format combining graphics and alphanumerics used to integrate system components into functionally oriented diagrams that reflect component relationships. For example, a mimic display may be used to provide a schematic representation of a system. A diagram is a special form of a picture in which details are only shown if they are necessary for a task. Mimics and diagrams should contain the minimum amount of detail required to yield a meaningful pictorial representation.*" (see page 2 and page 38, 1.2.8). (A simplified form of this definition is also found in NUREG/CR-6635, which preceded the -0700 definition).

2.4.1 Background and Technical Basis for Mimics

In the control room, a mimic diagram provides the operator with an overview of the status of the plant or system. Dynamic data shown on the mimic is updated automatically with telemetered, calculated and manually updated data from the plant process computer's database.

Mimics are used widely in process industries, especially as displays for supervisory control and data acquisition (SCADA) systems. These systems have evolved to the state where control systems now consist of networked, advanced control and monitoring devices.

The user interface for such control systems is often a direct visual representation of their controller architecture, in the form of flow diagrams and buttons to actuate system controllers. Modern displays usually include trending graphs and alarm displays. Some displays may even use animation.

The literature suggests the industry understands the main purpose of an operator mimic is to help monitor the system status and quickly identify problems and causes. Since the HMI is links the operator and the industrial process, the industry is aware of the importance of good design. Operators should be able to quickly recognize which information needs their attention and what it indicates. For that, the operator not only needs a good user interface but a system designed for effectiveness, efficiency, safety and user satisfaction.

Table 2: Mimic Literature References

Source	Comments
NUREG-0700, Section 1, p. 38*ff*	This guideline states that "Mimics and diagrams should contain the minimum amount of detail required to yield a meaningful pictorial representation." The source of the guideline dates back to an old (1994) version of NUREG/CR-5908 and no information is available on the technical basis for the recommendations.

NUREG/CR-6635 (2000) "*Soft Controls: Technical Basis and Human Factors Review Guidance*"	This report is the predecessor of many guidelines that were eventually incorporated in NUREG-0700. This is valuable background that is not available in NUREG-0700, e.g., the technical basis for interaction with mimics and system response (p. 4-4). The report also provides an extensive discussion on mitigating human error resulting from poor design, e.g., unintentional activation, description errors, mode confusion, capture errors, etc. (see p. 5-1*ff*). Mitigative measures include error detection, undo, confirmation, etc., all of which are also described in NUREG-0700.
Hollifield, B., Oliver, D., Nimmo, I. and Habibi, E. (2008) "*The High Performance HMI Handbook*". PAS	Excellent examples of mimic diagrams are provided. Also good explanations of the level of information in mimics, e.g., a mimic diagram is typically used for Level 1 or Level 2 displays. Other suggestions include not using P&IDs as basis for mimic design and to use process flow instead. P&IDs represent a low level in the information/control hierarchy, whereas a mimic is typically a high level in the hierarchy. Designers should resist the temptation to just import design drawings and diagrams, as this often creates a busy screen with excess detail. Pop-ups should be used sparingly, if at all.
https://www.appliancedesign.com/articles/92375-10-golden-rules-for-hmi-design	Simply mimicing the behavior and appearance of a traditional electro-mechanical device is the worst possible use of a state-of-the-art new touch screen. There are very few scenarios where this is a good option. With time to plan and the right set of tools, designers have a blank canvas upon which to completely re-innovate the product. Moreover, mechanical components don't always translate to a touch screen. A push button is a good one-to-one match, but what about a knob? Tracing a perfect arc on a smooth surface with a finger takes too much focus. There are different rules for ease of use for physical versus virtual components.
Ha. J.S. (2013) "*A Human-Machine Interface Evaluation Method Based on Balancing Principles*". Procedia Engineering	This study of mimics in NPP control rooms considers an attribute called "informational importance" – this is similar to "salience" and is considered an important contributor to situation awareness and thus an important design considerations for mimics. The study describes evaluation results that included evaluation of mimics of a typical NSSS. This study was designed and reported in a way that would make replication in the HSSL possible.
IEEE 1289-1998: "*IEEE Guide for the Application of Human Factors Engineering in*	This is the only standard that has meaningful information on the purpose and design of mimics and

the Design of Computer-Based Monitoring and Control Displays for Nuclear Power Generating Stations", Section 6.2, p. 14	mimic diagrams. It states that mimics are "useful for displaying system interrelationships and for tying information to specific systems or components. Mimics should be used where there is an interrelationship between components that is not otherwise apparent or where they will provide the quickest way of locating needed information or controls."
Health & Safety Executive: Control Room Design, Section "Man Machine Interface"	A short section on mimics includes the following statements: Mimics should follow current conventions for symbols etc. Mimics should be user tested prior to installation to ensure that they are compatible with the end users mental model of the plant.
ANSI/ISA-101.01 (2015) "Human Machine Interfaces for Process Automation Industries", Section 6, p. 40, 41	This standard does not use the term "mimic" but instead refers to "process graphics". A useful distinction is made between the following styles: P&ID-type graphics – graphic representation of process equipment, piping and instrumentation Schematic overview – Informational overview of an operator's span of control. The types of controls and indicators needed will depend on the functional requirements. (This makes it a Level 2 display) Functional overview (or "dashboard") – Representation of the functional relationship of data. (This is a Level 1 display) Additional display styles are described in the standard. These are associated with lower-level displays, including: Topology - this is also called a "system network", which is a representation of the logical layout of a system and could thus be regarded as a "navigation display" Graph – a chart-based representation of real-time or historical data, e.g. trend graphs Faceplates – typically used for low-level control of a system function.

2.4.2 System mimic design philosophy

1. Use process flow mimics where appropriate. Process flow mimics are appropriate when the configuration of the system changes the status, function, or outcome of the process. System mimics are appropriate when it is important to see the alignment of individual components in the overall context of the system in order to understand how the system will behave.
2. When system mimics are used, they should be simplified and only show the information relevant to understand all the system status or configuration.

3. System mimics should show embedded information including trends, alarms, set points, and any other information that is necessary to understand the status of the system.
4. Where possible, system mimics should show relevant functional information in addition to physical characteristics.

2.5 Use of color

Color encompasses a wide variety of meanings in nuclear power plants (e. g. distinguish categories, indicate component status, signals alarms, etc.) and is characterized on an analog control system differently compared to a digital control system.

2.5.1 Background and Technical Basis for Use of color

The following contains all applicable guidance derived from NUREG 0700 as well as EPRI 3002004310 guidance pertaining to color association in general nuclear power plants for a digital control system.

Table 3: Color Literature References

NUREG 0700 1.3.8-4	Colors for coding should be based on user conventions with particular colors. Color codes should conform to color meanings that already exist in the user's job. Color codes employing different meanings will be much more difficult to use.
NUREG 0700 1.3.8-8	When color coding is used, each color should represent only one category of displayed data.
EPRI 3002004310 4.2.6.8.1-1	Color use and the meanings attached to colors should be consistent throughout the plant as well as within a specific upgrade project.
EPRI 3002004310 4.2.6.8.1-2	Color should be utilized as part of the overall labeling and demarcation strategy.
EPRI 3002004310 4.2.6.8.1-3	Color should be used as part of the overall strategy to emphasize particular items of information.
EPRI 3002004310 4.2.6.8.1-4	Colors should be considered for use as part of the overall strategy to identify the status of components or systems.
EPRI 3002004310 4.2.6.8.1-5	Color should be considered for use as part of the overall strategy to convey the magnitude of measured quantities.
EPRI 3002004310 4.2.6.8.1-6	The number of colors should be limited to those that can be easily distinguished.
EPRI 3002004310 4.2.6.8.1-7	Colors should have adequate contrast and luminance with respect to the surroundings.
EPRI 3002004310 4.2.6.8.1-8	The uses of color as a coding should normally be backed up with another coding method.
EPRI 3002004310 4.2.6.8.1-9	When a user must distinguish rapidly among several discrete categories of data, a unique color should be used to display the data in each category.
EPRI 3002004310 4.2.6.8.1-10	When color coding is used, each color should represent only one category of displayed data.
EPRI 3002004310 4.2.6.8.1-11	Color coding should not create unplanned or obvious new patterns on the screen.
EPRI 3002004310 4.2.6.8.1-12	Colors and color combinations that may cause problems owing to the workings of color vision should be avoided.

According to these criteria a digitally represented system such as the BAC/LR mimics should possess colors that conform to the color meanings that already exist within the associated plant to avoid confusion on previously defined stereotypes. If no pre-existing color associations exist, there is basis to propose an all new color association scheme. Table 4 lists recommended color associations for general nuclear power plants.

Color	Associated Meanings	Attention-Getting Value
Red	Unsafe Danger Alarm State Hot Open/flowing Closed/stopped	Good
Yellow	Hazard Caution Abnormal State Oil	Good
Green	Safe Satisfactory Normal State Open/flowing Closed/stopped	Poor
Light Blue (cyan)	Advisory Aerated Water Cool	Poor
Dark Blue	Advisory Untreated Water	Poor
Magenta	Alarm State	Good
White	Advisory Steam	Poor
Black	Background	Poor

Table 4: Color Association Recommendations (NUREG 0700)

A common mistake among nuclear power plants is to overuse and/or misuse color within designs. A typical issue that arises among these plants is that color is not the sole discriminator of important status conditions. The same color is often used for multiple purposes. For example, a saturated red is meant to indicate alarms statuses but the same color is also used to designate various equipment indications (open/charged) which minimizes its overall significance.

2.5.2 Design Philosophy for use Of Color

The following contains the overall design philosophy for the use of color for a digital system.

1. The design should adopt a dull screen approach, using muted shades of grey for static display elements and reserve color for dynamic display elements.
2. Color coding may be used in rare circumstances where distinguishing between different display elements supports operation and would be challenging using shades of grey. The display should use muted colors for this type of color coding
3. The display should use saturated color only to identify abnormal operating conditions that require operator intervention.

This philosophy challenges the stereotypical nuclear red/green color schemes for determining the status of a valve or pump. Instead of using a saturated red and green to indicate the status of a pump; this design philosophy suggests using a white/gray color scheme.

2.6 HSI Navigation

NUREG/CR-6690 defines navigation as "*the access and retrieval of a specific aspect of the HSI, such as a display or control*. *Navigation may include accessing a single display page from a network of display pages or accessing a specific item from within a display page, when manipulations of the display system are necessary"* (p. 86)

2.6.1 Background and Technical Basis for HSI Navigation

The information architecture also influences the navigation scheme, and the hierarchy presented in Figure 2 can also serve as the basis for the structure of the HSI and the plant information interfaces, which then form the top of the hierarchy, as shown in the diagram. This means it can also serve as the basis for the navigation scheme implemented in the HSI.

Industry best practice suggests that a good navigation scheme would provide a visual metaphor relevant to the system to enable the operator to navigate effortlessly in and between the following information spaces:

- plant layout
- processes
- systems and components

Suitable navigation metaphors may range from abstract diagrams (for example process maps or functional flow block diagrams), to realistic representations of components.

A good visual navigation scheme would provide a way for the operator to seamlessly step backwards to the previous space or state. Wherever possible, the design should allow the operator to step backwards multiple steps, or provide a way to navigate directly to a checkpoint of the operator's choice.

As always, navigation metaphors must be tested for comprehensibility and communicability. Usability tests should reveal the following (see NUREG-0700, section 2.5.1.2-3 and section 8.3.2-3):

- Shortest path between two points (e.g. screens)
- Availability of a direct path to the main display from all screens
- Overview of the main architecture
- Traceable path ("breadcrumbs") on all displays

Table 5: Navigation Literature References

Source	Comments
O'Hara, J. et al. (2008) "*Human Factors Considerations with respect to Emerging Technology in NPPs",* Brookhaven NL. See Section A.7.9.8 and A.7.9.9, p. 134	This report addresses the issue of mental models and display organization, with specific reference to the navigation of display networks. The implementation of this concept is reflected in the "topology" described in ANSI/ISA-101.01. It emphasizes the importance of making the information architecture of the HSI visible

	and to provide it as a secondary means for the operator to access specific information easily.
NUREG/CR-6690 Vol 2 (2002) "*The effects of interface management tasks on crew performance and safety in complex, computer-based systems*", p. 86	This report emphasizes the importance of a rational spatial organization of information in a specific display in particular, and in the whole HSI in general. The design must enable operators to rapidly find information using perceptual skills similar to those used when scanning a natural environment. See p. 87 of the report for more.
Inductive Automation: "*Design like a Pro: Building better HMI Navigation Schemes*" Online webinar	It is recommended that everybody view this webinar. It explains in simple terms the common features of usable navigations schemes, starting with two typical information hierarchies: Narrow and deep – fewer links, more clicks Broad and shallow – more links, fewer clicks The presentation further explains the balance between the two approaches. It also offers one of the few design recommendation with a technical basis – eye tracking studies were conducted to derive layouts and navigation schemes that match users' mental model. The presentation also emphasizes the importance of affordance – making the intended action very clear in the design of objects, e.g. making clickable/touchable objects very obvious. It is also important to make a clear distinction between navigation and content. See https://inductiveautomation.com/resources/video/design-pro-building-better-hmi-navigation-schemes

2.6.1 Design Philosophy for HSI Navigation

1. HSI navigation should be presented in a logical manner that follows the information architecture and the mental model of the operators. The following is a conceptual scheme for accessibility and visibility of different display types:

Table 6: Operator Displays

Display Number	Display type	When	Options
1	Plant Overview Display (Critical Performance Parameters)	Always (this is vital for situation awareness)	Any one (full screen) or a combination of two of the following: 1. Dynamic State Transition Diagram 2. Plant Signature Diagram 3. Simplified Plant Mimic
2	High-Level Process Information (System Overviews)	All plant states from refueling to full power	Any one of the following: 1. Primary loop (Rx, RCS, SI, SFP, etc.) 2. Secondary Loop (S/G, FW, etc.) 3. Turbine-Generator Control 4. Reactor Control 5. Other System Overviews (e.g. CVCS)
3	Detail System & Process Information	All system states from shutdown to full power	Any SSC performance information, with faceplates as required.
4	Annunciator	Always (while DCS active)	Any two of the following: 1. Alarm tiles (more than one display page as required) 2. Alarm list (scrollable) 3. Event history (scrollable)
5	Operator Support	All states (while DCS active)	Any of the following: 1. Navigation display 2. Operating Procedures (graphical and text) 3. System drawings (P&IDs, process flow, layouts, etc) 4. Technical manuals (Operating Technical Specifications, Maintenance manuals, etc.)
6	Equipment Protection System Display	Always	(Out of scope for LWRS control room modernization)

2. Access to displays one level above or below the current level in the hierarchy should be no more than one action (e.g., click or keystroke) away.
3. All available functionality in the display should be continuously visible or no more than one action away.
4. Accessing the highest level display in the hierarchy should be no more than one action away.
5. The display shall provide a visual representation of the main navigation architecture for overview.

2.7 Controls

The current modernization plan expects to remove 60% of current analog controls and indications off the control boards and replaced by soft controls on workstations. Changing input devices requires careful attention to how controls are organized in relation to their component counterpart, communicate to operator what actions may be taken, and to the range and precision required for a control action. Further considerations include those related to performance metrics such as speed, accuracy, and economy of physical and cognitive workload. The majority of guidance here is a replication of the guidance found in NUREG-0700 section 3.1.1 Control Design Principles. Note, while the principles provide information as to the result of the control design, not all provide direction toward achieving such a result. One example is principle NUREG 0700-3.1.1-6 *Speed* states "A control should provide rapid positioning of cursors or selections of choices" without defining how to do so, the word "rapid", or what priority *Speed* is in relation to other design principles when trade-offs must be considered. As the modernization process matures, further investigation into how best to apply the following principles adding more concrete definition to them may be required to develop a technical basis for decision making.

2.7.1 Background and Technical Basis for Controls

Controller characteristics. The proposed method for component control is a mouse pad and keyboard located at either or both a workstation where the operator may sit down and at the control boards were redundant control systems may be located. The location within the control room as well as the equipment selected is based on best practice and ergonomically sound principles taking into consideration frequency, duration, and precision required of the physical tool to interact with the system.

Controller component relationship. A clear link between a control faceplates and the component of interest is necessary for accurate control interaction. A single spatial designation for all controller faceplates means highlighting the component being controlled with clear noun names, and equipment identifications on both the controller faceplate and equipment for redundant checks that controller matches the intended component. If a non-spatially designated area faceplate is used then both highlighting and proximity to component of interest is used as well as equipment identifications to confirm matching controller and component. If a control screen is more appropriate to a system then the system and all equipment controllable from the control screen is disambiguated from equipment not accessible from the current control screen. Equipment identification numbers and noun names will still be present and associated to each controller by proximity.

Controller faceplate content. A controller faceplate simultaneously represents all available control options to the operator when visible. All current settings, values, set points, equipment status, are available on the controller faceplate. Any content that does not aid equipment identification or control status and range is not included on the faceplate to avoid clutter. The controller faceplate also contains information related to availability of the equipment. If a piece of equipment is offline, the information should be presented alongside the controls.

Controller display area. The control display should be placed where it does not occlude the information needed to gain feedback from the current control actions. Furthermore, it should either disappear or be placed where the control faceplate does not impede long-term monitoring of the system.

Error prevention or correction. Equipment statuses are available at various display levels to feedback control action consequences to operators to ensure proper operation. All component controls will be continually accessible to change or alter a setting if an improper input or action was taken previously.

Control Availability. All controls on a system control screen are continuously available though not always present. Faceplates are accessible through intuitive interaction with components such as clicking the component requiring a control action. However, if the display containing the equipment information related to the control is not responding , the control should also not be available from that particular workstation.

Initiating action. Actions to control equipment are clearly distinguishable from actions that navigate HSI interfaces. Furthermore, the synchronizing of at least two actions must occur for each control action. Since a mouse is the primary tool for interaction hovering and clicking over the desired control must occur before a change in the system state does. Simply hovering may provide more information but cannot be sufficient for a control action. Some control actions may require three movements such as hovering, clicking, and dragging.

One control action for a complex sequence. Using a soft interface introduces the capability to automate a sequence of related actions initiated by a single control action. If appropriate and necessary to do so, the sequence of actions is clearly defined on the HSI and viewable from the operators position at the controller. The current action being performed by the automation is shown and visible to operator from the position at the controls. At any time, the automated actions can be halted unless doing so risks plant or operator safety.

Intuitive control actions (0700). Control movements should conform to population stereo types. NUREG-0700 section 3.1.1-16 provides a descriptive figure of how a control action may influence the system. Despite the figure referring to hard knob controls, the same stereotypes are applicable to soft control sliders and button organization.

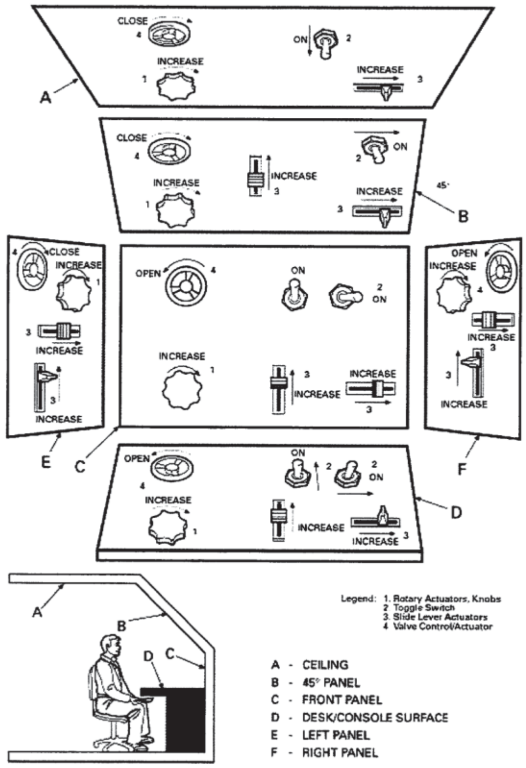


Figure 3: Controls Diagram

The technical basis of the control design philosophy is not always rooted in empirical findings suggesting the current philosophy is best practice. Challenges such as conflicting philosophy in specific situations will be met with critical approaches to determine how best to manage trade-offs in favor of the safest, most effective and efficient soft control design in a control room.

2.7.2 Design Philosophy for Controls

1. Controls should be presented within operational context (e.g. highlight equipment on overview or mimic display)
2. All available or routinely used functions for control of equipment or components should be continuously visible or a maximum of one click away
3. Controls faceplate should be designed such that the relevant information related to operating eth equipment is not obscured by the control faceplate.
4. Where ideal locations for control faceplates cannot be consistently identifies, control faceplate should appear on the screen in a manner that minimized the distance an operator needs to move the control to ensure it does not obscure
5. Controls should provide unambiguous feedback on the status of the equipment and related information such as current set points for control parameters

2.8 Integrated Displays

Integrated displays show multiple types of information (equipment status, alarm indications, etc) within the same space versus showing these types of information on separate screens to eliminate the practice of having to search in multiple places to determine relevant plant information (NUREG 0700).

2.8.1 Background and Technical Basis for Integrated Displays

The amount of information presented in a control room has the potential to overload an operator. An integrated display is designed to help lower the workload associated with obtaining useful information from the abundance of data in a control room. Table 7 contains applicable guidance derived from NUREG 0700 and EPRI 3002004310 pertaining to integrated displays in nuclear power plants for a digital control system.

Table 7. Guidance related to integrated displays

EPRI 3002004310 4.2.4.1-5	When displays are partitioned into multiple pages, function/task-related data items should be displayed together on one page. Relations among data sets should appear in an integrated display rather than partitioned into separate display pages.
NUREG 0700 1.2.10-1	Integral formats should be used to communicate high-level, status-at-a-glance information where users may not need information on individual parameters to interpret the display. Additional Information: Since integral displays do not display individual parameters, they are most appropriate for general status monitoring.6633

According to these criteria an integrated display should contain all task-related information within the same space to avoid causing the user to repeatedly toggle between multiple pages and remember information from one page while viewing another in the midst of performing a single task. Integrated displays are also meant to show high-level plant status at a glance where a user might not need specific parameters of each piece of equipment to comprehend the display.

2.8.2 Design Philosophy for Integrated Display

1. Displays should integrate or aggregate data for the operator wherever possible.
2. Displays should be designed to eliminate or minimize the need for mental calculation or retrieval of details from memory.
3. Displays should contain all information for the safe operation of a system including information from related systems if there are system dependencies that must be considered by the operator.

2.9 Use of Graphics

Graphics can be broadly defined as data that is specially formatted to show spatial, temporal, or other relations among data sets (i.e., see NUREG-0700, Rev.2). A *graphical display* is typically used to present graphics through pictorial representation of the object or data set.

2.9.1 Background and Technical Basis for Use of Graphics

There are various formats of graphical displays, including: Bar Charts and Histograms, Trend Graphs, Pie Charts, Flowcharts, Mimics and Diagrams, Maps, Integral and Configural Displays, and Graphic

Instrument Panels. NUREG-0700 1.1-1 provides guidance on selecting the appropriate display format, which should be based on the tasks the user will perform (see Figure 44). The ultimate benefit of using graphics (when used properly) is to present the data in a way that supports the operator performing informed actions or immediately detecting changes in plant conditions without having to perform other interface management tasks (NUREG-0700 1.1-14).

Table 1.1 Display formats for representative user tasks

Representative Task	Format	Condition for Appropriate Use
Comprehending Instructions or General Descriptions	Continuous Text	General
	Lists	Series of related items
	Speech Displays	User's attention not directed toward text display
	Flowcharts	Sequential decision process with no tradeoffs
Examining and Comparing Individual Numerical Values or Text	Tables	Detailed comparisons of ordered sets of data
	Data Forms	Detailed comparisons of related sets of data items from separately labeled fields
Examining Functional Relationships of Components of a System	Mimics and Diagrams	General
Examining Spatial Relationships of Objects or Places	Diagrams	General
	Maps	Geographical Data
Examining and Interpreting Patterns in Numerical Data	Bar Charts	Single variable viewed over several discrete entities or at discrete intervals
	Histograms	Frequency of occurrence viewed at discrete intervals of a single variable
	Pie Charts	Relative distribution of a single variable over several categories
	Graphs	Two or more continuous variables
	Graphs: Scatterplot	Spatial distribution of data within a coordinate system

Figure 4: Display Formats for Representative Tasks. Adopted from NUREG-0700 Rev. 2 Table 1.1.

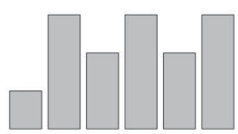
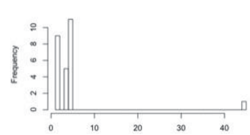
Graphical display conventions should be consistently (NUREG-0700 1.1-2) represented across displays and be displays consistent to the standards and conventions familiar to the users at hand (NUREG-0700 1.1-3). Graphical elements should have a one-to-one relationship with the plant entity/state that it represents (NUREG-0700 1.1-5). For instance, a change in a graphic should only be associated with one interpretation. Graphics should be presented at the level of abstraction necessary for operators to accomplish their goals (NUREG-0700 1.1-6) and also readily perceivable without ambiguity (NUREG-0700 1.1-7). The methods to which lower level data are analyzed to product higher-level graphical information should be understandable to users where access to the rules of their computations are readily accessible (NUREG-0700 1.1-8 & 1.1-9).

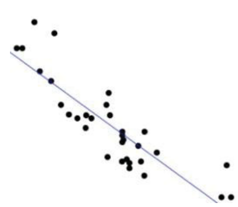
Display pages containing graphics should be presented with the simplest information consistent with their functions (NUREG-0700 1.5-6); information irrelevant to the task should not be displayed. Likewise, displays should be uncluttered as much as possible. NUREG-0700 1.5-8 suggests display packing density (i.e., or the amount of space in pixels used to present information) not exceed 50-percent.

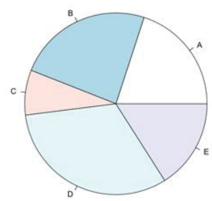
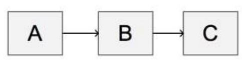
Specific design guidance for each type of graphical format can be traced in NUREG-0700 and EPRI 3002004310. See

Table below.

Table 8: Design Applications, Considerations, and Applicable Guidance for Specific Graphical Formats.

Graphical Format	Suggested Application and Considerations	Applicable Guidance	
		NUREG-0700 Rev. 2	**EPRI 3002004310**
Bar Charts and Histograms	*Bar Charts* are graphical figures that represent numeric quantities via the linear extent of parallel bars (i.e., horizontally or vertically). Bar charts are used to compare magnitudes of limited number of items on a single scale.  *Example of generic bar chart* *Histograms* is a type of bar chart that depicts a frequency distribution for a continuous variable.  *Example of generic histogram*	Section 1.2.4	Section 4.2.5.5
Graphs	A *graph* is a display that depicts values of one or more values with respect to another variable. *Line graphs* are a type of graph where one or more variable (y-axis – process value) is visualized over another variable (x-axis – time).	Section 1.2.5	Section 4.2.5.6

Graphical Format	Suggested Application and Considerations	Applicable Guidance	
		NUREG-0700 Rev. 2	EPRI 3002004310
	 *Example of generic line graph* A *linear profile chart* forms the upper boundary of a polygon by shading the area from the horizontal axis to the line. Linear profile charts are useful if recognizable contours are associated with specific conditions.  *Example of generic linear profile chart* *Scatterplots* visualizes the relationship between two variables (e.g., pressure as a function of temperature). The x-axis typically is not necessarily an indication of time. Data points are typically not connected as a line graph.  *Example of generic scatterplot*		
Pie Charts	*Pie charts* present relative proportions of a variable (i.e., the whole) in a circular format. Pie charts should be used with caution since they [1] do not provide means of absolute judgment, [2] cannot represent values greater than 100%, and [3] only represent a fixed point in time. Further, EPRI 3002004310 suggests that	Section 1.2.6	Section 4.2.5.7

Graphical Format	Suggested Application and Considerations	Applicable Guidance	
		NUREG-0700 Rev. 2	EPRI 3002004310
	estimates of relationships are better served with linear formats (see Bar Charts and Graphs).  *Example of generic pie chart*		
Flowcharts	*Flowcharts* illustrate the sequential relations among elements or events, typically visualized with boxes and arrows.  *Example of generic flowchart*	Section 1.2.7	Section 4.2.5.8
Mimic Displays and Diagrams	A *mimic display* combines graphics and alphanumeric characters to integrate system components into functionally oriented diagrams. See Section 2.4 of this document. *Diagrams* are special forms of a picture where the details are only shown to the extent necessary for completing a task. For example, diagrams might be used to represent an electrical wiring scheme. In this case, only the wiring would be presented, leaving out unnecessary details like other systems (e.g., plumbing).	Section 1.2.8	Section 4.2.5.9
Maps	*Maps* are graphical representations of an area or space (e.g., layout of a room).	Section 1.2.9	Section 4.2.5.10

Graphical Format	Suggested Application and Considerations	Applicable Guidance	
		NUREG-0700 Rev. 2	EPRI 3002004310
Integral and Configural Displays	*Integral displays* present information in an integrated format where individual parameters used to comprise the display are not represented in it. For example, an icon may be used to display the status of a system. The icon would change based on computational changes in lower-level parameters (i.e., which are not explicitly presented). *Configural displays* present the relationships among parameters as an 'emergent feature.' An emergent feature can be defined as a global perceptual feature (e.g., shape) produced by the interactions of many lines, contours, or shapes (i.e., denoting the individual parameters). Hence, configural displays provide both lower- and higher-level information. In the example below, several lower-level parameters are combined to form a polygon. A uniform shape may denote normal conditions whereas a change in the shape live below may indicate an abnormal condition. See Section 2.9.  *Example of generic configural display*	Section 1.2.10	Section 4.2.5.11
Graphic Instrument Panels	*Graphic instrument panels* provide graphical representations of the instruments in a control panel. These formats are best used when the user must verify that a parameter is within	Section 1.2.11	Section 4.2.5.12

Graphical Format	Suggested Application and Considerations	Applicable Guidance	
		NUREG-0700 Rev. 2	EPRI 3002004310
	range. Other techniques such as bar charts will better serve tasks such as comparing a value to another parameter or standard. Exact value reading is better served via numeric readout.		
Icons and Symbols (General)	*Icons* and *symbols* provide non-verbal representations of objects, states, characteristics, or actions. Icons and symbols are typically used to save space and support users in process visual representations through providing distinctive and easily recognizable representations. Icons and symbols are best represented when they are familiar to users, easily discriminable from each other, right-side up, and simple (i.e., without unnecessary detail).	Section 1.3.4	Section 4.2.6.4

2.9.2 Philosophy for Use of Graphics

4. The format of graphics should be selected based on the goals of user's tasks. Hence, design input from users should be collected to determine the appropriate graphical format for various data used in operations.
5. The selection and format of a display format should be consistently applied across display pages. For example, the rationale for selecting the use of a line graph should be consistent across display pages. The formatting of the line graphs should also be consistent (e.g., design of scales, axes, use of color, etc.) across displays.
6. Graphics should be presented in a way to which they are readily perceivable without ambiguity; the relationship of lower-level to higher-level information should be understandable to users.
7. The display should present simplified graphics and only present detail necessary to perform tasks. No unnecessary or gratuitous detail, such as 3D depiction of tanks or other equipment, should be used
8. No animation should be used to represent normal system states. Animation or flashing may be used to temporarily capture an operator's attention under abnormal conditions, but should be removed once the condition has acknowledged or resolved.
9. Guidance from applicable documents such as NUREG-0700 and EPRI 3002004310 should be considered where appropriate. Design tradeoffs between conflicting guidance (e.g., minimizing interface management tasks such as navigation versus minimizing visual clutter) should be documented and remediated through design activities such as tradeoff studies and

tests and evaluations throughout the course of the HSI Design process (see EPRI 3002004320 3.8.3.4).

2.10 Alarms

Alarms and alarm systems comprise a very large body of knowledge that cannot be covered comprehensively in this short review. For the purpose of the human factors aspects of control room modernization R&D planned for the current and upcoming phases, only the most significant issues were identified. These included:

- Current state of the art and industry best practice
- Alarm philosophy
- Alarm standards and guidelines

2.10.1 Background and Technical Basis for Alarms

Alarm: an alarm in a nuclear power plant is a visual and/or auditory signal that serves to call attention to, or alert a human to an impending or existing adverse condition in a system or in the environment.
Alarm System: a device or basic operator support system for managing abnormal situations and it has the following two functions:

1. The primary function of the alarm system is to notify human operators of out-of-parameter conditions that could threaten equipment, the environment, product quality and, of course, human life. The warning function helps the operator control the future behavior of a complex plant by attracting attention to undesired process conditions.
2. The secondary function of the alarm system is to serve as an alarm and event log that supports the operator's need to analyze the events that have led to the current or previous process conditions.

Thomas et al. (2010 **Error! Reference source not found.**) stated that Alarm Management/Event Diagnosis has become a key priority for U.S. nuclear power plants. It has become a pressing need to "*…replace the current alarm systems (annunciators, alarm logs, status lights, bi-stable indications, etc.) with an event diagnostic system and an audible announcement capability for plant events (as opposed to alarms based on symptoms). A system such as this would more quickly take operators to the needed recovery actions (if not automatically executed) relative to the time it now takes to work through symptom-based procedures. An intelligent alarm system could also prioritize alarms, presenting critical alarms for the given event and suppressing inconsequential alarms, to reduce the information overload on the control room*."

This remains an important vision that is likely to form a key component of the modernization strategies of utilities and it is with this vision in mind that INL intends to embark on an exploration of first-principle research for modern alarm system presentation. It is anticipated that lessons learned from current best practice in other industries will be an important contributor to human factors research under the control room modernization project of the II&C pathway.

Numerous alarm system design and management guidelines have been developed over the past thirty years. All of them reflect differences in the maturation of alarm system concepts across industries. Process industries still appear to rely heavily on EEMUA 191 guidelines from the Engineering Equipment and Materials User Association and the ANSI/ISA 18.2 standard. In contrast, the nuclear industry has relied exclusively on NUREG-0700, which provides only superficial guidance, since it was never meant to be a design guide for industry.

A short review of the available literature is provided in the table below. Close examination of the available standards and guidelines reveals that none could be considered exhaustive. The process industry guidelines tend to focus more on the management and procurement of alarm systems, while the nuclear industry tends to focus on the HSI components. These guidelines were written for different audiences, which means designers should consider using combinations of all of the relevant guidelines to best address their unique requirements.

INL researchers preparing to embark on alarm system prototyping and human performance evaluations should keep in mind that the available literature was produced by subject matter authors who have, at best, performed heuristic evaluations of existing alarm systems. Other authors may have considered the design of new alarm systems utilizing technology available at the time. Although advances have been made in the design of alarm system components, the quantity and quality of literature appears somewhat disproportionate to the rapidly evolving technological possibilities. The situation is exacerbated by the fact that, in spite of the excellent work done by the Abnormal Situation Management (ASM) Consortium and standards organizations, little research has been performed to evaluate how the new systems affect operator performance.

Operating experience continues to demonstrate the effects of false alarms and operator workload, but the last 15 years of research in human response to alarm has been relatively limited, leaving many issues unaddressed. Alarm management remains an area of concern in complex system design, but it is possible to learn from the years of experience other industries have gained working with a continually maturing alarm technology and avoid its mistakes and leverage its successes.

With extended life ahead of them and the inevitable obsolescence of exiting systems, asset owners and plant operators are looking to modernize their instrumentation and control systems. The control room modernization project has created a unique opportunity to address the human factors challenges of new alarm systems. However, researchers will find that there is no one size fits all design standard for NPP control rooms. Instead there are general principles that should be understood, controlled and optimized in every control room. These principles are covered extensively in the literature referenced below, but the main objective of the planned research is still to develop technical bases, or at least provide some empirical evidence, for the most salient aspect of modern alarm system design.

The following concepts are extracted from an alarm specification developed for a gas-cooled reactor (Hugo, J. (2008). "Alarm System: Human Factors Requirements Specification." PBMR (Pty) Ltd.). These concepts were based on a combination of company policy, engineering judgment, industry best practice, and established standards and guidelines:

- The alarm system shall be explicitly designed to take account of human factors and limitations. The design should ensure that the alarm system remains usable in all process conditions, by ensuring that unacceptable demands are not placed on operators by exceeding their perceptual and cognitive capabilities.
- Perceptual factors - there are limitations on the ability of the human brain to take in information. The perception of information requires a certain amount of time, and we can only hold about 7±2 units of information at the same time. (For example, having to remember an equipment ID number approaches the upper limit of working memory). Because of this it is important that, for all credible accident scenarios, the designer should demonstrate that the total number of safety related alarms and their maximum rate of presentation does not overload the operator.
- Cognitive factors - when several units of information can be combined into one single meaningful representation (i.e. an aggregated alarm), the brain capacity required for handling this particular information will be reduced, and the brain will be able to handle more information effectively. The brain also has other facilities that helps increase the capacity of perception, which can be

supported by information that is intuitively understood and pattern recognition in the information presented. (For example, displaying alarms in a 3 x 3 visual pattern helps the operator to exploit his pattern recognition abilities and thus to recognize the nature of the alarms at a glance).

- Actions - any claims made for operator action in response to alarms must be based upon sound human performance data and principles. The alarm system should be adapted to the operator's defined tasks, identified and described through systematic task analysis.
- The alarm system should be context sensitive - alarms should be designed so that they are worthy of operator attention in all the plant states and operating conditions in which they are displayed.
- The alarm system must be properly documented, and clear roles and responsibilities must be established for maintaining and improving the system.
- Performance requirements to the alarm system should be defined to ensure that the alarm system is useful to the operators in all relevant operational situations. To meet the requirements performance monitoring should serve as input to the process of improving the alarm system.
- There should be an administrative system for handling access control and documentation of changes made to the alarm system. The administrative system should prevent unauthorized modifications to the system and ensure that all changes are traceable and properly documented.
- The alarm system must be fault tolerant - a fault tolerant system ensures that safety critical information is always available to the operators, both in normal operation and in emergency situations.
- System response time must not exceed 2 seconds. Short system response times are essential for the system to remain useful in critical situations with high demands on operators.
- Safety critical functions should be identified and documented. Status information and failure alarms from these functions should be clearly presented and continuously visible on dedicated displays. If safety critical functions are degraded or threatened, operators should be immediately alerted due to the possible consequences of such failures.
- Status information related to safety system functions, such as blocking/inhibit and override, must be easily available on dedicated lists and in process displays.
- Every alarm that is triggered should require acceptance - the operator should be required to accept each alarm to confirm that the alarm message has been read and understood. An alternative practice is that the operator will accept an alarm only when the associated response has been carried out. The operation and alarm philosophy should describe whether an alarm should be accepted after it has been read or after it has actually been dealt with.
- Navigation in alarm displays should be quick and easy - this is to support effective operator response to alarms by allowing quick navigation to additional information. For example, it should be possible to navigate from the alarm lists to the process display where the alarm is shown. A minimum number of operator interactions should be required to do this. It should also be possible to interrogate (e.g. right-click) an alarm in any display to get more information about it, such as alarm response procedures. Table 9 presents a summary of relevant literature for the alarm design philosophy.

Table 9: Alarm Literature References

Source	Comments
ANSI/ISA-18.2-2009 "*Management of Alarm Systems for the Process Industries*" International Society of Automation	This standard addresses the development, design, installation, and management of alarm systems in the process industries. Although it does not specifically mention the nuclear industry, all of the terminology,

	principles, methods and best practices are applicable to the design of alarm systems in NPP control rooms. The focus of the standard is primarily on improving safety, quality, and productivity through the design of high performance alarm systems. The general principles and processes in this standard are intended for use in the lifecycle management of an alarm system based on programmable electronic controller and computer-based HSI technology. The standard provides detailed definitions and descriptions of common alarm system concepts, including, for example, alarm philosophy, alarm flood, setpoints, acknowledging, deadbands, shelving, suppressing, chatter, nuisance alarms, alarm overload, etc.
EEMUA 191 "*Alarm Systems, a Guide to Design, Procurement, and Managemen*t", Engineering Equipment and Materials Users Association	This document is still the most the most widely used reference worldwide.
Hollifield, B. & Habibi, E. (2006) "*Alarm Management Handbook*", PAS	This book is the most authoritative source on the practical and proven methods to optimize the performance of alarm systems. It derives much of its content from EEMUA 191 and provides some of the theoretical and technical background for what has widely become regarded as industry best practice, for both older alarm systems and more advanced digital systems. The book itself focuses primarily on the design of alarm systems based on modern DCS-based control systems. Although it is not specific to the nuclear industry, the principles apply to any implementation in the NPP control room. The book also emphasizes the importance of developing an Alarm Philosophy to serve as the basis for the seven steps of alarm system design: 1. Develop, Adopt and Maintain and Alarm Philosophy 2. Collect data and benchmark the systems being upgraded 3. Perform "bad actor" alarm resolution 4. Perform alarm documentation and rationalization 5. Implement alarm audit and enforcement technology 6. Implement real time alarm management 7. Control and maintain the improved system
NUREG-0700. See section 4, p. 251*ff*	This guideline explains the difference between the functional and physical aspects of the alarm system, as well as all important characteristics of a well-designed alarm system, including concepts like filtering, grouping, shelving, suppressing, prioritizing, nuisance alarms, etc.

	It is recommended that this section be read together with ANSI/ISA-18.2
NUREG/CR-6105 (1994), "*Human Factors Engineering Guidance for Advanced Alarm Systems*"	This guideline was superseded by NUREG/CR-6684 and later by NUREG-0700 (see above).
NUREG/CR-6684 (2000), "*Advanced Alarm Systems: Revision of Guidance and its Technical Basis*"	This report provides a review of literature available by the publication date (2000) and is therefore already outdated. However, it provides a useful reference for the basis of many alarm system design practices that have now become industry best practice. NUREG-0700 has more detailed HFE guidelines for implementation of alarms.
Braun, C., Grimes, J. and Shaver, E. (2011) "*A Human Factors Perspective on Alarm System Research and Development 2000 – 2010*". Benchmark Research & Safety, Inc.	This report was produced as result of the authors' collaboration with INL human factors staff on developing alarm system requirements for control room modernization. The report is an excellent review of the state of the art, the human factors challenges, and implications for future NPP control rooms. An extensive list of references is provided.

2.10.2 Design Philosophy for Alarms

1. Alarms should be used to identify abnormal operating conditions and only interrupt operators when there is an immediate action that they must take.
2. Alarms should be presented alongside guidance for operators on appropriate actions that should be taken in response to the alarm.
3. Alarms should not be used to identify normal operating conditions. Alarm set point should reflect the current operating condition of the plant under routine operation.
4. Parameters or equipment that are in an alarm state should highlighted on any overviews or system mimics.
5. Alarms should not be used for information only alerts. Information that does not require an immediate operator action or provide operationally relevant information should not produce and alarm.
6. Alarms presented on a list should be prioritized and should provide the operator with and easy methods of searching and sorting based on priority.

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