ENHANCED OPERATOR SUPPORT THROUGH INTEGRATED RESOURCES AND LARGE WALL PANEL DISPLAY APPLICATION WITHIN A COMPACT MAIN CONTROL ROOM

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ABSTRACT

Application of digital technology to control rooms for power generation units allows for significant enhancements in functionality; the challenge lies in cost effective implementation. Traditional hard panel and static mimic designs yield rigid interfaces covering large surface areas, and high device densities with large amounts of equipment to support such enhancements. Computer displays with soft controls can reduce board area required, however, issues can arise regarding navigation across resources and coordination of multiple crew members. Use of large wall panel display units to supplement standard size CRTs is a potential solution. Tests performed demonstrate that a control room utilizing soft control consoles in conjunction with large wall panels for overview displays can provide enhanced functionality and crew performance within a more compact design relative a traditional designs with similar capabilities. Such can be achieved without introducing operational issues if the design incorporates certain necessary characteristics. Design performance can be demonstrated through a test program incorporating full fidelity, dynamic simulation with live operators.

OVERVIEW

Use of digital technology in support of control room design for power generation units carries certain benefits inherent to the corresponding architecture, for example, fault tolerance through redundancy and self diagnostics. The major benefits, however, are to be derived from information processing capabilities which can be exploited to provide significant enhancements in functionality and operator support. Some of these come in the form of higher automation to reduce operator workload. Others relate to pre-processing, such as signal validation. The balance relate to the human-system interface (HSI), i.e. the manner in which information is organized then presented to the operator; it is this area which will be focused upon. The key objective is to design the HIS such that operators can take full advantage of information resources.

Models of operator response generally identify a sequential, iterative loop centered around several distinct phases of activity:

1. Monitoring and Detection
2. Interpretation and Task Identification
3. Task Execution
4. Feedback

The wider range of data and finer resolution afforded by digital technology make it possible to more directly support activity areas 1, 2, and 4. Presentation of both physical and functional views of process information is one way of doing so. Incorporating higher levels of data integration is another. The ability to simultaneously provide the "big picture", i.e. broad, plant-wide situation awareness, along with nearly microscopic detail is a third. There are many others, all of which contribute to enhanced performance in the areas most important to operators - speed, without sacrifice of accuracy. The challenge in applying such technology lies in cost effective implementation to achieve a reduced cost-to-performance ratio.

TRADITIONAL HARD PANELS

Traditional "Hard Panel" control boards consist of dedicated, hard-wired switches and indicators. Each device monitors or controls a single parameter, so the number of the devices installed on the control board approaches the number of field devices, which can be substantial. This requires not only a large panel (e.g., more than 15 metres long), but also installation of some devices on the back side of the board or alternate locations. Designers attempt to arrange the devices for direct access during various operational situations. However, since different devices must be used in each different plant operating mode (e.g., normal full power, start-up, cool-down, refueling…), it is impossible for "spatially dedicated" devices to provide the best arrangement for every mode. In some operational modes, certain indicators and switches which have to be monitored and manipulated concurrently may, in fact, be physically located apart. The large volume of devices and inability to physically integrate information results in a continuous, concurrent set of often widely distributed data. This situation forces operators to continuously sift and prioritize mentally in order to maintain focus on relevant subsets of information. Ultimately, the trend drives the need for more control room staff and, eventually, a greater risk of human error.

COMPUTER BASED APPROACH

A "Computer Based" control board moves plant state information from large, hard-wired display and control panels onto computer monitors (CRTs) within an integrated workstation. Increased information density and flexibility are achieved, with a corresponding reduction in volume of equipment and size of physical architecture. Software displays can reduce the volume of data presented while maintaining concurrent data processing across the full range of monitored scope. Prioritization and focus can be achieved cost effectively through an integrated set displays and presentation formats. The primary advantage of this approach is that plant state data can be better tied to the current context - that is, any single indication can potentially appear in the context of any other indication - and these data can be processed and presented in different formats. Such flexibility allows construction of data displays that better address specific process control issues.

LARGE WALL PANEL DISPLAYS

One drawback of this type of integrated interface is the potential to obscure the "big picture" view of plant status. Because procedures, indications, and controls can all be accessed from a single position, operators are more likely to remain focused at the workstation. They view isolated images of plant state data through a small set of "windows" (the CRT displays), and are therefore must integrate information mentally unless a broader view of plant state is made available. Second, plant state data is no longer "spatially dedicated"; instead, it exists in software space. As a result, operators' ability to maintain a continuously updated overview of plant state is impacted. A large screen display, also referred to as a wall panel information system (WPIS), can be an effective means for offsetting these shortfalls. The WPIS is conceptualized as a large wall-mounted display (with perhaps several panels) designed to support three primary objectives [1]:

- Maintain "big picture" plant status for all operating modes and conditions
- Support individual and group situation awareness; and,
- Support coordination, communication, and performance of control room staff through a 'common frame of reference'

There is an additional unique issue associated with a computer based main control room which a WPIS can address, specifically, navigation across resources (e.g. physical displays, functional displays, alarm/status displays, procedures, background information…). As above, because of the relatively small set of windows, it can be difficult to move from one focus area to another. A WPIS provides a high level launching point from which an operator can quickly navigate vertically down to the necessary level of detail, rather than horizontally through a progression of detailed information sets.

OVERVIEW DISPLAY CHARACTERISTICS

Endsley [2] defines situation awareness as "the perception of the elements in the environment within a volume of time and space, the comprehension of the meaning, and the projection of their status in the near future." The concept was first introduced in the context of aircraft pilot performance and has since been extended to cover other domains including nuclear power plants (NPP) [6, 7].

For the purpose of WPIS design and test in the context of NPP operations, situation awareness is defined to include:

- Awareness of current plant state;
- Awareness of changes in plant state;
- Awareness of task state; and
- Awareness of situation-relevant workstation displays and access to them (i.e., navigational links from WPIS displays to seated workstation displays).

In addition to supporting individual operators, the wall panel is intended to support multi-person team performance which requires:

- providing a *common frame of reference* so that operators have a shared understanding of plant state and task state;
- allowing operators to see how their control actions affect plant parameters other operators are trying to control;
- allowing operators to see how the control actions of others are affecting what they are trying to do;
- allowing supervisors to monitor individual operator's actions by determining if expected changes occurred

To support these various elements of individual and group situation awareness the WPIS displays must therefore include:

- A plant overview that provides key plant parameters organized around major plant functions [8];
- Alarm and status messages that are graphically integrated into the plant overview;
- Information on equipment and system availability;
- A plant schedule;
- A procedure overview that provides a high level overview of the current procedure being followed;
- An operator configurable area that allows operators to put up situation specific displays.
- Navigation links to other resources

In addition to the above, an effective WPIS overview display design includes a number of features which are not characteristic of typical overview displays. Specifically:

- It is organized functionally
- It embeds alarms within the graphics of plant process state
- It includes extensive, detailed process state information, including presentation of trends

In contrast to the above, traditional approaches to computer-based overview displays have presented key plant parameter data primarily as digital values organized around a physical mimic of the plant. The benefits of a design as described above relative to the traditional approach can be demonstrated through test.

MULTI-PHASE TEST PROGRAM

In a recent joint program, MELCO and Westinghouse developed and configured a prototype test environment to demonstrate the feasibility of implementing a compact control room design with a WPIS and to demonstrate the viability and superiority of the design in addressing the noted situation awareness, navigation, and coordination concerns. A multi-phase test series was defined, and several have been concluded to date. The following provides background regarding those tests which have been completed.

Man-in-the-loop concept testing is defined as a key component of the functional design phase in the human-system interface (HSI) design process. It is during the this phase that the core conceptual design for a HSI resource and corresponding functional requirements are developed. An integral part of this phase is rapid prototyping and testing of design concepts [4].

Man-in-the-loop testing during the functional design phase serves two main purposes:

1. It establishes the adequacy of the design concept and functional requirements. A main objective of man-in-the-loop testing is to establish that the conceptual design is adequate to support operator performance in the range of situations anticipated to arise. Concept testing enables problems and opportunities for improvement to be identified early, in the functional design phase, when it is less costly to make changes.

2. It provides input to aid designers in resolving design issues for which there is no well-established human factors guidance. An example might be assessing whether a system response time is adequate to support operator performance on a time-critical task.

PROTOTYPE ENVIRONMENT

A prototype system was constructed at Westinghouse Waltz Mill site, Madison Pennsylvania to evaluate concepts of the compact design. It consists principally of computer hardware and software, and a large screen wall panel display system. These systems are arranged physically to give some semblance of their expected positioning within the future control room, so that visibility and legibility issues can be investigated. Figure 1 illustrates the prototype system configuration of the compact control room.

(1) Wall Panel Display Systems

Figure 2 shows the test facility room layout (approximately 8 m x 13 m). Two types of display units were evaluated so that the suitability of either or both for future use could be properly assessed. There are three large screen display units, one rear projection with high resolution, and other two front projection with lower resolution.

(2) Operator Workstations

There are two movable operator workstations, each of which include six CRT displays. One is used as a Reactor Operator (RO)'s station, and the other is used as the second RO station or Supervisor (SRO) station alternatively. The distance between workstations are consistent with current control room design, approximately 3.5 m and 7.0 m from the WPIS to the RO station and SRO station respectively.

(3) Plant Simulator System

A full fidelity plant simulation of the type used for operator training was interfaced with the WPIS Prototype Environment to allow real-time dynamic testing.

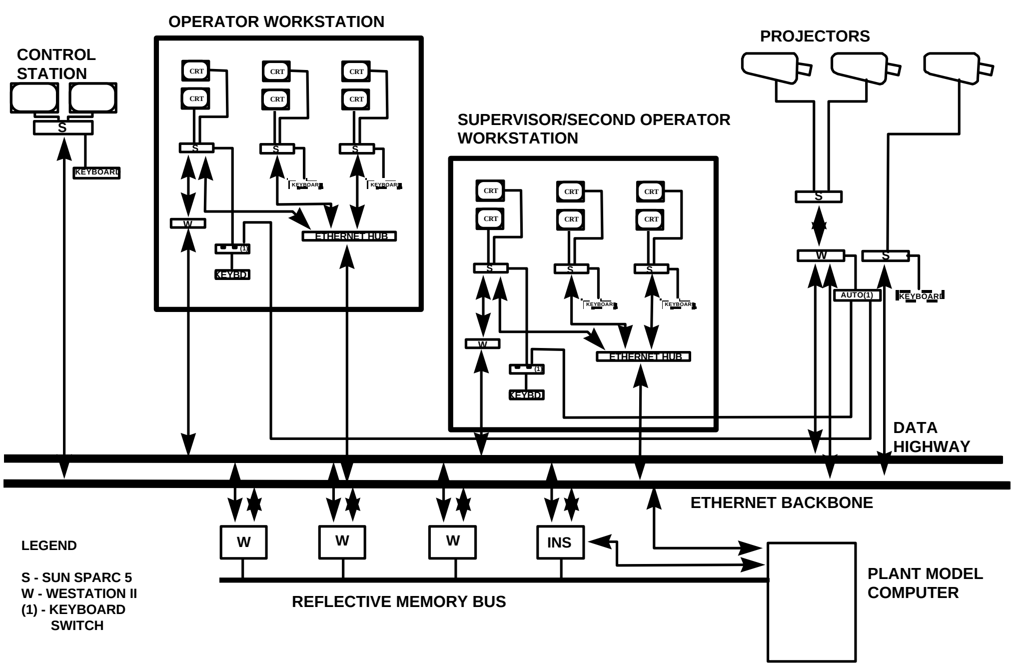

Figure 1: Compact Control Room Prototype Test Environment

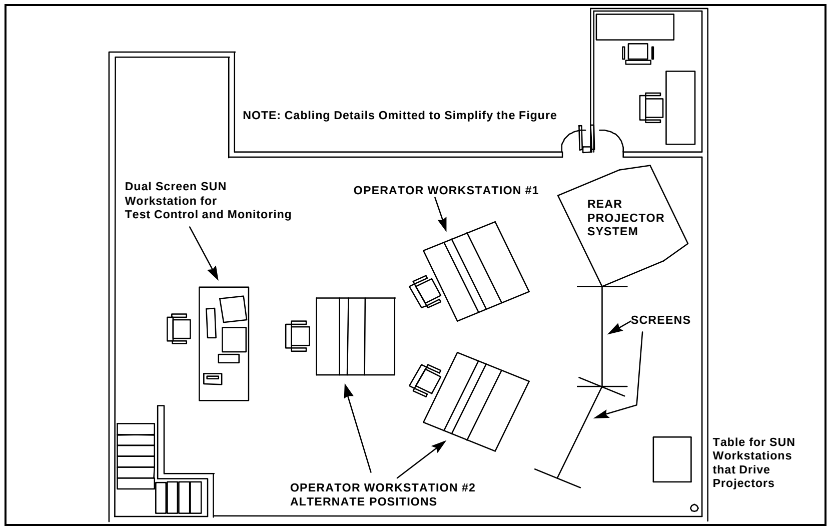

Figure 2 : Compact Control Room Prototype Layout

Figure 3 : View of Prototype Test Environment

TEST OVERVIEW

Two tests of the WPIS conceptual design are defined as part of a series of man-in-the-loop 'concept tests' intended to systematically examine the impact of different planned advanced control room resources (e.g., alarm system, workstation displays, computerized procedures, soft controls), both individually and in combination, on operating crew performance [3 - 5]. The first preliminary test was static; the second was dynamic and involved interaction with a full fidelity plant simulation. Details of the second dynamic test and corresponding results are discussed.

In this test, the primary objective of the test was to evaluate effectiveness of the WPIS in supporting situation awareness of multiple-operator crews in a dynamic environment with realistic scenarios. Crew performance with the WPIS, either on large wall-mounted display units (l*arge-screen WPIS overview display*), or on workstation CRTs (*local WPIS overview display*), was compared to performance with a more traditional display (a*lternate overview display*).

A series of real-time *scenarios* were presented to 2-member crews. Test participants alternated as RO and SRO in 6 of the scenarios. Two scenarios were presented for each display condition (*large-screen WPIS overview*, *local WPIS overview*, and a*lternate* o*verview*), allowing participants to experience both the RO and SRO roles for every display condition. The order in which these display conditions were presented was counterbalanced across crews, whereas the order of the scenarios was fixed across all crews. In another 3 scenarios, both participants in the crew acted as ROs, with the training instructor acting as the SRO. In this RO-RO configuration, crews were presented with one scenario for each of the 3 display conditions. Again, order of presentation of display conditions was counterbalanced across crews, and order of scenarios was fixed.

A total of 12 individuals participated in the testing. All participants have held either a Senior Reactor Operation (SRO) (9) or Reactor Operation (RO) (3) license at one time with operational experience ranging from 2 to 17 years (average 7.8 years).

TEST PROCEDURE

Testing was conducted over a 6 week period. Each week, a pair of test participants participated as a crew for 5 days. The first two days were devoted to training and practice (4 scenarios). Nine test scenarios were conducted over the third and fourth days. On the final day, test participants completed a written questionnaire and were led through a structured debriefing session to solicit their feedback and comments.

In the test scenarios, the training instructor provided participants with initial conditions of the plant and assigned shift activities (primary tasks) to be completed by the crew. As the scenario evolved, pre-defined *malfunctions* were initiated without the knowledge of the test participants to cause observable changes in plant variables (*target events*) that could be detected from the overview displays. Examples of the major plant transients included: steam line break outside containment, steam generator tube rupture, and loss of coolant accident. Test administrators relied upon participants' verbal communication with each other to determine whether they detected the set of target events associated with specific scenario malfunctions and whether they correctly diagnosed the problem. When participants recognized abnormalities in plant condition, they were required to take appropriate control actions which would at times entail following emergency procedures.

PERFORMANCE MEASURES

To assess effectiveness of the WPIS compared to the more traditional Alternate display, the following objective and subjective measures were collected and analyzed: (i) ability to identify *target events* which characterize the dynamically evolving state of the plant, (ii) ability to correctly diagnose *malfunctions*, the source of perturbations in plant state, (iii) subjective ratings of operator workload obtained with the NASA-task load index [10], and (iv) detailed comments and suggestions collected via a questionnaire and structured debrief session.

SUMMARY OF TEST RESULTS

Results of the test confirm that the basic assumptions and approach being taken in designing the WPIS are on target. The performance measures provide converging evidence of superiority of the WPIS overview displays over the alternate overview displays.

Analysis of performance data indicated that the WPIS supports broad individual and crew situation awareness. Participants performed better with the WPIS than with the alternate overview display in identifying target events (24% improvement) and in diagnosing plant disturbances (27% improvement). A chi-squared test found these enhancements in crew performance to be statistically significant ($p<0.025$ and $p<0.05$, respectively).

Evidence of superiority of the WPIS in providing a broad overview of plant state also comes from examination of display navigation performance. The SRO navigated to twice the number of information displays at the operator workstation with the alternate overview condition compared with the WPIS conditions, suggesting that the alternate display was less effective in supporting broad situation awareness (i.e. requiring the operator to navigate to more lower level displays to get an assessment of plant state). A paired t-test found this difference in navigation to be statistically significant ($p<0.02$, one-tailed).

Workload ratings indicated that subjective operator workload was lower with the WPIS displays than with the alternative overview displays. There was an 11% reduction in workload with the WPIS conditions over the alternate overview condition for the RO/SRO scenarios. An analysis of variance found this reduction in workload to be statistically significant ($p<0.048$).

Operator comments during the debrief sessions, as well as results of the questionnaire, indicated that participants felt the design goals and approach for the WPIS were appropriate. Test participants provided positive feedback on: the functional organization of information; the alarm organization and coding scheme; and the level of detail of the information displayed. Participants indicated that the WPIS displays were more effective than the alternate overview displays for: maintaining broad situation awareness; being alerted to changes in equipment state, automatic system actuation, and parameter values; and assessing the nature and implications of abnormalities.

In addition to results showing quantifiable improvements in crew performance with the WPIS over the alternate displays, the results of this test also showed that crew performance on the test scenarios and workload ratings were equally good in both the large-screen and local WPIS overview conditions. Further, questionnaire ratings and final debrief comments indicated that test participants felt the WPIS overview displays were an effective resource on the workstation CRTs as well as on the large wall-mounted display units.

Collectively, the results of this test provide quantitative evidence of the superiority of the conceptual approach taken for the design of the WPIS overview display design, i.e. hybrid physical/functional organization, as compared to more traditional approaches which organize plant state information purely around a physical mimic.

CONCLUDING REMARKS

In summary, the experience discussed demonstrates that a control room design utilizing soft control consoles in conjunction with large wall panels for overview displays can provide enhanced functionality and performance within a more compact design relative to implementation of a traditional control board with similar capabilities. This can be done without introducing operational issues if the design incorporates a number of necessary features and design characteristics. A high degree of confidence in design performance can be ensured through a test program if the program incorporates full fidelity, dynamic simulation with live operators.

ACKNOWLEDGEMENTS

The authors would like to thank members of the WPIS test team, L.A. Rusnica, C.S. Brockhoff, S.P. Kerch, S.J. Kenney, B. Morris, G. Simmons, A. Lee, T. Giunta, and J.Birsa who all worked tirelessly to make this test a success. Thanks also goes to Mr. Tadashi Ohi for his insightful input and contributions; M. Jones and M. Halverson at the Simulator Training Facility at Waltz Mill for their help in defining and running the test scenarios. Finally, we would like to extend our sincere gratitude to the test participants for the time they committed to the test and their invaluable input.

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Man-machine Interface, Large Screen Display, Wall Panel, Control Room, Power Plant, Crew