AN ELECTRONIC INSTRUCTION MANUAL AND CHECKLIST FOR STEAM BOILER START-UP

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Development of an electronic user manual/checklist for a steam-generating power plant boiler start-up is described. Human factors guidelines for development of effective instructional materials were reviewed. Subject matter experts (experienced operators at the power plant) were used to gain requisite knowledge in the procedures and tasks involved in start-up of a steam boiler. Functions of the main components in the power plant and boilers were studied in relevant literature. The new manual/checklist includes description of the system components as part of operative actions and separate actions are arranged into categorical groups, each associated with informative headings. Flowcharts are used to guide users through complex procedures and pictures of critical plant components are provided. All sentences to explain actions are simple and have fewer than 20 words. Several operators have checked and proofread the new manual multiple times and agreed that its contents are accurate and error-free.

INTRODUCTION

The Abbott Power Plant on the University of Illinois at Urbana-Champaign campus is currently undergoing a major modernization effort. The old controls located at each boiler and the series of master alarms in the main control room are being replaced by digital control technology and centrally located boiler control interfaces. Eventually, the entire plant will be controlled from the control room, with little need for the operators to walk to individual boilers or turbines. Compared to the old human-machine interfaces (HMI) in the plant, the digital control system and its HMI represent a quantum leap in usability and operator safety and comfort. However, managing such a large amount of information on a single, 17-inch CRT screen may initially be difficult for the operators. To support transition to the new HMI an electronic manual and checklist was created for boiler start-up procedures. The old manual, which showed how to operate the boilers in a text form, was reviewed for shortcomings and improved upon in the new manual, which was created independently from the original manual.

The new manual considered both novice users (such as operators in training), who need a fuller explanation of procedure in order to effectively learn boiler control tasks, as well as experienced operators, who may benefit from support materials while transitioning to the new control system. The new manual was constructed entirely as a hypertext document, which will allow it to be accessed through any of the computer terminals in the plant, either at the control room or by the boilers on the plant floor.

THESIS

The old manual started with the description of the main components of the power plant, such as economizer, lower drum, steam drum, boiler water wall tubes, superheater, and burners. The description alone was difficult to understand without knowing the operative actions, even for expert operators. This order of the presentation tended to make readers skip the overly technical and poorly worded description, which may have led to errors due to the lack of necessary background knowledge. In the "Operation" section of the original manual, too much information was presented without logical sequencing. For example, under the heading of "Startup of Gas Burner," the original manual contained 22 sequences of actions without sufficiently descriptive headings or thorough explanation of the relevance of the required actions. The language used in the original manual was often difficult to understand and several of the procedures utilized over 200 words to explain a single action. Such excessive use of language violated the guideline that instructive sentences should be simple and easy to comprehend (Wright 1977). An additional difficulty with the original manual was a lack of visual depictions of the required actions or the materials involved in the procedure. In complex environments, visual aids assist operators by identifying vital controls and components of the boilers. Although domain-specific technical and instructive manuals must use jargon to represent names of equipment, lack of pictures and explanations made it impossible to know what a given component was, where it was located, and how it was to be used without extensive training.

SOURCES

Veteran operators at Abbott found the original manual to be of little help. Instead, they often developed work-around or personalized procedures instead of maintaining adherence to the out-of-date procedures. In order to increase safety through procedural standardization and to ease the transition to an unfamiliar and complicated digital control system a new manual was needed. Creation of the manual involved two distinct processes: (1) a comprehensive review of the human factors literature for guidelines related to developing effective instructional materials, and (2) gaining knowledge of the procedures and tasks involved in the start-up of a steam boiler. The process of gaining knowledge of power plant operation

was facilitated by consulting with the most experienced operators at Abbott power plant. They provided walk- and talk-throughs of every step in the procedures. To augment their explanation, the functions of the main components in the power plant were studied in relevant literature (e.g., Woodruff, Lammers, & Lammers, 1998) and associated with procedural steps. Gordon, Schmierer, and Gill (1993) and Gordon, Kinghorn, and Schmierer (1991) provided useful strategies for transferring expert knowledge into a manual. Additional materials were found to assist in (1) creating flowcharts or other visual aids (Booher, 1975; Kammann, 1975; Kontogiannis & Linou, 2000; Krohn, 1983; Moore & Gordon, 1988; Rodriguez, 2000), (2) general guidelines for procedural creation (Stern, 1984; Wright, 1977), as well as (3) design of web-based applications (Bernard & Chaparro, 2000; Gordon & Lewis, 1990; Hillinger & Leu, 1994; Lacy, Chignell, & Kinnell, 1998). Finally, the new manual was evaluated by experienced operators at the power plant for usability.

FINDINGS

Forms of Instructions

Current human factors literature indicates that the inclusion of tables, flow charts, and checklists facilitates the comprehension and processing of instruction (Wright, 1977) though they are less versatile than prose. When there is only one critical component to a decision, tables are the most efficient way to display the information. However, as the number of decision criteria increases, flow charts decrease decision making time. Unfortunately, designing a flowchart is often difficult, especially when the decisions operators are required to make are not binary. Further, Kammann (1975) found that experienced users were faster to do a task using flowcharts than prose instructions. Checklists are more versatile than tables or flowcharts, but require more time for operators to process and initiate.

Visual aids

Visual aids, such as graphs and illustrations, help users to understand instructions (Wright, 1977). Several investigations support this ascertation. For example, Stern (1984) found that instructions with both text and graphics were faster for users to find a successful action, caused fewer number of errors, and led to a higher completion rate than instructions with only text or only graphics on an ATM task study. Stern (1984) also compared the performance among the instructions with single mode, either graphics alone, text alone, or voice alone. Instructions with voice alone or text alone allowed for faster task completion and caused fewer errors than instructions with graphics alone. Voice alone led to slightly better performance than text alone. Booher (1975) found that instructions with pictures alone were faster to make users correctly complete a task than instructions with words alone but caused more errors than instructions with only words. To overcome this trade-off, Booher put explanatory words besides the pictures in the redundant combination model. The results showed that the redundant instructions with both main explanation by pictures

and complimentary explanation by concise words was as fast for users to correctly complete a task as instructions with pictures alone, and as less error-prone as instructions with words alone. Further, Hillinger and Leu (1994) studied pictorial instructions with pop-up screens (called "guide windows") on computers. Their participants (novice graduate students) showed better comprehension of the content of the instructions when the computer showed them pop-up screens with relevant information than when instructions with all information were in one page with no pop-up screens, highlighting the importance of manner and timing of presenting relevant instructional information.

However, these guidelines are not entirely uncontroversial. Rodriguez (2001) insisted that pictorial instructions without texts could be more accurate and faster than instructions with both pictures and texts and offered 8 rules to improve pictorial instructions to make them faster to understand and cause less error. These rules were stated by Rodriguez (2001) as follows: (1) parsing rule: "Divide the information into logical, uncomplicated sections;" (2) object of focus rule: "Specify the subtask to be performed;" (3) location rule: "Show general then specific location;" (4) grasping point rule: "Show where to hold & touch objects;" (5) action rule: "Show required action;" (6) motion rule: "Show movement of objects;" (7) sequence rule: "Show most efficient order to perform tasks & actions;" and (8) feedback rule: "Show the expected outcome of each action." It is impossible to compare the two studies by Rodriguez (2001) and Stern (1984) because they used different tasks. Rodriguez used a single purpose task of printer set-up, while Stern used a more complex task of withdrawing money from ATM. Our conclusion is that pictures in instructions can improve understanding and be more precise with certain rules, but that complicated tasks might also need explanation by text along with pictures

Headers

In addition to the types of form of instruction, Wright (1977) suggested the use of effective, good headings that are informative and have Arabic numbering if necessary. Headers improve reading speed, help readers to integrate information, and make information-search easier. Since readers do not always read entire documents, headers should be informative enough to tell readers which paragraphs are important for them. Integrating information with similar topics also helps readers understand the information effectively. Many cognitive psychology theories support that meaningful connections help memory retrieval. The same thing can be said in instruction comprehension. Bernard & Chaparro (2000) found that people preferred and comprehended better with categorical menus than alphabetical menus on instructions. Consequently, informative headers help readers integrate and comprehend information.

Sentences

Sentences should be simple (Wright, 1977). One or two propositions per sentence are usually sufficient. Sentences with a large number of propositions (such as: "George got into an argument with Harry, hit him, and then left the bar;" Carroll,

1999) are more difficult to understand than those with a small number of propositions. Moreover, sentences should employ active rather than passive voice, and use the affirmative rather than negative. Positive words (such as "more") are easier to understand than negative words ("less"), which require more processing. Also, contingencies (such as "if" and "then") and qualifications (e.g., "except") tend to slow down reading speed (Wright 1977). Carroll's (1999) data showed that complicated sentences took readers more time to comprehend than easy structure sentences, as the latter presumably reduce burden on working memory.

Transfer of Expert Knowledge

According to Gordon, Schmierer, & Gill (1993), the reason why many instructions are so difficult to read is that their writers are usually not professional writers but machine operators. Hence, such instructions violate many human factors principles (Wright, 1977). Further, the authors have established a technique to re-write operator-made instructions utilizing the principles that are so commonly violated. Their results showed that jargon-free instructions were comprehended more accurately and faster than operator-made instructions. Moore and Gordon (1988) presented some techniques to elicit abstract knowledge from subject matter experts using conceptual graphs. Besides established techniques to build conceptual graphs, such as free recall, sorting, and ordering, Moore and Gordon (1988) also introduced a new technique, a question probe method, in which an interview asks SMEs three general types of questions to elicit their knowledge. These questions were (1) definitions (what is ___?), (2) reasons for the action taken, and (3) the manner in which the action is to be completed. These questions help to clarify expert's abstract knowledge and make instructional materials easy for less experienced users to understand.

Gordon and Lewis (1990) have since refined the usage of conceptual graphs. Since concepts are linked to each other like nodes and lines, the model of conceptual graphs is similar to hypertext links on the web. Exploiting this similarity, Gordon and Lewis (1990) offered to apply hypertexts to instructional manuals, linking conceptually relevant ideas together. Gordon, Kinghorn, & Schmierer (1991) further developed the use of conceptual graphs. While they tried to elicit expert knowledge from SMEs, they also tried to find rules underlying the expert's knowledge, based on Rasmussen's (1986) SRK framework (skill-, rule-, and knowledge-based processing).

Fonts

Unformatted text is comprehended most quickly (Wright, 1977). Other formatting styles, such as italic, all capital, bold, etc., tend to slow reading speed by as much as 10%. Hence, these styles should be used infrequently so that emphasis is gained without slowing down the reading speed. Both small (6 points or smaller) and large font (12 points or larger) also decrease reading speed (Wright, 1977). However, current innovations in printed materials and computer displays must also be taken into account. Six to eight point font may have been considered legible on print materials at the time of

Wright's (1977) original research. Unfortunately, fonts of that size are too small to read on computer display due to their lower resolution compared that of print materials. General printers have resolution of 600 dpi (dots per inch) or higher while current LCD displays have only 86 dpi. Therefore, when instructions are shown on computer displays, font sizes should be bigger than on print materials.

Procedures

In general, procedures exist to specify unambiguously six things (Degani & Wiener, 1997): (1) what the task is, (2) when the task is conducted (time and sequence), (3) by whom it is conducted, (4) how the task is done (actions), (5) the sequence of actions, and (6) what type of feedback is given (callout, actions, etc.). A location procedure context is "procedure information that clarifies the relationship of each procedure step to other procedure steps and to the procedure as a whole" (Ockerman and Pritchett, 2000). This idea of integrating procedural information for the user in order to bring relevance of the procedure into the context of the work has also been supported by Wright and McCarthy (2003). Location procedure context includes four components: (1) Previous actions that have already been completed and occur before the current step in the procedure; these items may be relevant or useful to the user by giving them a context in which the current action must be taken and they serve as a memory aid if the user is interrupted during completion of the task. (2) Following actions identifies the next step in the procedure, so that the user then knows what task comes next and how the current task is to be completed as well as in what state the current task will result. (3) Location indication indicates the current step in the procedure and also gives the user insight into their progress in the task. (4) Forking is information that gives an overview of forks in hierarchical procedures. It also gives information on future and past forks.

Often, users of procedure create "work-arounds" or personalize routines when the procedure is unclear. When questioned, users comment that they deviate from procedure because they do not understand why the procedure has been established. Wright and McCarthy (2003) recently conducted a case study on individualized procedural clarification (i.e., additions) in the pilots Quick Reference Handbook (QRH) by an expert pilot. Of all the entries, 65% fell under two main headings, each with two items. Thirty eight percent of the notations were accounted for by the rationale of "why the procedure is the way it is," and included (1) clarifying the reason for the procedure and (2) additional relevant background systems information. The second heading, "modifications to the actions in the procedure" accounted for 26% of the entries and involved, including (3) addition of extra actions or procedure and (4) alternative procedure or uncertainty about the effectiveness of the current procedure. In terms of Abbott Power Plant, it is important to provide enough background information for infrequently performed steps or unclear information in order to increase the chances of procedural adherence and standardization.

DESIGN OF THE ELECTRONIC CHECKLIST

The design of the electronic checklist for boiler start-up closely followed the guidelines provided by the studies reviewed. A flowchart was chosen as the underlying organizational scheme, since such instructional format is best when procedures are complicated (Wright, 1977; Kammann, 1975). Each step of the flowchart should furthermore consists of two parts, required action and feedback from the boiler or the computer. Each action was defined in two ways: what the user should do and how the user can accomplish it. They are similar to two of the Rodriguez's (2001) Action rule and Grasping Point rule. Providing feedback is consistent with the Feedback rule by Rodriguez (2001) as well. Since illustrations help readers understand the instructions (Wright, 1977, Rodriguez, 2001), the new manual used many pictures of equipments and expected computer screens. Also the new manual used different scales of maps. Users could know general locations first and then find the specific locations of items. We applied the Location Rule by Rodriguez (2001) to show the locations. A screenshot of the manual is presented in Figure 1.
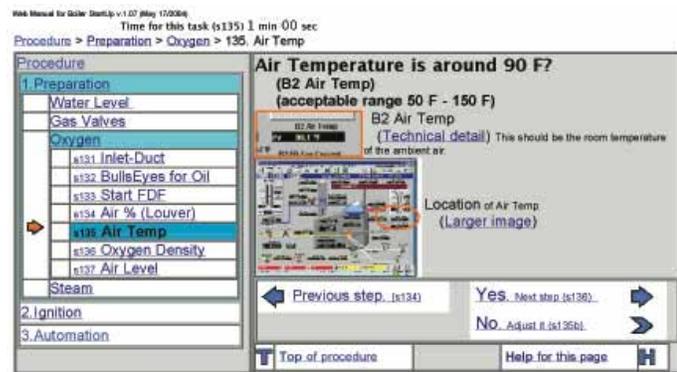

Figure 1. A screenshot from the electronic manual for steam boiler start-up. The overall procedure is always visible at left, while the righ-hand side of the screen describes each separate step. Further details can be brought up by following a hyperlink.

An informative header was attached to each section of the manual, using good Arabic numberings (Wright, 1977). Furthermore, only one set of numbering was used on each page to avoid confusion by similar numberings. Headings also help orient readers to the following paragraphs (Wright, 1977). Applying this insight, a heading page for the entire manual was created in which goals of the power plant were explained. Headers are also important because many readers often merely skim the main point of writing without reading whole paragraphs. Therefore, the amount of the writing in the manual was reduced and less important parts of the instructions and information for advanced users were eclipsed by using smaller fonts or shading with gray color background. This way, users can focus on important actions and the risk of skipping important points should be reduced. In addition, all the actions of the tasks were framed with a black-lined box, so that they

stood out from other text. Bernard & Chaparro (2000) found that categorical menus were better understood than alphabetical-order menus for the main page of web sites. Categorically similar tasks were hence put together, so that the users could picture the flow of the tasks without interference by the other tasks.

To make the categorical flow smoother, we first decomposed the old manual, then rearranged the order of the tasks to the extent that the start-up operation works, applying the parsing rule (Rodriguez 2001). The old manual had 22 separate steps. Since some of these steps had multiple required actions in one step, the total number of the actions was 41. We rearranged the order of those 41 actions and created 9 categories, such as Water Level Preparation, Gas Valves Preparation, Oxygen Preparation, Steam Preparation, Before Ignition, Purge Attempt, Complete Purge, Steam Automation, and Boiler Adjustment. Informative headings were assigned to each of the 9 categories and 41 actions.

Some words were effectively emphasized in the new manual. The sentences of the actions were emphasized with bold, 28-point fonts while less important sentences such as explanation of location or possible alternative actions were shadowed by using small 16 or 18-point fonts.

The checklist closely follows the recommended location procedure context. The main page of the procedure is clearly labeled by the name of the task. Redundancy could be increased by moving the title of the page and subtask into the main window, thus increasing its proximity to the task. This might help decrease working memory load and confusion but also increase clutter. The person conducting the procedure is not explicitly stated in the manual, but this was deemed unnecessary since only one operator at a time generally starts a boiler. The technical details link on every page is useful for experts who are familiar with the task but may need extra information about infrequent events or problems.

EVALUATION OF THE CHECKLIST

The checklist was evaluated by three experienced operators at Abbott power plant. Each operator followed the procedure as presented in the manual and commented on the correctness of the instructed actions. They were also timed for this walk-through, and any errors made in the use of the manual (e.g., incorrect navigation, clicking on wrong icons, etc.) were tallied.

All operators found the manual useful significantly improved over the old manual. In particular, pictures were found very helpful and there were several suggestions for using even more of them. For example, Slide 100 doesn't have pictures, but could use a picture of Sight Glass ("Bull's Eye" with 7 green and red indicators).

The fact that each task was shown on one screen and that the next task emerges on command of the user was found to improve the manual's ease of use. Also, seeing other tasks on the menu while completing one task received favorable comments, helping navigation through the procedure (i.e., location procedure context; Ockerman & Pritchett, 2000).

One particular type of error that was discovered during the evaluation was that one operator kept skipping some tasks by

choosing a task way ahead in the menu on the left-hand side instead of clicking the "next" buttons on the main task instruction screen to move forward to the next step. However, this case appears to be due to unfamiliarity with hypertext navigation, consistent with the results of Hillinger and Leu (1994) who found that old people had a disadvantage on using computer-based manuals. This operator was in his 60s, but also he learned to use the manual perfectly during the relatively short evaluation period.

DISCUSSION

The prototype checklist presented here could be improved in several ways. For example, Byrne (2003) suggested using ACT-R 5.0 modeling software to evaluate procedures and to predict the types of routine error a worker would make before the procedures are implemented. Using such modeling software, errors in procedure can be demonstrated and revised before reaching the workplace.

The procedure for boiler start-up is very specific in terms of how the task is to be completed and in what order. Making procedures more flexible would allow operators to make independent judgment based on situational variables. However, reduced conformity between operators, which may lead to difficulty. Jamieson and Miller (2000) have identified four tradeoffs inherent to procedure creation and writing:

(1) Context Sensitivity vs. Completeness. This tradeoff refers to the difficulty of providing a complete procedure that is but allows for flexibility required by dynamic environments.

(2) Autonomy vs. Reliability. Granting the worker more responsibility in decision-making in order to address the context in which he or she will be working implies that there will be less control over the worker's actions.

(3) Autonomy vs. Co-operation. This tradeoff illustrates that the more autonomy an employee is given the less his or her coworkers will be able to predict his or her behavior and act accordingly.

(4) Autonomy vs. Optimization. If a procedure is left "open" to be context sensitive, then it is less likely to be optimally completed by the employee.

Presently, there is a justifiable need to standardize operators' actions in performing procedures in the Abbott plant as new boiler control interfaces and forms of automation are introduced to operational use. The electronic manual/checklist described here could serve as a means towards that goal. The very favorable comments the operators made about the prototype manual and their willingness to embrace new technology to aid them in their task was indeed encouraging.

REFERENCES

Bernard, M. L. & Chaparro, B. S. (2000). Searching within websites: a comparison of three types of sitemap menu structures. *Proc. IEA 2000/HFES 2000 Congress*. (pp. 441-444).

Booher, H. R. (1975). Relative comprehensibility of pictorial information and printed words in proceduralized instruction. *Human Factors, 17*(3), 266-277.

Byrne, M. D. (2003). A mechanism-based framework for predicting routine procedural errors. In R. Alterman & D. Kirsh (Eds.), *Proc. 25th Annual Conf. of the Cognitive Science Society*. Austin, TX: Cognitive Science Society.

Carroll, David. (1999). *Psychology of Language*, 3rd ed. New York: Brooks Cole

Degani, A., & Wiener, E. (1997). Philosophy, policies, procedures, and practices: The four 'P's of flight deck operations. In N. Johnston et al. (eds.). *Aviation Psychology in Practice* (pp. 45-67). Brookfield: Ashgate

Gordon, S. E., & Lewis, V. R. (1990). Knowledge engineering for hypertext instructional systems. *Proc. 34th HFES Meeting* (pp. 1412 –).

Gordon, S. E., Kinghorn, R. A., & Schmierer, K. A. (1991). Representing expert knowledge for instructional system design. *Proc. 35th HFES Mtg*.

Gordon, S. E., Schmierer, K. A., & Gill, R. T. (1993). Conceptual graph analysis: knowledge acquisition for instructional system design. *Human Factors, 35*, 459-481.

Hillinger, M. L., & Leu, D. J. (1994). Guiding instruction in hypermedia. *Proc. 38th HFES Mtg*

Jamieson, G. A., & Miller, C. A. (2000). Exploring the "Culture of Procedures." *Proc. 5th Int'l Conf. on Human Interaction with Complex Systems* (pp. 141-145).

Kammann, R. (1975). The comprehensibility of printed instructions and the flowchart alternative. *Human Factors, 17*(2). 183-191.

Kontogiannis, T., & Linou, N. (2000). Making Instructions Visible: Implications for Training and Interface Design. *Proc. 44th HFES Mtg*.

Krohn, G. S. (1983). Flowcharts used for procedural instructions. *Human Factors, 25*, 573-581.

Lacy, R. M., Chignell, M. H., & Kinnell, S. K. (1988). Authoring hypermedia for computer-based instruction. *Proc. 32nd HFES Mtg* (pp. 313 –)

Moore, J. L., & Gordon, S. E. (1988). Conceptual graphs as instructional tools. *Proc. 32nd HFES Mtg* (pp. 1289 -)

Ockerman, J., & Pritchett, A. (2000). A review and reappraisal of task guidance: Aiding workers in procedure following. *Int'l Journal of Cognitive Ergonomics, 4*(3), 191-121.

Rasmussen, J. (1986). Information processing and human-machine interaction: *An approach to cognitive engineering*. New York: Elsevier.

Rodriguez, M. A. (2001). Development of diagrammatic procedural instructions for performing complex one-time tasks. *Proc. 45th HFES Mtg.* (pp. 687-691).

Stern, K. R. (1984). An evaluation of written, graphics, and voice messages in proceduralized instructions. *Proc. 28th HFES Mtg* (pp. 314 -)

Woodruff, E. B., Lammers, H. B., & Lammers, T. F. (1998). *Steam Plant Operation*. New York: McGraw-Hill.

Wright, P. (1977). Presenting Technical Information: A Survey Of Research Findings. *Instructional Science, 6* (93-134)

Wright, P., & McCarthy, J. (2003). Analysis of Procedure Following as Concerned Work. In E. Hollnagel (Ed.). *Handbook of Cognitive Task Design*. New Jersey: Erlbaum.