Human Factors Methods for Nuclear Control Room Design

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Prepared by
Lockheed Missiles & Space Co., Inc.
Sunnyvale, California

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NOTICE

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EPRI PERSPECTIVE

An earlier review of the control rooms of operating nuclear power plants uncovered many design problems having potential for degrading operator performance. As a result, the formal application of human factors principles was found to be needed.

This report demonstrates the use of human factors in the design of power plant control rooms. The approaches shown in the report can be applied to operating power plants, as well as to those in the design stage.

This study documented human factors techniques required to provide a sustained concern for the man-machine interface from control room concept definition to system implementation. It goes far beyond present control board design practices. However, control board designers intending to use this report as a design model should be aware of three limitations of the study. First, although design engineers supported the human factors analyses, the depth of the study was limited by the lack of their participation as an integral part of a design team. Second, the use of only three selected subsystems limited the study scope, so that overall control room layout and systems integration aspects were scarcely addressed. Third, the designs were based on analyses of startup, change of power level, and shutdown operations, and were modified by less detailed analyses of a few emergency sequences. A more thorough design approach would include detailed analyses of all events shown to be significant by safety and reliability studies and by reviews of plant operating histories.

The summary report will be of interest to anyone involved in control room design or in operator performance. The full report will be of interest to anyone deeply involved in the design of power plant control rooms. Designers of other types of control rooms, such as dispatch centers or process plants, may also benefit from the report.

Three closely related projects are in progress. Publication of the final report for RP1126, "Human Factors Review of Power Plant Maintainability," is expected in late 1979. Completion of an improved approach for procedures, RP1396, "Test of Job Performance Aids for Power Plants," is scheduled for early 1980. Final report publication for RP769, "Performance Measurement System for Training Simulators," is planned for late 1980. These studies address both nuclear and fossil fuel power plants.

Randall W. Pack, Project Manager
Nuclear Power Division

ABSTRACT

Human factors engineering is an interdisciplinary specialty concerned with influencing the design of equipment systems, facilities, and operational environments to promote safe, efficient, and reliable operator performance. Human factors approaches were applied in the design of representative nuclear power plant control panels. First, methods for upgrading existing operational control panels were examined. Then, based on detailed human factors analyses of operator information and control requirements, designs of reactor, feedwater, and turbine-generator control panels were developed to improve the operator-control board interface, thereby reducing the potential for operator errors.

In addition to examining present-generation concepts, human factors aspects of advanced systems and of hybrid combinations of advanced and conventional designs were investigated. Special attention was given to warning system designs. Also, a survey was conducted among control board designers to (1) develop an overview of design practices in the industry, and (2) establish appropriate measures leading to a more systematic concern for human factors in control board design. The study concludes that there is an urgent need for a human factors engineering design guide, tailored to the special demands of the utility industry. Similarly, there is a need for a human factors standard which the utilities could use in specifying, developing, or evaluating new control room designs. The study also provides suggestions for future research directions.

ACKNOWLEDGMENTS

We are indebted to many individuals and organizations for their assistance, guidance, and cooperation in the design and execution of this study. While we were fortunate in obtaining the cooperation of all major reactor vendor organizations and several Architect-Engineering (A-E) firms, the Westinghouse Corporation assumed a lead vendor role in providing the study team with systems information required for human factors analyses. Also, Westinghouse made available its Training Center and staff for operational reviews of many of the design concepts presented in this report. Joe Franz, Manager of the Process Computer Activity, and John O'Brien, a member of the Human Sciences organization, were our primary contacts with Westinghouse.

Several consultants participated in the study. Jeff Barnum, of the NUS Corporation, provided the study team with the initial system familiarization training and insights into operational practices. Tom Sheridan, of the Massachusetts Institute of Technology, served as a consultant in the areas of human performance modeling and computer automation.

Joseph L. Seminara, LMSC
Randall W. Pack, EPRI
June 1979

Section 1
INTRODUCTION AND SUMMARY

This study explored the feasibility and value of applying human factors engineering methods developed in the aerospace and military contexts to the design of selected nuclear power plant control panels. Human factors aspects of both conventional and advanced control and display approaches were considered. The study also reviewed present control board design practices to determine how best to incorporate human factors concerns in the design process.

This study was the direct outgrowth of an earlier eighteen month study identified as EPRI RP (Research Project) 501-1 and entitled, "Human Factors Review of Nuclear Power Plant Control Room Design." In the earlier effort, a Lockheed Missiles & Space Company human factors team reviewed five present-generation operational control rooms and their corresponding simulators.

By means of extensive structured interviews with operators in operational plants and with trainers associated with simulator-based operator training centers, a number of operational problems were uncovered. Human factors checklists, based on aerospace standards and design criteria, were applied in evaluating man-machine interfaces in the five control rooms reviewed. The study team also spent many hours directly observing operator tasks in both operational and simulated control rooms. Analyses of representative operator emergency tasks were conducted along with procedure evaluations. Reported operational errors were probed for human factors implications and a variety of physical measures were taken in defining the operational environment and in evaluating anthropometric features of control rooms. The human factors problems revealed by these methods were extensively photo-documented for post-site visit analyses and to illustrate the problems observed in the final reports.

The study revealed both major and minor problems in the design of control rooms, which increased the potential for operational errors and unnecessarily added to the training burden and the rigor of selection criteria for operator candidates. The results of this initial study are documented in a summary report (EPRI NP

309SY, dated November 1976) and an extensive 400 page final report (EPRI NP 309, dated November 1976).

Although human factors engineering has a history of over thirty years, the human factors design principles initially developed for military and space programs to ensure operator effectiveness and reliability have not been generally or consistently applied to the design of power plant operational work spaces. For example, four out of the five control rooms reviewed revealed serious violations of anthropometric standards where indications were placed beyond viewing limits and controls were located beyond acceptable reach limits. Control room configurations varied widely, with some designs making for awkward operations necessitating additional manning when compared with more efficient configurations. The extensive use of backrack areas which take operators away from the primary sphere of control and the practice of mirror-imaging control boards in multi-unit control rooms were found to be particularly disadvantageous from the human factors standpoint. Control board designs were generally found to be excessive in size, lacking in functional arrangement of elements (sometimes necessitating a two-man operation of a control and its associated display), and generally lacking in clarity of interrelationships between panel elements. In short, the control boards reviewed had not been designed to promote error-free operation, especially during potentially stressful circumstances.

The number and magnitude of problems revealed in the initial human factors effort clearly indicated the need for additional research and led to the follow-on effort, EPRI RP 501-3, described in this report. The present study applied human factors engineering approaches in deriving solutions and recommendations pertaining to the problems highlighted in the earlier study. The study scope ranged from an investigation of means for upgrading existing operational control rooms to an examination of human factors concerns in advanced control rooms of the future.

METHODOLOGY

This study applied well-established methodologies in developing and evaluating various control board design concepts. Figure 1-1 depicts typical human factors program elements extending from the initial concept development phase to system operation. The present study simulated an actual control board development program including (1) system analysis, (2) functions and task analysis, (3) preliminary board design efforts, and (4) design verification efforts using mockups and representative members of the operator population. It was beyond the scope of this study to implement dynamic simulations for test and evaluation purposes. In addition,

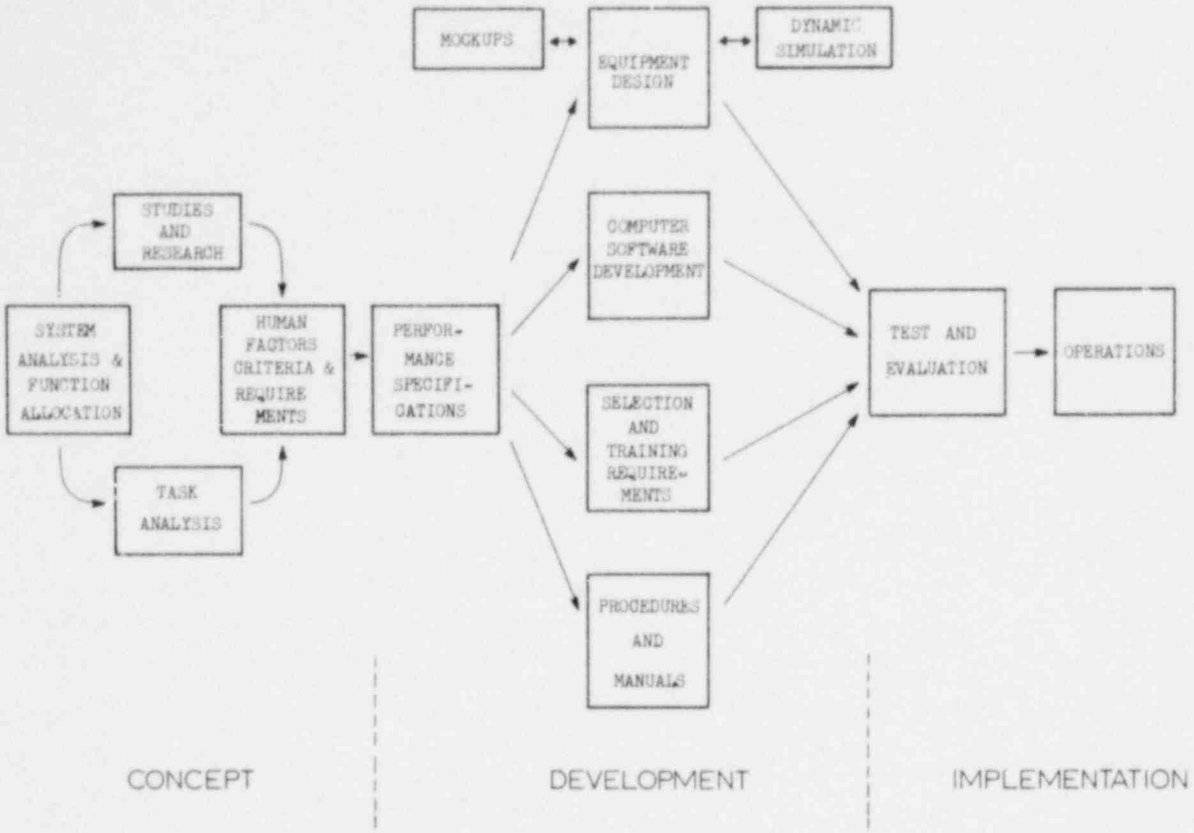


Figure 1-1. Human Factors Program Elements

the study was aimed not at developing hardware designs ready for production, but rather at showing how to incorporate human factors methods and design principles into control board designs for nuclear power plant control rooms.

Subsystem Selection

A review of control and display approaches for the entire nuclear power plant control room is beyond the scope of the present study. It was therefore necessary to limit the study to a set of representative subsystems within the bounds of project funding. Selected subsystems had to be those that, in combination, would represent the design problems that typify the control board design process, and those that had evoked general operator and trainer concern in EPRI RP 501-1. The subsystems selected were reactor control, steam generator feedwater control, and the turbine-generator.

Study Tasks

Subsequent to a review of the relevant literature, the following tasks were conducted:

- Analyses of Control and Display Requirements. A series of analyses, from broad systems analyses to detailed task analyses, were conducted to identify and examine relevant man-machine interfaces. The end-product of this series of analytic efforts was a determination of the operator's informational needs and control options.

- Upgrading Existing Control Boards. The first concern in investigating control board design approaches was to enhance control board designs that are currently operational or those that are near-operational and consequently difficult to modify in any substantial way. Recognizing that a 40-year life span is projected for nuclear power plants, the study explored measures that might be taken to upgrade the existing configurations from the human factors standpoint, without interrupting or delaying power generation.

- Human Engineering Conventional Control Boards. This task involved the development of new conventional control board designs. Starting with the control and display requirements identified in the analysis task, human factors panel-design principles were applied in arriving at panel layouts for the three systems of concern in this study.

- Warning System Approaches. Problems with existing annunciator warning designs were reviewed and candidate approaches were developed to resolve observed deficiencies. Characteristics of visual and auditory cueing devices were reviewed and a number of candidate audio-visual warning concepts were advanced.

- Design Verification. The human factors design approaches developed in the preceding tasks were subjected to the scrutiny of board design personnel and trainers with operational backgrounds. Designers reviewed the proposed arrangements from the standpoint of such constraints as separation and seismic requirements, while reviewers with operational experience examined the panel layouts in terms of the demands of a representative set of normal and off-normal operational scenarios.

- Advanced Computer-Based Cathode-Ray Tube (CRT) Approaches. Each of the major control room design organizations was visited to determine future trends in control room design. A detailed examination of the major directions being followed in CRT formatting was conducted in the light of human factors considerations.

- Hybrid Systems. A readily discernible future trend is the integration of advanced computer-based CRT capability with conventional board designs. The advantages and potential drawbacks of these "hybrid" concepts were examined.

- Design Practices Survey. In order to establish the feasibility of incorporating human factors principles and considerations in control board designs, it was necessary to develop some appreciation of current design practices and an understanding of the constraints facing the designer. Accordingly, a 30-item structured interview was developed and administered to 20 designers from major design organizations.

- Future Study Needs. This study revealed a number of possible extensions to the work conducted to date, including the need for human factors design guides and standards. Also, research topics are advanced for developing empirical data bearing on a number of pressing design issues raised in this effort.

This brief outline of study tasks is intended to serve as a road map through the remainder of this report.

ANALYSES OF CONTROL AND DISPLAY REQUIREMENTS

A necessary initial phase of the human factors approach to equipment design is to develop a detailed understanding of the man-machine interface. This requires the application of a variety of analytic techniques based on a comprehensive understanding of the system and its functional characteristics, and a delineation of operator information needs and associated control options.

Systems Analysis

Systems analysis was initiated with an intensive review of nuclear power plant configurations, the physical hardware and basic elements of the systems selected for study, control system characteristics, control board elements for a Pressurized Water Reactor (PWR) plant, and operational practices associated with normal and off-normal operations. In the course of this review and analysis of the selected systems, representative system schematics for a generic plant were developed. A functional interface sequence analysis was also performed, as shown in Table 1-1, to interrelate the operations of the three selected systems.

In addition to these preliminary systems analysis activities, the study team visited the Nuclear Steam Supply Systems (NSSS) vendor organizations in order to expand the base of system inputs required for analysis. While all the major NSSS vendors supported the study at various stages of the program, it was still necessary to select a lead vendor for the primary source of systems data. Analysis could not be performed expeditiously on all vendor designs because of variations in system design approaches. Westinghouse assumed the role of lead vendor and invited the study team to spend one week in detailed discussions with the various functional system designers. Westinghouse also provided relevant system description documentation required for subsequent analytic efforts.

Table 1-1

SEGMENT OF FUNCTIONAL INTERFACE SEQUENCE FOR START-UP

Reactor Control System	Feedwater System	Turbine-Generator System
Pull shutdown rods		
Prepare to go critical		
Take the reactor critical		
Increase to baseline	Transfer control of steam-generator water level from auxiliary feedwater to main feedwater regulating bypass valves	Prepare for roll
Increase to 5% power		Begin roll
		Increase speed
Control coolant temperature while turbine is brought up to speed and generator is synchronized		Perform trip tests
		Achieve operating speed
Begin to pull rods and increase power with turbine load		Establish operating voltage
		Synchronize to grid
	Transfer control to main feedwater regulating valves	Increase load (1%/min)
Place in automatic control	Transfer main steam generator feedwater control to automatic control	
	Monitor steam generator level, steam flow, pressure, and feedwater pumps	
	Warm-up standby main feedwater pump and place standby pump in operation	Achieve desired load level
On-going monitoring	On-going monitoring	On-going monitoring

Functions and Task Analyses

Based on the systems analysis, the study team was able to identify the major functions and subfunctions that the operator must perform in the course of monitoring and regulating the system. Operator involvement in these subfunctions was further broken down into discrete tasks. In analyzing each specific task or man-machine interaction, the following factors were considered:

- Decisions to be made
- Actions to be taken
- Ongoing plant processes
- Control parameters
- Control limits

This process resulted in the listings illustrated in Table 1-2. This systematic examination of sequential operator-control board interfaces was intended to reveal display requirements and control options to be included on the control boards.

Decision-Making Analyses

In the course of conducting functions and task analyses, the more important or complex decisions facing the operator were singled out for more detailed decision-making analysis. A graphic logic flow for use by the operator in arriving at a decision was developed. For example, the decision-making process required to determine if the rods are moving properly is illustrated in Figure 1-2. At each step in the process, the analysis attempted to determine the informational needs of the operator to allow him to resolve the problem appropriately.

Precautions Analysis

Plant operating procedures sometimes provide the operator with separate listings of special precautions. These listings proved to be a useful source of analytic data. Each precaution relating to specific subsystems was examined in terms of error potential and possible means for ensuring error-free operation. In some instances, it was apparent that a suitable indication or alarm was required to prevent a potential operation error. In other cases, reliance on procedures appeared adequate. In still other instances, the possibility for error seemed sufficiently great that mechanical or electrical interlocks to "design out" errors appeared worthy of further investigation. Table 1-3 provides a segment of the precautions analysis performed for the reactor control system.

Control-Display Requirements

Based on the series of analyses described above, lists of control and display requirements were developed, some of which are presented in Table 1-4. These requirements served as the foundation for the designs presented in this report.

Table 1-2

SEGMENT OF THE FUNCTIONS AND TASK ANALYSIS FOR REACTOR CONTROL SYSTEM

ID	Function	Task		Process Response	Process Parameters	Control Parameters
	Subfunction	Decisions	Actions			
4	Increase Power to Baseline Power Level (10^{-8} amps)					
	Establish start-up rate (SUR) less than 1 decade per minute (DPM)	SUR less than 1 DPM?	Pull rods	Rods withdraw CR increases SUR increases	LVDT position CR trend SUR	Digital counter
	Monitor intermediate range (IR) level to determine when on range	IR level greater than 10^{-11}?			IR level	
	Switch nuclear instrumentation system (NIS) recorder from lowest source range (SR) to highest IR	1 decade overlap? IR level displayed?	Reposition NIS recorder switch	IR level on recorder		Switch position IR level
	Continuously monitor SUR	SUR less than 1 DPM?			CR trend; SUR IR and SR level	
	Switch second NIS recorder pen to IR channel	1 decade overlap? IR level greater than 5 x 10^{-11}? IR displayed?	Reposition switch			Switch position IR level displayed

It is important to note that, for economy of effort, the analyses were based on three operational modes: start-up, change of load, and shut down. These modes, however, do not begin to describe the full range of normal and off-normal operational scenarios. Consequently, at a later date, when the first cut at panel designs was completed, a visit was made to the Westinghouse Training Center to review the initial analytic conclusions with respect to a more varied series of normal and emergency operations. These activities will be discussed further in the context of the design verification task.

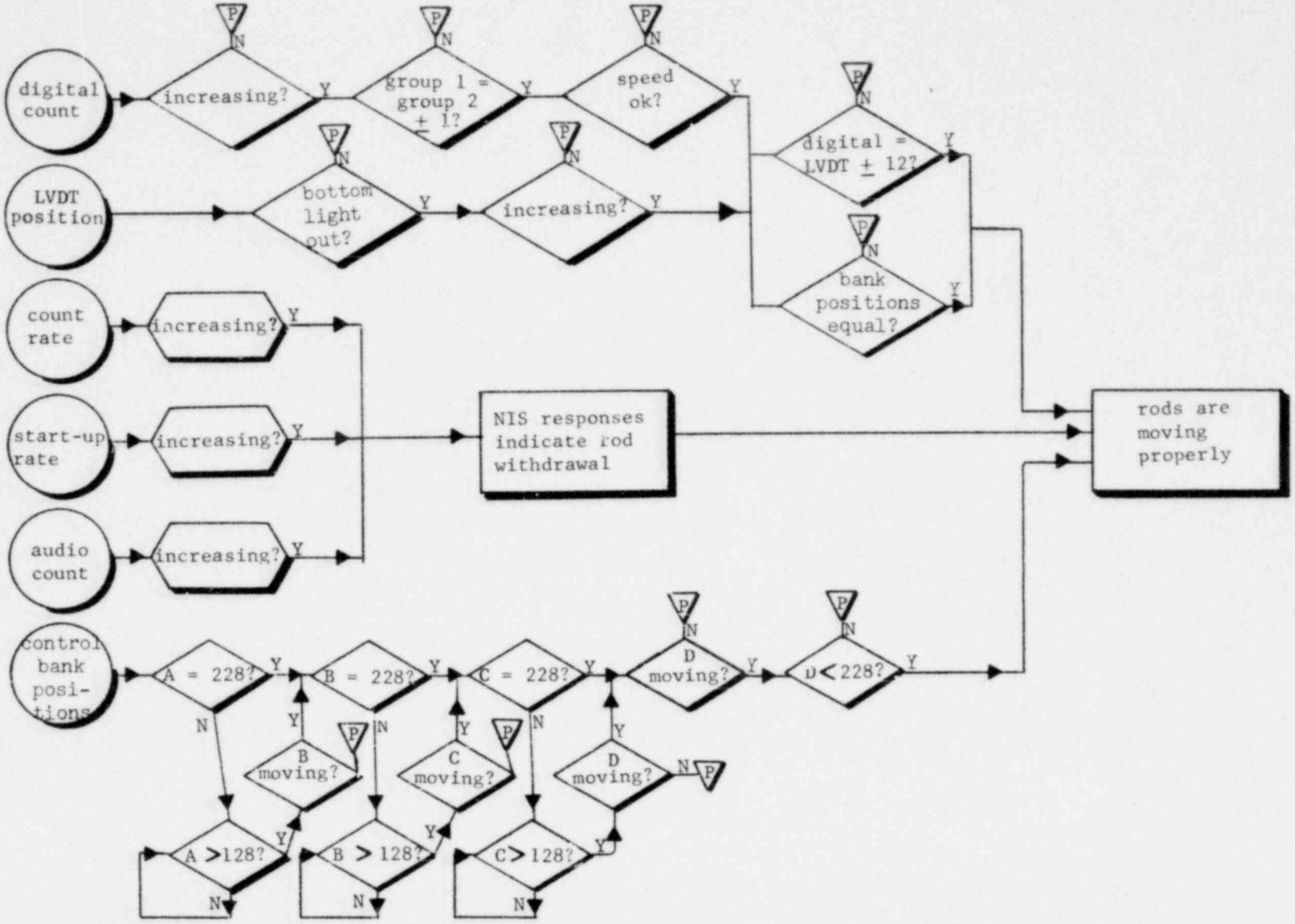


Figure 1-2. Decision-Making Analysis: Are Rods Moving Properly?

Table 1-3

SEGMENT OF THE PRECAUTIONS ANALYSIS FOR THE REACTOR CONTROL SYSTEM

PRECAUTIONS AND LIMITATIONS	SYSTEM DESIGN RECOMMENDATIONS
3. Criticality must be anticipated any time the control rods are being withdrawn or when boron dilution operations are in progress.	The estimated critical position could be input, and a computer could examine this ECP and the actual rod position. An interlock could be provided to prevent rod withdrawal if an ECP is not input.
4. If criticality is to occur at conditions (i.e., temperature, xenon, and boron concentrations) different from those for which previous criticality data is available and the differences are such as to cause an increase of 0.5% $\Delta K/K$ (500 cpm) or more in core reactivity (as determined by procedure F, "Estimated Critical Rod Position Calculation" of Chapter 50), the approach to criticality must be guided by plotting an inverse count rate versus control rod position.	This is currently handled procedurally. It is good practice to always utilize an inverse count rate curve. If this were done automatically by the computer, it could always be plotted to monitor approach to criticality.
5. Do not exceed a startup rate (SUR) of one decade per minute (1 DPM) unless authorized for special tests.	The NIS trips would probably prevent reactor start-up much faster than 1 DPM. It may be beneficial to have a separate trip on SUR.
6. When the reactor is subcritical, positive reactivity shall not be added by more than one method at a time.	This is currently handled procedurally. An interlock could prevent rod withdrawal simultaneously with dilution when subcritical.
7. The rod withdrawal and insertion program shall be followed except during low power physics tests, control rod exercises and special approved tests.	There are currently rod blockages and trips to ensure the rod program is being followed. A direct display of rod program position and actual rod position would assist the operator in satisfying this precaution.

UPGRADING EXISTING CONTROL BOARDS

In addressing control board design approaches in terms of human factors considerations, our first concern was with the modifications that can be made to existing control boards that are operational or near-operational. There are presently about seventy operational plants and more than an equal number of new plants where the control boards either have been designed or are in various stages of assembly and checkout. In applying human factors to existing operational designs, however, a number of compromises must be made, since there is little opportunity to change the position of components, rewire panel elements, change circuitry logic, etc. Consequently, much of the analytical work described above could not be applied to existing boards, because interruption of plant operation may not be allowed. This groundrule limited us to a variety of surface or "cosmetic" approaches which, if implemented, would considerably improve board operation, but would not fundamentally optimize the boards.

Board Enhancement Possibilities

Problems commonly observed in the course of earlier control room reviews were categorized as follows: (1) those that could be addressed on a backfit basis

Table 1-4

DISPLAY REQUIREMENTS FOR THE REACTOR CONTROL SYSTEM

Parameter	Units	Range	Accuracy	Essential	Valuable	Comments
NUCLEAR INSTRUMENTATION						
1. Source Range (2 channels) a. Count rate	Counts per second	1 to 10^6	±7% of the linear full scale analog voltage	X		Need quantitative display plus trending capability
b. Startup rate	Decades per minute	-0.5 to 5.0	±7% of the linear full scale analog voltage	X		
2. Intermediate Range (2 channels) a. Flux level	Amperes (A)	10^{-11} to 10^{-3}	+7% of the linear full scale analog voltage and ±3% of the linear full scale voltage in the range of 10^{-4} to 10^{-3} A	X		Need quantitative display plus trending capability
b. Startup rate	Decades per minute	-0.5 to 5.0	±7% of the linear full scale analog voltage	X		
3. Power Range (4 channels, 2 chambers-each) a. Calibrated ion chamber current (top and bottom uncompensated ion chambers)	Percentage of full power current	0 to 125%	±2% full power current	X		Need quantitative display of all 8 values, plus trending capability
b. Flux difference of the top and bottom ion chambers	Percent different	-30 to +30%	±4%		X	
c. Average flux of the top and bottom ion chamber	Percent of full power	0 to 120%	±3% of full power for indication ±2% for recording		X	

while the plant remained operational, (2) those that could be remedied during an extended planned outage, and (3) those that did not lend themselves to backfit remedies. The first category is of immediate interest here and included the following concerns and remedial measures:

- Functional Demarcation of Related Panel Elements. While related panel elements are often grouped in meaningful clusters on the boards, these clusters of controls and displays are usually not functionally demarcated such that the relationships are immediately apparent to operators. Figure 1-3 shows a massive array of undifferentiated panel elements which force a "hunt and peck" search for specific controls imbedded in a mass of many other identical controls. Where the panel elements have been arranged in a logical operational format (though this is not always the case), taped lines of demarcation can be added to highlight subgroups of panel components.

- Labeling. Demarcation of panel groupings should be supplemented by a system of labeling that accentuates functional subdivisions and avoids the repetitiveness of present labeling practices. Each subpanel area should be provided with a distinctive summary

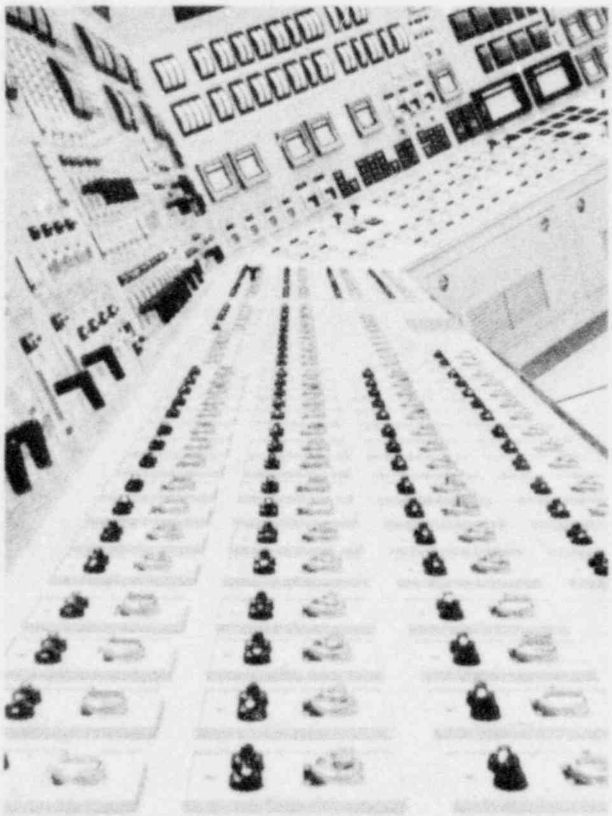


Figure 1-3. Massive array of identical control and display units with no clearly identified subpanel groupings or summary labeling.

label, larger than labels applied to individual panel elements. Labels should also be placed consistently in relation to panel components, preferably above the components. Label coding practices should be instituted uniformly, such as using red backgrounds for important controls; the consistency and clarity of abbreviations should also be reviewed.

- Coding of Controls. One of the most serious problems with coding of controls is the presence of large arrays of undifferentiated or identical controls collocated in a given area of the control boards. Such arrangements have caused inadvertent operation of improper controls. Existing control boards should be examined for control coding possibilities, e.g., shape coding, color coding, or combinations of such coding practices. Substitutions of control handles of different shapes can generally be accomplished with little or no impact on operations.

- Meters. Meter limits should be reviewed for each panel and a consistent coding practice should be developed, such as green normal operating band, amber marginal bands on either side of normal, and red out-of-limit bands on the high and low side as appropriate. These color bands should be affixed directly to the meter scale where it is possible to do so by easy removal of the meter cover. Meter scales which do not conform to human factors principles of design should be replaced, and room illumination should be modified where glare and reflections from meter faces obscures their readability.

- Indicator Lights. The color coding of indicator lights should be reviewed to ensure consistency. Coding possibilities for the annunciator system should be examined to differentiate between major problems and less significant information displays.

- Chart Recorders. Some of the chart recorders currently in use are overloaded and largely illegible. Some parameters of immediate interest to the operator are buried and not available for as much as four minutes. Either additional recorders must be added, or meters should be substituted for important parameters, or a fast recorder cycle provision should be added to existing recorders.

This list of possibilities for improving current operational control rooms is not complete because each control room is a unique situation and should be reviewed on an individual basis for specific human factors recommendations. For example, multi-unit control rooms where two units have been mirror-imaged offer special problems and no easy solutions.

It is important to note that operators have been quick to discover the abovementioned control room deficiencies. They have attempted to make "quick fixes" to the boards to improve their operability and avoid operational errors. For example, adjacent identical control knobs have been painted different colors for coding purposes. Many such fixes have, unfortunately, been prompted by an operational mishap. Also, remedial measures have not been applied systematically to the boards or in any controlled fashion. Proper enhancement of existing control rooms will require a carefully planned and concerted effort between plant operations, engineering, and management.

Human Factors Enhancement: Examples

To provide examples of methods for retrofitting existing operational panels, several representative panels were selected for study. An analysis was made of human factors problems, and modification possibilities were considered. The cases illustrated reveal a number of surface changes possible within the limits described in the introductory remarks for this section. Applying human factors on an "after-the-fact" basis is generally a compromise and not always satisfying from either a human factors or aesthetic viewpoint.

Figure 1-4 shows a Steam Generator Feedwater System control panel. The panel allows monitoring and control of three steam generators having two motor driven main feedwater pumps and one steam driven auxiliary pump. The most striking observation in reviewing this panel is the lack of apparent relationships between discrete panel elements. The operator must examine the legend on each individual switch, indicator, or meter to make any sense out of the panel.

Figure 1-5 shows an attempt to functionally demarcate the panel shown in Figure 1-4. The various functional groups of panel elements are bound together by taped lines. Within each grouping, summary labels are introduced, thereby reducing the time required in scanning each individual panel element label. Space constraints made it impossible to place labels consistently above or consistently below components. Furthermore, a white/black/gray coding approach is adopted for controls associated respectively with Steam Generators A, B, and C. In assigning this code to the panel elements, it readily becomes apparent that no consistency was observed in the ordering of A, B, C Steam Generator elements. In some cases, a top-to-bottom A, B, C orientation is observed, such as MAIN FEEDWATER ISOLATION. In other cases, a contradictory bottom-to-top A, B, C order exists, such as AUXILIARY FEEDWATER THROTTLE VALVES. In other cases, a left-to-right A, B, C order is presented. In addition to coding the controls by color or shape, meters should be color-banded to highlight normal and out-of-tolerance readings.

Reorganization of Existing Control Boards

In the preceding paragraphs, a number of surface changes to the existing boards were proposed for consideration in an attempt to improve the operator-control board interface. Since we established as a groundrule the avoidance of disrupting plant operations, such retrofits were minor in nature and the improvements achievable were correspondingly limited. In this subsection we will consider more extensive modifications to existing operational boards, assuming that the plant will be down for several months and that this outage has been planned for some time. This planned down-time provides an opportunity to upgrade control boards that have proven especially troublesome from an operational or training standpoint, in some cases because of extensive backfits over the years.

Redesign of control boards under the circumstances described will, in addition to all the factors considered earlier in this section, allow freedom to regroup panel elements in more logical functional relationships than might have originally been the case. Also, panel elements that have proven useless or obsolete can be removed from the boards to eliminate unnecessary clutter or distractions. Sufficient space may be saved on benchboards to allow room for resting procedures on the board without risking inadvertent activation of controls.

Figures 1-6 and 1-7 provide an example of the possible modifications. Techniques of outlining, bordering, color coding, and labeling were incorporated into the revisions. Panel elements were retained within their respective major console sections and the primary organization of major elements was not changed. A major change accomplished is the vertical alignment of the series of control-display elements associated with each of four steam generators.

HUMAN ENGINEERING CONVENTIONAL CONTROL BOARDS

Up to this point, the focus has been on human factors approaches for upgrading existing operational control boards. In this section, however, conventional control panel designs were developed based on the requirements of a totally new plant.

During the analysis, control and display requirements for the operator to safely monitor and control the plant were identified. The decision-making and task activities of the operator were examined to ascertain the actual usage of these data. From this information, any adjacency requirements and appropriate presentation modes were also identified. For example, in the decision making analysis presented in Figure 1-2, we find that the operator is required to compare the rod positions indicated on the digital counters with the LVDT position indicators. It would be operationally desirable to present these displays in the same form and in the same general area on the control panel. However, in most operational plants, the digital counters are placed on the benchboard while the LVDT's are on the vertical panel and present rod position in analog form. In the human

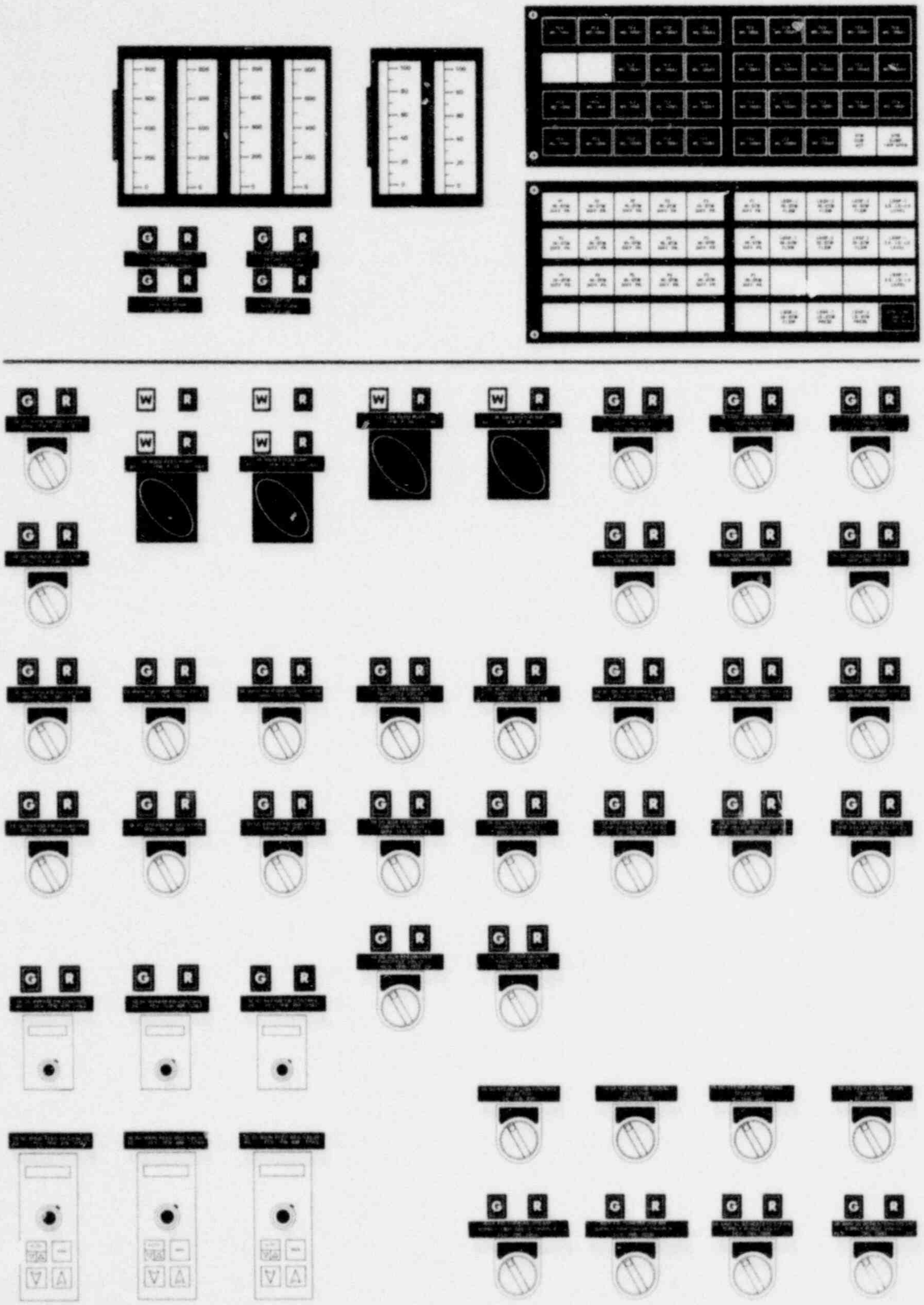


Figure 1-4. Representative Steam Generator Feedwater Control Panel Design

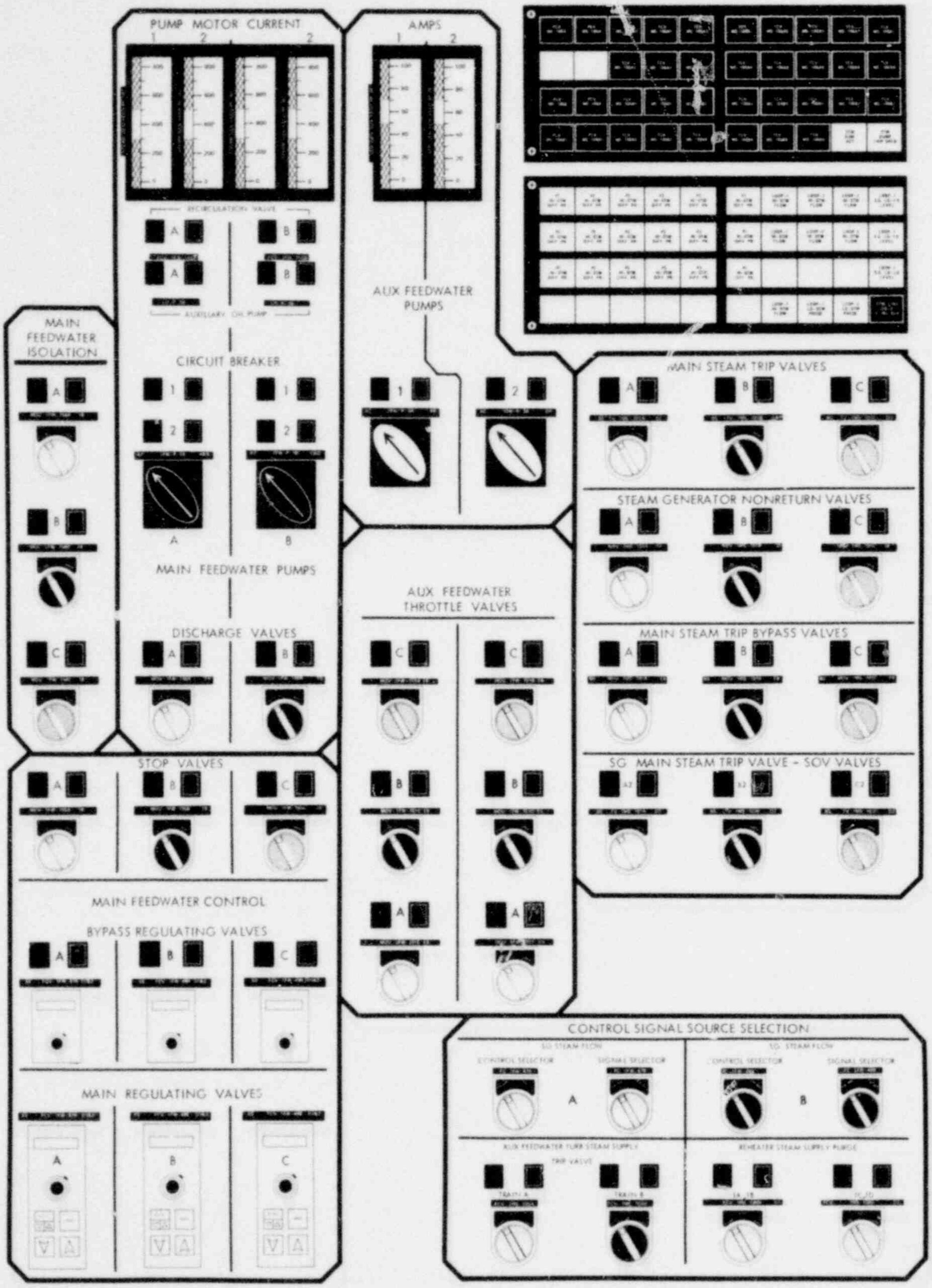


Figure 1-5. Enhancement of panel shown in Figure 1-4 by means of functional demarcation, relabeling, and coding of controls and meters. No controls or displays have been moved or replaced.

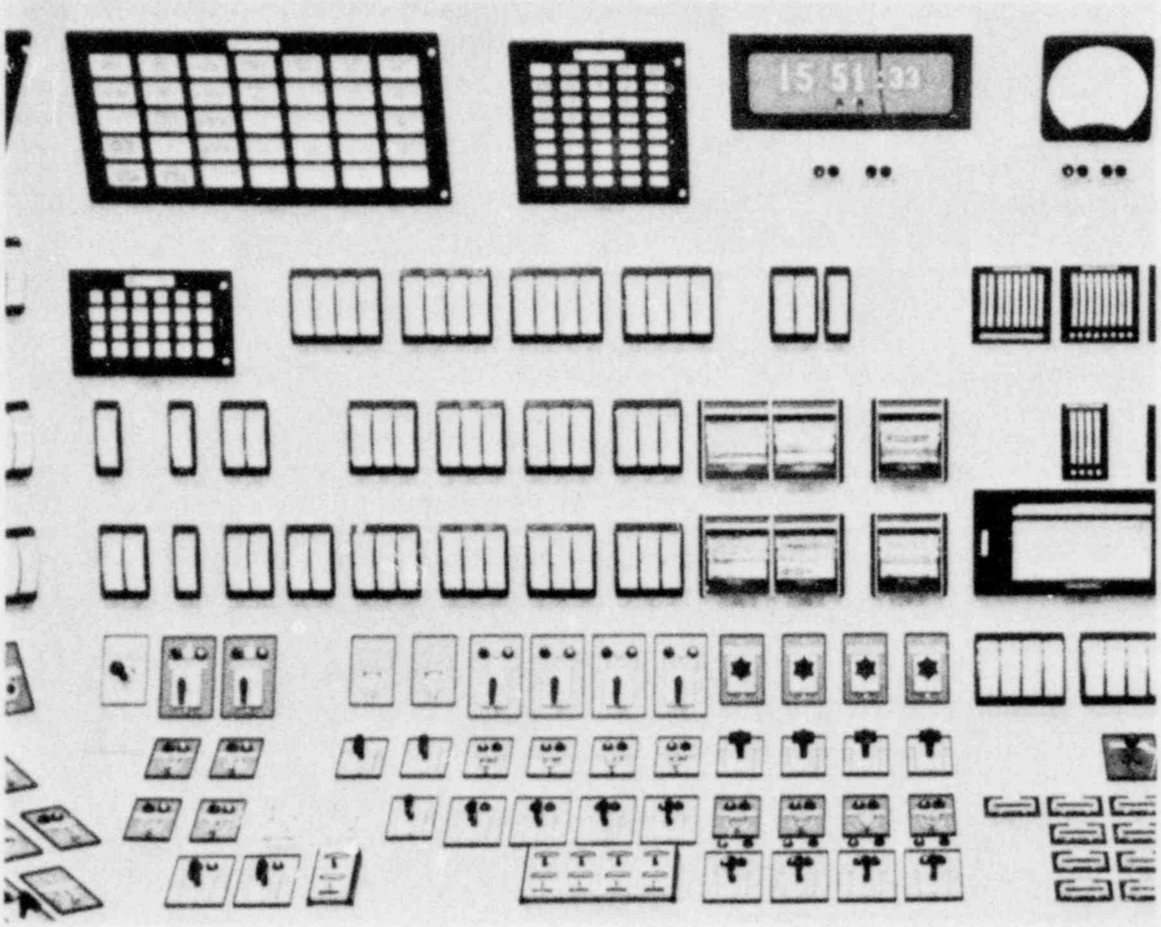


Figure 1-6. Existing Feedwater Control Configuration

engineered design, the two position indicators were collocated in the same panel area and presented rod positions in the same form. Similarly, in the precautions analysis presented in Table 1-3 (Item 7), it is required that rod movement follow the withdrawal and insertion program. A direct presentation of the program position would help meet this requirement. Therefore, a direct display of actual bank position versus program limits was incorporated in the human-engineered reactor control panel.

Control Console Design

As a first step, a control console configuration was required that (1) allowed enough space for necessary panel elements and (2) addressed the anthropometric characteristics of the operator. Unfortunately, comprehensive data describing the operator population is lacking. Therefore, reliance on military data was considered to be a necessary and suitable expedient. It was also necessary to

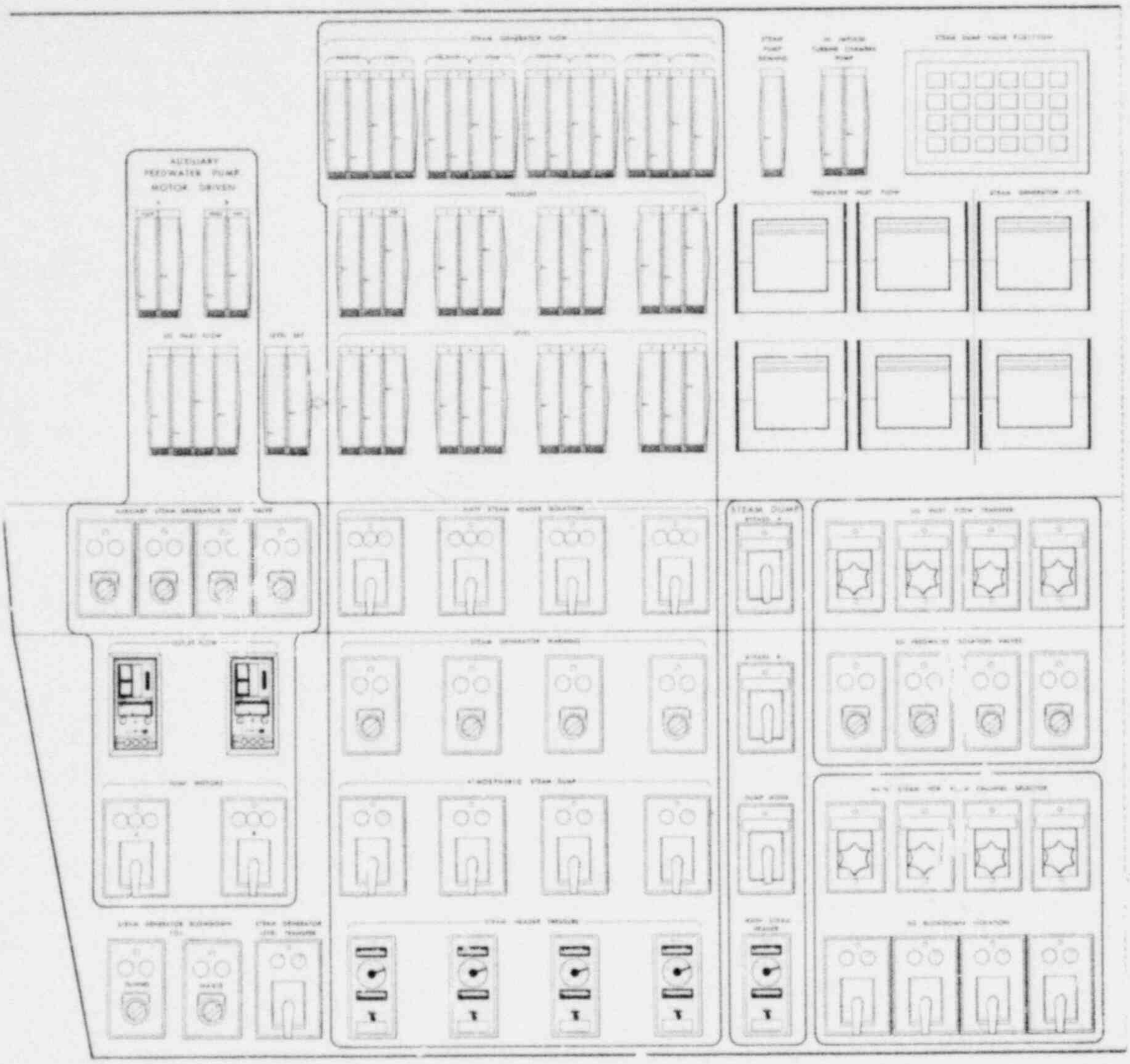


Figure 1-7. Reorganized Feedwater Control Panel (to be compared with Figure 1-6)

consider that a higher percentage of female operators may enter the control room in the future. Present generation control consoles have been found to violate anthropometric limits for male operators, and would obviously present even greater problems in accommodating the generally smaller female operators. Figure 1-8 provides the configurations and dimensions for a stand-up console designed to accommodate the anthropometric range extending from the 5th percentile female operator to the 95th percentile male. The dimensions given are based on dynamic or extended motion capabilities rather than static operator postures. Mockup evaluations were conducted with suitably sized test subjects to verify these dimensions.

Control and Display Selection

Given the console dimensions, it was necessary to select the panel elements that would be used to form the three subsystem panel configurations. Human factors criteria for control-display selection were reviewed against currently available panel components. Based on the analysis, determinations were made on the need for qualitative, quantitative, or combinations of these display forms. When quantitative data was required, the best format for presenting such data was considered: meters, chart recorders, counters, or variable format displays. Similarly, required control options were examined in terms of the need for continuous versus discrete settings, and in terms of the most appropriate device: pushbutton, toggle switch, rotary selector switch, knobs, etc. Many instances of improper control device selection had been uncovered in EPRI RP501-1. Also, the earlier study revealed that the use of excessively large controls unnecessarily increased panel size. Therefore, an effort was made to select panel elements that took as little space as possible, but still satisfied other operational requirements.

Panel Arrangements

Five basic principles of control panel arrangement were reviewed for application: sequential ordering of panel elements, mimic or graphic-pictorial presentations, prime locations for important or critical displays, location preference based on frequency of use, and functional grouping of related panel elements into distinctive subpanels. Also, where it was a consideration, location preference was given to right-handed operation. These panel layout principles are not mutually exclusive and all were used to some extent. However, the predominant layout principle, as will be shown below, was the functional grouping approach. Mimic arrangements, which operators tend to prefer in comparison with their existing boards, were attempted but generally use up too much panel space and offer no substantial advantages over a well organized panel grouped by function.

Other major concerns in the development of panel arrangement included (1) use of clearcut labeling practices to aid rapid and accurate identification of panel elements, (2) review of control locations to determine what measures were required to safeguard critical controls from accidental activation, (3) allowance of room for procedures on the bench boards, and (4) determination of the best control-display coding practices. The latter design topic raised questions which were difficult to resolve. The study team concluded that the military "green board" display coding and logic approach has many merits, even though its use of colors is in direct conflict with the tradition of the power industry which uses red for a normal open, running, or flow condition and green for a closed, non-running,

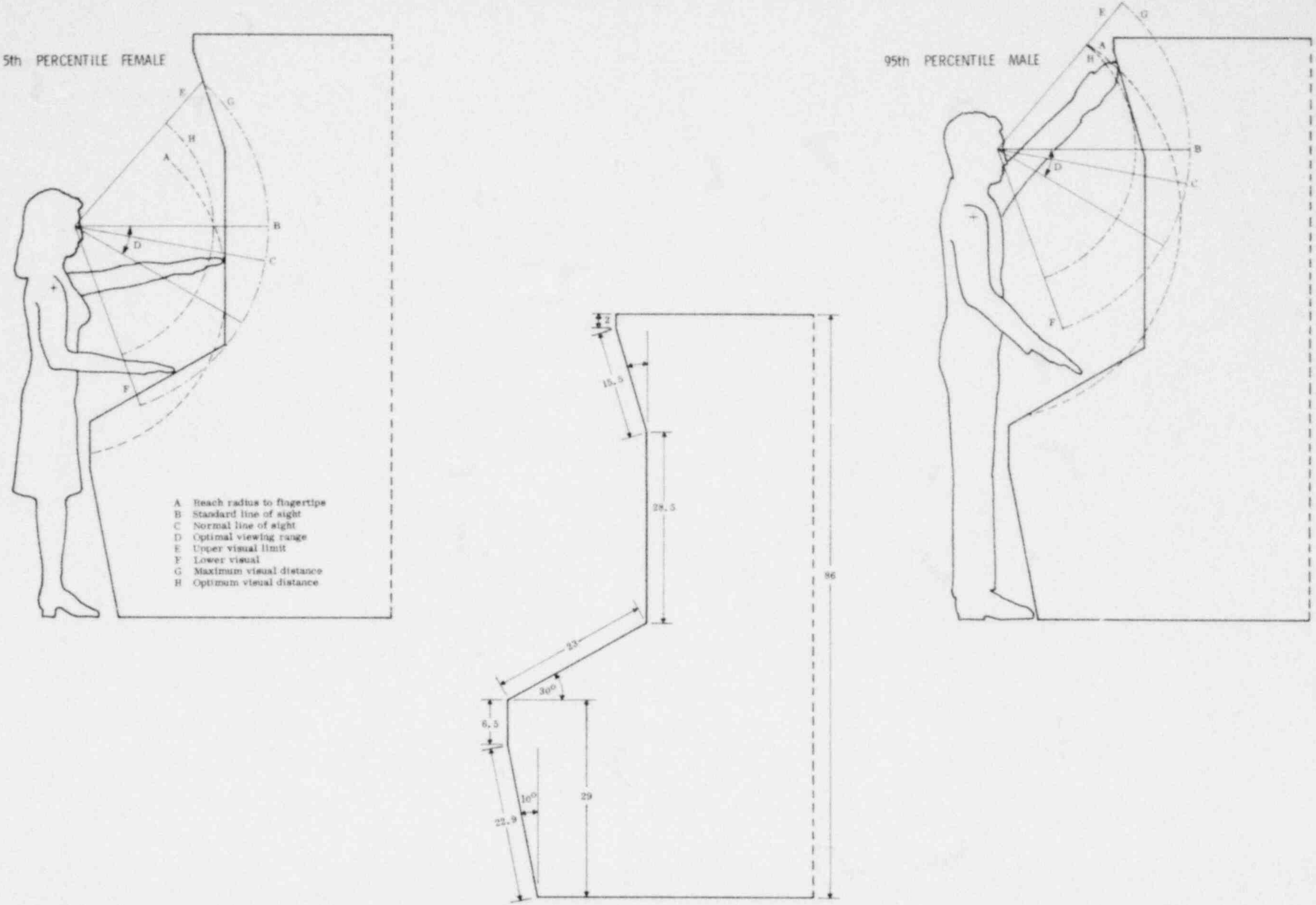


Figure 1-8. Recommended dimensions for a standup console to accomodate the 5th to 95th percentile operator population.

no-flow condition. The military operator is trained to respond to exceptions to the normally green pattern of panel displays. Such exceptions would be amber lights for cautions or the early states of a malfunction trend, and red indications for a more serious malfunction. Furthermore, present dedicated control boards do not incorporate the circuitry logic to inform the operator when a red-open condition or a green-closed condition is either a normal or abnormal condition which the operator should attend to. Some feel that it would be extremely difficult to forsake the traditional color code and that retraining of experienced operators would present too many problems. The study team feels, however, that the merits of a "green board" approach to display coding strongly outweigh the disadvantages of this break with tradition.

Human Engineered Panel Layouts

Based on the foregoing analyses and applications of human factors design principles, layouts were developed for the three subsystems dealt with in this study. Several versions of these layouts were developed as will be described below in the context of a discussion of design evaluation methods.

Figure 1-9 depicts the reactor control panel and reveals the layout of functional groups of control and display elements. Similarly, Figure 1-10 presents the feedwater control panel and provides the underlying framework of subpanel groupings. These panels should be compared with current operational panel designs shown in Figures 1-3 and 1-11. The most salient difference is the amorphous character of existing designs as compared to the clear-cut, functionally demarcated panels resulting from the human factors effort. This difference accounts for the numerous attempts made by operators to modify existing boards using taped lines of demarcation to clarify panel relationships and facilitate rapid identification of individual controls and displays.

WARNING SYSTEM APPROACHES

A primary task of the operator is to maintain cognizance over plant status and processes. He must be alerted to minor and major changes in plant condition as soon as they occur. Once his attention is obtained, he must be given the means to determine the nature of anomalies or temporary conditions, diagnose symptoms, assign priorities to corrective courses of action, and effect remedial control actions. Beyond this, he must confirm the effectiveness of his actions and restore the warning system to a state of readiness to respond to any subsequent problems.

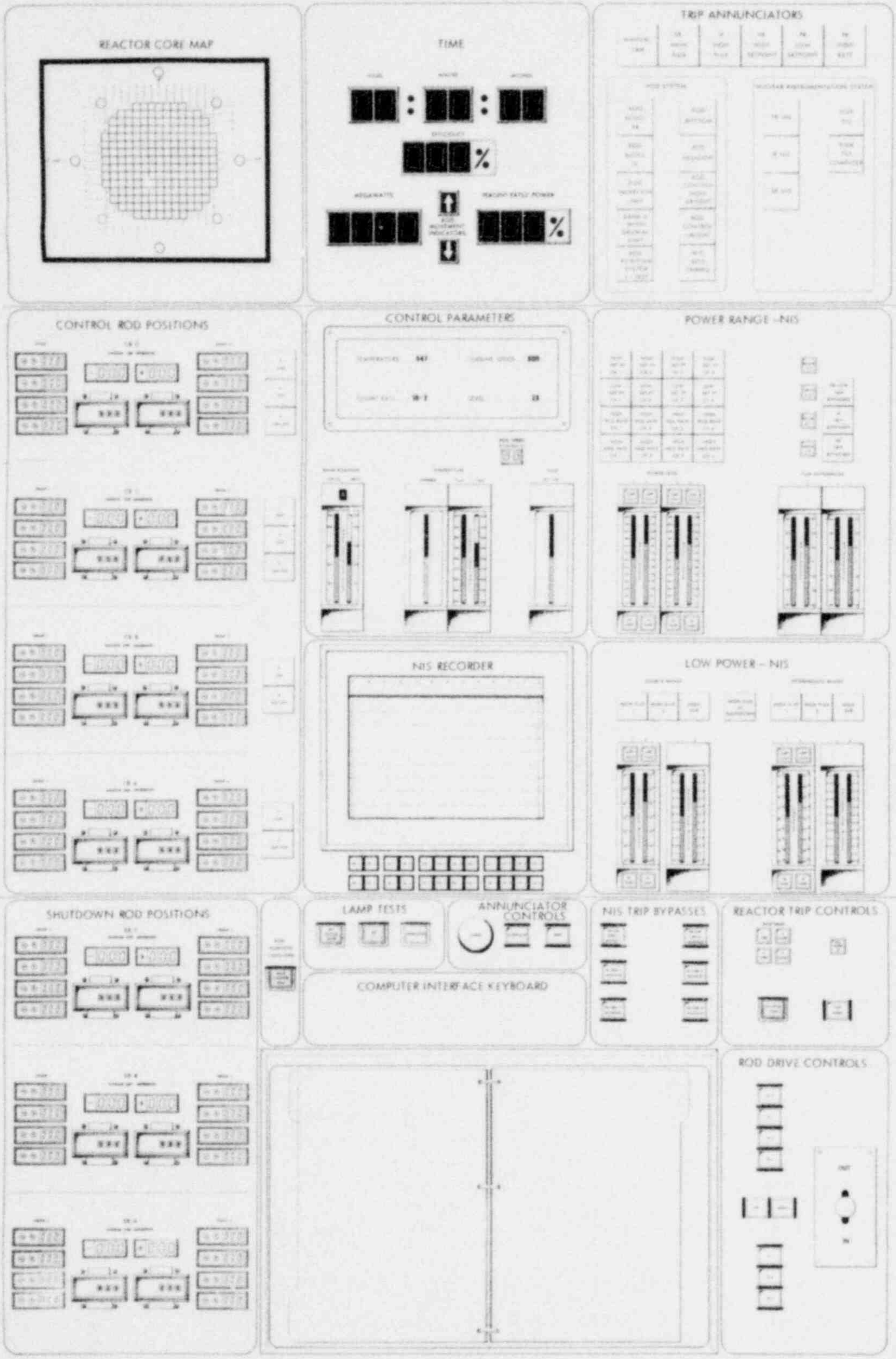


Figure 1-9. Candidate Reactor Control Panel Incorporating Human Engineering Design Practices

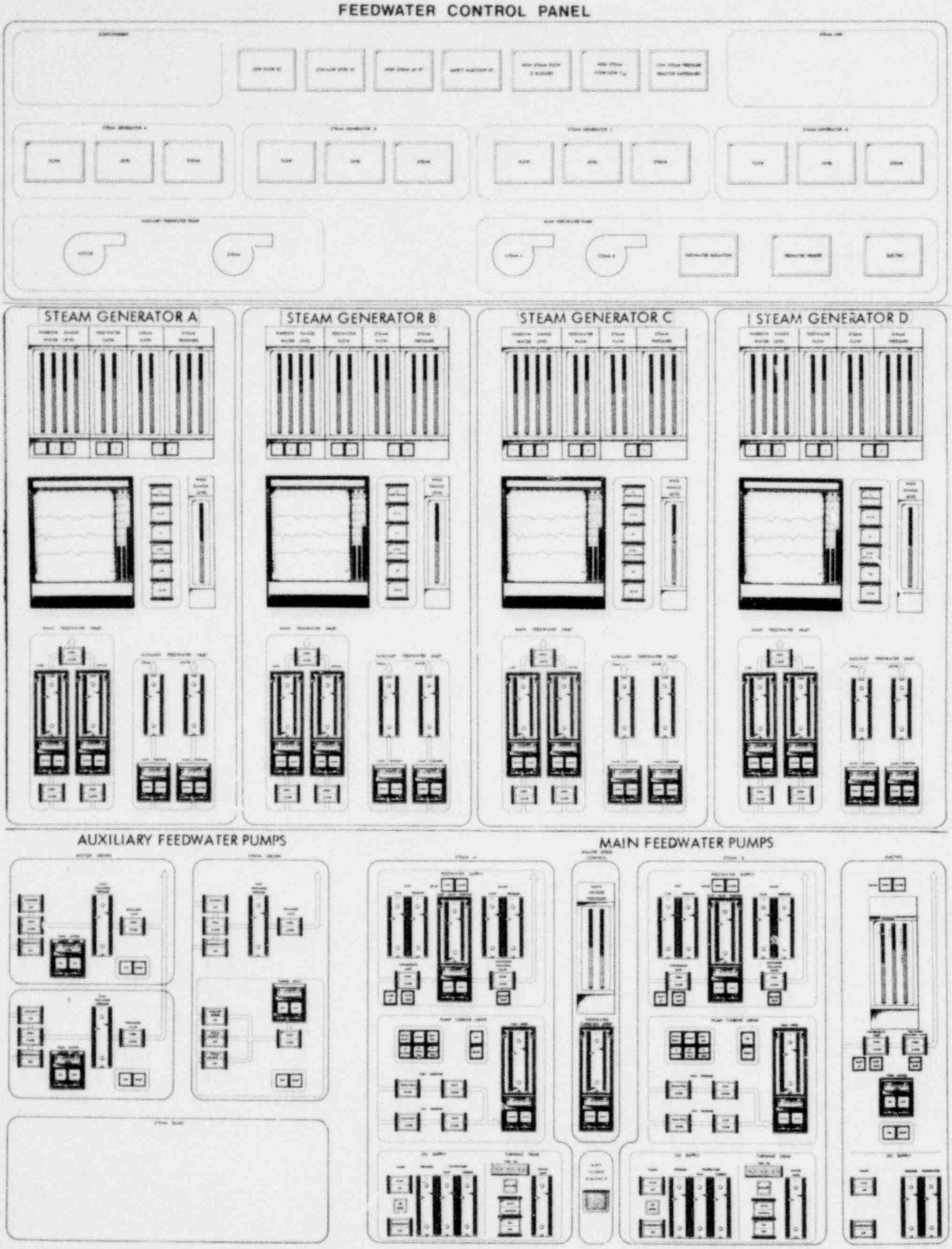


Figure 1-10. Feedwater Control Panel Design Based on Human Engineering Analyses and Design Principles

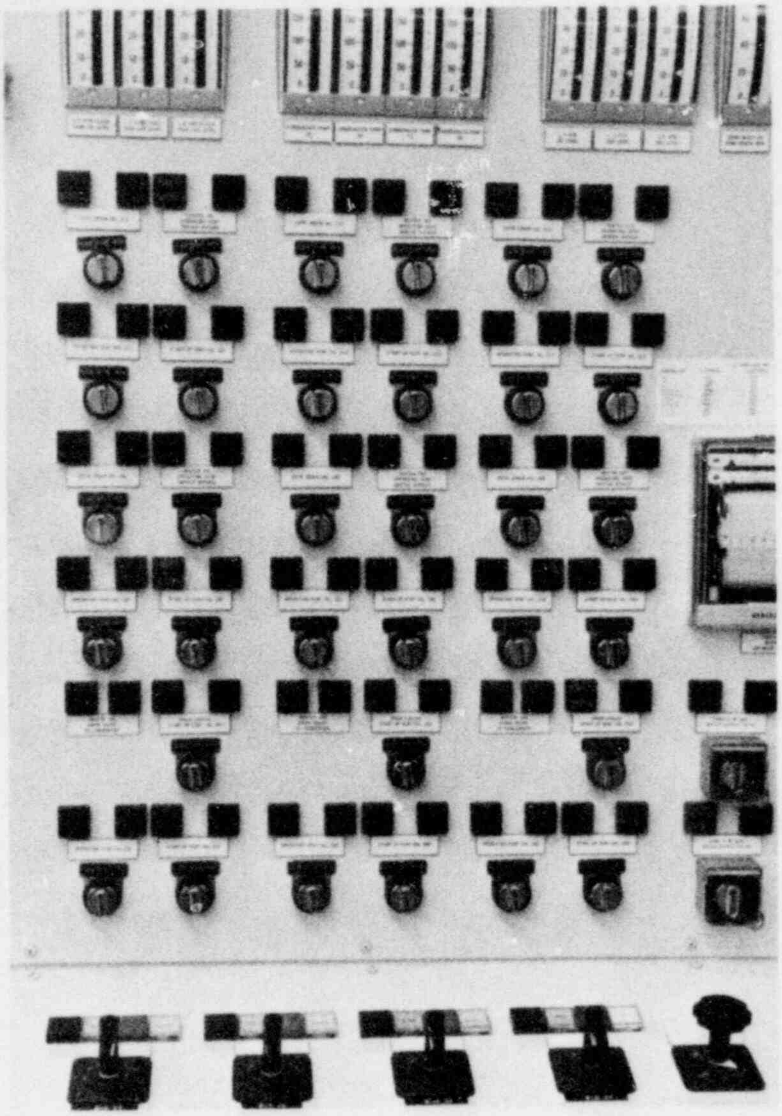


Figure 1-11. Undifferentiated Panel Design Which Operators Later Modified by Adding Taped Lines of Demarcation

The earlier survey of five present-generation control rooms (EPRI RP 501-1) revealed significant problems with existing warning systems. Briefly, anywhere from 400 to more than 2000 annunciator lights are typically arrayed in matrices running along the upper periphery of the control boards as shown in Figure 1-12. Some of the major problems with these systems are the following:

- Operators are given far more information than they can reasonably assimilate when a major anomaly occurs.
- The annunciator panels have become a catch-all for a wide variety of qualitative indications without differentiation as to importance beyond isolation of "first-out" annunciators.

Figure 1-12. A horizontal band of indicator lights above the control boards plus associated auditory cues constitutes the warning system.

- Annunciator legends are not sized to be read reliably from the operator's normal station.
- Specific annunciators are not always located above or in clear proximity to their associated quantitative displays and controls on the control board panels below the annunciator matrices.
- Operators are plagued by false or nuisance alarms which tend to induce the "cry wolf" phenomenon.

In view of the special importance of the warning system, it was isolated for separate consideration in the present study. First, general human factors requirements for warning systems were reviewed, and the following conclusions drawn: (1) alerting signals must attract the operator's attention regardless of his position in the control room, including backrack areas, (2) while commanding the operator's attention, alerting signals should not be so startling or disruptive that on-going activities are compromised, and (3) it is advisable to give the operator some indication of the severity of an annunciated problem so that he can assign proper response priorities. Once general operational guidelines were developed, candidate visual and auditory warning approaches were explored.

Visual Warning Approaches

Seven candidate visual warning approaches were examined and are briefly described as follows:

- Integration of Warning Signals Into Primary Control Panels. Rather than isolating all qualitative warning displays into a separate annunciator panel, it is possible to integrate such qualitative displays with associated qualitative read-outs and controls. This requires that such warning displays be highly distinctive, such as flashing red warning lights incorporated in a well-designed "green board" panel layout.

- Master Warning Displays. To reduce the visual scan time associated with the first approach, a master or summary alarm indication could be assigned to each major system or corresponding board segment. Each summary indication, which would flash on and off when activated, could be placed above the panel segment of direct relevance (see Figure 1-13), or the summary annunciators could be integrated into one centrally located annunciator panel shaped to provide geographic correspondence with the control board layout as shown in Figure 1-14.

- Redundant Warning Information. One method for providing an overview of plant status via an annunciator band of qualitative indicators and also satisfying the requirement of functionally grouping qualitative and quantitative information is to provide redundancy of information on the upper and lower areas of control boards. This approach is already being followed to some extent in some plants.

- Prioritized Annunciator Displays. Rather than assigning all qualitative indications to the traditional annunciator panel location, a review of such indications reveals that a fraction of those usually placed within annunciator matrices can be left there as summary indications while the majority can be integrated directly into the Control Board panels below. This prioritization reflects the need to be able to oversee, at a glance, plant and process status while relegating lesser or more detailed indications to the subpanels where system diagnosis and control can be effected. The feedwater annunciator panel shown in Figure 1-10 represents this approach.

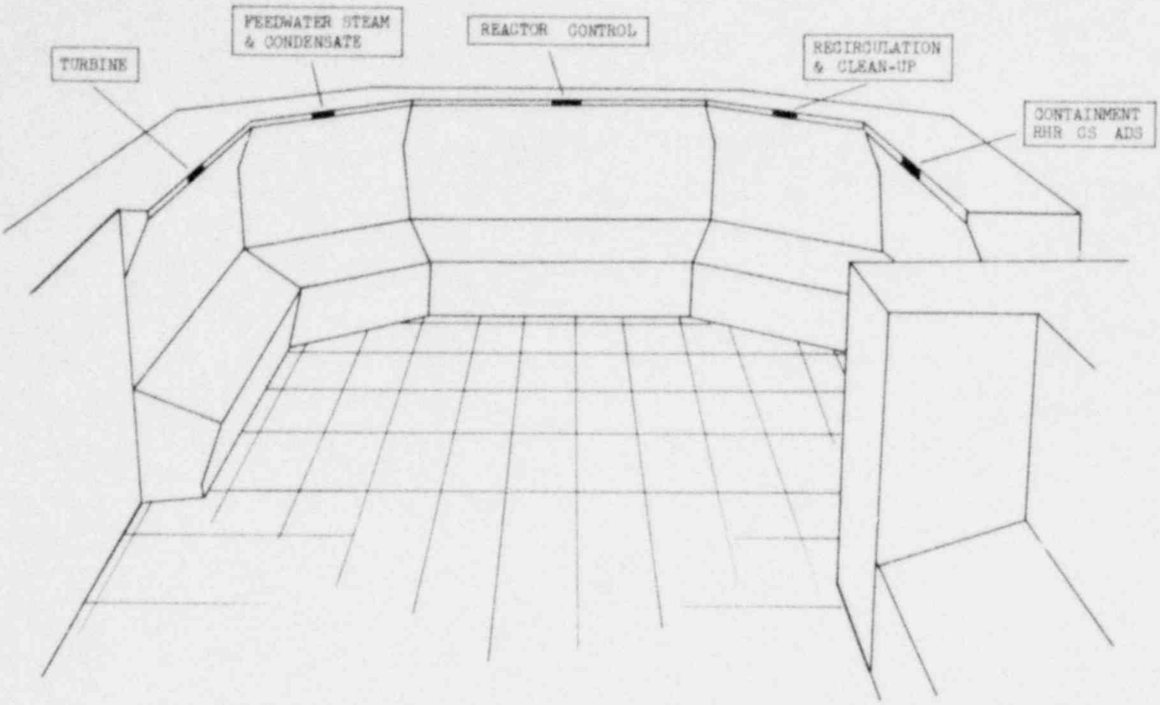


Figure 1-13. Master Warning Displays That Double as Major Panel Labels

- <u>Correlated Annunciator Panel and Control Board Arrangements.</u> Present day annunciator panels give no clue as to the relationship of a given annunciator light to the location of its related quantitative displays below. The operator learns such associations through experience. However, by configuring the annunciator panel so that its arrangement is correlated with the arrangement of the subpanels below, using the same logic as was illustrated in Figure 1-14, the transition from annunciator to the control boards is less likely to produce errors of misassociations and will produce a reduction in visual scan time. As in the preceding paragraph, only summary indications would be included.

- <u>Mimic Annunciator Panel Arrangements.</u> Operators have indicated a strong preference for mimic panel arrangements. Generally, such arrangements require more panel space than desirable and do not offer clear advantages over a well-designed panel based on principles of clearly demarcated functional grouping of panel elements. However, there may be an application for mimic arrangements of annunciator panels (see Figure 1-15). Such panels would provide some insight into the relationship of a given malfunction indication to the system or subsystem in which the problem occurs and should, thereby, aid diagnosis and control of the problem.

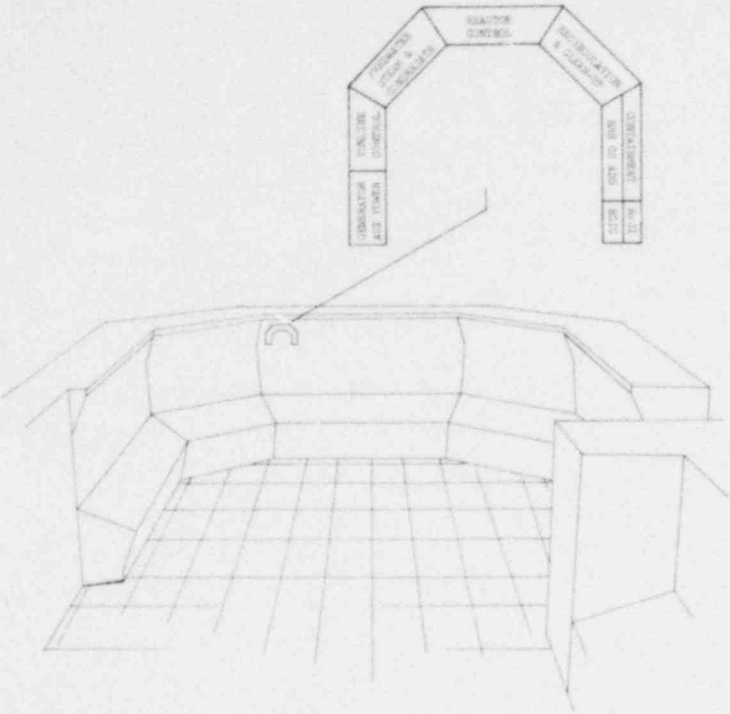


Figure 1-14. Summary master warning display located in a central board area and arranged to mimic the location of panels on the control boards by major system.

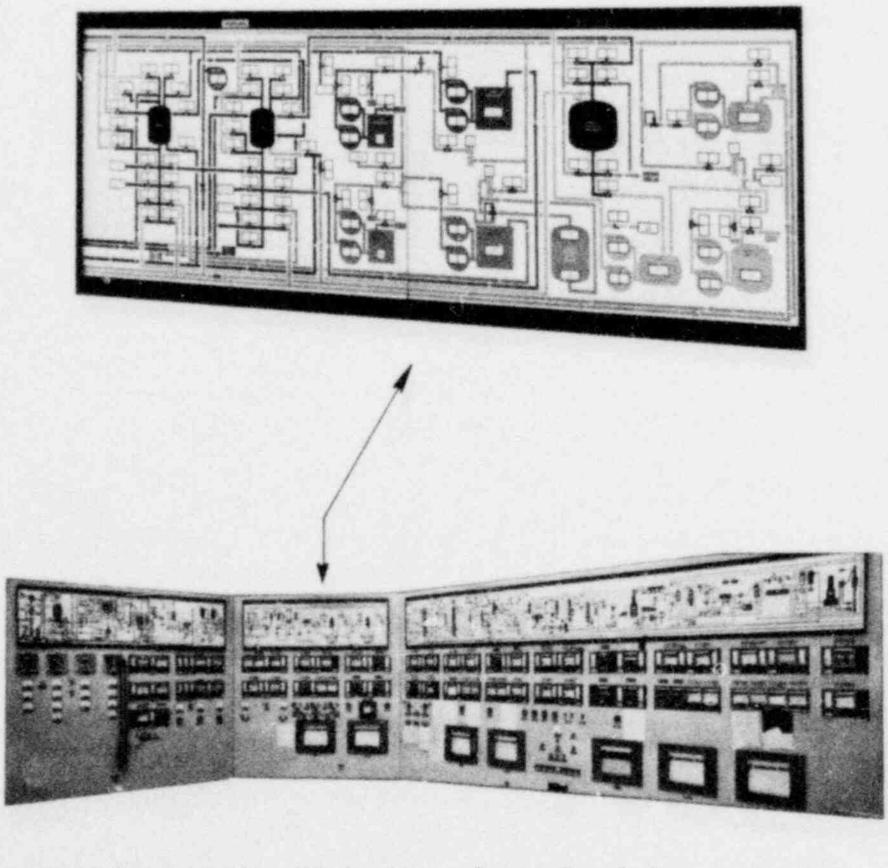


Figure 1-15. Mimic Annunciator Panel Arrangements

- Hierarchical Annunciators Panels. Another variation of the prioritized annunciator concept described above is to arrange the annunciators in a hierarchical or pyramidal order from the most general to the most specific. At the apex of the pyramid we might have FEEDWATER SYSTEM. The next level might include individual summary STEAM GENERATOR lights, followed by a third tier of STEAM GENERATOR FLOW, LEVEL, and STEAM alarms for each steam generator, etc. A hierarchical arrangement based on importance is also possible. Such an arrangement might be useful in allowing the operator to address the more important problem when confronted with simultaneous alarms.

Auditory Warning Signals

Visual warning systems may suffice when an operator is confined to a fixed station and his control panels are always in view. Such is certainly not the case in a nuclear power plant control room where the boards are relatively large and the operator must constantly move around, sometimes outside the primary control sphere. Consequently, visual alerts, which are highly directional, must be supplemented with auditory cues which are omni-directional, that is, capable of acquiring the operator's attention regardless of his location within the control room. While all the control rooms visited by the study team use auditory cues in association with visual annunciator systems, the information presently conveyed via the auditory channel is generally limited to a distinctive sound, directing the operator's attention to the boards.

This study examined a variety of possible auditory signals that can be used in conjunction with the visual warning candidates outlined above. The aim was to expand the information content of the auditory warning system so that board scan time could be reduced, correspondingly reducing the time required to identify the nature of the alarm. The auditory candidates considered were as follows:

- General Auditory Alert. Generally, one distinctive sound can be used simply to direct the operator's visual attention to the boards. A variation of this approach, observed at one plant, is to have the warning signal emanate from only one of a number of speakers, the one located in association with the affected annunciator matrix.

- Two-Level Auditory Alert. A two-tone auditory alert system could be devised to differentiate between urgent warnings and less significant cautions or advisory information. This two-level sound code would allow the operator to determine whether he should stop what he is doing at the moment of the alert, or continue what may be a more critical task until possible to leave. This system could also be correlated with color coded annunciator displays, e.g., red for major warnings, and amber for cautions.

- Coded Non-Verbal Signals. Six to ten distinctive sounds could be employed for coding purposes. For example, warnings associated with the various major plant systems could be coded auditorily so that the operator would immediately direct his eyes to the appropriate section of the boards. Alternatively, distinctive sounds could be associated with major emergencies, such as MAIN STEAM TUBE RUPTURE, assuming that the warning system logic (a disturbance analysis system) was capable of signalling a major disturbance directly. Since such emergencies would be so infrequent, periodic rehearsals of code meanings would be necessary.

- Verbal Warning Systems. Considering that present day control rooms can have from 400 to 2000 visual annunciations, coded auditory signals may not be the best supplement to a visual warning system. Verbal warning approaches, initially developed for aircraft applications, may hold greater promise. Such warning systems could present taped or synthetic speech messages over a control room speaker. Such messages would be prioritized so that in the case of simultaneous warnings the most important would be delivered first.

Preferred Audio-Visual Candidates

It is apparent from the foregoing that numerous alternative combinations of audio and visual warning approaches are possible. Research is insufficient to allow the selection of the one best audio-visual warning system. The most promising audio-visual candidates were selected by applying the following criteria:

- The operator should be alerted to the onset of a cautionary trend, system malfunction, unsafe condition, or process disturbance in the shortest possible time.

- The operator should be provided the means to correlate qualitative alerting information with associated quantitative displays, in order to allow an accurate determination, in the shortest possible time, of the nature and cause of changes in system or process status

- The operator should be able to identify and associate available control options with specific disturbances quickly and accurately so that appropriate control actions can be effected manually or the initiation of automatic system response can be easily verified.

- The operator should be able to identify the gravity of any alerting signal from any position in the control room so that he can determine whether to interrupt or continue on-going tasks.

- The operator, watch foreman, and other interested parties who frequent the control room should be able to make summary judgments regarding plant status by means of the annunciator-warning system, without having to make a detailed scrutiny of all or most discrete control panel elements.

Using these evaluation criteria, the following audio-visual combinations appear most promising:

- Correlated annunciator panel and control board arrangements coupled with a verbal warning system

- Correlated annunciator panel and control board arrangements coupled with coded non-verbal auditory signals

- Mimic annunciator panels coupled with a verbal warning system

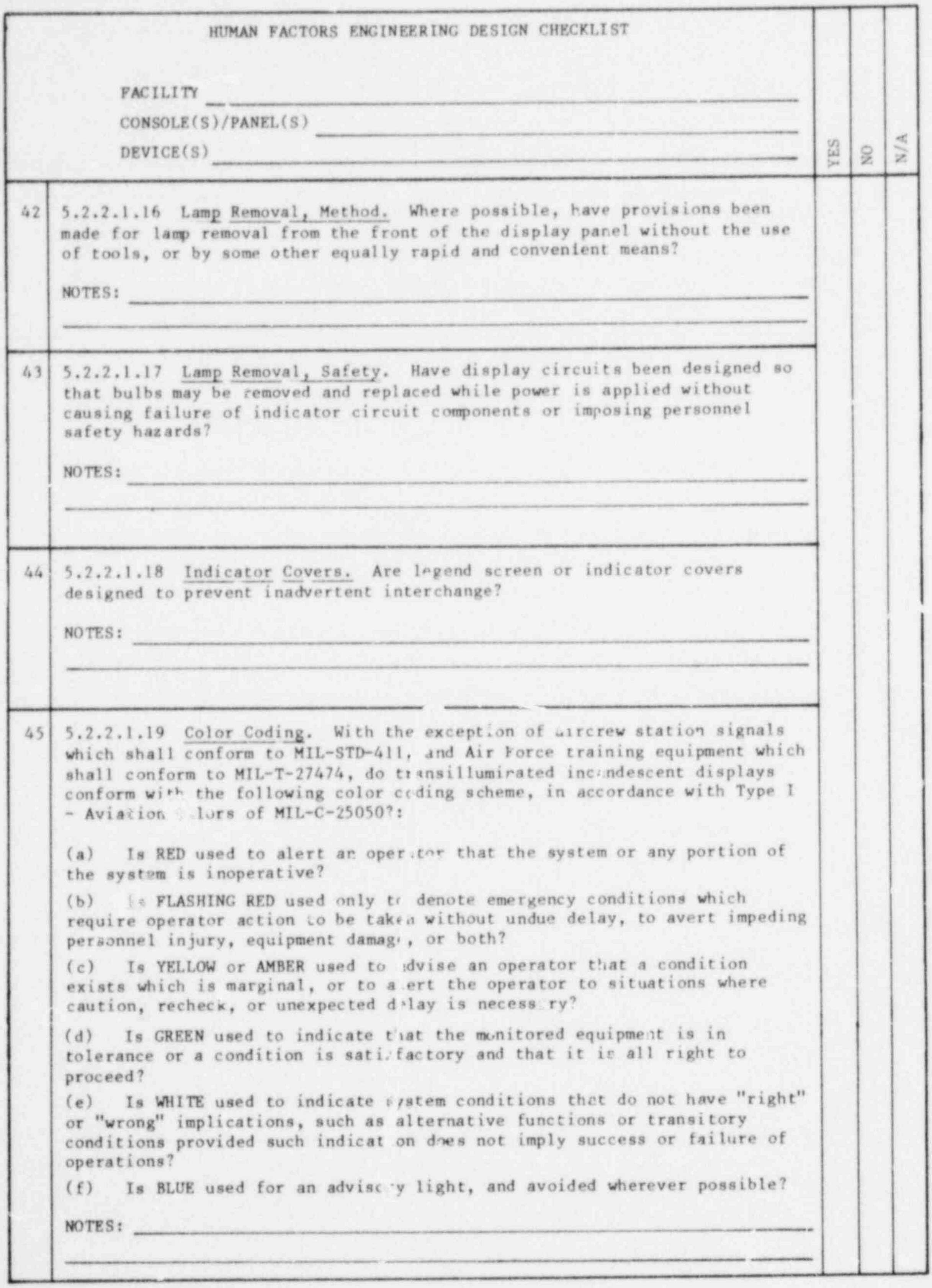
- Mimic annunciator panels coupled with coded non-verbal auditory signals

These preferred candidates were chosen because of operational efficiency, with insufficient consideration of design complexity factors. These judgmental evaluations should be substantiated by empirically derived measures of the relative effectiveness of alternative audio-visual warning approaches. For example, there is some concern that operators might object to the chattering of a verbal warning system if the alarm rate were excessive.

CONTROL BOARD DESIGN EVALUATIONS

An essential step in the human factors approach to control board design is design evaluation or verification. Analytic approaches, no matter how systematic or thorough, can overlook or fail to anticipate operational realities or deep-seated operator preferences. There is always the concern that long established operational response patterns may lead to a negative transfer of training when the operator is confronted with new board configurations that depart from traditional designs.

It is, therefore, important to interface with operational personnel, not only when establishing preliminary design requirements, but also at periodic intervals during the design process. The use of three-dimensional mockups of candidate design concepts are an indispensible aid in verifying the adequacy of man-machine interfaces. Such mockups permit static simulations or walk-throughs of operational sequences, both normal and off-normal. These so-called static simulations allow evaluations of anthropometric factors, panel layout efficiency, sufficiency of displayed information, and adequacy of control options, among a host of other variables. In fact, a human factor design checklist (see Figure 1-16) is advisable to ensure that no significant factors are overlooked. Such checklists should be used, not only by human factors specialists on the design team, but more importantly by the customer to ensure compliance with human factors standards.



HUMAN FACTORS ENGINEERING DESIGN CHECKLIST

FACILITY ______________________________

CONSOLE(S)/PANEL(S) ______________________________

DEVICE(S) ______________________________

		YES	NO	N/A
42	5.2.2.1.16 <u>Lamp Removal, Method.</u> Where possible, have provisions been made for lamp removal from the front of the display panel without the use of tools, or by some other equally rapid and convenient means? NOTES: ______________________________ ______________________________			
43	5.2.2.1.17 <u>Lamp Removal, Safety</u>. Have display circuits been designed so that bulbs may be removed and replaced while power is applied without causing failure of indicator circuit components or imposing personnel safety hazards? NOTES: ______________________________ ______________________________			
44	5.2.2.1.18 <u>Indicator Covers.</u> Are legend screen or indicator covers designed to prevent inadvertent interchange? NOTES: ______________________________ ______________________________			
45	5.2.2.1.19 <u>Color Coding</u>. With the exception of aircrew station signals which shall conform to MIL-STD-411, and Air Force training equipment which shall conform to MIL-T-27474, do transilluminated incandescent displays conform with the following color coding scheme, in accordance with Type I - Aviation Colors of MIL-C-25050?: (a) Is RED used to alert an operator that the system or any portion of the system is inoperative? (b) Is FLASHING RED used only to denote emergency conditions which require operator action to be taken without undue delay, to avert impeding personnel injury, equipment damage, or both? (c) Is YELLOW or AMBER used to advise an operator that a condition exists which is marginal, or to alert the operator to situations where caution, recheck, or unexpected delay is necessary? (d) Is GREEN used to indicate that the monitored equipment is in tolerance or a condition is satisfactory and that it is all right to proceed? (e) Is WHITE used to indicate system conditions that do not have "right" or "wrong" implications, such as alternative functions or transitory conditions provided such indication does not imply success or failure of operations? (f) Is BLUE used for an advisory light, and avoided wherever possible? NOTES: ______________________________ ______________________________			

Figure 1-16. Sample page from a military human factors design evaluation checklist.

The present study provided for two forms of design reviews or evaluations: the first with a group of operationally oriented trainers at the Westinghouse Operator Training Center, Zion, Illinois, and the second with a sample of 25 control board designers distributed across the major Nuclear Steam Supply System (NSSS) and Architect-Engineering (A-E) firms. The operational review took place when the control panel designs presented in the preceding sections were at a preliminary stage of development. The reviews by board designers were scheduled subsequent to refinements made to the panels as a result of the operational critique.

Operational Review

The "first-cut" at the three major panel layouts developed was based on an analysis of control-display requirements associated with start-up, load change, and shutdown operations. Analyses of these three modes served as a good beginning for study purposes but fell far short of the analytic foundation required for an actual design and development program.

To more fully explore the range of operator activities, a week was spent with four trainers having extensive operational background on Westinghouse systems. The trainers first reviewed the panel layouts in terms of the operational modes on which the analyses were predicated. Subsequently, the panels were reviewed in terms of a series of standard major emergency sequences used in the training programs at the Zion training center: main steam line break, loss of a feedwater pump, a dropped rod, and condenser vacuum problems. The number of emergency operational scenarios reviewed had to be constrained by the time and budget limitations of the study. The study team felt that a fairly comprehensive evaluation of design concepts was obtained from these walk-throughs. Had this been an actual board development effort, however, an attempt would have been made to walk-through all or most normal and off-normal operational sequences.

The setting for these operational reviews proved very favorable. The mockups to be evaluated were placed in a special training room that included a half-scale mockup of the Zion plant control room. When some questions arose as to current operational or design practices, a ready comparison to the Zion control room design was available. Also, when the dynamic training simulator was not in use for training purposes, the study team was invited to witness the pattern of indications and control manipulations associated with the selected emergency operations in a realistic real-time mode.

Based on these reviews, a number of changes to the initial panel designs were indicated. A comparison of Figures 1-17 and 1-18 provides an indication of the modifications made to accommodate operator judgment and experience. The initial arrangement of Nuclear Instrumentation System (NIS) and control rod position information on the veritical panel is shown in Figure 1-17. This arrangment was based on the operational anaylses that preceded the panel design effort. During the walk-through of start-up operations, the test operators found this arrangement to be awkward. When moving control rods, the operators initially check the rod position information to verify movement, and subsequently check the NIS displays. To promote a more natural left-to-right progression, it became apparent that the rod positional information should be placed to the left and the NIS information to the right as shown in Figure 1-18.

The operationally oriented trainers who reviewed the proposed designs appeared totally sympathetic to the aims of the study team in introducing human factors considerations in panel design. It was their general consensus that improved functional groupings of panel elements, enhanced labeling, and the simplified warning system proposed would ease the task of the trainer and tend to reduce operational errors.

Design Engineering Review

Human factors specialists typically make their contributions to equipment design in a design team setting. Day-to-day interactions with other designers, each with a special focus, allows resolution of numerous trade-off decisions typical of most design and development efforts. The present study lacked such constant interactions with other design specialists, periodic reviews with management personnel, or expressions of client preferences. To partially compensate for the absence of these crucial tests of design approaches, visits were made to the major control room design organizations for critiques.

The 25 designers who participated in these reviews were invited to comment on such design factors as (1) compliance with seismic and separation criteria, (2) producibility of the panel designs, (3) operational characteristics of the panels, and (4) the value and feasibility of incorporating human factors engineering principles into panel designs. The designers were helpful in raising concerns over instances where separation of components was inadequate or where seismic criteria were only marginally satisfied. While recommended design features such as "green board" logic coding of indicator lights were perceived as introducing added design complexity and costs, all of the human factors recommendations were felt to be both

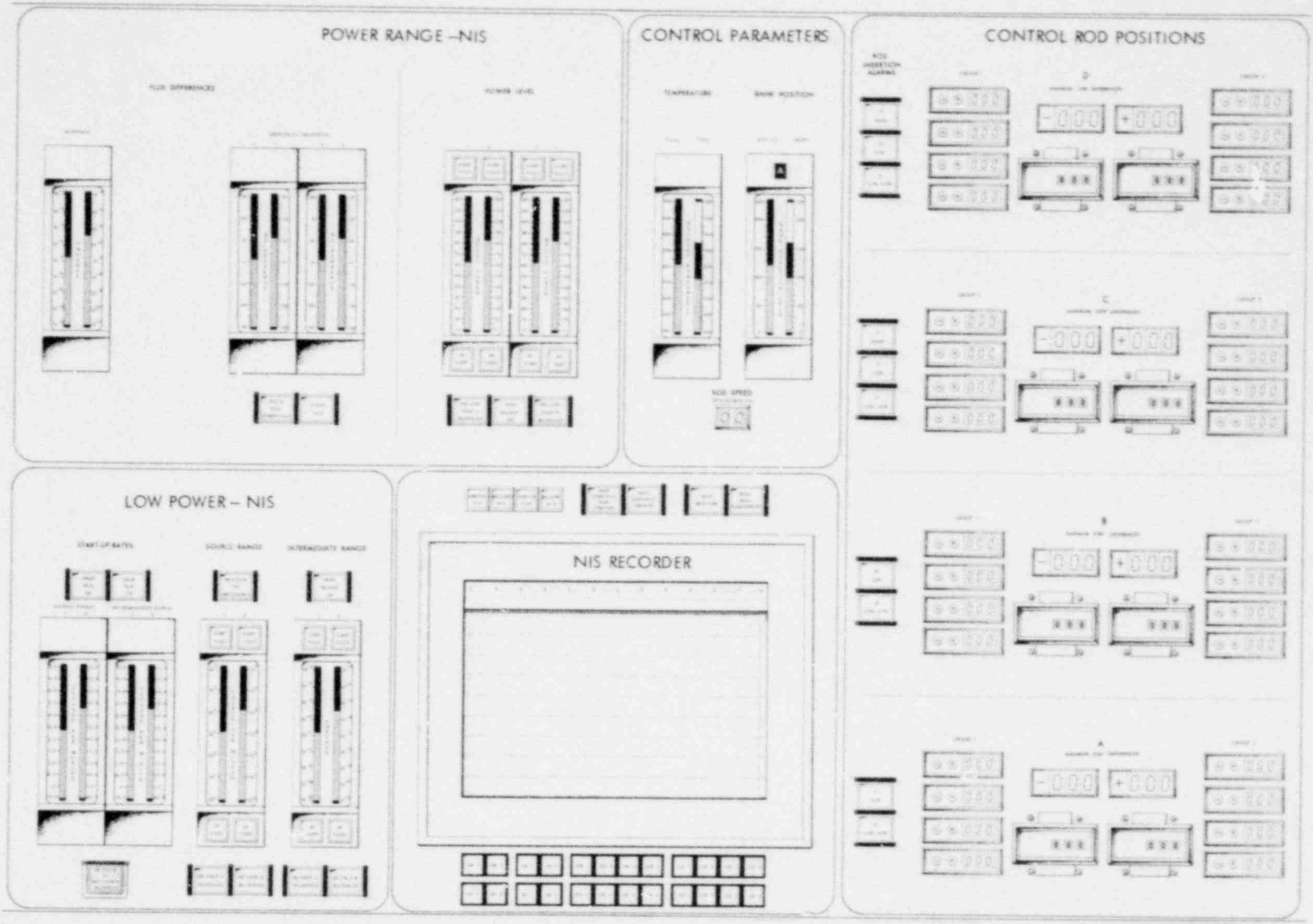


Figure 1-17. Initial arrangement of NIS and rod position indications.

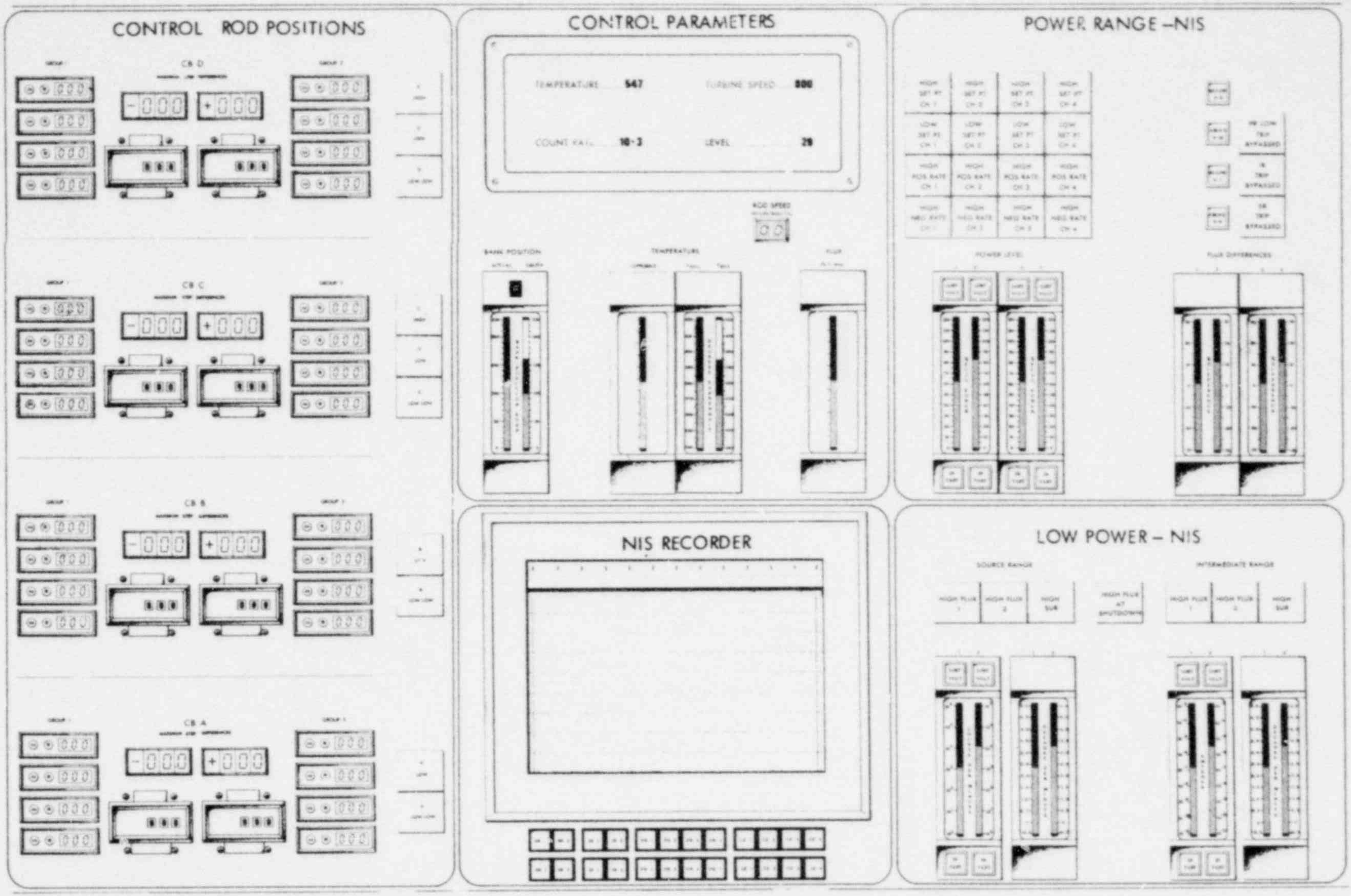


Figure 1-18. Modified arrangement of the NIS and rod position indicators based on the operational review.

well within the state of the art and successfully applied in other industries. On the whole, the response of designers, as was the case with the trainers, was essentially and uniformly positive. One designer noted with some envy in his voice that the study team was allowed to create human engineered designs due to the lack of changes introduced by the client and the absence of last-minute additions made by functional system designers after the layout was supposedly "frozen."

ADVANCED COMPUTER-BASED CRT APPROACHES

There is a marked trend towards advanced computer-based CRT control rooms. As one advanced system designer observed, "This is the last major industry to move in the direction of advanced control-display techniques!" Each of the major NSSS vendor organizations is developing advanced control rooms, with some on the drawing boards, others in mockup or prototype form, and still others being assembled and prepared for operation within a year or two.

To obtain an overview of developments and trends in future control room design, a tour was made of the primary advanced control room design organizations. Discussions with design engineers and design reviews permitted the study team to delineate the key issues involving human factors concerns discussed in this section.

General Characteristics of Advanced CRT Approaches

Advanced control room concepts are defined as those designs that incorporate CRTs as the primary display interface instead of conventional hardwired indicators and recorders, thus allowing for much more flexibility in the presentation of information to the operator. This increased flexibility provides the greatest inherent potential for improved operations. At the same time, if the man-machine interface is not human engineered, this flexibility can create, and in some cases has created the setting for a degraded operator-control console interface.

In addition to this increased flexibility of the man-machine interfaces in an advanced control room, the mode of presentation is different from that of a conventional control room where information is presented in parallel. With dedicated instrumentation, all information is continuously available to the operators, and based upc their training and experience, they extract specific information and data depending on the situation. In a CRT-based display system, the information is presented primarily in a sequential manner. The designer predetermines what specific group of data to present on a given display page, and the operators take specific actions to retrieve the display page of interest. The ease with which the operator can retrieve pertinent data in the advanced control room depends to a large extent on the degree to which the designer (1) considered the operational interface and accessing strategy when structuring the information, and (2) organized it in terms of display pages. The information structure and accessing scheme should be developed primarily to aid operational use, rather than to minimize design or software requirements.

The human factors engineering effort required to ensure an operationally efficient interface is more extensive for the advanced control room. It is easier to compensate for a poorly human-engineered conventional control room through extra training and staffing efforts than it will be for an advanced system with a cumbersome accessing strategy or excessively high-density displays.

Analytic Requirements

The analytic foundation for the advanced control room is necessarily more extensive than that for a conventional control room. Whereas the designer of a conventional control room has to decide only once what information to include on the panel, in what form, and where, the advanced control room designer addresses these issues over and over for a multitude of display pages. Therefore, the analyses must be conducted at a much more detailed task level for the advanced control room.

Information Accessing Schemes

One of the greatest challenges confronting designers of advanced control rooms is the development of schemes to enable the operator to access required information effectively. Advanced CRT displays provide a narrow window into the system, presenting at any given time no more than 5 to 10 percent of the total available information. Ideally, it should be as easy and natural for operators to extract information from the computer as it is for them to scan the conventional control room to obtain pertinent information. During a major transient, it is extremely important to provide the operator with means to focus on diagnosis of the problem and identification of appropriate corrective action. At such times, the operator should not be preoccupied with the intricacies of the display system logic to retrieve desired information.

Two accessing schemes were examined, both of which are being developed by NSSS suppliers. The first organizes the information by system and then by the level of detail within a system. The second technique also is organized by system, but the subgrouping is based upon the plant operating state and the information set required by the operator for each particular mode.

Although an organization based upon the information requirements of a particular state offers the opportunity for a very smooth and efficient interface, it is only as good as the operational analyses that determined the information requirements for each state. If time and effort are not invested in operational analyses early in display development, the potential for a degraded interface is high.

Organizing by information detail leaves the operator with the task of searching out required information from the indexing structure. However, as the operator becomes increasingly familiar with this structure, he will probably be able to find the desired information quickly in the same way that he can find a particular control or indicator on a massive conventional control board. In all likelihood, some combination of the two information-accessing approaches will be most effective.

Response time is an important consideration in developing an information accessing system. If an operator requests a particular display, it should be on the screen within 2 to 3 seconds. If the system does not respond within one second, an "in-progress" message should be provided to the operator.

Interfacing Hardware

Having developed an information structure and accessing scheme, the actual interfacing hardware requirements can be addressed. Once an operator has determined the display page desired, this selection information must be input to the system. A communication strategy and operational plan encompassing the entire control room with its multi-CRTs should be developed. Some of the items to consider include the following: (1) Should there be a dedicated interface device assigned to each CRT or is one device for every two or three CRTs sufficient? (2) Should there be a master interface device from which all CRTs can be controlled? Answers to such questions regarding the overall operational interfaces will influence the selection of the actual interface devices. Several alternative hardware options reviewed include the following: alpha-numeric keyboards, light pens, cursor controls, joysticks, acoustic pens, and trackballs.

Information Coding

With a system as complex as a nuclear power plant and its associated instrumentation, the coding of information to aid operator processing and interpreting is essential. The best format should be developed for presenting the information to the operator prior to including the coding features; coding should not be expected to "crutch" a poorly formatted display, but should enhance an otherwise acceptable display format. The designer should optimize use of all coding techniques (e.g., intensity, reverse video, symbology, line textures, size) and not rely exclusively on color, which is the most frequently used coding dimension with the CRT display systems. In fact, because most color CRT systems furnish eight colors, it is frequently overused and may well result in degraded, rather than improved, operation. Color should only be used where a functional need exists to differentiate two items. Frequently a designer will group similar things (examples are labels, units, system titles, and components) and assign a different color to each one, even though in actual operations there is no functional requirement for an operator to discriminate among these various items. The use of color in this way may result in a more aesthetically pleasing display with all things clearly categorized, but the color is irrevelant to actual operations, complicates the operator's task, and may in fact degrade operations. Figure 1-19 illustrates a preliminary display format where color has not been used to its best advantage. Figure 1-20 shows how the CRT format might be enhanced through more effective use of color coding. Color is a very strong coding dimension and is best reserved for items of greatest functional importance, such as dynamic information and alarm conditions. Other coding dimensions should be incorporated for the more routine differentiations in the display.

Interactive Techniques

Coding techniques are not the only means available to aid operator processing and interpretation of complex CRT displays. Interactive capabilities can be incorporated into the system design, enabling operators to modify and amplify displays to reduce clutter. Experienced operators will only infrequently need to refer to parameter labels and engineering units; therefore, this information could be suppressed on the display page unless requested. Limits could be provided interactively at the operator's request, but would be suppressed at other times to reduce clutter in the display. Grid-lines and scales on graphical displays could be provided on request only. On trend or graphic displays, an operator could interactively request a digital display on the coordinate of some specific point on a curve. Interactive trend graphs could be provided when an operator suspects a developing problem. The operator could input the desired time period for the trend and specify other variables for simultaneous trending if he suspects there is a relationship between them and wishes to compare them. Although interactive features require extra efforts for developing the supporting data structures and software, they will provide a smoother, less frustrating interface for the life of the system.

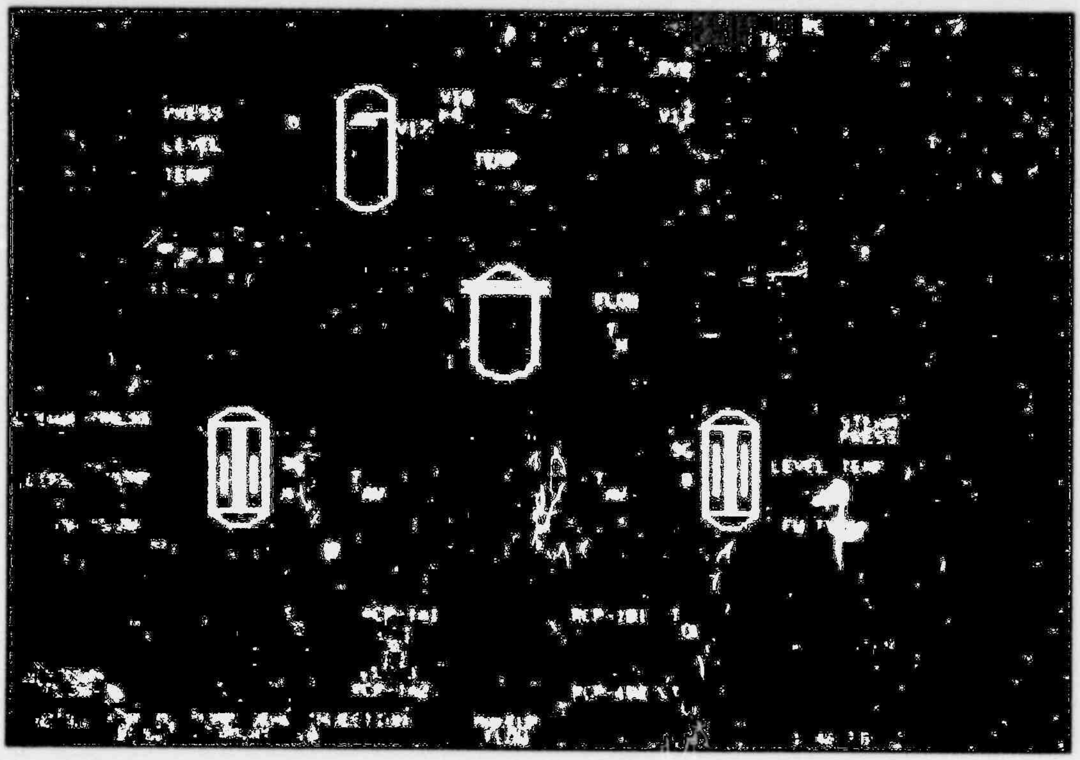


Figure 1-19. System components are assigned the most conspicuous color. Yellow should have been used to highlight more important information.

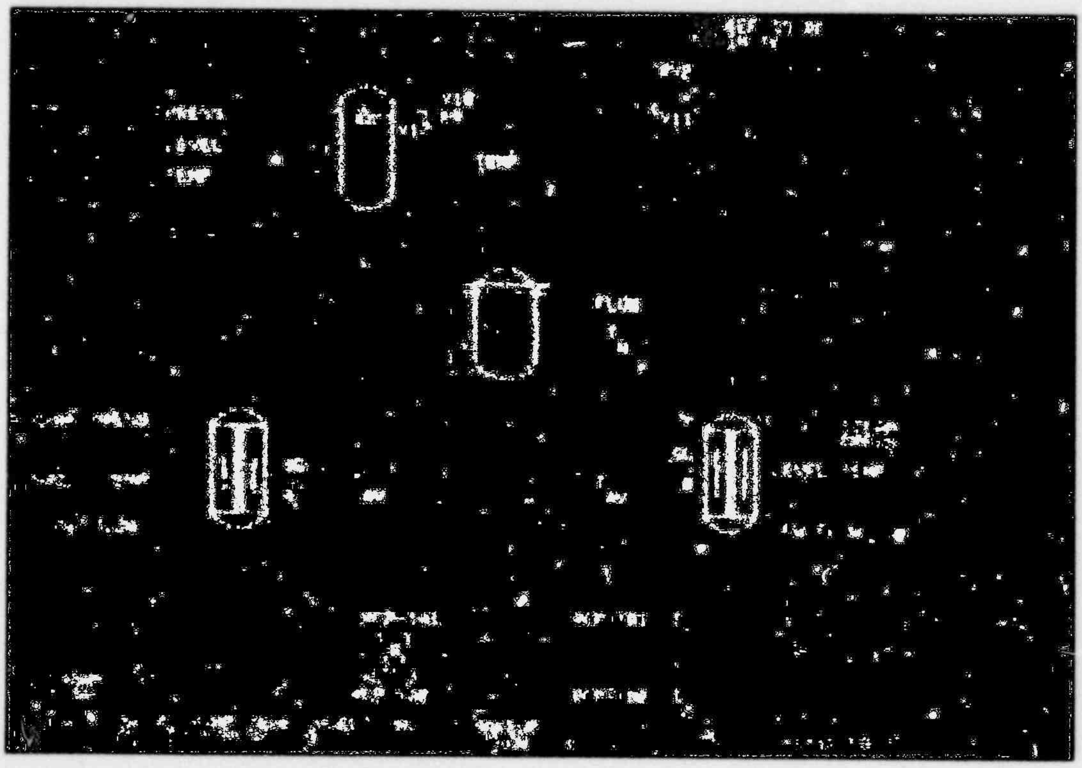


Figure 1-20. System components shown in Figure 1-19 have been coded dark blue. Yellow is reserved for more important information.

Alarms

One of the major unsolved issues confronting the designer of an advanced control room is the presentation of alarm information to alert the operator to a system anomaly or pending problem. Integrating alarm information into regular CRT display pages by changing the color of the display parameter and blinking the value to attract the operator's attention to the change is fairly straight-forward. While this can effectively handle the situations where a handful of alarm conditions occur, such a strategy will soon become overburdened when confronted with the mass of alarms generated almost simultaneously during a major casualty. Although CRT-based alarm displays can present a lot of information in a small space, care must be taken to develop the appropriate mix of dedicated and CRT-based alarm indications. The use of CRT-based alarming may not eliminate the need for dedicated annunciators in the advanced control room.

Integration of Controls and Displays

As with conventional control rooms, the designer is confronted with the problem of functional integration of controls and displays. With CRTs as the primary source of display information, it is impossible to locate all associated controls adjacent to the affected parameter displays. Other schemes for achieving readily apparent control and display relationships, without the benefit of actual geographic grouping, must be devised. Two control arrangements were examined: mimic or flow layouts and functional grouping arrangements, both helping the operator to quickly and accurately locate a specific control of interest and associate it with the related CRT display . A computer-based display system can further assist the operator in associating a control action with the affected parametric display by highlighting that display on the CRT screen when an operator inputs a change in valve position or switch status. Thus, by systematically arranging the controls and by highlighting the affected parameter, the impact of the physical separation of controls and displays can be minimized. Also, some approaches allow interactive control directly on the screen, as with light pens.

Procedural Integration

In the advanced multi-CRT control room, it is possible to display procedural information on a CRT, allowing operators in different locations to access the same procedure. During an emergency, the procedure could be displayed automatically, or a functional keyboard could be provided so that the emergency operating procedures are one keystroke away. A section of each display page could also be used to present relevant procedural information directly to the operator; however, one designer indicated that there were legal liability reasons preventing the implementation of this approach by the vendor.

Environmental Considerations

There are many factors to consider when designing an integrated, advanced control room. Two of these that can significantly impact operability are viewing distance and viewing angle for CRTs. The distance from which an operator can read a CRT is a function of the CRT size, ambient illumination, contrast, and specified character size and configuration. A control room should be designed with maximum and minimum viewing distances and line of sight angles to the display surface.

Glare is another problem to consider when designing both the console configuration and ambient illumination system for an advanced control room. Although there are some surface measures that can reduce glare from the CRT surface, there is no substitute for an integrated approach to control room illumination design. Glare minimization should be a design goal when determining the control room illumination source and the positions of the CRT display units within the control board.

Display System Parameters

In developing the specification for an advanced CRT control room, there are many display system parameters affecting the interface with the operator. From a human factors standpoint, it is important that these parameters be defined with consideration for the operational use of the system and the limitations and capabilities of the human operator. Character attributes that affect operability include character height, resolution, viewing angles, strokewidth, aspect ratio, case, spacing, and character matrix configuration. Hardware features that impact operability include refresh rate, misregistration, response time, and contrast ratio.

The parameters in Table 1-5 represent the recommended values based on available research data for a human engineered CRT based display system. Shown are the most desirable values for each parameter in terms of the man-machine interface. In the process of actual display design, trade-offs will be required which may force compromises. The value of these guidelines is that compromises become visible and the relative degradations introduced by alternative compromises can be evaluated.

Table 1-5

RECOMMENDED VALUES FOR SELECTED DISPLAY SYSTEM PARAMETERS

Parameter	Recommendation
Character Height	21 min of visual arc for color (1/6 in. at 28 in. viewing distance) min.; 50 minutes maximum 30 min. for off-axis viewing (1/4 in. at 28 in. viewing distance)
Resolution Alphanumerics	9 to 10 lines minimum 14 lines for off-axis viewing
Symbolic	17 lines minimum 25 lines for off-axis viewing
Strokewidth	1:10 maximum Narrower lines okay because of irradiation on CRT
Aspect Ratio	5:7 to 2:3 minimum 1:1 for off-axis viewing
Character Case	Capital Letters
Spacing	75% Intercharacter and Interline
Character Matrix	System Dependent (picture element dimensions determine desirable matrix configuration)
Refresh Rate	60 Hertz minimum
Misregistration	50% maximum
Response Time (operator request/ action)	2 to 3 seconds maximum 1 second desirable
Contrast Ratio	10:1 minimum (variable operator control)

Display Formatting

Little hard research exists regarding the most effective way to format information on a CRT screen. We know in general what information an operator needs to be able to access, but we have little empirical or operational data to determine whether the information is best displayed on mimic diagrams, in digital form, on analog bar charts, on trend diagrams, or in other formats. There are, however, some general principles and guidelines for display formatting that should be observed when arranging information for an operator to interpret:

- The density of a display page should be managed so that information is not too tightly packed on the page. Empirical evidence shows that an operator will scan the upper right quadrant of a CRT display significantly more often than the other quadrants. The upper left quadrant is the next most frequently scanned quadrant, followed by the lower left and lower right. Therefore, the designer should attempt to place important information, like alarm status information, in the upper right hand quadrant to decrease operator response time.

- The approximate effective visual field for detail is 5^{o} cone about the focal line of sight. At a 28-inch viewing distance, the resulting field is a circle of 2.4 inches in diameter on the CRT face. Field size impacts label and numeric length in the format and placement of related or unrelated groups of information on the screen.
- Where it is impossible to provide sufficient open space between groups of information, it is recommended that boxes and lines be used to group the data into clearly defined areas on the display page. Although less effective than open space, a box around a set of data tends to focus the operator's attention and remove some of the distractions from adjacent data and information.
- Every display page should have a header; every header should contain the same set of information about the display, and the information should be positioned in the same general location on the display page. The header format should be established early in system development, and it should be consistently used for all display pages on both the primary and the secondary sides of the plant.
- Nomenclature should be standardized early in system development and should be consistently applied on all display pages. A standardized list of abbreviations should be developed and rigorously applied.
- Consistent coding techniques should be used for every display page. A symbol set should be selected and used throughout. One color coding scheme should be used for every display page on both the primary and the secondary sides of the plant, and color should not be overused or misused just because it is an available coding technique.

Lack of Standardization

In reviewing the advanced design directions being pursued by the various NSSS vendors, it is apparent that future control rooms will not be any more standardized than present generation control boards. For example, console designs incorporating CRTs run the gamut from sit-down to sit-stand to stand-up operation. Similarly, color coding practices vary from vendor to vendor. Some vendors are using the traditional industry red-green color coding scheme for active-passive designations of the status of valves and breakers, as well as the status of flow in interconnecting piping. One vendor is using symbology, rather than color, to designate active versus passive devices and is reserving red for presenting alarm information to the operator. One vendor uses cyan to designate dynamic, real-time data; another uses amber for this function. As discussed earlier, the information accessing schemes vary from vendor to vendor. The interactive strategies and devices employed for accessing information also vary widely.

An obvious case can be made for standardization in terms of reduced training needs and the transfer of skills as operators move from one advanced control room to another. However, perhaps an even more important concern is the lack of an empirical data base to favor one approach versus another among the widely divergent courses being pursued.

HYBRID SYSTEMS

While there is an unmistakable trend toward computer-based control and display designs, there are also indications that many plants will take a middle ground between the conventional and advanced control rooms. We have chosen the term "hybrid systems" to refer to combinations of conventional and advanced designs. This section will explore various possible hybrid systems and some of the human factors implications associated with these control room configurations.

As noted earlier, conventional hard-wired instrumentation (meters, charts recorders, counters, and indicators) provides a parallel presentation of information in a fixed display mode. The information is continuously available to operators and all those who frequent the control room. An electronic display device, on the other hand, presents information serially to the operator in a variety of presentation modes or formats. The information is available on request and can be incorporated on more than one display page providing a dynamic set of relationships among variables. Hybrid control room arrangements can build on the characteristics and strengths of both conventional and advanced electronic displays and hence have potential for providing the most effective control-room alternative in the near future.

Advanced Computer Capabilities That May Be Added to Conventional Control Rooms

Most existing conventional control rooms already encompass a process computer and associated readouts: either a CRT display or a printout device or both. The computers generally supplement the hard-wired boards by, for example, assisting with complex calculations or automatic logging of events. These capabilities could be extended in the following ways:

- Disturbance Diagnosis. There is a serious problem with present board designs: when a major transient of disturbance occurs, the operator is overwhelmed by a large number of visual indications accompanied by successive auditory alerting signals, all of which must be acknowledged and silenced. There is simply too much information displayed to be readily absorbed and integrated. The addition of advanced computer capability to existing control rooms may take the form of improved diagnostic techniques. Two levels of alarm handling are currently being developed for use in advanced CRT-based control rooms, and these capabilities, when available, could be integrated into existing control rooms.

- Improved Plant Monitoring. Advanced computer capabilities can be used to structure the presentation of information in a way that assists an operator in monitoring the plant and anticipating anomalous conditions. Plant status information can be presented alphanumerically in digital form or in analog form as bar graphs for operator surveillance. Key parameters can be presented together on one display page rather than being physically dispersed about the control room. For periodic, procedural reviews, information can be presented in a form that permits immediate reading without requiring the operator to wander about the control room. Thus, the flexibility of formatting and presentation modes with electronic display devices may enable an operator to perform routine monitoring tasks more effectively. Mimic arrangements, which operators favor, can be readily incorporated in CRT formats.

- Improved Plant Control. Present control board designs sometimes separate controls and associated displays, requiring the operator to be in two places at the same time. If the control board allows for the incorporation of CRT displays at discrete spatial intervals, required display information could be called up in the vicinity of the control being actuated. This redundancy of information would "shrink" the control room size and also aid multi-operator tasks such as startup.

Human Factors Concerns and Issues

The development of hybrid arrangements, both those involving modifications to existing plants and those involving future plants, introduces some basic questions regarding the best integration of conventional and advanced control display capability within one control room. How should operators divide their attention between advanced CRT displays and conventional boards? Should the advanced displays and controls be integrated into the same console with conventional instrumentation, or should an auxiliary console be provided with the advanced capability? There is always the possibility of conflicting information from the conventional and advanced displays, presenting the operator with the dilemma of deciding which displays to believe.

The development of a thorough operational concept is the first task to undertake either when adding advanced computer capability to existing control rooms or when developing a hybrid control room from the outset. During normal operations, will an operator be primarily interfacing with the conventional display, the advanced displays, or both forms of display? Similarly, operational requirements associated with start-up, shutdown, and plant disturbances need to be defined. Some control rooms are designed for one-man operation. With the addition of advanced capability, manning requirements may correspondingly increase depending on the manner in which the advanced control and display features are integrated into an existing control room. One approach taken in the oil refining industry has considerable appeal from a human factors standpoint: to incorporate the advanced capability in a separate console and assign a more senior control room operator or supervisor to it while the control room operator continues to monitor the conventional displays as per normal practices. In multi-unit plants, the center desk operator might assume responsibility for the advanced console.

If the operational analysis indicates that one operator can simultaneously handle the workload imposed by both the conventional and advanced components of the control room, then it might be best to integrate both capabilities into one major control board. Integration would allow a functional grouping of conventional and advanced displays with associated controls. Otherwise, the operator would be required to alternate his attention between two consoles: one conventional and the other advanced.

While the potential benefits for hybrid systems are clear, there are many unresolved human factors issues in attempting to design the most effective hybrid capability. Control room simulator-based research is required to resolve some of the pressing design and operational issues raised.

DESIGN PRACTICES SURVEY

To help implementation of human factors approaches in the power industry, some understanding is needed of the existing control board design process and constraints. Accordingly, a survey was conducted, based on interviews with a sample of board designers. A 30-item structured interview form, requiring about two hours to administer, was developed with questions spanning a variety of design issues ranging from control room dimensions and control board configuration, to the design review process. The questions were designed to address the major human factors deficiencies noted in the earlier review of control rooms (EPRI RP 501-1). The interview sample consisted of 20 designers, with half of them in a supervisory or lead engineer role. These designers were selected from six firms, with eight employed by A-E companies and the remaining 12 associated with NSSS firms. The major findings and conclusions that emerged from this survey are presented below.

Lack of Systematic Concern for Human Factors

Human factors considerations are not applied to the determination of control room size, location, or configuration. No systematic functions and task analyses are conducted as prerequisites to establishing the manning concept, control display requirements, traffic patterns, or an overall initial control room concept. Rather, the designer is faced with a set of "givens" he must accommodate, and which are, with the exception of advanced computer-based concepts, standard reference control boards or the most recent project worked on. These precedents, likewise, are not based on human factors concerns, so the same set of problems persist from generation to generation.

In the course of the detailed design process, no individual or group is dedicated to concern for the operational aspects of the boards. Responsibility is diffuse and assumed to be a common concern of all parties involved. The designers, whose efforts are often directed by "client preference" either directly, or through A-E project management acting as the client's agent, may lose any sense of responsibility for operational aspects of the design. After all, the client has to operate the boards, so why not leave all such decisions to the client? One designer expressed these sentiments as follows: "I have no pride of authorship in the layout of the boards. The client has to live with them. Nobody here cares that much. The NRC is only interested in knowing whether or not a certain function is covered on the boards - either in front or back, and is it separated. Besides, we won't be here when the boards become operational." In short, the operator does not have a steadfast and dedicated representative at the design table or in the design review.

Lack of an Integrated Human Factors Approach to Control Room Design

Various systems designers are each responsible for a segment of the overall plant design and each one impacts the control room and control board design where the systems all come together for monitoring and control functions. However, there is little cross-talk between the individuals. The facility design people establish the size and configuration of the control room and do not consult with the control board designers. The designers of the reactor systems do not cross-check with the turbine designers; there may be inadequate communication between the client's engineering organization and the operations group; and the NSSS control board designer may never talk to the client directly but only through the A-E firm representing the clients. The board designer is given lists of disparate instrumentation requirements from a host of participants in the design process. There is no intermediate systems-integration function setting common groundrules for all subsystem designers. Furthermore, in at least half of the cases, there is no full-scale mockup to serve as a design integration tool. In many military and space system developments, a human factors and industrial design team assumes the responsibility for the integration of control and display requirements, panel design practices, and operational evaluations of candidate approaches.

Lack of Human Factors Design Guidelines

The designers interviewed are severely limited both in possession of human factors information and in access to human factors specialists. While scattered articles on such subjects as anthropometrics are accumulated, none of the common human engineering references or standards used in the aerospace industry were in evidence. Human factors guidelines tailored to the needs of the power industry are urgently required. However, for the present, designers should rely on existing guides:

- MIL-STD-1472B, Human Engineering Design Criteria for Military Systems, Equipment and Facilities, 1974.
- Van Cott and Kinkade, Human Engineering Guide to Equipment Design, 1972.
- McCormick, Human Factors Engineering, 1976.
- Woodson and Conover, Human Engineering Guide for Equipment Designers, 1973.

More importantly, utilities generally have no formal procedures for ensuring the adoption and implementation of human factors principles and methods in control room design. Such attention to human factors is a matter of contractual requirements in the development of military systems. The most repetitive phrase heard during the interviews was "client preference." If the client indicates a preference for human-engineered control rooms, and has the means to evaluate proposed designs, design organizations will follow suit as did all of the major aerospace firms when the military insisted on human-engineered weapon systems.

Overreliance on the Operator

The utilities, in varying degrees, attempt to human-engineer control rooms by relying on the operations department to either design the boards or revamp proposed reference boards submitted by the contractors. While it is essential to consult the operators in the design and evaluation process, operators are not equipped by training or experience to design control rooms. The designer needs to tap the operator's experience and preference as an important input to design rather than turning over this responsibility to the operator. The design organization should acquaint the operators with the operational features of candidate control room designs and use them in performance evaluation studies of the candidates. In the present survey, it was learned that the designer is generally far too remote from the operational environment; many have never set foot in an operational control room.

Mockups, Simulators, and Demonstrations

More extensive use should be made of mockups and simulators because, as noted above, they serve as important design integration aids. In addition, mockups provide an essential evaluation tool through which the utilities can review a particular design for human factors concerns before any metal is bent. However, mockups were used in only 40 to 50 percent of the projects covered by our sample. Simulation is even rarer and only used in some instances of advanced systems development. On many aerospace developments the contractor is required to demonstrate the operability of the boards against contractual obligations set by the client. Mockups can later serve as valuable training aids, so the cost can be justified beyond design costs. Similarly, where new and untested advanced control room concepts are being procured, dynamic simulation is often required to provide the assurance that the man-machine interface will be effective and reliable.

Lack of Feedback

The designers get no formal feedback from the plants regarding the adequacy of their control board designs. They may hear informally of problems that surfaced during plant start-up. However, there are no formal procedures for accumulating user reaction to guide future design efforts. For one reason, three or more years may elapse between the times that the design work is completed and the boards become operational. Typically, a separate field service group, and not the designer, oversees the console through assembly, test, and start-up. By the time feedback might be available, the designer has long since moved to another project, is employed by another company, or has retired.

CONCLUSIONS AND FUTURE STUDY NEEDS

This study has examined the applicability of human factors engineering methods in resolving problems noted in an earlier study of nuclear power plant control room designs. In developing control board concepts based on human factor principles and in exposing these candidates to the scrutiny of operational and design personnel, it became evident that the human factors principles and methods developed in the military-aerospace context are applicable and relevant to the needs and concerns of the power industry. While board designers might question the development cost or schedule impact of some recommendations, overall there was good acceptance of underlying human factors principles. Operational personnel were even quicker to perceive and endorse the proposed design features aimed at improved operator-control board interfaces.

In comparing human factors approaches with current board design practices, certain salient differences emerge. First, human factors specialists place greater emphasis on systematic analyses of the man-machine interfaces to determine control and display requirements and groupings as prerequisites to design. Also, these specialists have evolved a set of rules or guidelines based on laboratory experimentation and field evaluations that are consistently applied in the layout of control panels. Additionally, a great deal of emphasis is placed on verification of design concepts by means of mockups and simulators using representative test subjects.

The general acceptance for human factors impact on control board design observed in this study, coupled with a highly responsive reaction to the findings of the antecedent study (EPRI RP501-1), impels a consideration of steps that should be taken to ensure a more systematic concern for human factors in future design efforts. First, and foremost, there is an urgent need for a human factors design guide tailored to the needs of the power industry. A corollary need exists for a human factors standard to be invoked for control room procurement purposes. The survey of current control board design practices revealed that design organizations associated with A-E and NSSS firms are extremely responsive to "client preference" in the development of new control room designs. However, the utilities presently provide little or no formal guidance in ensuring that human factors considerations are taken into account by the designer. With the emergence of human factors design guides and standards, it can be anticipated that more of the attention of the 3,000 or so human factors specialists in this country would be focussed on human factors problems in the power industry. At present, less than a handful of such specialists, with bona fide credentials, are participating directly in solving power industry problems.

Beyond the high priority measures described above, the following research avenues have been identified as leading to a significant expansion of the human factors data base to aid control room designers and utility decision-makers:

- The present study has identified a variety of measures for upgrading existing operational control rooms both to improve the operator-control board interface and to minimize the potential for human error. The feasibility and value of such measures should be examined in greater depth in the operational evironment. Several nuclear power plant control rooms, where a corresponding training simulator exists, should be reviewed in detail with the objective of modifying the boards systematically without interruption of power production. Human factors recommendations for up-grading each control room should be formulated and discussed with plant operations, engineering, and management personnel. These modifications should first be attempted and evaluated in the control room simulators. Subsequently, specific backfit recommendations should be offered to each plant, and general recommendations should be offered to plants not participating in this study.

- A review of existing control rooms has revealed a number of major deficiencies with present annunciator warning systems. This study has defined a number of possible alternatives to existing designs. The candidate audio-visual annunciator warning approaches developed should be evaluated experimentally to ensure that they offer substantial operational benefits over existing operational approaches. The candidates that prove most effective from the human factors standpoint should be examined in terms of design complexity and cost factors.

- Advanced CRT formatting and color usage approaches being developed vary widely from vendor to vendor. Research is needed to determine the relative effectiveness of competing advanced control and display concepts and to provide human factors guidelines for future developments. Much might also be learned from a human factors review of foreign approaches to advanced control room design. Significant advances are being made in Japan, Sweden, Germany, the USSR, Great Britain, Denmark, and Norway. The utility industry might avoid needless duplication of effort and learn from the experiences of other countries. For example, the British ran into serious problems in the advanced control room area; the operators experienced severe information retrieval problems.

- Each of the major NSSS vendors is focussing on advanced computer-based control room designs as an option to the present generation hard-wired control rooms. A trend towards advanced systems exists, even though the operational benefits of the advanced systems have not been demonstrated with hard evidence within the utility industry. When the first advanced control room simulator becomes available in 1980, the opportunity will be at hand for a detailed human factors review of initial operational experiences with advanced systems. Consideration should also be given to extending EPRI RP 769 (Performance Measurement System For Training Simulators) to an advanced control-room simulator. The performance measurement methods being developed by EPRI RP 769 could provide comparative human performance data on conventional versus advanced systems.

- The analytic efforts conducted in the present study revealed instances in which a particular display might profitably be added to the current repertoire of information provided to operators, or in which an interlock might have been included in the design to preclude the possibility of operator error in conducting a specific task. These and other control board design enhancement possibilities should be pursued further in a design team setting so that appropriate engineering trade-offs can be conducted to establish cost-benefit factors in evaluating individual human factors proposals.

- The conventional hard-wired panels developed in the present study, and based on human factors methods and principles, should be compared experimentally with their current operational counterparts within existing control room simulators and by recruiting representative operators as test subjects. Dynamic simulation would have to be supplied to the existing mockups of feedwater, reactor, and turbine-generator control panels. Operator performance measures associated with existing and proposed designs should be obtained under both normal and degraded operational conditions, such as excessive operator fatigue or the first graveyard shift after four days off work.

- A review of control-display coding practices in present day nuclear power plants indicates that available coding dimensions are applied inconsistently or are underused. Color coding practices, such as the green board concept, should be compared experimentally with conventional display codes in terms of operator performance measures. Uniquely shape-coded controls should be developed to minimize the potential for inadvertent control activation. The complexity and feasibility of adapting coding techniques developed in space and military contexts should be assessed in design engineering terms.

- It was indicated in this study that many utilities will opt for hybrid control rooms or some middle ground between advanced control rooms and the dedicated control-display conventional control rooms. Hybrid concepts raise significant human factors issues regarding the division of operational attention between advanced and conventional components of the hybrid control room. Research is needed to evaluate alternative ways of integrating advanced and conventional components of hybrid control rooms, such as a separate console for advanced displays versus the physical integration of CRTs within conventional control boards. As prototype advanced system elements are developed, alternative methods for integrating their capabilities in a conventional control room can be assessed using existing control-room simulators.