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Human Factors Engineering Enhancement of Nuclear Power-Plant Control Rooms*

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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. A human factors review of five representative nuclear power-plant control rooms reported in the November–December 1977 issue of* Nuclear Safety *revealed that operational control rooms deviate in many significant ways from human factors principles of design. The present article deals with methods for upgrading operational control rooms to improve the man–machine interface. Two levels of enhancement are considered: (1) a variety of surface changes that could be effected without interrupting power generation and (2) modifications that are possible during scheduled extended outages. Both levels of enhancement would result in substantial improvements, but it is important to state that neither approach will fully optimize the control boards from the human factors standpoint. Ideally, human factors methods should be applied throughout the design process—from concept development to system implementation—rather than on a backfit basis.*

*This article summarizes a portion of the work conducted in a study sponsored by the Electric Power Research Institute (EPRI) entitled "Human Factors Methods for Nuclear Control Room Design." An overview of the entire study is provided in Report EPRI NP-1118-SY. Report EPRI NP-1118-Vol. I deals with human factors methods for enhancing existing control rooms in a more extensive manner than reported in this article. The reader can obtain these EPRI reports by contacting the Research Reports Center, P. O. Box 10090, Palo Alto, CA 94303.

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(Footnotes continue on the next page.)

A study[1] of the human factors aspects of five operational nuclear power-plant control rooms, which was sponsored by the Electric Power Research Institute (EPRI), was summarized in the November–December 1977 issue of *Nuclear Safety*.[2] The study revealed a series of minor and major human factors deficiencies and the need for further work to resolve some of the problems noted. Accordingly, EPRI initiated a follow-on research project (EPRI RP 501-3) to investigate conventional and advanced human factors design approaches aimed at improving man–machine interfaces to reduce the likelihood of operational errors. This article deals with one part of the follow-on study, namely: What can be done to upgrade existing nuclear power-plant control rooms from the human factors standpoint?

There are presently about 70 operational nuclear power plants in the United States and more than an equal number of new plants for which the control boards either have been designed or are in various stages of assembly and checkout. In the attempt to introduce human factors engineering considerations in nuclear power-plant control rooms, the most immediate payoff would result from an upgrading of operational or near-operational control boards. Of course, there are limits to what can be done on a backfit basis. A number of compromises must be made since there is little or no opportunity to make major changes in the position of panel elements, to rewire panel components, to change circuitry logic, etc.

Two levels of control-board enhancement were considered. The first level deals with a variety of surface, or "cosmetic," modifications that could be effected without interruption of plant operations. The second level considered assumes that a particular plant anticipates an extended outage that allows the time and opportunity for a more in-depth reworking of the boards. Both levels of enhancement discussed would considerably improve board operations but would not fully optimize them. Optimization of the control boards from the human factors standpoint requires specialized and systematic attention to the man–machine interaction from the concept stage of design to system implementation. This obviously cannot be done retroactively; however, we hope to show that the potential for operator error can be significantly reduced by some minor and inexpensive surface changes to the control boards.

CONTROL-BOARD ENHANCEMENT POSSIBILITIES

Problems commonly observed in the course of earlier control-room reviews were categorized as follows: (1) those which could be addressed on a backfit basis while the plant remained operational, (2) those which could be remedied during an extended planned outage, and (3) those which did not lend themselves to backfit remedies. The first category is of immediate interest here and includes the concerns and remedial measures listed below. It is important to note that all of these measures have been attempted by operators in one context or another, but not with much consistency and usually as a result of an operational mishap or a perceived deficiency in the original design of the control boards.

Functional Demarcation of Related Panel Elements

While related groups of panel elements are often grouped in meaningful clusters on the boards, these clusters of controls and displays are usually not functionally demarcated in such a manner that the relationships are immediately apparent to operators. Figure 1 shows a massive array of undifferentiated panel elements. An arrangement such as this forces the operator to adopt a "hunt-and-peck" method in searching for specific controls imbedded in a mass of many other identical controls. The need for more distinctive functional groupings of elements is clear both from a human factors judgment standpoint and from the lengths to which operators have gone to achieve such demarcations at some plants. Consequently, a first and major step in upgrading existing

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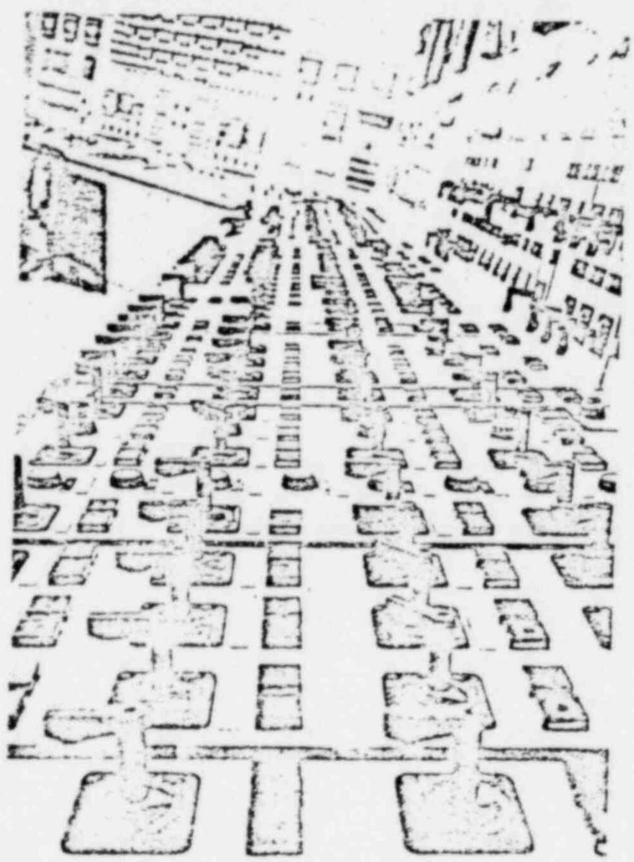

Fig. 1 Massive array of identical panel elements. Color coding of the modules identifies the system to which these modules pertain, but subpanel groupings are not evident.

designs is to find ways to apply functional demarcation techniques to operational or near-operational panels.

Labeling

An important part of functional demarcation of panel groupings is the implementation of a system of hierarchical labeling which accentuates logical groupings of panel elements, thereby avoiding the repetitiveness observed in present labeling practices. Figure 2 shows the repetition of ACCUM TK PRESSURE or LEVEL for each panel element. Similarly, the designations 1A, 1B, 1C, and 1D are repeated for each half of eight pairs of meters. This repetition slows down the operator in locating a meter or control of immediate interest because the distinctive or identifying element of a given meter is not highlighted but rather is buried in a mass of repetitive labeling. A comparison of Figs. 2 and 3 illustrates the difference between existing and recommended labeling practices.

Along with this hierarchical labeling approach, it is advisable to introduce size coding of labels where the largest labels are reserved for panel identifiers and the smallest ones are used for identification codes (e.g., 1PI-960) with the console schematics. In Fig. 3, ACCUMULATOR TANKS is the largest label used since it identifies the largest number of elements shown. The labels PRESSURE and LEVEL are of intermediate size.

Controls

One of the most serious problems observed with controls is the presence of large arrays of undifferentiated or identical controls collocated in a given area of the control boards (see Fig. 1). Such arrangements can and have caused inadvertent operation of improper controls. Some operators have taken pains to paint troublesome controls different colors or substitute one control handle or knob shape for another. Existing control boards should be reexamined 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.

Another major category of problems in this area has to do with the location of controls in areas or orientations that render them vulnerable to accidental contacts and disturbance from operators or others who frequent the control room. In order to safeguard existing control rooms from these error-prone situations, a thorough review of each panel is required to identify those controls which are susceptible to disturbance and the gravity of the consequences of inadvertent control activation. Such a review will reveal those controls which operators have attempted to safeguard through experience with operational mishaps or near-mishaps. When the potential "troublemakers" are identified, steps should be taken to either substitute less error-prone controls or provide raised protective barriers, covers, built-in position-locking controls, or possibly guard rails at the point of contact between the operator and the boards (see Fig. 4).

Meters

A major improvement to present control boards could be effected by developing and applying consistent coding practices for scales to indicate normal, marginal, and out-of-limit operating bands. Meter limits should be reviewed for each panel, and a consistent coding practice should be developed, e.g., a green normal operating band, amber marginal bands on either

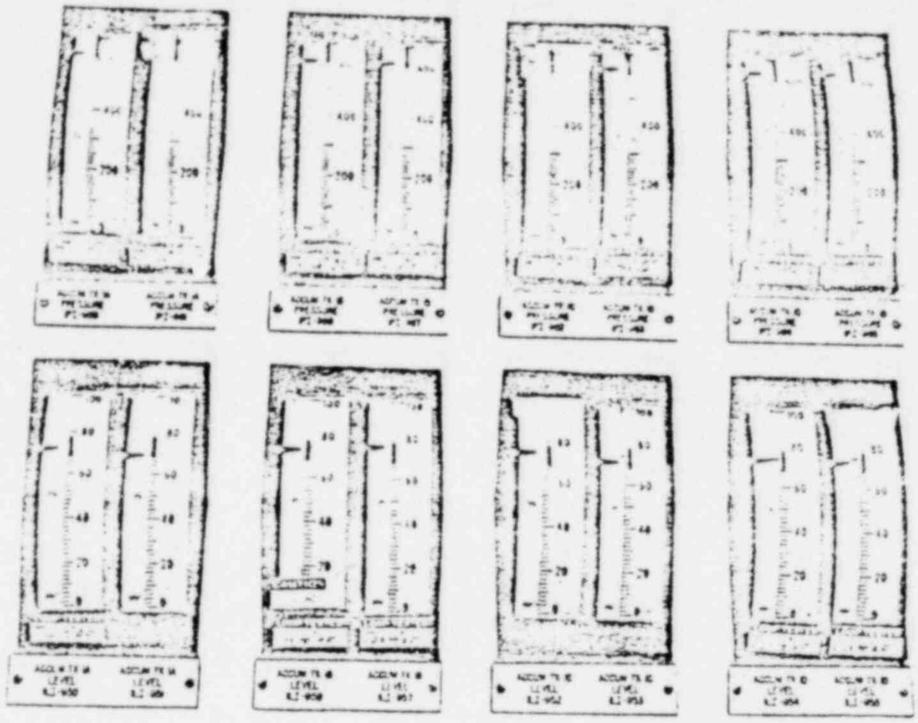

Fig. 2 Repetition of ACCUM TK PRESSURE or LEVEL for each panel element label. (Compare with Fig. 3.)

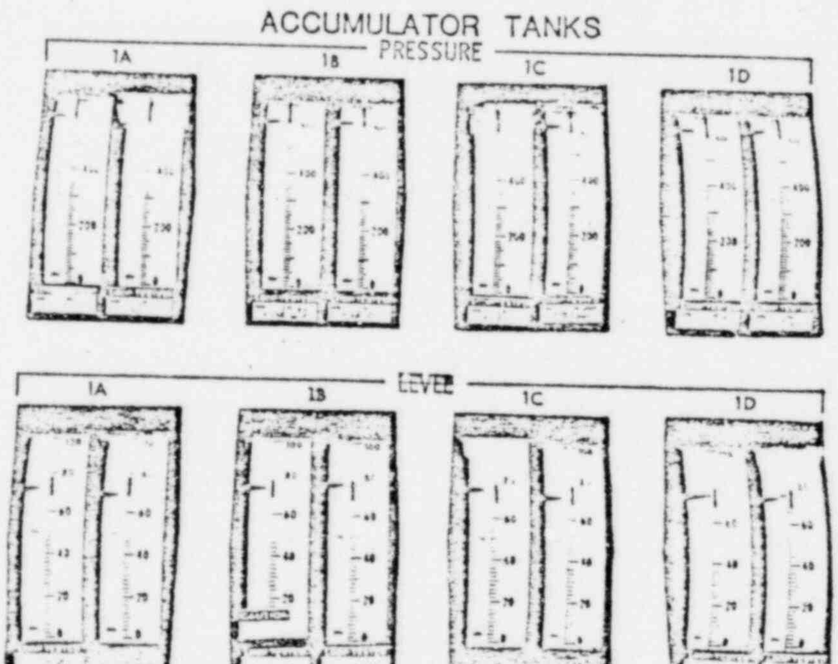

Fig. 3 Relabeling of panel shown in Fig. 2 showing the use of major and minor labelings. With this approach, fewer individual labels are needed and there is less need for abbreviations.

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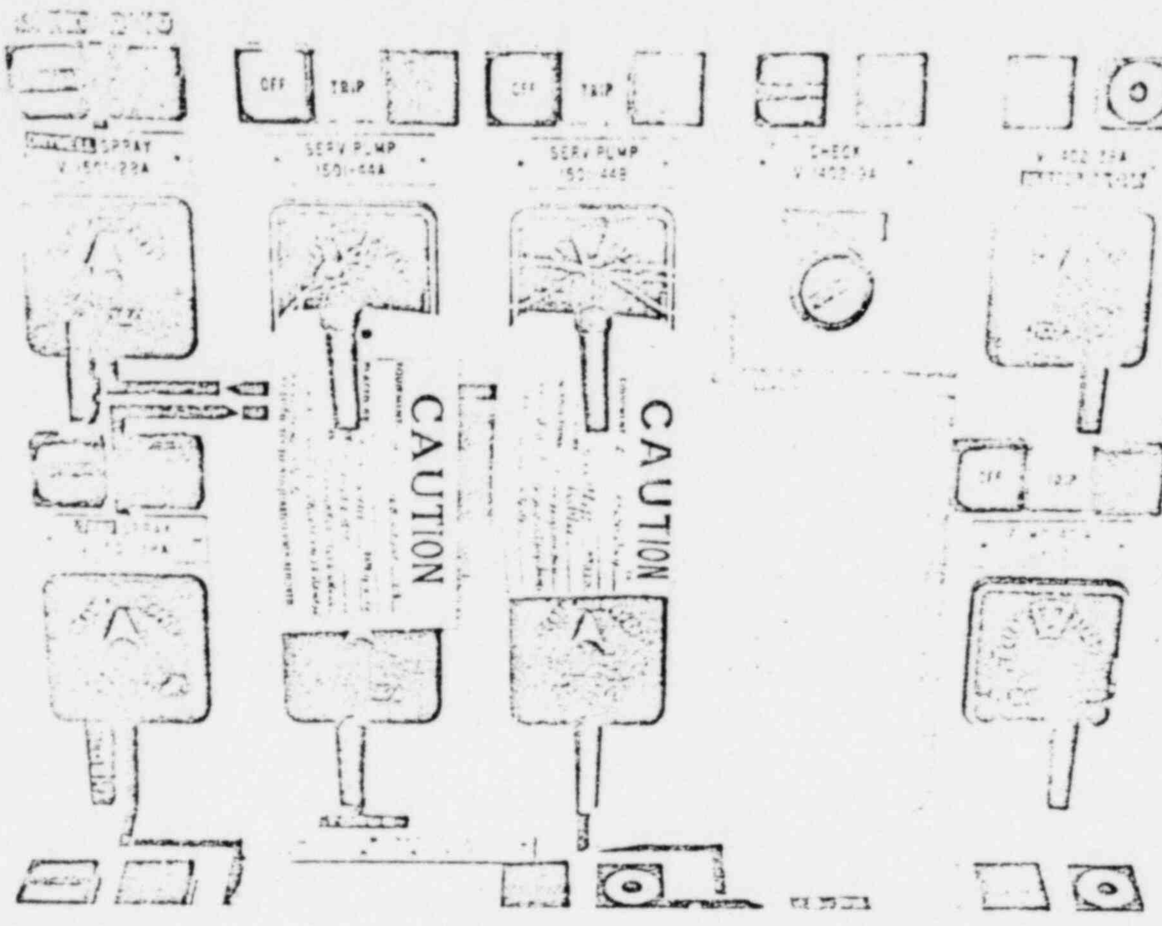

Fig. 6 Doughnut and bar symbols on indicators represent open and closed status. Green and red lights are used to indicate normal and abnormal. Incidentally, what displayed information is obscured by the caution tags?

Miscellaneous

The foregoing description of enhancement possibilities for current operational control rooms is not intended to be exhaustive. Each control room is unique and should be reviewed on an individual basis for specific human factors recommendations. For example, multiunit control rooms that have been mirror-imaged offer special problems and no easy solutions. The most effective way to handle this problem would be to assign operators permanently to one unit or the other, but this solution would obviously reduce management flexibility in the use of operational manpower.

EXAMPLES OF HUMAN FACTORS ENHANCEMENT

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

Example A

Figure 7 shows a steam-generator feedwater system control panel. The panel allows monitoring and control of three steam generators with two motor-driven main feedwater pumps associated with one steam-driven and two motor-driven auxiliary pumps. The most striking observation in reviewing this panel is the lack of apparent relationship between discrete panel elements.

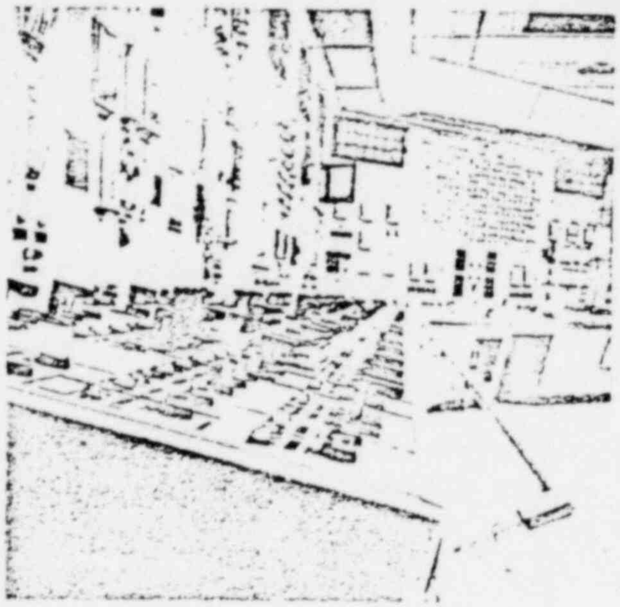

Fig. 4 Guard rails affixed to the console to prevent the operator from accidentally activating the pistol grip controls.

side of normal, and red out-of-limit bands on the high and low sides as appropriate (see Fig. 5). These color bands should be affixed directly on the meter scale where it is possible to do so by easy removal of the meter cover. Meters can also be improved by replacing some present scales that violate human factors engineering principles.

Indicator Lights

The indicators and annunciators within the control room should be reviewed to ensure appropriate use of color-coding techniques. Often this means no more than changing the color of a lamp cover. Operators at one plant have made an elaborate attempt to introduce special logic in the coding of indicator lights on the control boards. Doughnut and bar symbols have been incorporated into the legend face of the square indicator lights (see Fig. 6). These symbols represent, respectively, open and closed status of valves. In addition to this symbology, the lights have been color-coded red or green to denote, respectively, abnormal and normal situations. Consequently, a red doughnut tells the operator that the valve is open when it should be closed, and a green doughnut signifies that the valve is open and this position is the proper one. This type of approach to display coding, if fully implemented so that the logic holds for all plant conditions from shutdown to full power, is much more informative than the more common coding approaches where green indicators simply signify a closed valve and red stands for an open valve. Whether the existing display system lends itself to recoding must be determined on a case by case basis.

Chart Recorders

Some of the chart recorders currently in use are overloaded. Recorders designed for monitoring 24 parameters are sometimes assigned twice that many points. Recorder printouts are often illegible, and cycle time between each printout can be excessive. Rather than relying on the recorder printout for the necessary data, the operator monitors the pointer and scale reading, which occurs at the time each parameter value is sampled in a fixed sequence. The problem with this approach is that cycle time can be as long as 4 min, and in that time irreversible damage can occur to the subsystem involved. As a minimum solution for this problem, some chart recorders can be modified with a fast cycle control option so that the operator can rapidly move to the parameter of immediate interest. More elaborate solutions for this problem require more extensive changes to the control boards, e.g., substituting meters for important parameters now assigned to chart recorders or installing additional recorders.

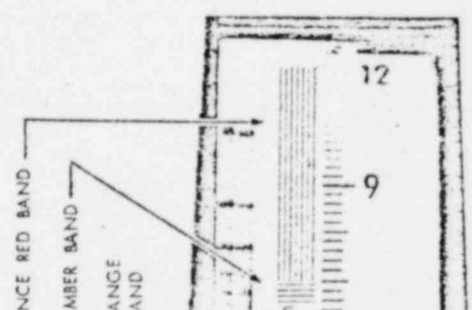

Fig. 5 Recommended approach for modifying meter faces to indicate normal, marginal, and out-of-tolerance conditions.

The operator must examine the legend on each individual switch, indicator, or meter to make any sense out of the panel.

Figure 8 shows an attempt to functionally demarcate the panel shown in Fig. 7. The various functional groups of panel elements are bound together by taped lines of demarcation. Within each grouping, summary labels are introduced, thereby reducing the time required to scan the label of each individual panel element. Space constraints made it impossible to place labels consistently above or consistently below components. Furthermore, a color coding (white, black, and gray) has been 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, and C steam-generator elements. In some cases a top-to-bottom A, B, C orientation is observed, such as in MAIN FEEDWATER ISOLATION. In other cases the opposite order (C, B, A) is employed from top to bottom, e.g., in AUXILIARY FEEDWATER THROTTLE VALVES. In another case a left-to-right A, B, C order is presented. In addition to color or shape coding of the controls, meters should be color-banded to highlight out-of-tolerance readings.

Example B

The feedwater control system panels at a second plant, shown in Fig. 9, are characterized by the use of large color-coded modules for each control element. The modules on the control boards are coded by major systems, so all feedwater modules are the same color. The use of such modular arrangements has distinct advantages from a maintenance standpoint, since the modules can be removed from the front of the boards for servicing. However, the use of many discrete modules, each color-coded to be distinctive in comparison with the background console color, tends to heighten the individuality of each separate control and its associated indicators. This obscures the interrelationships between groups of associated control elements. The use of one color to tie together all feedwater panel elements wastes this coding dimension with regard to functional subgroupings within the feedwater system panels.

The grouping of modules shown in Fig. 10 is organized in a rough matrix format, with vertical columns representing the four steam generators and horizontal rows dedicated to the same control or display function for each of the four steam generators.

It is apparent from Fig. 10 that the original layout did not organize columns relating to the four steam generators in a precise or aesthetic fashion. For example, the valve controls for steam generator 4 are directly below the meters for steam generator 2. The lines of demarcation make such disparities more obvious than the original design did. Had the designer been required to functionally demarcate control panel elements from the outset, he most likely would have provided a more logical and coherent arrangement.

As was the case with example A, the control switch handles are coded distinctively to differentiate between steam generators. In addition, all meters should be color-banded to indicate normal and off-normal limits.

REORGANIZATION OF EXISTING CONTROL BOARDS

Up to this point a number of surface changes to existing control boards were proposed for consideration. Here we will consider more extensive modifications to existing operational boards. The assumption here is that the plant will not be in operation for several months and that this outage has been planned for some time. This scheduled downtime is seen as an opportune time to upgrade control boards that have proven especially troublesome from an operational or training standpoint. In other cases, owing to extensive backfits over the years, the panel layout has become operationally unwieldy.

The redesign of control boards under the circumstances described will, in addition to all the factors considered earlier in this section, allow the freedom to regroup panel elements in more logical functional relationships than might have been the case in the original designs. Also, panel elements that have proved to be useless or obsolete can be removed from the boards to eliminate unnecessary clutter or distractions.

There will be obvious limitations to the extent to which the original design can be modified. The freedom to relocate panel elements will be limited by the lengths of the existing cables or the cost of extending the cables. There is also the concern that the panel may have to be seismically requalified. It is unlikely that any major revisions involving circuit design will be practical. Therefore the latitude available for enhancing the boards during an extended planned outage is greater than that available when the plant remains in operation, but far less than the freedom available when the boards were initially designed.

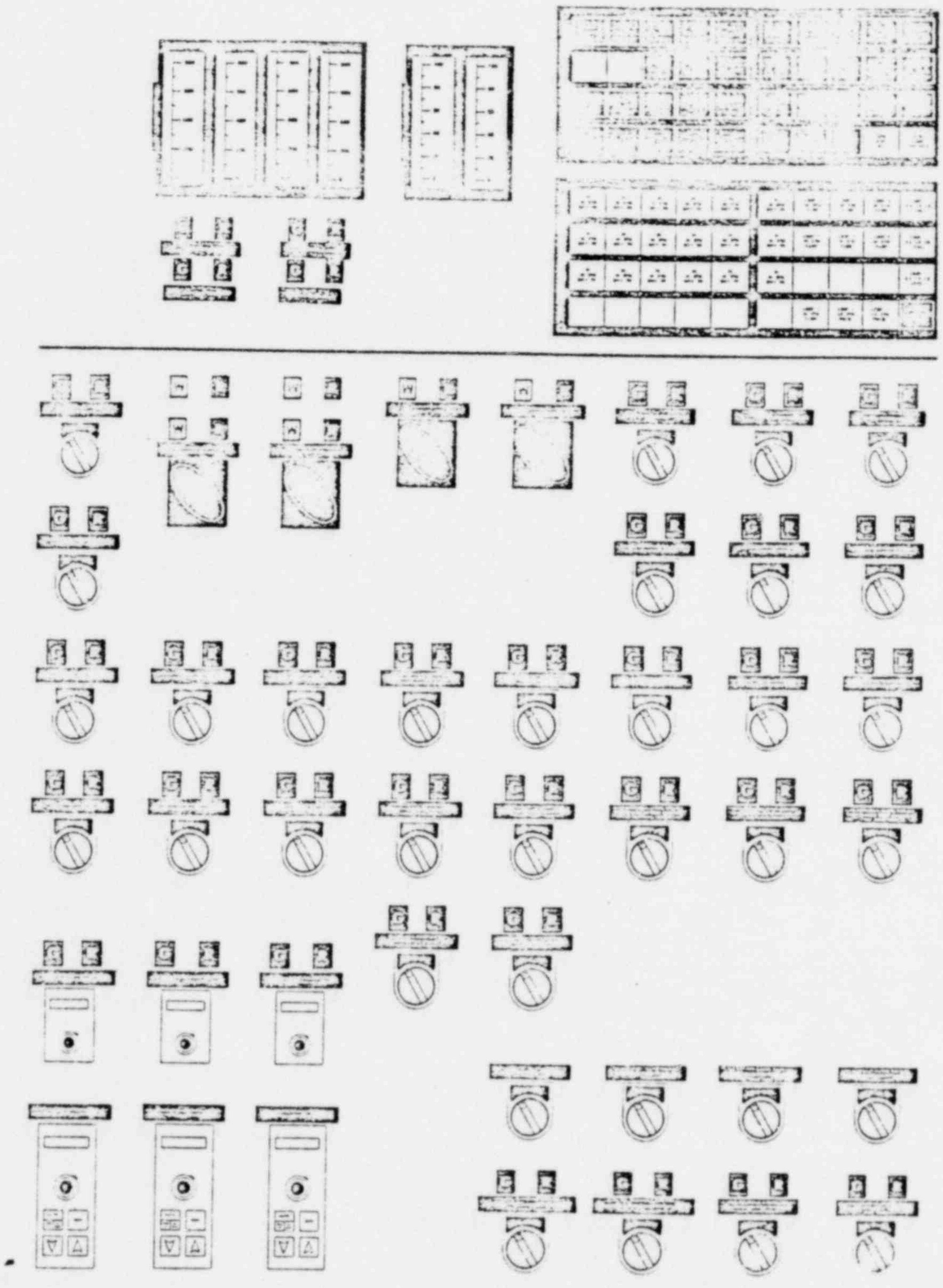

Fig. 7 Representative steam-generator feedwater control panel.

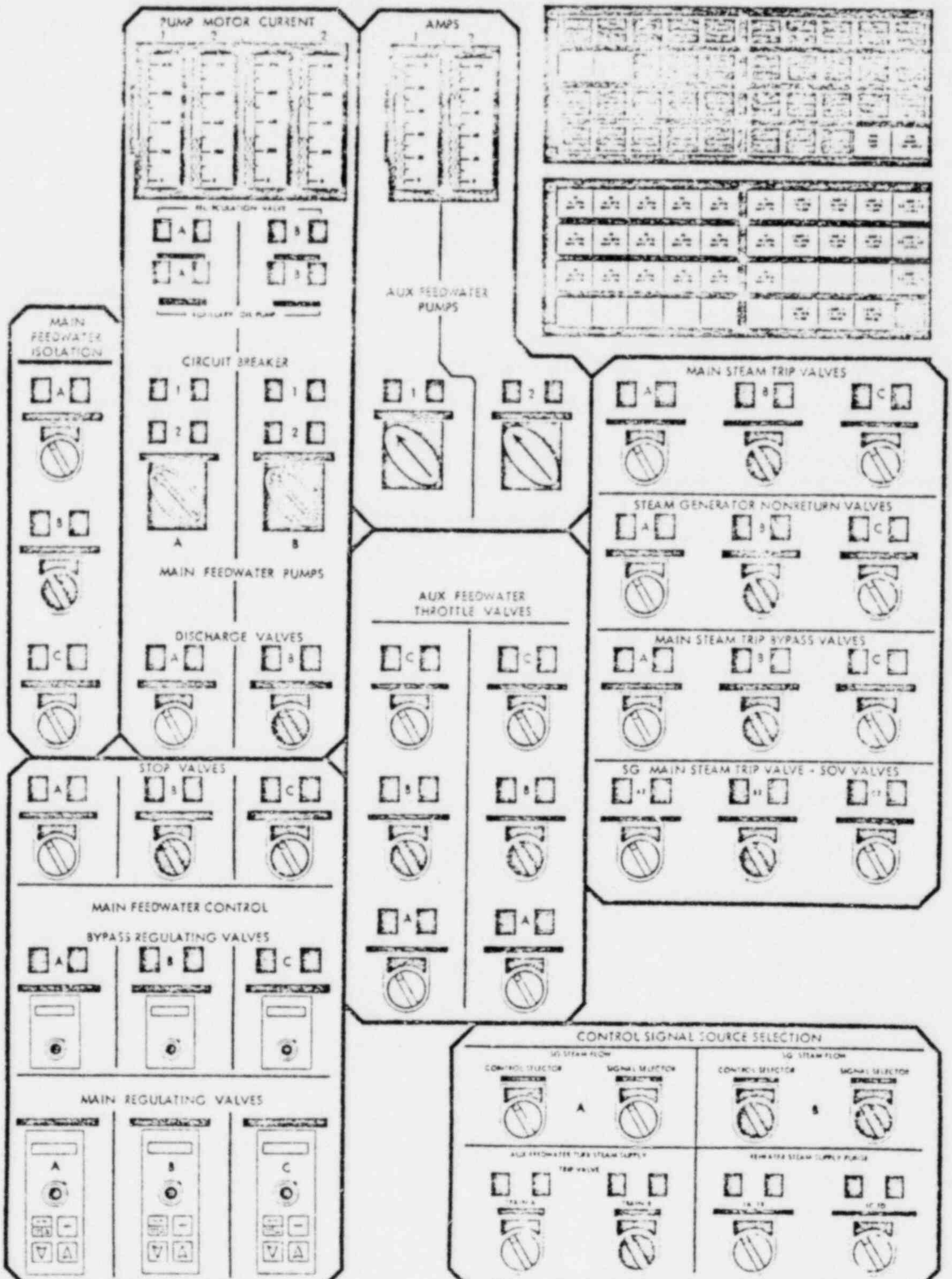

Fig. 8 Human factors enhancement of the panel shown in Fig. 7. Note that none of the panel elements have been moved. This effect is achieved by means of functional demarcation and relabeling and coding of controls and meters.

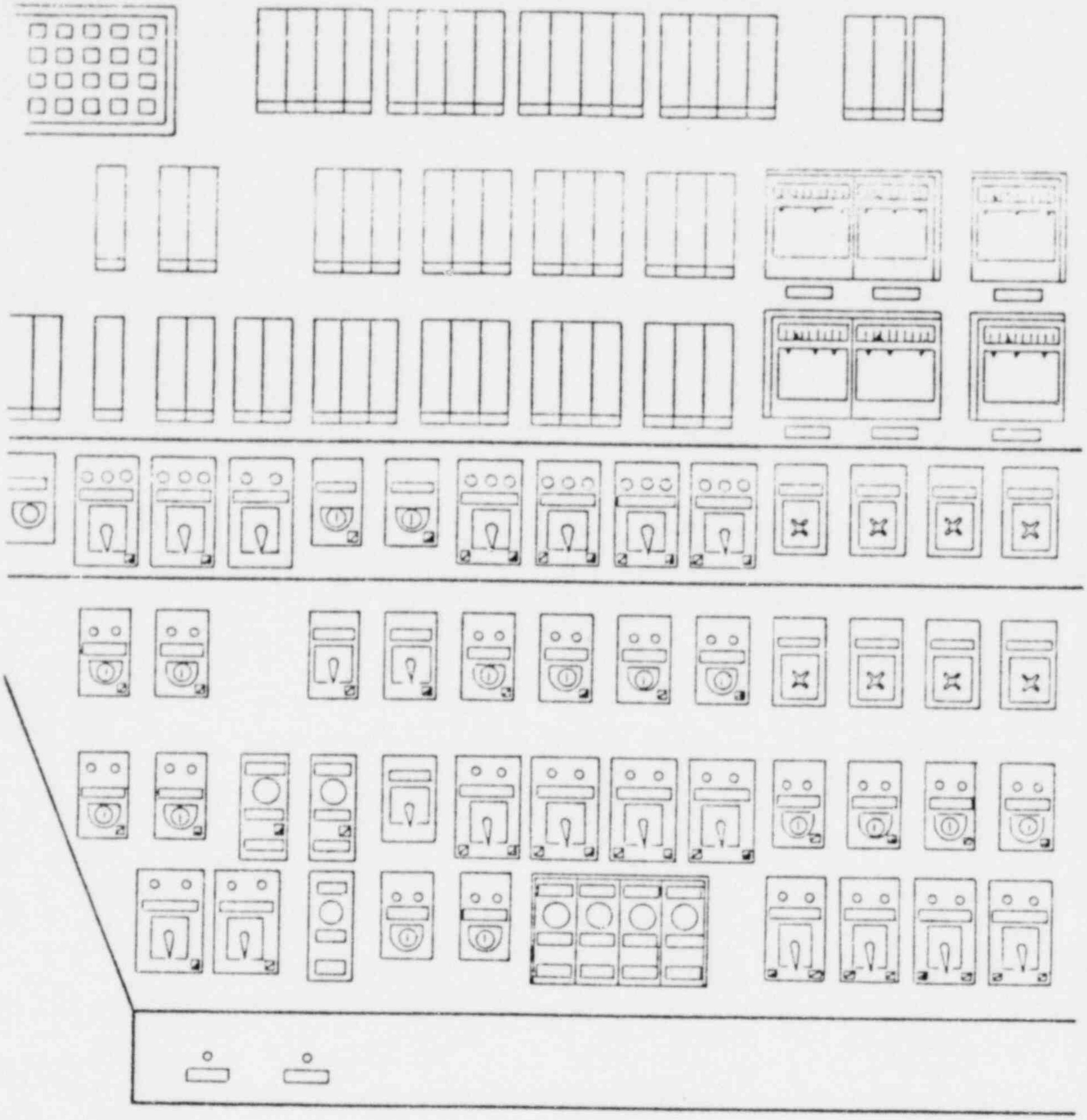

Fig. 9 Segment of the feedwater control system panels selected for human factors enhancement.

In the rearrangement of the feedwater control panel shown in Fig. 10, the elements present in the existing control panel (see Fig. 9) were reorganized and relocated on the panel within the same general area with the same spacing as on the existing board. 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.

Major changes were made in regrouping and reorganizing the elements of a particular subsystem to place associated display and control elements in a closer and more systematic relationship to one another as compared with the original configuration. However, the basic arrangement of the steam-generator displays and

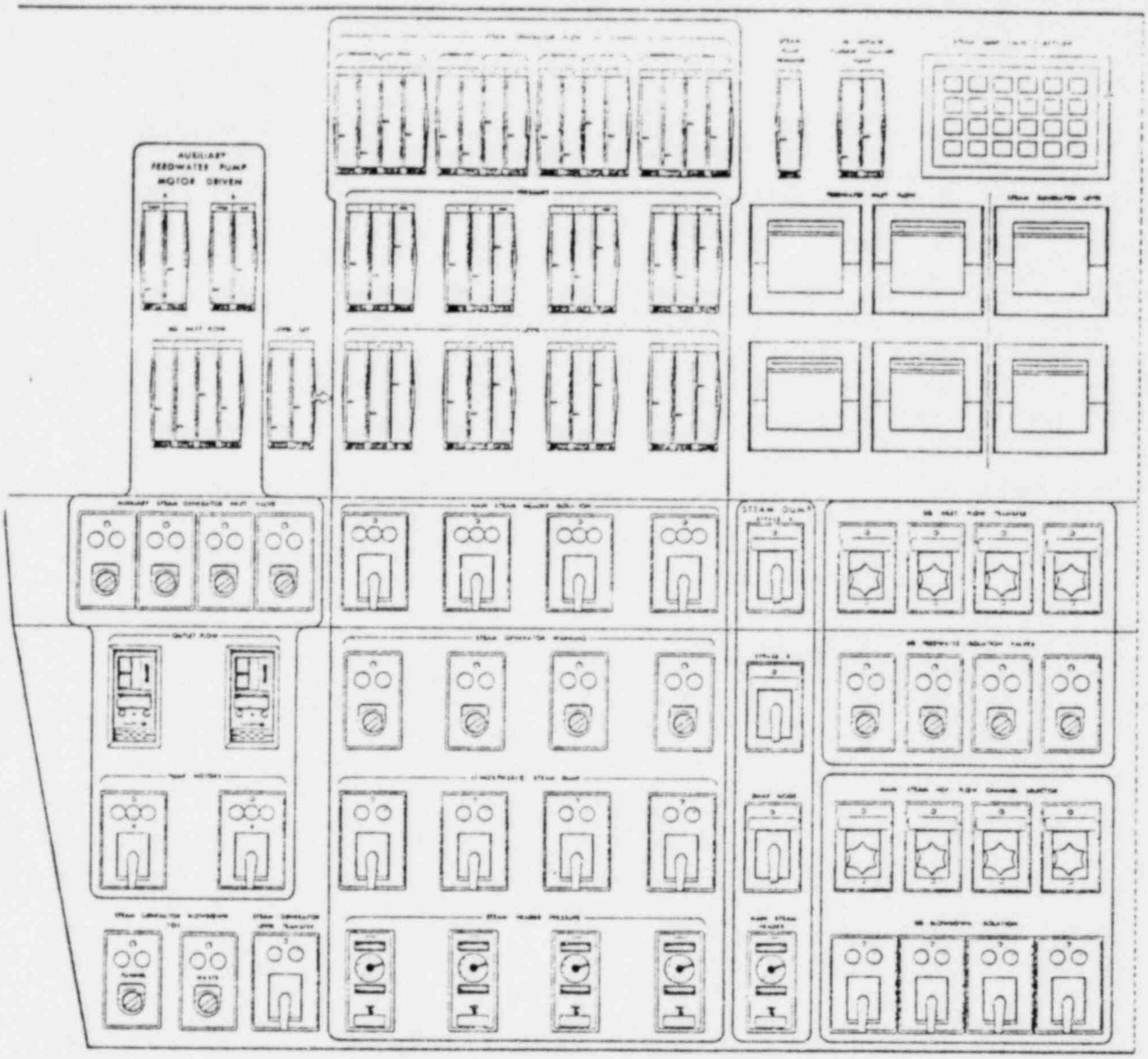

Fig. 10 Slightly rearranged feedwater control panel to provide a more logical grouping of panel elements. (Compare with Fig. 9.)

associated controls was not disturbed except to modify the lateral spacing to emphasize the vertical organization of controls and displays for each steam generator. Labels were added to identify the functions for each row of controls, and coding techniques were used to differentiate each of the four steam generators.

While such panel rearrangements would be considerably more costly than the surface modifications first discussed, at some point in the life of the control room they may be required. At the rate that changing requirements call for additions and deletions of panel elements on the control boards, it does not appear likely that the boards will survive their nominal 40-yr life unchanged. This "face-lifting" process should be preceded by an analysis of the new information display requirements and the control options revealed by operational experience with the boards.

SUMMARY AND CONCLUSIONS

We have attempted to show how existing operational or near-operational control boards can be upgraded to improve the operator–control-board interface. As was stated at the outset, the two levels of modification considered would not yield control panels that were completely satisfactory from the human factors standpoint, but they would represent a considerable improvement. As evidenced by the numerous attempts made by operators to enhance their boards (usually as the result of an operational mishap), the need to upgrade the human factors aspects of present-generation control rooms is acute.

We are recommending a more systematic examination of operational control boards to establish specific enhancement requirements and possibilities. Some of the general recommendations made in this section will apply to all control rooms, e.g., improved labeling, functional grouping of controls, and color banding of meters. However, each control room needs to be reviewed on a case by case basis for specific enhancement recommendations. The following steps are recommended to arrive at a comprehensive set of remedial measures specific to each plant:

1. The existing boards should be reviewed carefully for signs of operator modifications, e.g., coding of meters, improvised labels, and pencil scribblings on the boards. Such additions to the boards are indicative of panel design deficiencies and may call for more formal or precise design remedies.

2. Each member of the operational department (or most of them) should be interviewed individually by means of the structured interview approach. Such interviews should preferably be conducted by a neutral third party, and the anonymity of those who are interviewed should be safeguarded. These interviews would probe control-board design deficiencies.

3. The history of operator errors and near-errors or accidents should be examined carefully in terms of the human factors engineering components of the problem. Were identical controls placed side by side and one mistaken for the other? Was an essential bit of displayed information obscured by a maintenance clearance tag? Many so-called "operator errors" are in fact attributable to control-board design deficiencies that the customary "retraining" cure will not remedy. The critical incident technique,[3] a method for systematically exploring the causes for accidents or near-accidents, errors or near-errors, is especially useful in this context.

4. The boards should be reviewed in terms of human factors engineering design standards and criteria. The following documents are especially useful for this purpose:

a. H. P. Van Cott and R. G. Kinkade (Eds.), *Human Engineering Guide to Equipment Design*, Rev. ed., Department of Defense, GPO, 1972.

b. E. J. McCormick, *Human Factors Engineering*, 3rd ed., McGraw-Hill Book Co., New York, 1970.

c. W. E. Woodson and D. W. Conover, *Human Engineering Guide for Equipment Designers*, 2nd ed., University of California Press, 1964.

d. *MIL-STD-1472B, Human Engineering Design Criteria for Military Systems, Equipment, and Facilities* (U.S. military standard), Dec 31, 1974 (change 1 issued May 10, 1976).

5. The data developed from the foregoing activities should be integrated and summarized to provide a set of plant-specific recommendations in three categories of implementation: (1) those which can be implemented immediately without interrupting power production, (2) those which should be implemented during the next major foreseeable outage, and (3) those which can only be applied in the design of the next control room procured by the utility.

6. Modification proposals should be reviewed by plant operations, engineering, and management to ensure that the changes are acceptable to all concerned and do not introduce unforeseen problems. If a control-room simulator is available, some of the cosmetic changes can be attempted in the simulator and evaluated prior to implementation in the operational control room. In the absence of a simulator, mock-ups may serve the same purpose.

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