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A REVIEW OF HUMAN-SYSTEM INTERFACE DESIGN ISSUES OBSERVED DURING ANALOG-TO-DIGITAL AND DIGITAL-TO-DIGITAL MIGRATIONS IN U.S. NUCLEAR POWER PLANTS

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A REVIEW OF HUMAN-SYSTEM INTERFACE DESIGN ISSUES OBSERVED DURING ANALOG-TO-DIGITAL AND DIGITAL-TO-DIGITAL MIGRATIONS IN U.S. NUCLEAR POWER PLANTS

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ABSTRACT

The United States (U.S.) Department of Energy (DOE) Light Water Reactor Sustainability (LWRS) program is developing a scientific basis through targeted research and development (R&D) to support the U.S. nuclear power plant (NPP) fleet in extending their existing licensing period and ensuring their long-term reliability, productivity, safety, and security. Over the last several years, human factors engineering (HFE) professionals at the Idaho National Laboratory (INL) have supported the LWRS Advanced Instrumentation, Information, and Control (II&C) System Technologies pathway across several U.S. commercial NPPs in analog-to-digital migrations (i.e., turbine control systems) and digital-to-digital migrations (i.e., Safety Parameter Display System). These efforts have included in-depth human factors evaluation of proposed human-system interface (HSI) design concepts against established U.S. Nuclear Regulatory Commission (NRC) design guidelines from NUREG-0700, Rev 2 to inform subsequent HSI design prior to transitioning into Verification and Validation. This paper discusses some of the overarching design issues observed from these past HFE evaluations. In addition, this work presents some observed challenges such as common tradeoffs utilities are likely to face when introducing new HSI technologies into NPP hybrid control rooms. The primary purpose of this work is to distill these observed design issues into general HSI design guidance that industry can use in early stages of HSI design.

Key Words: control room modernization, human-system interface design, human factors engineering, NUREG-0700 review

1 INTRODUCTION

As domestic energy demands continue to grow, it will be important that the existing United States (U.S.) commercial nuclear power plants (NPPs) continue to operate beyond their current 60-year operating life. Moreover, the continued safe and economical operation of these existing the U.S. NPPs is a lower-risk option that can be used to meet the domestic energy demands at a fraction of the cost compared to building new NPPs. The U.S. Department of Energy (DOE) Light Water Reactor Sustainability (LWRS) program is developing a technical basis through targeted research and development (R&D) to support the U.S. NPP fleet in extending their existing licensing period and ensuring their long-term reliability, productivity, safety, and security. The LWRS provides a technical basis through multiple R&D pathways. The Advanced Instrumentation, Information, and Control (II&C) System Technologies, addresses concerns with long-term aging of the existing instrument and control (I&C) technologies through development, demonstration, and testing of new first-of-a-kind I&C technologies.

The Idaho National Laboratory (INL) has played an integral role in this effort for several U.S. NPPs by serving as an expert resource in the application of human factors engineering (HFE) for planned main control room (MCR) upgrades. These upgrades can be categorized into either analog-to-digital migrations or digital-to-digital migrations. In the last few years, INL has supported three major utilities in analog-to-digital migrations for both boiling water reactors (BWRs) and pressurized water reactors (PWRs), with a variety of systems such as Boric Acid Blender, Charging Flow Control, Pressurizer, Reactor Coolant Pumps (RCPs), Steam Dump, Residual Heat Removal (RHR), and Turbine Control System (TCS). In addition, INL recently supported a utility with digital-to-digital migration of a plant process computer and safety parameter display system (SPDS). All analog-to-digital and digital-to-digital migrations entailed implementation of a new human-system interface (HSI) to be integrated on the MCR control panels.

It is worth noting that there are definite advantages with modernizing various NPP plant systems such as a turbine control system (TCS) from legacy analog to new digital technology. For example, legacy analog indications and controls (I&C) often unreliably convey plant state where gauges can become stuck in the wrong position and light-emitting diode (LED) bulbs can burn out [1]. It is worth noting that availability of replacement legacy I&C can be expensive and even limited [2]. There is also very little integration of key information from analog I&C, so operators cannot take advantage of emergent features for quick monitoring of the plant at a glance. Essentially, operators must integrate the individual analog I&C throughout the MCR during monitoring operations, which places additional cognitive burden on them. Further, older digital technology may not utilize the most current HFE design guidance. For instance, the SPDS was introduced in the early 1980's to address human factors deficiencies identified after Three Mile Island (TMI) [3, 4]. During this era, digital technology had technical limitations with human factors implications that are no longer as relevant with today's digital technologies. These technical limitations include but are not limited to refresh rates, usage of color, screen resolution, touch screen input, and use of automation.

The inclusion of new digital technology for analog-to-digital and digital-to-digital migrations can address these concerns and limitations described. As U.S. NPPs begin upgrading to new digital technologies such as advanced displays and automation, the HFE support provided by INL will ensure that these technologies do not introduce any new failure modes, while also optimizing operator performance across normal, abnormal, and emergency conditions. To this end, it should be recognized that the U.S. Nuclear Regulatory Commission (NRC) includes HFE as a major component [5] in supporting overall plant safety through providing 'defense in depth.' This view of HFE as an important contributor to plant safety became notable through studies of the TMI, Chernobyl, and other NPP accidents where human factors deficiencies such as poor control design, procedures, and training were significant contributors to these NPP incidents and accidents. The NRC hence expects that the applicants (e.g., NPP utility) integrate a HFE program into the NPP upgrades that will:

- Ensure HFE is integrated into the development, design, and evaluation of the plant,
- Provide HFE products such as HSIs that facilitate safe, efficient, and reliable performance of operations, maintenance, tests, inspections, and surveillance tasks, and
- Reflect state-of-the-art human factors principles ([5], p. 2).

These expectations set by the NRC were addressed in INL's HFE efforts of analog-to-digital migrations and digital-to-digital migrations through:

- Providing design recommendations early in the development cycle,
- Accounting for operator performance and preferences through a human-centered approach including tests and evaluations with licensed NPP operators, as well as
- Using state-of-the-art HFE design guidelines from the U.S. NRC's *Human-System Interface Design Review Guidelines* (NUREG-0700, Rev. 2) [6].

This paper presents the overarching HFE design issues that were identified from INL's HFE technical analyses using state-of-the-art HFE design guidelines from NUREG-0700 [6]. These overarching HFE design guidelines may be used to guide the design of HSIs for utilities that are deciding to upgrade their existing MCR technologies with advanced displays. As described in NUREG-0711 [5], one of the Verification and Validation activities conducted by the NRC entails Design Verification using a style guide or NUREG-0700. In addition, this work presents some observed challenges such as common tradeoffs utilities are likely to face when introducing new HSI technologies into the NPP MCR.

The goal of this paper is to summarize generalizable HFE design guidance that can be used early in the development process of new HSI displays, to ensure that these new technologies are designed to accommodate the operator's perceptual, cognitive, and physical capabilities. The HFE design guidance presented here are specific to the *visual display characteristics* (e.g., use of color) and *static display characteristics* (e.g., button size) of advanced HSI displays that are relevant to human performance. While this guidance is not comprehensive to HFE of new digital technologies, it is worth noting that the guidance from this paper can generally be applied very early in the development process, when only static displays are available. Potential applications of guidance may be used as an initial HFE checklist to verify that the prospective HSI displays conform to state-of-the-art HFE design principles. This early feedback can help refine the design of the HSI when changes are less costly as compared to later efforts.

2 SELECTION OF NUREG-0700 GUIDELINES

A total of three DOE-sponsored HFE reports, each prepared for different utilities, were used in this review. All reports comprised a technical HFE analysis, using NUREG-0700 guidelines (i.e., refer to [6]), to evaluate the HSI displays that were intended for implementation into the NPP MCRs. These technical analyses entailed systematically evaluating each static HSI display against a NUREG-0700 guideline to determine if the guideline was met or not met. Since distribution of these reports was limited, the HSI design guidance provided in this report has been sanitized to include no proprietary information.

A total of 135 NUREG-0700 guidelines were used from the three technical HFE analyses. These guidelines comprised the following sections of NUREG-0700: (1) *Information Display*, (2) *User-Interface Interaction and Management*, (3) *Controls*, (4) *Alarm Systems*, (5) *Safety Function and Parameter Monitoring Systems* (e.g., SPDS), and (6) *Soft Control Systems*. '*Information display*' is described as HFE guidelines that capture visual aspects of various display elements (e.g., color, data forms, graphs, labeling, mimic displays, trends, etc.). '*User-interface interaction and management*' is described as HFE guidelines that capture the interaction between plant personnel and the HSI such as navigation, entering information, system messages, and prompts. 'C*ontrols*' is described as HFE guidelines that capture aspects such as information entry, display control, information manipulation, and display-control integration. Additionally, '*Alarm Systems*', '*Safety Function and Parameter Monitoring Systems*' (e.g., SPDS), and '*Soft Control Systems*' present system-specific guidance. Table I summarizes the number of unmet guidelines identified from these NUREG-0700 sections.

Table I. Summary identified NUREG-0700 selected and unmet guidelines.

NUREG-0700 Sections	Unmet (n=38)	Met (n=97)	Total (n=135)
Information Display	35	65	100
User-interface interaction and management	0	16	16
Controls	1	1	2
Alarm Systems	0	9	9
Safety Function and Parameter Monitoring Systems	1	2	3
Soft Control Systems	1	4	5

These 38 unmet guidelines serve the basis for the design guidance provided in this paper. As such, these guidelines were grouped into mutually exclusive categories to summarize how these guidelines apply to specific HSI display elements, which correspond to NUREG-0700. Additionally, these unmet guidelines where categorized by HFE priority level. The priority level is intended to show the relative effect each finding potentially has on the plant personnel performance when interacting with the HSI. However, these ratings were not completed with a formal risk assessment and are intended for general guidance. The scale was defined as follows:

- *High*:* A serious condition that impairs the operation, or continued operation, of one or more product functions and cannot be easily circumvented or avoided. The software does not prevent the user from making a serious mistake. The usability problem is frequent, persistent, and affects many users. There is a serious violation of standards.
- *Medium:* A non-critical, limited problem (no data lost or system failure). It does not hinder operation and can be temporarily circumvented or avoided. The problem causes users moderate confusion or irritation.
- *Low:* Non-critical problems or general questions about the product. There are minor inconsistencies that cause hesitation or small aesthetic issues like labels and fields that are not aligned properly.

Fig. 1 summarizes how these 38 unmet guidelines were grouped into design guidance categories by priority level. Illustrations of 'High*' priority guidelines are provided for each following section where they were identified.

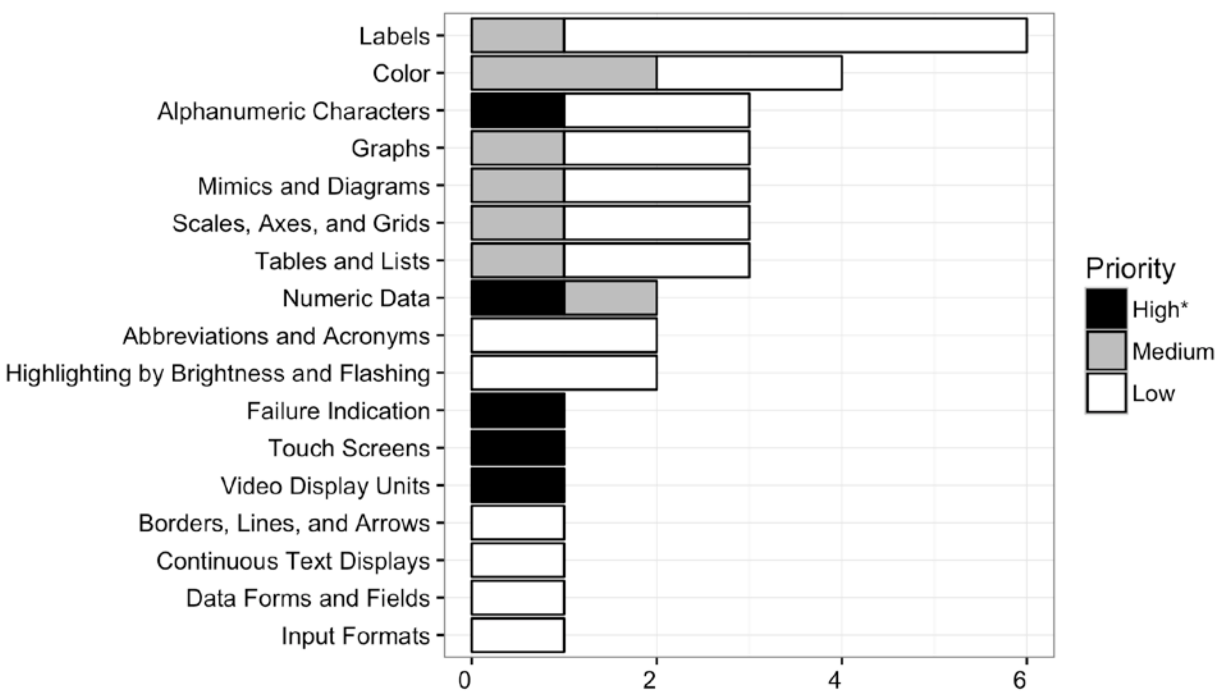

Figure 1. Frequency of unmet guidelines for each guidance category coded by priority.

3 HSI DESIGN GUIDANCE

3.1 Labels

Common unmet guidelines for Labels on HSI displays concerned (1) lacking of group labels, (2) inconsistent labeling formatting, (3) inconsistent placement of labels, (4) inconsistent wording of labels, (5) inadequate label separation, and (6) lacking of normal label orientation. Having group label offers an additional cue to help differentiate groups of information (e.g., collection of related I&C) from other groups. Lacking group labels presents a risk of making groups of information less distinguishable from other groups of information. It is also important to ensure labels are consistently formatted, located, and worded. Inconsistencies with label formatting (e.g., presenting some labels italicized and some not) and placement (e.g., presenting some data group headings as left-aligned and others centered) can negatively impact visual search and create confusion over the information hierarchy of the display. Similarly, inconsistently worded labels can create human error traps to which user may misidentify important information. Finally, labels must be legible in order to be effective. The lack of adequate label separation and normal orientation for reading can reduce legibility.

Applicable guidelines from NUREG-0700: 1.1-2 (Low), 1.3.3-1 (Low), 1.3.3-3 (Low), 1.3.3-4 (Low), 1.3.3-6 (Low), and 1.3.3-7 (Medium).

3.2 Color

Common unmet guidelines for the use of color pertained to (1) lack of conservative use of color, (2) selection of non-discriminable colors, (3) lack of unique color assignment, and (4) use of red-green color combinations. Color is an effective method used to support rapid detection, tie information together spatially separated information, as well as convey important information (e.g., plant state). However if not implemented conservatively, excessive use of color reduces its effectiveness to support these qualities and can create unnecessary visual clutter to a display. Common violations of this design guideline were observed with HSI displays that use high contrast colors for non-critical information (e.g., static labels), which take away conspicuity of key plant indications.

Also if color is used to convey important information, selection of colors should be discriminable from each other. For example, an indicator that changes from orange to red would be less discriminable then an indicator that changes from grey to red. Any given color used on the HSI display should be used for a single category of data. For example, using the color red to convey alarms and valve or breaker status is not recommended unless there is strong reason in doing so (e.g., accepted plant conventions). Finally since a small percentage of the population is red-green colorblind, solely using red-green color combinations should be avoided. One way to meet this guideline is to use a redundant cue such as location or a label; for example, breaker or valve status conveyed through a red-green color combination should also include other way of visually representing its status such as with a label (e.g., Open/ Close) or by design an indication that uses location too (i.e., the traffic light analogy).

Applicable guidelines from NUREG-0700: 1.3.8-1 (Medium), 1.3.8-7 (Low), 1.3.8-8 (Medium), 1.3.8-12 (Low).

3.3 Alphanumeric Characters

Common unmet guidelines when displaying alphanumeric characters pertained to (1) the presentation of text that was too small (i.e., < 16 minutes of arc), (2) use of only upper case characters when presenting text to be read, and (3) too large of a inter-character spacing when presenting words or abbreviations. When presenting important information (e.g., plant parameters), the font size should be large enough to be legible given consideration of operational context. NUREG-0700 suggests that text be at least 16 minutes of arc for adequate legibility, which is a function of viewing distance and font size. That is, the perceived font size of the text presented to the user will vary based on how far away he or she is viewing the text from, as well as how large the font size being used is. From an operational standpoint, a smaller font may be appropriate if the operator is expected to view this information from directly at the control board compared to indicators that need to be legible from all areas of the control room. Careful consideration of the operational context is needed when determining adequate font size, as presenting information that is illegible can create human engineering deficiencies depending on the importance of that information. The first equation is from NUREG-0700, and is used to express the relationship of viewing distance in inches (D) with suggested minutes of arc (MA) at 16 to determine font size (H) in inches. The second equation provides a way to solve for MA if one has font size (H) and viewing distance (D).

$$H = 6.283D(MA)21600 \tag{1}$$

$$MA = [(H/6.283)/D]21600 \tag{2}$$

Fig. 2 illustrates how these parameters from the equations above apply to evaluating legibility with a particular font size provided an intended viewing distance.

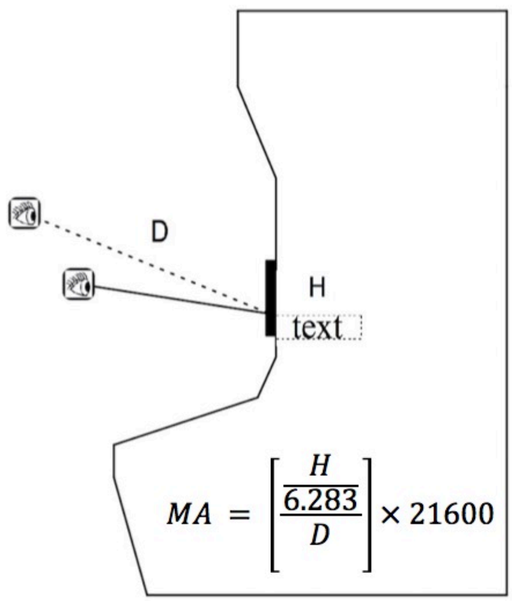

Figure 2. Illustration of how font size is measured to evaluate legibility.

Secondly when presenting text that is to be read (e.g., text bodies in paragraph form), the conventional presentation of mixed upper/ lower case is suggested to optimize readability. However, this recommendation is not applicable for the design of labels or text that is intended to gain the user's attention. It should be noted that older video display units (VDUs) were limited in resolution, which posed legibility problems with lower case text. With today's VDU technology such as use of liquid crystal displays (LCDs), lower case text can be presented without these legibility concerns as the resolution to these VDUs are capable of adequately presenting letter descenders. Finally, inter-character spacing (e.g., the spacing between each letter within a word or abbreviation) should be no larger than 65 percent of the font's character height. When characters are spaced too far apart, it can negatively impact readability of labels.

Applicable guidelines from NUREG-0700: 1.3.1-1 (Low), 1.3.1-4 (High*), and 1.3.1-7 (Low).

3.4 Graphs

Common unmet guidelines regarding the design of graphs pertained to (1) failure of displaying numerical values within graphs when precise reading was required, (2) lack of highlighting significant curves for limit bands and (3) lack of target area definition by defining X- and Y-axis labels. Presenting information numerically reduces risk of perceptual errors accompanied with analog displays if precise reading is required. As display real estate allows, a combination of graphs with numerical values is recommended. The latter two issues regard potential human factors concerns resulting from the absence of explicit information. That is, failing to provide differentiation between limit bands when appropriate or eliminating axes labels places burden on the operator to rely on their own knowledge for sensing making of the graph.

Applicable guidelines from NUREG-0700: 1.1-35 (Low), 1.2.5-6 (Medium), and 1.2.5-14 (Low).

3.5 Mimics and Diagrams

Common unmet guidelines for the design of mimics and diagrams pertained to (1) use of an unnecessary level of graphic detail, (2) lacking identification of component identification, and (3) lacking directional arrowheads to depict flow directions. Mimic displays and diagrams should contain the least amount of detail required to make a meaningful interpretation of its representation. In other words, having too much graphic detail can be distracting and take away the salience of more meaningful information. The read is referred to Hollifield and colleagues, which provides many examples of poorly designed and highly suggested mimic-based HSI displays to reiterate this point [7]. Further as with other types of displays, it is important to ensure that the components presented on mimics and diagrams are adequately labeled so that operators do not need to rely on existing knowledge for component identification. Similarly, mimics that present flow directions should be explicitly depicted through directional arrowheads to avoid unnecessary memory reliance of operators. Indeed, providing labeling of components and directional arrowheads can support operators in developing an accurate mental model.

Applicable guidelines from NUREG-0700: 1.2.8-1 (Low), 1.2.8-2 (Medium), and 1.2.8-5 (Low).

3.6 Scales, Axes, and Grids

Common unmet guidelines for the design of Scales, Axes, and Grids pertained to lacking (1) standard intervals for axes, (2) axis labels, and (3) identification of units of measurement. The scaling of graphs sometimes used non-standard intervals (e.g., intervals of 47, 94, 141, etc.). From a human factors perspective, lacking standard intervals (e.g., intervals of 1, 2, 5, or 10) make graph interpretation difficult. Finally, axes of some graphs sometimes lacked labels and their units of measurement. While one may argue that operators should already have knowledge of the variables and their units of measurement being presented on graphs based on their familiarity of the plant, providing explicit labels can reduce cognitive burden of having to rely on memory.

Applicable guidelines from NUREG-0700: 1.3.6-3 (Low), 1.3.6-5 (Medium), and 1.3.6-6 (Low).

3.7 Tables and Lists

Common unmet guidelines for tables and lists pertained to (1) lack of logical organization, (2) lack of row and column labels, and (3) inadequate row separation of tables. Common violations concerning the organization for tables regarded instances where the content was arranged alphabetically or sequentially, as opposed to being arranged by functional importance (i.e., as defined per operator feedback). Feedback from intended users should always be collected in order to verify that the information presented within tables and lists are logically arranged from an operational standpoint. Further, tables provided should contain a uniquely and informatively label that is visually distinct from entries. Creating a distinction for rows and columns helps with navigating large tables. As an example for a template, the Microsoft Excel spreadsheet convention using letters for columns and numbers for rows is a familiar convention for users. Finally for tables with many rows, there should be a distinctive feature (e.g., such as a line) to aid in horizontal scanning. This guideline is particularly relevant to the design of alarm displays when in a serial list format.

Applicable guidelines from NUREG-0700: 1.2.2-1 (Medium), 1.2.2-3 (Low), and 1.2.2-7 (Low).

3.8 Numeric Data

Common unmet guidelines regarding Numeric Data pertained to (1) displaying information in an unusable format and (2) a need for select HSI displays to provide directional change of indications (i.e., via visual directional arrows) for information that must be rapidly discerned. Information presented on HSI displays should be presented in a format that is readily usable for plant personnel. For example, the units of measurement or scaling of various numerical fields displayed should be in the units that are readily useful for the task; otherwise, information that requires additional mental calculations or conversions create unnecessary cognitive burden and even present risk for human error. Secondly in one instance, critical information (e.g., RAD Release) was presented in a table as discrete values. While this information was useful for operators, it was difficult for operators to judge rate of change. Hence, the addition of directional arrows was suggested to explicitly show the directional change of RAD Release. This guideline nevertheless applies to all information that requires plant personnel to rapidly discern directionality of key information. Fig. 3 illustrates the difference between a usable format versus a unusable format based on a hypothetical procedural step.

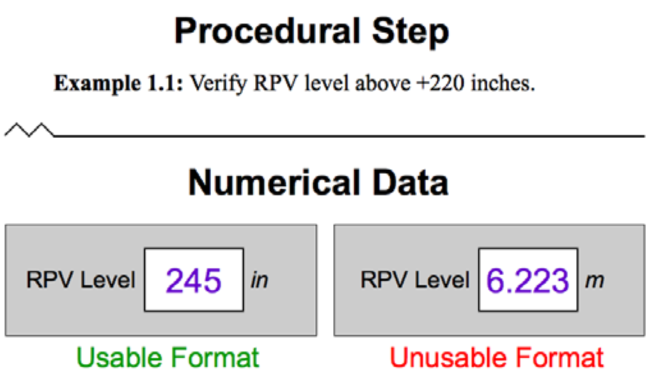

Figure 3. Comparison of a usable and unusable numerical data format.

Applicable guideline from NUREG-0700: 1.1-33 (High*) and 1.3.5-6 (Medium).

3.9 Abbreviations and Acronyms

Common unmet guidelines regarding the presentation of abbreviations and acronyms pertained to (1) use of abbreviations that were uncommon to plant personnel and (2) inadequate distinction between multiple abbreviations when used in a single label. In general, abbreviations should be avoided unless there are space constraints on the display. This is common when presenting labels for various indications and controls. Abbreviations, when implemented, should thus be familiar to plant personnel. During analog-to-digital and digital-to-digital migration, carrying over previous abbreviation terminology is suggested to ensure proper terminology such as abbreviations is familiar. Additionally, utilities can access NRC *Collection of Abbreviations*, NUREG-0544 Rev. 4 and Rev. 5 [8, 9], as a resource for common abbreviations used throughout the industry. Lastly when multiple abbreviations/ acronyms are provided in sequentially to each other such as when in a label, each abbreviation/ acronym should be separated from each other so that they are distinctive to improve readability. For example, ‘Steam Generator A’ is more clearly conveyed through ‘SG-A’ then ‘SGA.’

Applicable guidelines from NUREG-0700: 1.3.2-1 (Low) and 1.3.2-3 (Low).

3.10 Highlighting by Brightness and Flashing

Common unmet guidelines regarding highlighting by brightness and flashing pertained to (1) overuse of highlighting (i.e., color) for non-critical information such as static labels and mimic components and (2) inconsistent use of highlighting information throughout the HSI displays. While the use of color is effective in attracting attention, its usefulness has diminishing returns when it is overly used. For instance, the attention gaining quality of color such as when presenting an alarm can be reduced and become ineffective if a display carelessly applies colors to ancillary information (e.g., low priority information, static labeling, mimic components, etc.). Per NUREG-0700, a display should limit highlighting (e.g., via color) to 10% when presenting normal conditions. As such, use of high contrast colors against background can increase the amount of highlighting and should be avoided for information that does not lend itself to immediate action. Finally, a particular highlighting method that is used should be executed throughout the HSI consistently. In some instances indications of various parameter states were presented inconsistently throughout, which creates additional cognitive burden on operators by required them to remember rule exceptions of certain indications based on differences in the way they present plant status.

Applicable guidelines from NUREG-0700: 1.3.10-2 (Low) and 1.3.10-3 (Low).

3.11 Failure Indication

One issue for Failure Indication concerned a SPDS system that did not have trending capability for presenting certain plant information identified from operator feedback. Trends support situation awareness by explicitly providing parameter status in relation to historical information; this information can be invaluable when magnitude of change is important. Fig. 4 illustrates how use of trending can provide explicit (i.e., visual) historical data of various indications in relation to current state. This data can be used to depict the magnitude of change for important parameters.

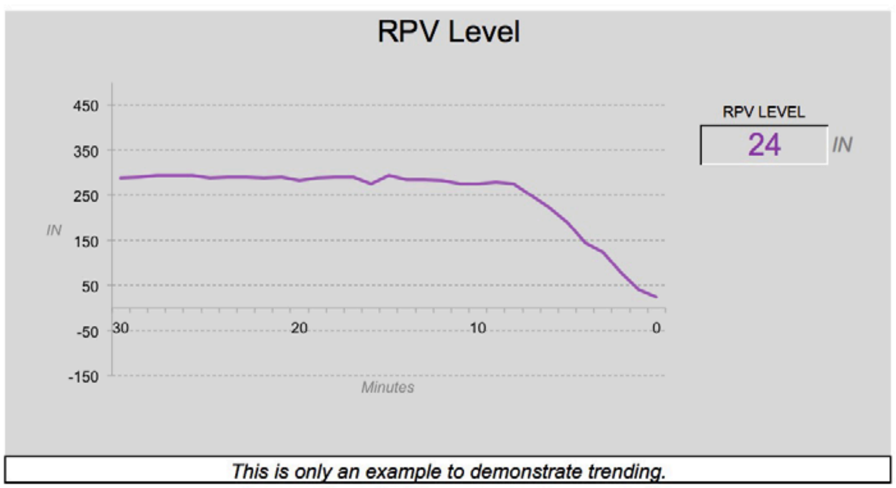

Figure 4. Illustration of a trend to support situation awareness.

Applicable guideline from NUREG-0700: 5.1-10 (High*).

3.12 Touch Screens

One issue for Touch Screens concerned inadequate touch zone spacing and size when touch interaction was a primary mode of interaction. NUREG-0700 suggests that touch zones of buttons be at least 0.6 inches high and long, while being spaced at least 0.1 inches apart to allow for adequate space to press. For important controls (e.g., turbine speed control), inadequate button size or spacing can create risk of inadvertent option selection. It should be noted that inadequate button size could result from scaling down various HSI displays to fit smaller VDUs. That is if a standard HSI display template was designed for a 22 inch VDU, the presentation of the very same display on a smaller VDU (e.g., 19 inch) may create touch zone problems if the buttons are scaled proportional to the other display elements. In these cases, careful consideration of redesigning these HSI displays to smaller VDUs must be considered. With enlarging the sizes of buttons on a display, there is a tradeoff of how much information can be adequately presented on any single HSI display. Fig. 5 illustrates how touch zone (i.e., button) height and length can be measured, as well as spacing.

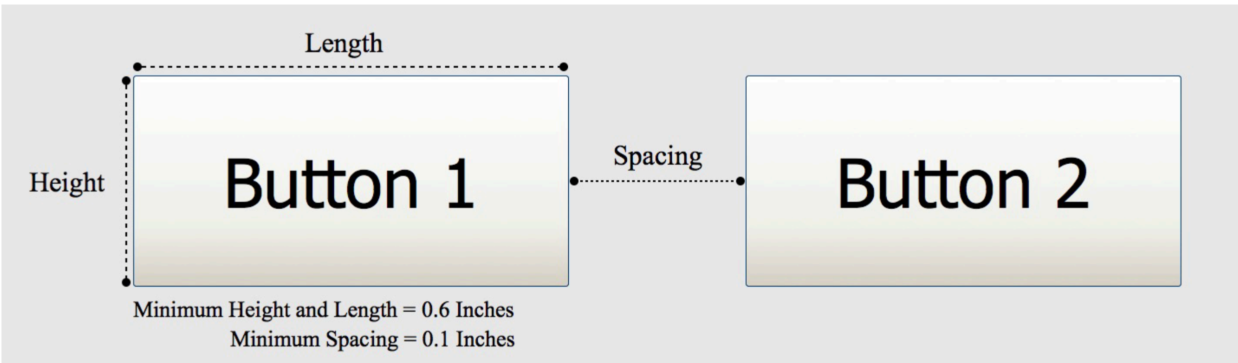

Figure 5. Measurements of touch zone size and spacing.

Applicable guideline from NUREG-0700: 3.2.4-10 (High*).

3.13 Video Display Units

One issue for Video Display Units concerned a lack of adequate luminance contrast between displayed information (e.g., plant parameters) to its background. To no surprise, other HSI research identified color contrast as a common ergonomic design principle violated [10]. Insufficient contrast can lead to poor readability resulting in potentially misreading critical information. A minimum of a 3:1 contrast ratio is recommended, and contrast ratios above 7:1 are optimal for readability. The color combination using black on white provides the absolute highest contrast ratio of 21:1.

Fig. 6 illustrates contrast ratios for three colors (i.e., Yellow, Green, and Black) over a light gray background (i.e., Hex #E8E8E8). The solid red horizontal line depicts the minimum contrast (i.e., 3:1) while the black dashed horizontal line depicts the preferred contrast (i.e., 7:1). Values above these thresholds show that the color has met a contrast threshold. In general, labeling and important information should use darker colors if using a light gray background. It should be emphasized that changing the background to a dark color (e.g., black) is not advised, as other human factors issues such as fatigue and glare are common with negative polarity color combinations. A final point worth mentioning is that care should be taken when choosing colors for various types of information. The most important information should have the highest luminance contrast (e.g., contrast ratios above 7:1). Ancillary information may yield a lower contrast, but should meet the minimum.

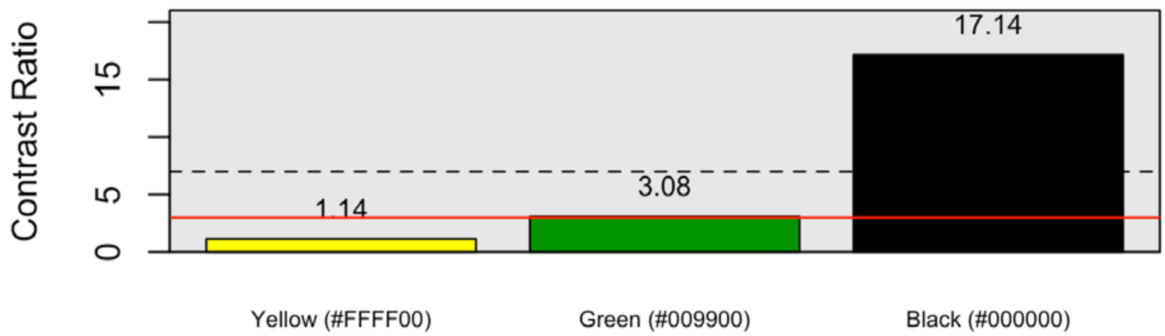

Figure 6. Luminance contrast ratios for colors yellow, green, and black over light gray background.

Applicable guideline from NUREG-0700: 1.6.1-2 (High*).

3.14 Borders, Lines and Arrows

One issue for Borders, Lines, and Arrows concerned groups of data that did not contain a border to improve readability. In other words, the use of borders around groups of information is one way to group related information so that they can easily be distinguished from unrelated information.

Applicable guideline from NUREG-0700: 1.3.7-4 (Low).

3.15 Continuous Text Displays

One issue for Continuous Text Displays concerned text that was inadequately vertically spaced between subsequent lines. NUREG-0700 suggests that inter-line spacing be at a minimum two stroke widths or 15% of the character height. If line spacing is not too close, then the text may be less readable and cluttered.

Applicable guideline from NUREG-0700: 1.2.1-16 (Low).

3.16 Data Forms and Fields

One issue for Data Forms and Fields concerned the presentation of data group labels that were not centered over its group. While this concern is relatively low priority, the centering of labels over groups can provide a way to adequately present information hierarchy. That is, centering group headings can help plant personnel better distinguish these labels from other labels such as ones linked to indications.

Applicable guideline from NUREG-0700: 1.2.3-16 (Low).

3.17 Input Formats

One issue for Input Formats concerned unclear selection options for discrete controls due to poor labeling (i.e., symbol use). Generally, symbols should be coupled with a text label to optimize meaningfulness. If there is limited space for a label, the meaningfulness of select symbols should be verified with plant personnel.

Applicable guideline from NUREG-0700: 7.2.4-2 (Low).

4 CONCLUSIONS

This paper presents 38 unique guidelines from NUREG-0700 [8] observed as being unmet when reviewing the previous HFE technical evaluations of both analog-to-digital and digital-to-digital migrations. These technical evaluations were all conducted as early design feedback to help improve the HSI by ensuring state-of-the-art HFE guidelines and operator feedback were incorporated. Hence, the state of these HSIs evaluated was very low fidelity (i.e., static displays) and were used to support design improvement concurrently throughout the development lifecycle, as opposed to a final-stage evaluation of these HSIs. The intent of presenting these guidelines is to offer future utilities interested in CRM practical guidance to some of the most frequent human factors issues observed to consider when designing HSIs. These findings are particularly useful in very early stages of the CRM process; although, guidance from this paper should not be a sole resource for HFE integration to CRM efforts. Additional resources such as NUREG-0700 [6], NUREG-0711 [5], and recent Electric Power Research Institute (EPRI) *Human Factors Guidance for Control Room and Digital Human-System Interface Design and Modification* (i.e., 4002004310) [11] are strongly encouraged to comprehensively integrate HFE into the CRM process.

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