HUMAN FACTORS REVIEW OF NUCLEAR POWER PLANT CONTROL ROOM DESIGN

EPRI NP-309
(Research Project 501)

Final Report

November 1976

Prepared by

Lockheed Missiles & Space Company, Inc.
P.O. Box 504
Sunnyvale, California 94088

Principal Investigators
Joseph L. Seminara
Wayne R. Gonzalez
Stuart O. Parsons

Prepared for

Electric Power Research Institute
3412 Hillview Avenue
Palo Alto, California 94304

Project Manager
Randall W. Pack

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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. The human factors aspects of five representative nuclear power plant control rooms were evaluated using such methods as a checklist guided observation system, structured interviews with operators and trainers, direct observations of operator behavior, task analyses and procedure evaluation, and historical error analyses. The human factors aspects of design practices are illustrated, and many improvements in current practices are suggested. The study recommends that a detailed set of applicable human factors standards be developed to stimulate a uniform and systematic concern for human factors in design considerations.

ACKNOWLEDGMENTS

We are indebted to many individuals and organizations for their assistance, guidance, and cooperation in the design and execution of this study. Special thanks are extended to G.H. Kaiz, J. Barnum, P. Ahern, M. Daniels, E. Conner, and J. Lucas of the NUS Corporation. NUS provided the LMSC study team with a Nuclear Power Orientation Training Program which included several operational plant tours. NUS assisted Lockheed in the review of methods for human factors analyses of control room design and an NUS staff member accompanied the study team on each of the data gathering visits to power plants and simulator training centers. Finally, NUS participated in a review of the data, applicable standards and regulatory guides, and the final report.

Thanks are also due to S. Seidenstein and S. Eckert, of LMSC, who contributed extensively to all phases of this study.

The study team is also grateful to the management and staffs of the simulator training centers who made their facilities available for our review despite pressing schedules. Similarly, we wish to extend our gratitude to the many control room operators, their supervisors, in-house training staffs, and plant managers who allowed us into the five operational control rooms investigated and reviewed the draft copy of our final report for technical accuracy.

Finally, we wish to thank the advanced design personnel with General Electric, Westinghouse, Combustion Engineering, Babcock and Wilcox, and Bechtel for sharing with us their present efforts in the area of future control room design concepts.

Joseph L. Seminara, LMSC
Randall W. Pack, EPRI
November 1976

FOREWORD

The Reactor Safety Study, WASH-1400, criticized the design of controls and displays and their arrangements on operator panels in nuclear power plants as deviating from human engineering standards generally accepted in other industries and specified for the design of man-machine systems. The EPRI Task Force for Nuclear Engineering and Operations expressed similar criticism and suggested EPRI retain an organization to review the human factors aspects of the control rooms of nuclear power plants that had recently become operational. The review covered five representative plants and evaluated current nuclear practices in the light of knowledge developed in other industries and estimated the significance of the differences in terms of their potential effects on reactor safety and plant reliability. The review also covered the training simulators corresponding to the selected power plants due both to the high accessibility of simulators relative to operational plants and to the availability of opportunities to study operator actions during simulation of major plant transient operations.

A separate but related EPRI research project, RP769, "Performance Measurement System for Training Simulators," will design, install, and test run on a nuclear power plant training simulator a system capable of automatic recording of statistical information on operator actions and plant response. The objective of RP769 is to initiate a system capable of providing an empirical data base for use both in probabilistic safety studies and in studies directed at improved hardware design. The system also should provide direct measures of effectiveness both for training programs and for proposed operating and casualty procedures.

Funding has been authorized for continuation of the research described in this report. Using the findings of the completed review, the human factors team will develop and evaluate several approaches to control board design. The categories of control boards to be evaluated will range from hardware systems with dedicated displays to computer-based information processing systems with decision analysis included, and will include varying degrees of control automation. The project will describe effective methods for developing and selecting control board designs, and will demonstrate design approaches that integrally include human factors considerations.

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Section 1

INTRODUCTION AND SUMMARY

Human factors engineering began to develop as a scientific and technical discipline during World War II. This interdisciplinary specialty is concerned with influencing the design of equipment systems, facilities, and operational environments to promote safe, efficient, and reliable operator performance. Approximately 3000 human factors specialists now participate in the development of a wide spectrum of military, space, industrial, and consumer products and work environments.

Over the past 15 years several investigators have pointed to the need for the application of human factors engineering principles to the development of nuclear power plant control rooms. The need for optimum man-machine relations in the nuclear power industry is no less acute than that for military and space programs. While the nuclear industry can take great pride from its enviable safety record, the adverse public reaction to radioactive releases that could be caused by operator error makes it essential that the operator-control room interface be optimized. Also, less than optimal man-machine interfaces can lead to costly equipment damage and serious losses in utility revenues.

The Electric Power Research Institute (EPRI) sponsored this study in response to technical criticisms regarding the lack of attention to human factors in nuclear power plants. This 16-month study was designed to provide a thorough evaluation of 5 representative control rooms. It was conducted by Lockheed Missiles and Space Company (LMSC) specialists, experienced in aerospace human factors, and with no vested interest in nuclear power systems. By means of a separate, corollary contract, EPRI retained the services of the NUS Corporation to guide the LMSC study team within the nuclear power industry community, provide basic nuclear systems familiarization training to the study team members, and assist in the data acquisition and review phases of the study.

This report may prove especially timely; the present Nuclear Regulatory Commission Standardized Review Plan for proposed new nuclear plants poses questions regarding the manner in which utilities will develop and assign responsibility for achieving human engineering design objectives appropriate to proposed control room layouts. It is hoped that in addition to influencing the shape of future control rooms, the results of this study will be useful for upgrading the human factors aspects of existing operational control rooms.

METHODOLOGY

EPRI selected 5 control room simulators and their corresponding operational plants to be investigated. A human factors measurement system was developed and then pretested at the first site visited. This initial, or pilot, study was conducted over a 15-day period. Subsequently, with assurance that the methods developed for this study would prove fruitful, the 4 remaining control room designs were reviewed, with approximately one week devoted to an investigation of each design and associated operational practices and procedures.

The methods used to gather the data in this report are as follows:

- Checklist Guided Observation System: A detailed 111-page checklist containing human factors engineering evaluation criteria was developed. It was derived primarily from military standards and applied in reviewing the 5 control room designs.
- Structured Interviews: A 51-question interview was developed to learn the human-factors concerns of operators and trainers. Forty operational personnel and 13 trainers were interviewed; the average interview required approximately 2½ hours.
- Direct Observations of Operator Behavior: Approximately 260 hours were spent in simulators and control rooms observing operator performance in response to normal and off-normal situations.
- Task Analyses and Procedure Evaluation: Representative operator tasks and associated procedures were reviewed using task analysis techniques. This produced data that were used to evaluate the adequacy of control room and control board arrangements, control panel designs, and the clarity of procedures.
- Historical Error Analyses: Records of reported operational errors were obtained prior to each site visit. These were discussed with operational personnel to review the man-machine contributions to each reported incident.
- Physical Measurements: The control rooms' dimensions, illumination, and control actuation force requirements were accurately measured. Additionally, a comprehensive photographic record of observations was obtained.

The data which form the basis of this report were acquired during the fall and winter of 1975-76. In addition to the human factors evaluation of existing control room designs, the study team contacted the designers of advanced control rooms to examine future trends in control room design.

STUDY RESULTS

This study revealed a variety of areas in which application of human factors engineering would improve the operability of present generation control rooms. These areas are outlined below and detailed in the body of the report NP-309. An attempt was made to preserve the anonymity of both the plants and the individuals expressing specific concerns. Our intent was not to criticize any given design, but rather to uncover general problem areas where human factors guidelines could profitably be applied to the next generation of nuclear power plants. A secondary aim was to identify problem areas within existing power plants where relatively minor and cost-effective retrofits could significantly upgrade the quality of the man-machine interface. In general, the study findings paint a rather negative picture. However, our intent was to explore potential improvement areas. Thus, rather than emphasize what is right with present designs, we have focused on what is needed to optimize control room designs.

Human factors engineering attention to the problem areas uncovered will promote more effective and reliable operator performance, will reduce the training burden on the utilities and trainees, and will ease the selection criteria in recruiting operators.

Control Room Design

There is a clear relation between the size and configuration factors and the ease of operation and required manning levels. Measurements were made of each operational control board area, the maximum viewing distance from the operator's desk, the maximum walking distance between the control board extremities, and the floor area enclosed by the operational control boards. (Consideration was also given to space occupied by such items as bookcases and special consoles.) These dimensions were correlated with the attitudes of operators with respect to control room size and ease of operation. A majority of our sample (58.5%) felt that its control rooms were too large.

When the responses were analyzed on a plant-by-plant basis, some interesting relations emerged. Perception of control room size is directly related to the configuration of the control boards, rather than simply to the absolute size of the room or the control boards. There is a perfect correlation between the degree of dissatisfaction with control room size and two factors: maximum viewing distance from the operator's desk and maximum walking distance from one end of the control board to the other. For example, the control room shown in Figure 1-1, the second largest control room in terms of control board area, engendered dissatisfaction from 100% of the interviewees because of the unwieldy L-shaped configuration. Conversely, the control room shown in Figure 1-2, the largest control board, ranked third in terms of dissatisfaction because of size. The wing-shaped configuration of this board allows a better operator-control board interface.

In contrast to military and space workspace envelopes, control room designers have made little attempt to conserve space. The designs reviewed maximized, rather than minimized, the required operator visual span and the distances the operator had to walk to manage his control boards. The more acute this problem, the greater the manpower required to operate the boards and, it follows, the greater the cost to the utility. In general it was concluded that insufficient attention is paid to the abilities and limitations of the operator in developing control room configurations.

In addition to problems of primary control board configuration, all five plants relegate instrumentation and controls to "back panel" areas or areas remote from the operator's primary duty station. This creates serious difficulties for the operators: their attention to primary panels must be diverted during both normal and emergency operations.

The arrangements of control room consoles and stations produced problems unique to each plant. In some cases, a proliferation of add-on consoles impeded traffic flows and visual pathways between a center desk position and the control boards. The most serious problem of this sort occurs where the operators' desks are placed with their backs to the control boards (see Figure 1-3). Four of the five plants lacked a resting place for the operator's procedures manuals making it difficult to use the manuals in conjunction with the control board operation. In only one of the plants did the supervisor's office have immediate access to the control room.

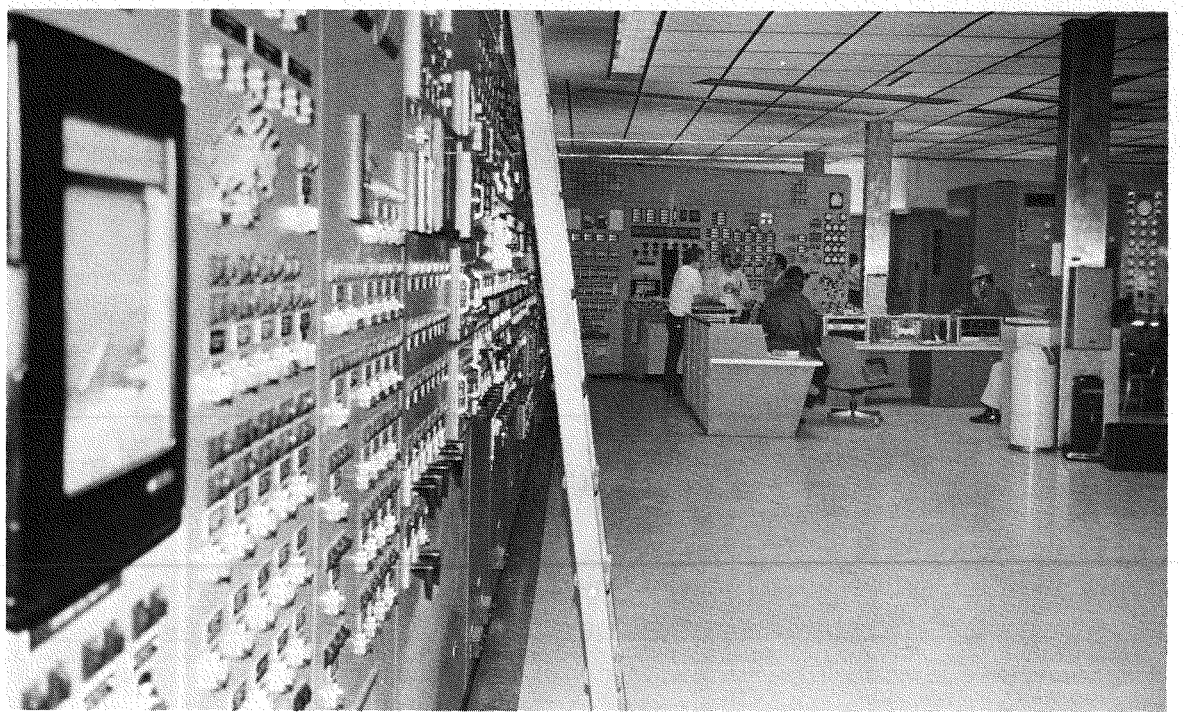


Fig. 1-1. Unwieldy, L-shaped control board configuration.

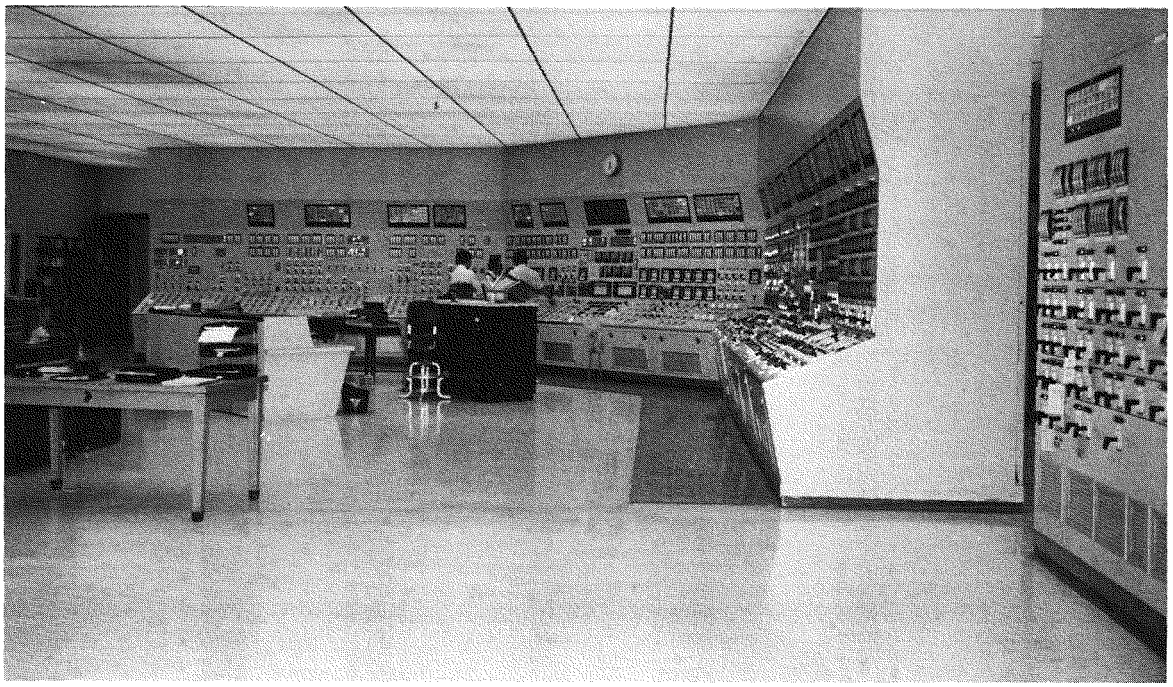


Fig. 1-2. Wing-shaped control board arrangement, though larger than the L-shaped board, is perceived as smaller and easier to operate.

Eating and restroom facilities, initially intended solely for operational personnel, were often overburdened through use by others. This created problems for operators who had to compete for the use of these facilities. While improvements are being made in restricting access to control rooms, the flow of visitors is still described by operators as a real problem, especially during day shifts. As one operator put it, "When there is a unit trip we have wall-to-wall people in the control room."

A surprisingly high frequency of complaints surfaced in regard to control room environmental factors. These concerned inadequate air conditioning and heating systems, and, at two plants, diesel generator exhaust fumes that managed to occasionally penetrate the control room.

Control room illumination was generally inadequate in four of the plants studied. The operators often maintain room illumination at a low intensity to reduce glare and reflections on instruments. Spotty maintenance of overhead diffusion panels accounted for poor illumination at one plant.

Complaints regarding noise were heard at all plants, although the causes varied. In some cases, excessive noise was attributed to nonoperational people in the control room. In other cases, the noise of operating equipment, e.g., computer typewriters, was the problem. In some plants, the control room was not sufficiently isolated from the outside plant equipment.

Finally, while largely a subjective matter, the study team perceived most existing control rooms reviewed as rather drab and dingy. Dramatic and inexpensive improvements could be made in room decor to provide a more pleasant work space envelope for the operator who is confined to his station for many long hours.

Control Board Design

Control board layouts were reviewed for conformance with human factors engineering requirements. The major criticisms of the layouts are as follows:

- Excessive Board Size. Large, expansive control boards require too great a visual and control span for the operator. Designers have used large control and display elements and little effort has been devoted to conserving panel space in most of the plants visited (see Figure 1-4).

- Control Boards Not Optimized for Minimum Manning. As noted earlier, some control board configurations demand more personnel than should be necessary. For example, the control panels can be separated into an inner primary area and an outer-wall-mounted secondary area, as shown in Figure 1-5. This sometimes requires the operator to be in two places at once. Two operators are generally provided, though Technical Specifications require only one operator.
- Lack of Functionally Demarcated Panel Areas. The control boards have massive arrays of components, many of which are identical, and which are not sorted out into clearly identifiable panels and subpanels containing related panel elements. (see Figure 1-6)
- Separation of Associated Panel Elements. Closely related control and display elements are sometimes widely separated on the control boards. Figures 1-7 and 1-8 illustrate two cases where a two-man operation is made necessary by the separation of directly related panel components.
- Mirror Imaged Control Boards. Mirror imaged control boards in multi-unit control rooms grossly violate human factors principles of transfer-of-training, i.e., these arrangements preclude consistency of operator response patterns in moving from one to the other mirrored half of the control room. Figures 1-9 and 1-10 show the mirror-imaged panels in one control room.

Designers of control boards have segregated the controls (on benchboards), the quantitative displays (on vertical portions of the boards immediately above the benchboard), and the qualitative displays that form extensive arrays of annunciator lights (in a horizontal band located uppermost on the control boards). These practices do not allow cohesive functional groupings. The operator is required to integrate scattered bits of data and relate them to relevant control options. Operators have a strong preference for mimic panel arrangements largely because such layouts organize panel elements into descriptions of system components. Some operators attempt to modify panels not originally so designed with tape to superimpose mimic logic (see Figure 1-11). In other cases, tape is used to functionally group or isolate related panel elements (see Figure 1-12).

A cursory review of in-plant control consoles outside of the main control room, (e.g., emergency shut-down panels), reveals an even more serious lack of human factors principles than was noted in the central control room. Such consoles are often poorly illuminated, inadequately labeled, and totally ignore anthropometric considerations as shown in Figures 1-13 and 1-14.

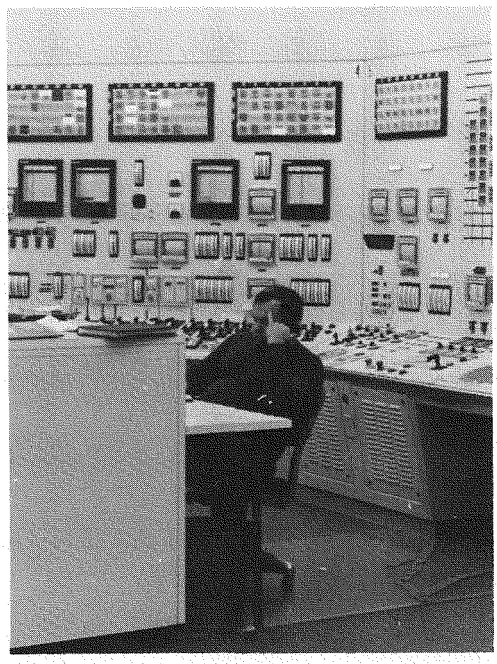


Fig. 1-3. Operator sits with his back to control boards.

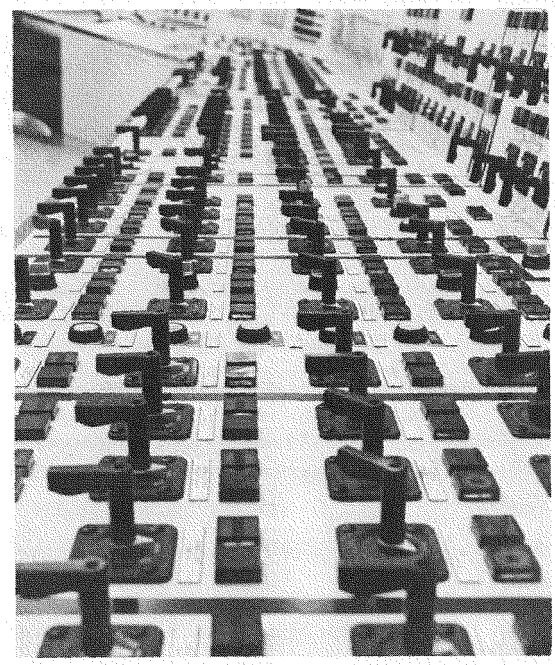


Fig. 1-4. Use of many large controls expands control board size.

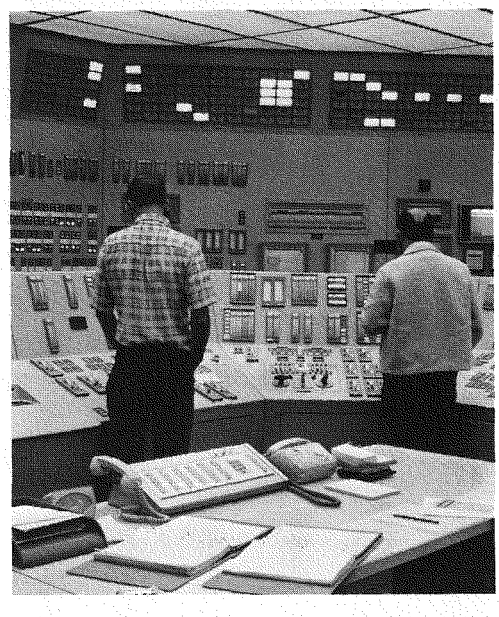


Fig. 1-5. Separation of panels into primary and secondary areas requires two operators.

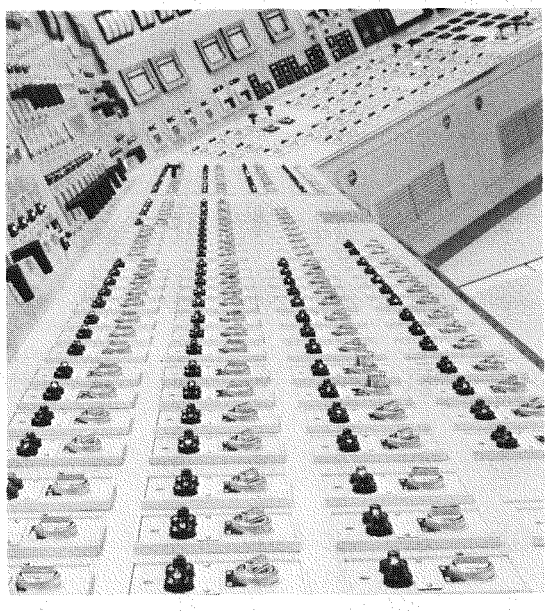


Fig. 1-6. Massive arrays of identical control/display units with no clearly identified subpanel grouping.

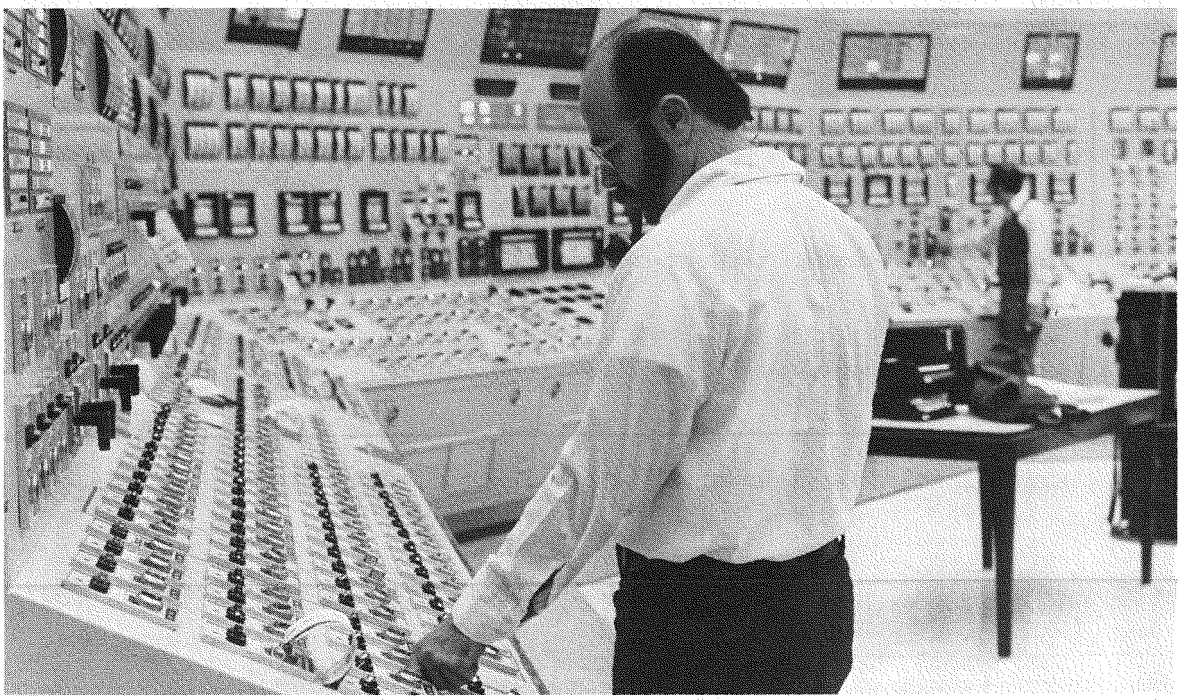


Fig. 1-7. The feedwater isolation valve controls are separated from the feedwater regulating valves as shown by the position of the two men.

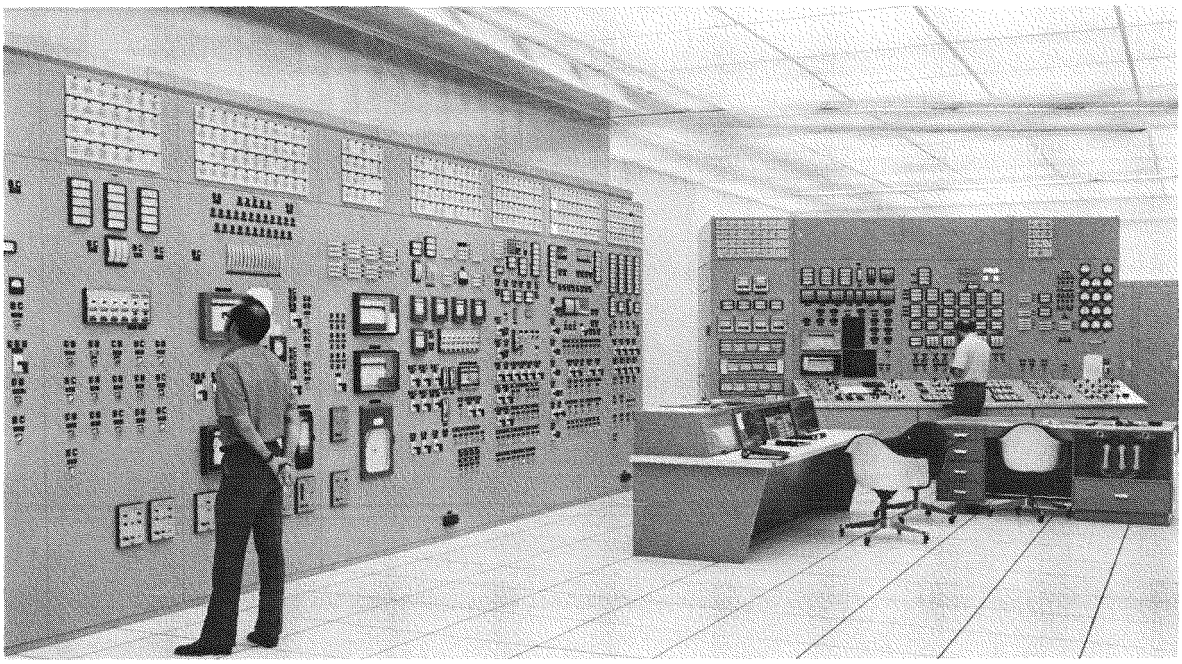


Fig. 1-8. The CVCS controls are placed on the main console to the right, while most CVCS alarms are located near the man on the left.

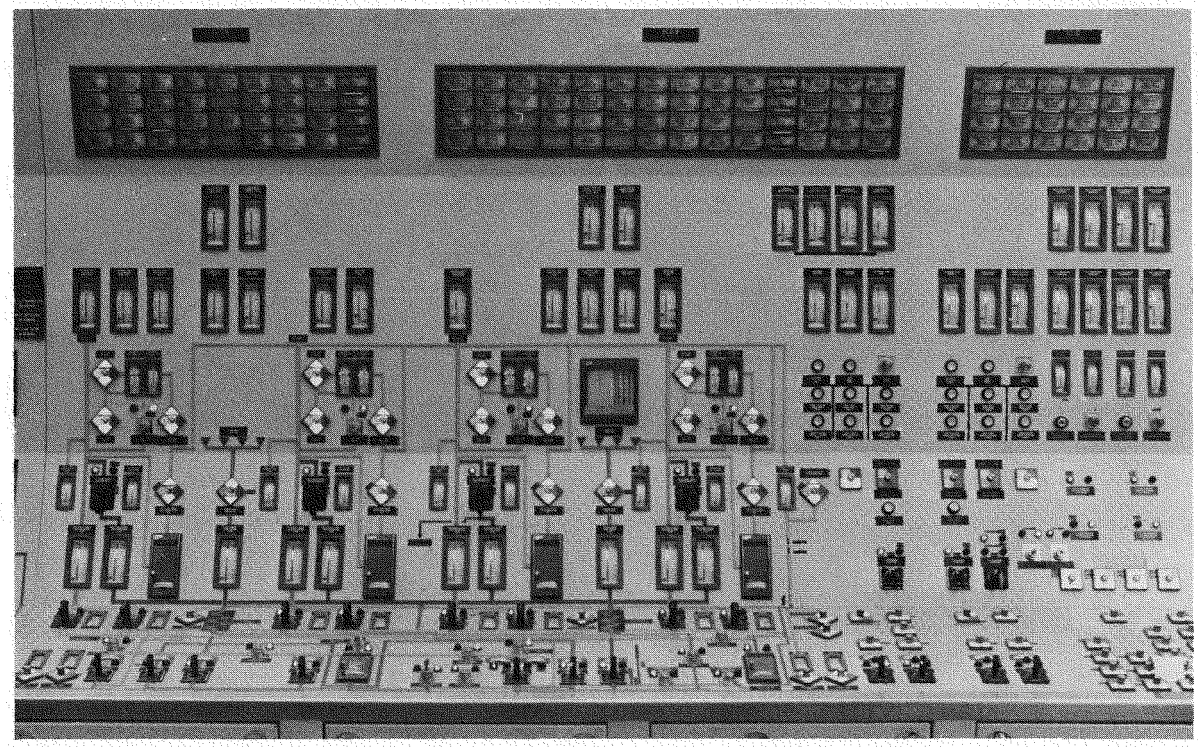


Fig. 1-9. Compare this board layout with its mirror image in Fig. 1-10.

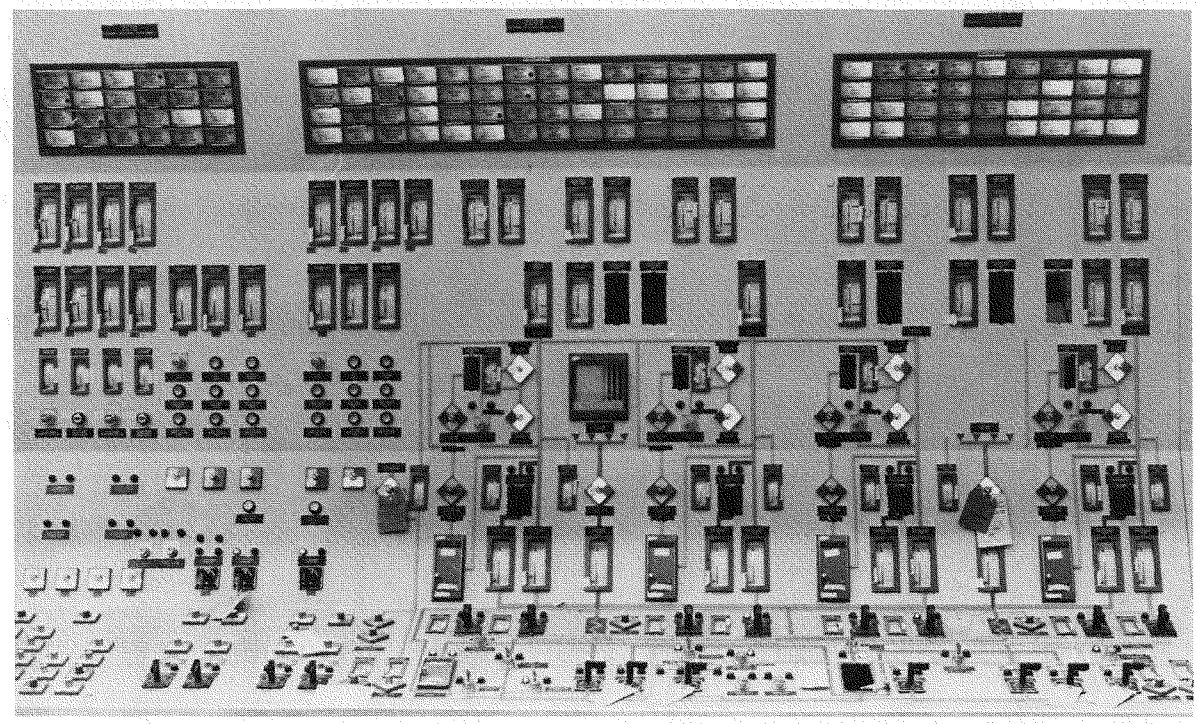


Fig. 1-10. Mirror imaged board layout in a multiunit control room.

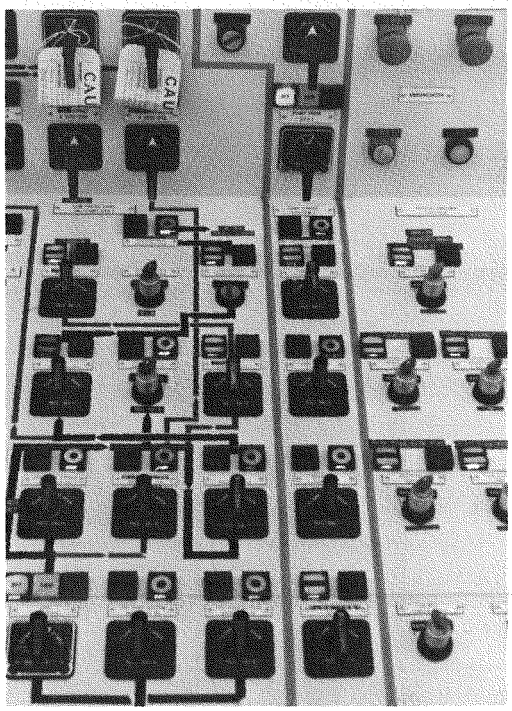


Fig. 1-11. Operators improvise mimic lines on boards.

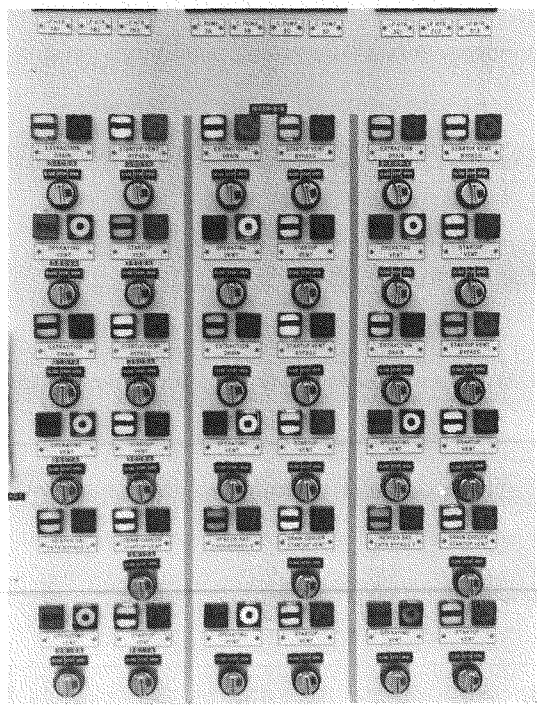


Fig. 1-12. Operators use tape to segregate related panel elements.

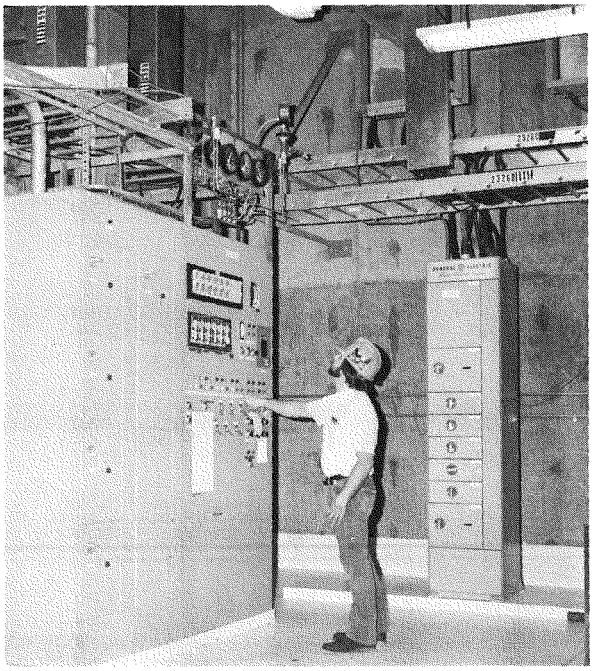


Fig. 1-13. Operator must monitor gauges placed about 12 feet above floor level.

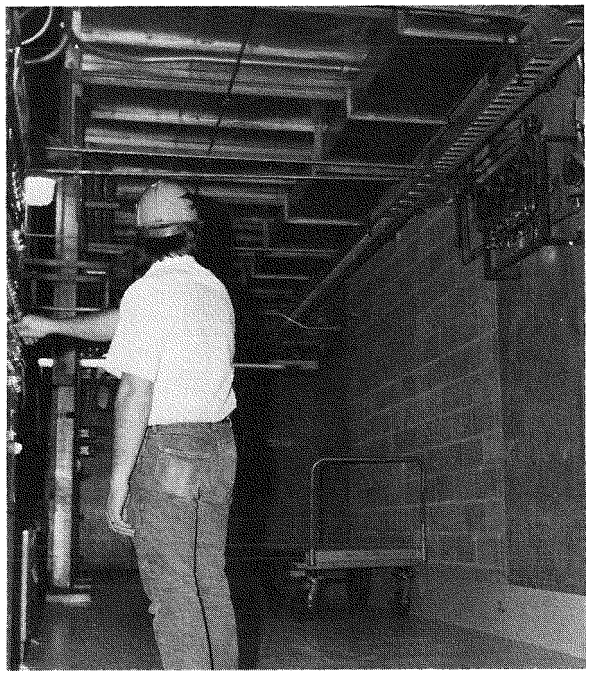


Fig. 1-14. Operator must monitor gauges placed across aisleway while operating controls shown.

Anthropometrics

A major human factors engineering concern is the degree to which equipment and facilities are tailored to match the physical dimensions of the men and women who operate these systems. We lack comprehensive data that describe the physical dimensions of the nuclear power plant operator population. This study generated some preliminary data regarding ages, heights, and weights of the interview sample. Assuming that our sample is representative, nuclear power plant operators are slightly older, heavier, and taller than military populations.

We found serious problems in four boards that have an entire horizontal band of meters beyond the range of operators (see Figure 1-15). Operator comments confirmed the difficulties that were being experienced in reading these instruments. The placement of instruments and controls too high or too low for convenient use was observed to be an even greater problem with back panels and peripheral consoles. These awkward arrangements often require foot stools or step ladders to provide operators visual and reach access to control and display elements.

Controls

In four of the control rooms large and cumbersome selector switches are used for operator selection between 2 or 3 control options. Much smaller control devices, (e.g., toggle switches), would serve as well or better. These large controls impact overall control board size. Some control pointers have pointing and nonpointing ends that can be confused, and some control configurations introduce parallax problems. In other cases, it is not possible visually to differentiate a simple indicator from an adjacent indicator that incorporates switching functions. The control operation is not always apparent from the associated control labeling. In one case (see Figure 1-16), excessive control actuation force requires a special device chained to the control board to apply sufficient leverage.

Accidental Activation of Controls

The control rooms were reviewed to determine the degree to which controls are susceptible to accidental activation. There are a variety of ways to reduce the possibility of inadvertent control settings. The major problems occur in the following categories:

- Inadvertent operation of adjacent controls having identical appearance, shape, and texture, but having different functions; i.e., the absence of coding to differentiate between identical controls (see Figures 1-4 and 1-6)
- Location of controls in areas and orientations that render them vulnerable to accidental contact and disturbance from both operators and nonoperational personnel who frequent the control room (see Figure 1-17)
- Accident-prone activities that are required of the operator and are unrelated to control board operation; e.g., removal and replacement of expended annunciator lamps (see Figure 1-18)
- Miscellaneous factors such as the potential for slipping or tripping over raised floor mats in the vicinity of the control boards (see Figure 1-19)

The operators have instituted a variety of remedial measures to reduce the possibility of accidental control activation. They have shape-coded some controls, added markings to control panels to indicate related groups of panel elements, and placed barriers and guards over special controls. These safeguards are usually the result of operational mishaps. Most of these measures should have been anticipated during the development of the control boards.

Indicator Lights

There are instances of improper use of qualitative indicators where quantitative displays such as meters would be more effective. Indicator reliability is a problem and there are a surprising number of burned-out, single-lamp indicators at any given time. The importance of easy access for lamp removal and replacement is pointed out, with appropriate examples of problems that operators encounter. The use of so-called negative indications, (the absence of an indication is to convey information to an operator), is discouraged (see Figure 1-20). Standardization of indicators within a given control room and the use of indicator designs that conserve panel space are recommended.

Meters

Meters are the most commonly used vehicle for transmitting quantitative information to the operators. The meters currently used in nuclear power plants reveal a tremendous potential for human factors improvements. The most common problems observed, some of which are shown in Figure 1-21, are as follows:

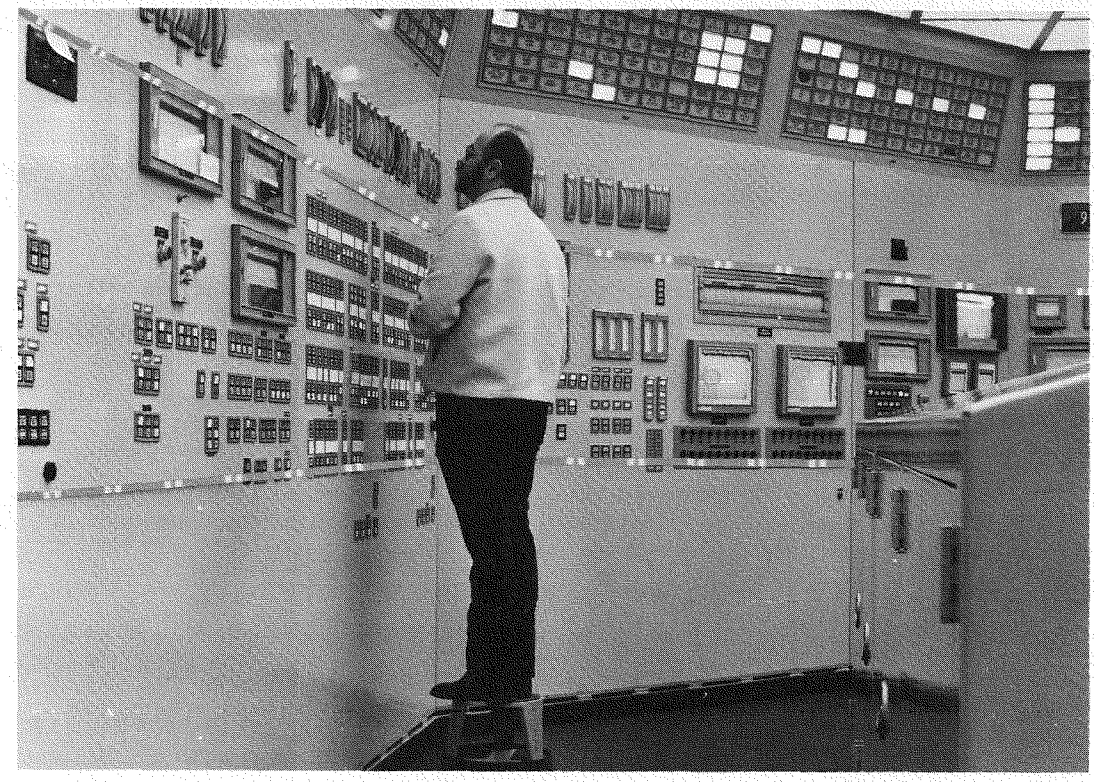


Fig. 1-15. Meters placed too high require use of stool. Dashed lines describe recommended anthropometric limits for display placement.

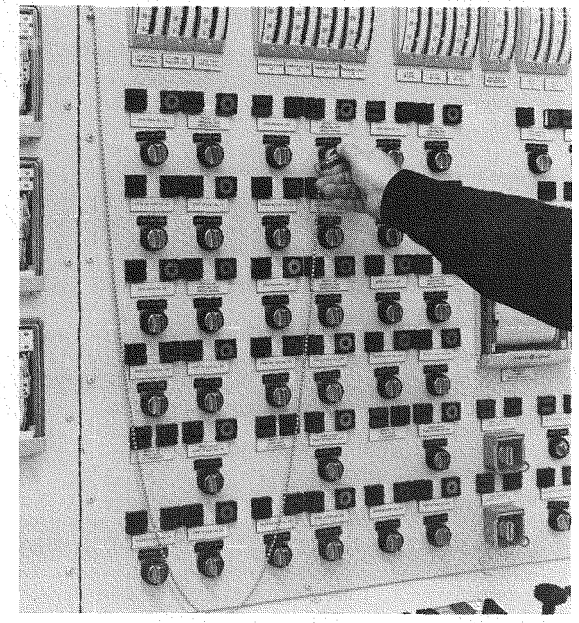


Fig. 1-16. Device for controls requiring excessive actuation force.

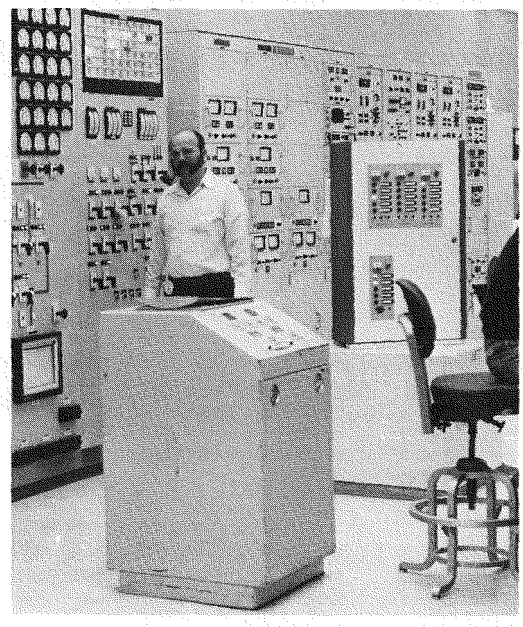


Fig. 1-17. High traffic area where passerby can snag projecting controls.

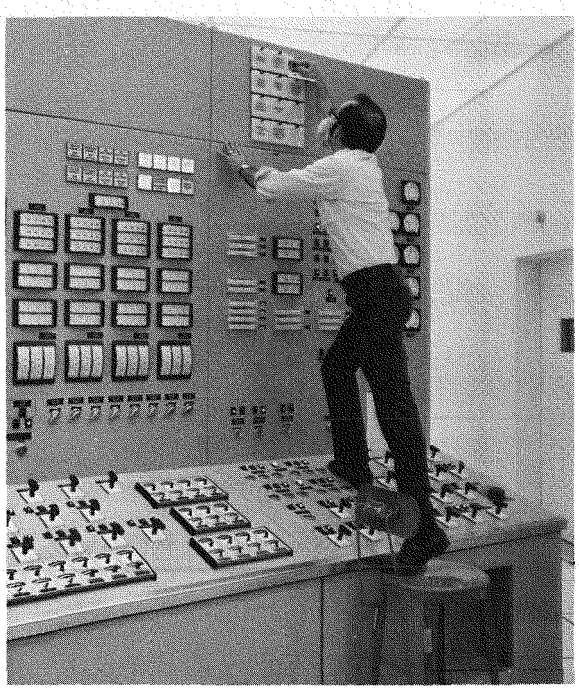


Fig. 1-18. The benchboard provides a natural foothold to replace expended lamps.



Fig. 1-19. Raised matting invites accidents; operators could fall against the controls.

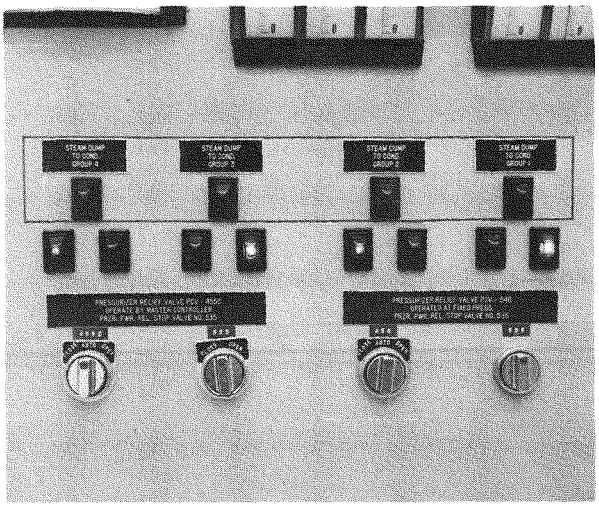


Fig. 1-20. Absence of illuminated lights (in taped area) indicate valve closed.

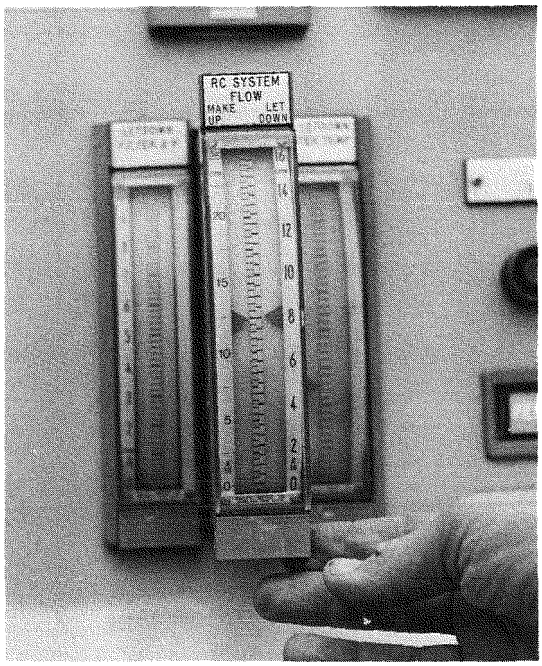


Fig. 1-21. Inoperable meter reads in the "normal" zone. Scale markings confusing.

- Improper use of minor, intermediate, and major scale markings in association with scale numerals
- Selection of scale numeral progressions that are difficult to interpret
- Parallax problems
- Placement of meters above and below eye level, making the upper or lower segment of the scale difficult to read, especially with curved scales
- Meters that fail with the pointer reading in the normal operating band of the scale
- Glare and reflections from overhead illumination sources

The most serious (and universal) problem observed with meters is lack of meter coding to allow the operator to readily differentiate between the normal, marginal, and out-of-limits segments of the meter scale. Operators, when allowed to do so, make numerous attempts to code meters as shown in Figure 1-22. However, such coding attempts are inconsistent and makeshift in nature. Present control rooms could be measurably improved by means of a systematic review of all meter limits and the adoption of consistent coding practices. This would enable the operator to tell at a glance whether the meter is reading in the normal, marginal, or out-of-tolerance zone.

Chart Recorders

Nuclear power plant control room operators make extensive use of chart recorders in monitoring system performance. While these chart recorders generally serve a useful purpose, they are sometimes inappropriately used in place of meters or other more readily accessible quantitative readout devices. Severe problems were observed in connection with some chart recorders with numerical printouts. One example illustrates very well the human factors problems associated with improperly designed or utilized chart recorders.

This particular chart recorder was designed to monitor 24 parameters. In the interests of economy, 42 points were incorporated into the recorder, with six spare channels. The parameter identification window in the upper right-hand corner of the recorder (see Figure 1-23) provides code numbers from one to twenty-four. Therefore, when this display window reads "5," the operator must first determine whether the pointer is reading parameter "5" or "29."

Because so many numerical points are printed on the chart paper, it is extremely difficult to sort out the individual number printed (see Figure 1-24). And the

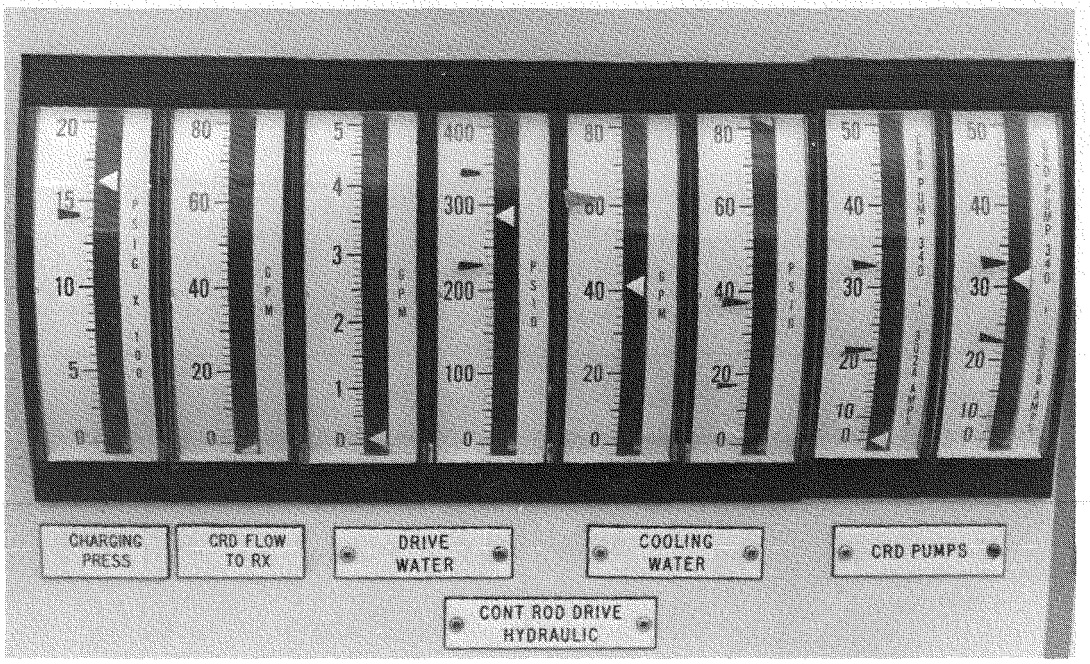


Fig. 1-22. Confusing array of improvised meter limits.

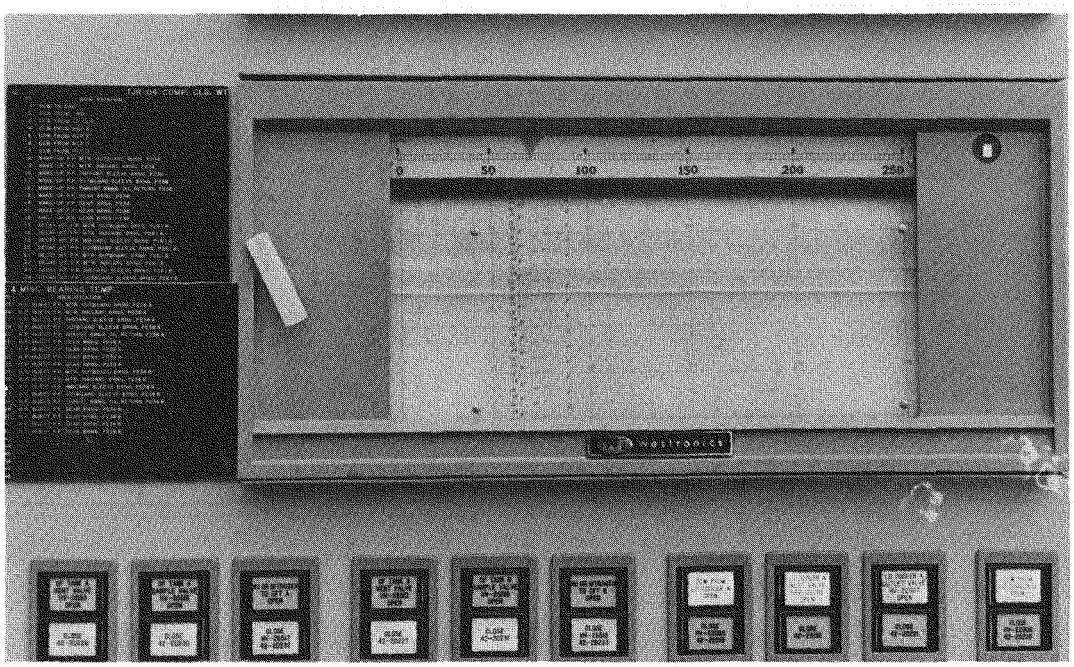


Fig. 1-23. Overtaxed chart recorder which tracks 42 parameters.

operator does not attempt to do so. Instead, the operator waits for the recorder to cycle to the parameter of interest and he reads the associated value provided by the recorder pointer and scale. In one instance, an operator who was alerted to a problem by means of the annunciator alarm system had to wait several minutes for the chart recorder to cycle to the parameter of specific interest. In this interval, a high pressure injection pump that could have been saved was destroyed. This case of an overtaxed chart recorder is not an isolated one. Too often, chart recorders that are useful for recording trends are improperly used in place of meters or other direct readouts.

Other factors discussed in this section of the report include labeling of recorders, scaling factors, overlays, and access for recording paper replacement.

Annunciator-Warning Systems

Each control room examined is provided with an annunciator-warning system consisting of a horizontal band of hundreds of indicators spanning the uppermost segment of the control board (Figure 1-25). These arrays of indicator matrices are accompanied by a variety of auditory alarms and sets of controls distributed on the control boards for acknowledging, silencing, testing, and resetting alarms.

The annunciator-warning systems currently in use are too complex and have become the catch-all for a wide variety of qualitative indicators. Present segregation of these qualitative displays in the annunciator band has served to separate them from functionally related groups of controls and quantitative readouts placed on the control boards. This functional isolation of associated qualitative and quantitative displays compounds the difficulty of integrating disparate sources of information to allow diagnoses of malfunction or abnormal situations. When an emergency occurs, the excessively large number of indicators that are illuminated, in concert with blaring horns, startle the operator and overload his sensory mechanisms rather than shed light on the problem at hand. Annunciator light systems should contain the minimum number of indications required to alert the operator to a problem and direct the operator to the appropriate segment of the control board where the problem can be diagnosed and where corrective control action can be effected.

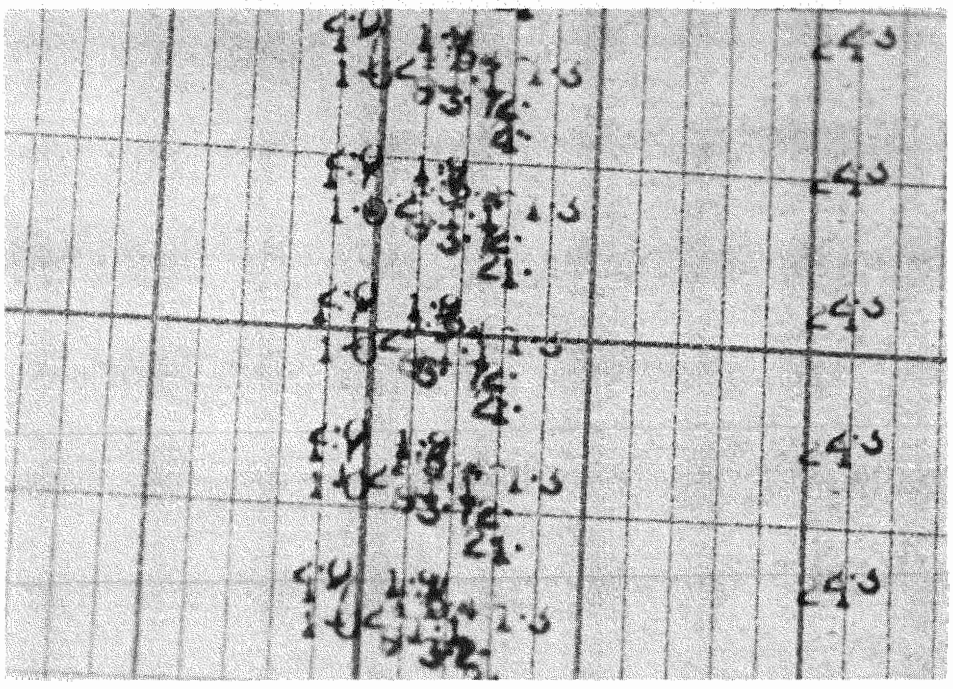


Fig. 1-24. Sample chart recorder printout where points are difficult to read.

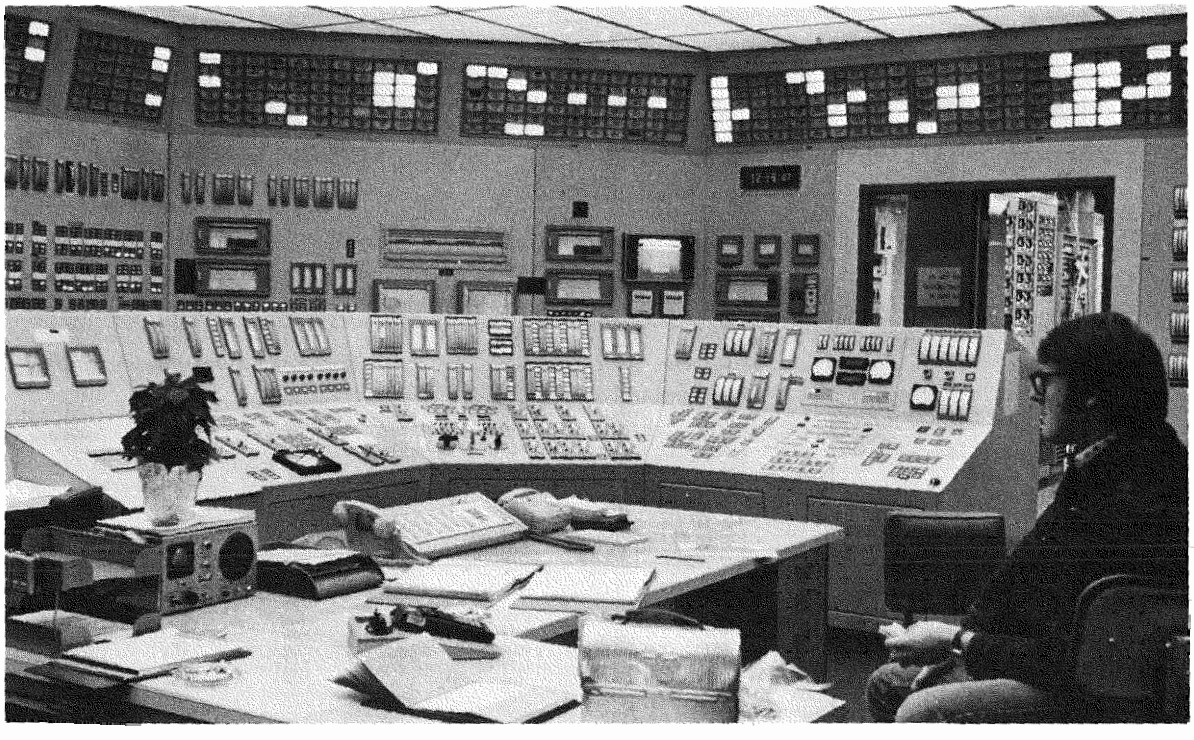


Fig. 1-25. Operators at all five plants visited learn to live with nuisance alarms.

In addition to this major criticism of existing annunciator-warning systems, the following problems were observed by the study team and confirmed by operator reports:

- Annunciators are sometimes located far from the control board panel elements that they are related to.
- None of the control rooms visited has fully resolved the problem of nuisance or false alarms that frequently cry wolf to the operator.
- Some alarms lack specificity. These multi-input alarms, e.g. XYZ PRESSURE/LEVELS, HI/LO, serve more to frustrate than to inform operators.
- Alarms that refer the operator to a remote station make the operator dependent on an auxiliary operator who may be hard to reach or require the operator to leave his primary duty station.
- Better use should be made of auditory coding techniques for alerting signals and control coding techniques should more distinctly differentiate annunciator related controls.

Coding of Displays and Controls

The control room designs underutilize proven coding techniques that could help the operator discern plant status and prevent misidentification of control elements. The color codes that have been evolved for the control boards have not been applied systematically and code meanings vary from panel to panel. For example, in most cases red is reserved for a normal flow or closed circuit condition, whereas in other cases red is used to denote danger or an out-of-limit condition or to alert the operator to especially important controls.

The operator cannot immediately spot an abnormal condition by virtue of appropriate and consistent color coding as is possible with the "Green Board" often used in military or space systems. Present coding of indicators, for example, tells the operator whether a valve is closed or open but do not convey any information as to whether the valve should or should not be closed. This type of logic should be built into the color coding system to promote error-free operator performance.

The lack of control coding is almost as serious as the lack of effective color coding. The majority of operators and trainers interviewed (89%) indicated problems in distinguishing between identical controls placed in proximity as shown in Figures 1-4 and 1-6. The operators have improvised various means to differentiate between identical controls. Note the original design of two

identical rod motion controls shown in Figure 1-26. Compare this with the novel shape coding devised by operators as shown in Figure 1-27. However, a more systematic approach to color and shape coding controls should be taken during the design phase of control room development. Lack of adequate attention to control and display coding practices invites errors of misidentification and places an unnecessary burden on the operator's memory, especially during times of stress.

Labeling

Effective labeling practices can assist the operators. Most problems in this area are easily corrected. The best indication of labeling inadequacies is the extensive hand-made labeling that operators have added to the consoles. These added labels have generally attempted to clarify operation of given controls (see Figure 1-28) or clarify the meaning of display readings.

Labels have not been placed consistently above or below the panel elements being identified. Consequently, it is possible to misidentify some panel elements. In some cases, labels have been obscured by projecting panel controls, making them hard to observe from the operator's normal position.

A major problem is the lack of size coding or differentiation of labels used to identify major console panels, sub-panels, and panel elements. Often the same element of a label is repeated in describing a group of related panel elements. One large label would eliminate this repetitiveness and serve to functionally group associated panel elements. Present labeling and panel layout practices force a hunt-and-peck operational mode, especially with seldom used panels.

Label abbreviations are often inconsistent. On one panel the following four ways of labeling the word "pump" were used: PU, PP, PMP and PUMP.

Communications

Four of five operators interviewed pointed to inadequacies in their ability to communicate with plant personnel outside the control room. These problems stem largely from the inability of communications systems to reliably penetrate or overcome the high ambient noise levels in the plant. A variety of communication devices are currently in use--telephone, verbal and nonverbal auditory paging systems, portable two-way radios, and an audiovisual Auto-Call system.



Fig. 1-26. Original configuration of controls shown in Fig. 1-27.



Fig. 1-27. Novel shape coding of rod motion controls.

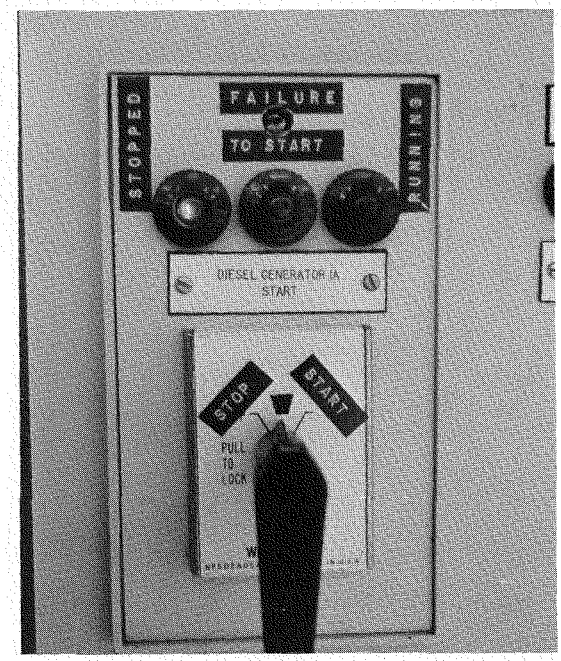


Fig. 1-28. Operators make extensive changes to board labeling.

Despite these many communications channels, only one of the five plants seemed relatively free of major communications problems.

The arrangement of communications gear was also studied. The communication equipment is sometimes oriented so that its use either interferes with monitoring control boards or limits the operator's access to controls.

The design of the control room makes the operator highly dependent on auxiliary operators in the plant and he must be able to reach outside personnel in an emergency, a frustrating experience for the operator when he is unable to reach his manpower resources in the field. Either the control room must be designed to eliminate operator dependence on auxiliary personnel, or a more dependable communications link is required.

Task Analysis

Task analysis is a systematic examination of operations sequences to evaluate the man-machine interface and procedures. This approach was applied to an emergency procedure at each plant visited. The technique assures a more comprehensive and detailed look at human factors issues than is available through the other approaches used in this study.

For example, the operator activities in the control room in response to a steam generator tube rupture showed how relevant controls and displays were not arranged for effective operator response. Figure 1-29 shows the movement of two operators at one plant. Among other things, the panels located in the "back rack" area should be located closer to, or integrated with, the main control room area.

This technique was also applied in the evaluation of specific panel arrangements. The results of the task analysis further substantiated data derived from the human factors checklist evaluation and the structured interview.

Procedures

A serious effort is being made to upgrade plant operations procedures. A 55-item checklist was developed and applied to a sample of existing procedures. A 74% compliance with the evaluation criteria selected was found. Some typical problems are the clarity of procedural content, disparities between measurement

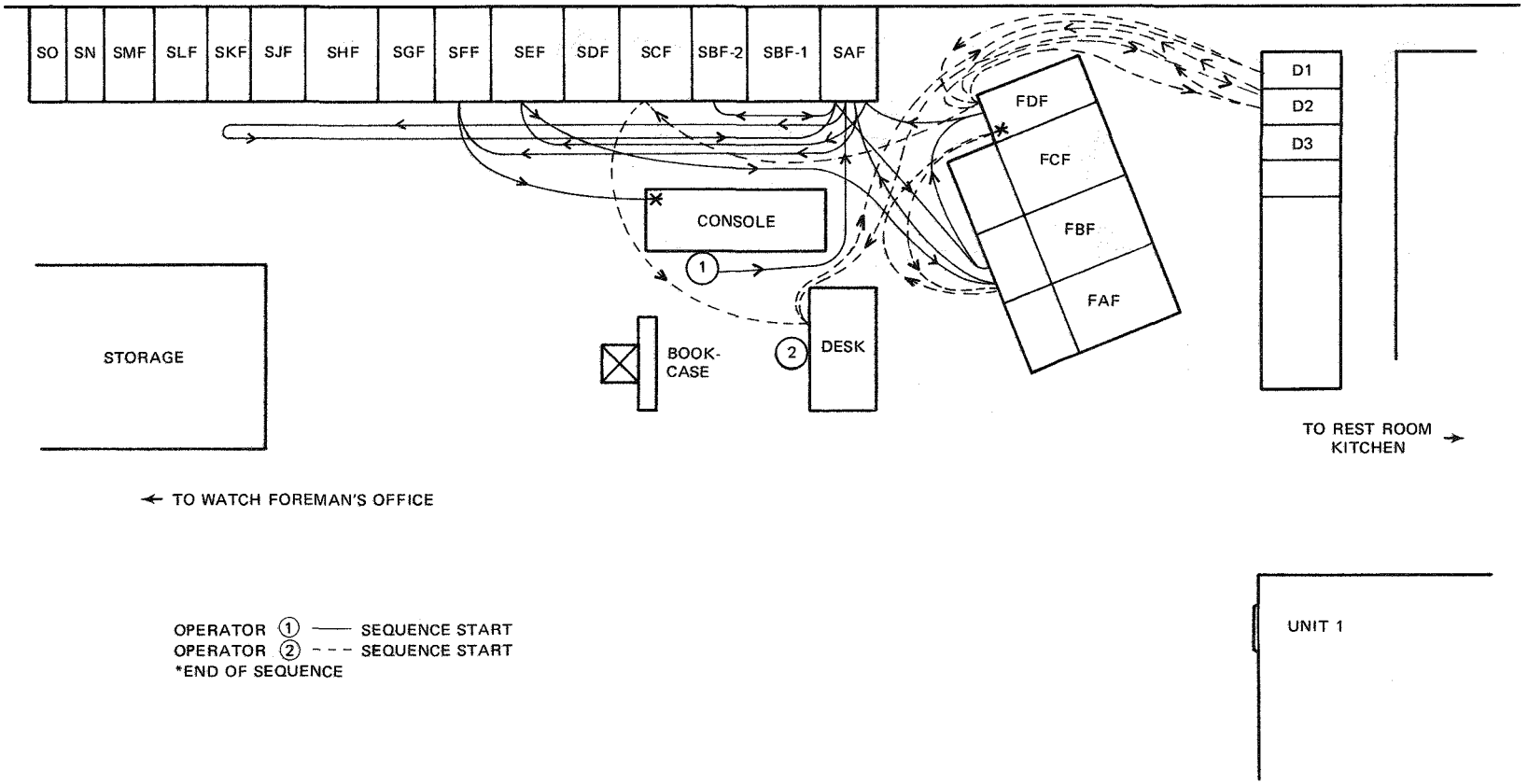


Fig. 1-29. Operator movements in response to a steam generator tube rupture indicate that panels located on back racks should be in the primary control room area. This arrangement requires operator to make three trips to the back racks.

units provided in the procedure and the values indicated on displays, and a lack of correspondence between written procedures and actual operating practices.

It is interesting to note that operator satisfaction or dissatisfaction with operating procedures varies as a function of the role assigned to the operator in establishing the procedures. In plants where the operator has primary responsibility for developing procedures, there is less dissatisfaction. By a two-to-one margin, operators and trainers feel it is important to upgrade and rely on procedures.

As noted earlier, none of the control boards designs reviewed makes provisions for simultaneous use of procedures and operation of the control boards, although one plant has devised a unique and practical expedient - a bookcase on wheels - which allows the operator to effectively utilize procedures within reach of the controls.

Operational Practices and Training

Operator performance can be affected by a variety of plant practices and conditions that shape the man-machine interface: watch turnover practices, shift crew composition, shift change adaptation, operator morale, overtime practices, boredom and stress.

Inadequate safeguards are currently in effect for ensuring a successful and error-free transition from one crew to another. Most operators say that it takes between 15 to 30 minutes of unpaid overlap at each end of a shift to conduct the tasks necessary for an effective watch turnover. This has led to watch turnover practices that depend on the individual conscientiousness of the operators.

Operational practices used to compose shift crews also present problems. At several plants operators basically select shift teammates on the basis of preference according to seniority. Where this is practiced, senior people choose to work with other senior people. Thus, there are some shifts manned entirely with junior and relatively inexperienced operators, not a balanced mix of talent and experience.

There is a chronic shortage of control room operational personnel, and considerable overtime work is required. Operators generally work between 200 and 600

hours of overtime per year, but overtime can reach 1000 hours. Also, it is not unusual for an operator to work 16 consecutive hours if his relief does not show up. This can sometimes happen several days in a row. Excessive overtime demands can adversely affect operator responsiveness and quality of performance.

A majority of operators (55%) feels that shift work takes its toll in reduced operator effectiveness. Adaptation to shift work appears to be an individual matter. Aside from the fatigue and sleep deprivation aspects of shift work, sometimes coupled with excessive overtime demands, these aspects of the job can create personal or family problems for operators which may affect job performance. Alternate shift scheduling approaches, e.g., permanent shifts, need to be examined.

A large majority of the operators and trainers (69.2%) sees the control room operator's job as one in which there is a large boredom component, especially when all goes well within the plant. The operators offer many suggestions for dispelling the boredom. It may be possible to restructure the operator's job to break up long stretches in the control room with training, walks through the plant, and preparation of procedures. If boredom is dispelled, and an adequate level of operator vigilance is maintained, job satisfaction is enhanced. The utilities then obtain a better return on the dollars spent for the operators' time. The infrequent, though intense, stress associated with the operator's job also must be alleviated. Operators and trainers see extensive rehearsal of emergency responses on the simulator as an effective antidote to stressful situations that can arise in the control room.

One of the major benefits of applying human factors engineering to control room design is that greater attention to the man-machine interface reduces the operator training required. To the extent that control-display arrangements are logical and interrelationships are self-evident, the operators more easily master the operation of the control boards. Accordingly, the structured interview posed a series of questions dealing with operator training prior to licensing and subsequent requalification training. Operators felt that learning to operate the control boards would be best facilitated by greater use of mimic panel arrangements. Some also pointed to a need for better functional grouping of panels, improved coding of displays and controls, more comprehensive labeling, and standardization within the control room.

The most frequently voiced recommendation for change in operator training programs was increased emphasis on operational training and experience and a corresponding de-emphasis of formal training in theoretical subject matter. As a corollary, the majority of operators and trainers felt that if the NRC licensing examination is to predict effective operator performance, it should be more operationally oriented and less theoretical. This study did not explore the most appropriate balance of theoretical and operational training in relation to the subjective estimates of the interviewees.

Operators feel simulators provide the best operational training. Many operators receive simulator training on control board configurations that are dissimilar from the operational control boards that they will eventually operate. This introduces a possibility of negative transfer of training and the situation is analogous to training a Boeing 747 pilot on a Lockheed L-1011 training simulator or vice versa.

There was unanimity of opinion in favor of requalification training, especially when the programs include simulator "hands on" experience. However, since the power plants are generally understaffed, such training often is done on an overtime basis.

Operator Errors

By interviewing operators and analyzing reported operational errors, we were able to categorize these errors. The emphasis of this analysis was to identify the man-machine implications of the errors.

The largest category of operator mishaps is caused by the absence of a timely, attention-getting indication (either qualitative or quantitative) that informs the operator that some element of the system is not operating properly. The second most common error category results from incorrect lineup of valves. Lack of control coding and inadequate watch turnover problems also contribute to operator errors. The operators and trainers emphasized three human-engineering factors: (1) unclear, illogical, overly complex, or mirror-imaged control board or panel layout arrangements, (2) lack of control coding or separation of identical controls, and (3) inadequate information display formats, e.g., illegible chart recorders.

Advanced Control Rooms

We surveyed advanced control room concepts to determine whether future control rooms will avoid some or all of the human factors problems highlighted by the present study. The most significant development is extensive use of computers and computer-graphic techniques in displaying information to operators (see Figure 1-30). This will lead to more compact operator control stations and the potential for better integration of information displays than is currently available.

However, our brief survey of future trends is not totally reassuring. It is apparent that future systems will be as unstandardized as present systems. For example, different vendors are developing different color codings and CRT display symbols. Furthermore, there are no substantive attempts underway to evaluate the quality of the man-machine interface with advanced concepts. Before we can be sure that the transition between present and future designs will be successful, empirical human performance evaluation studies must be conducted.

Most of the operators and trainers interviewed were skeptical or negative towards the trend to computer-generated CRT displays. Much of this negativism stems from the reported unreliability of computers presently in the control room.

CONCLUSIONS AND FUTURE RESEARCH NEEDS

The study clearly indicates the need for additional research. While it is relatively easy to criticize existing control room design and operational practices, it is difficult to determine how best to optimize control rooms from the outset. As a first priority, a detailed set of applicable human factors standards must be developed and industry-wide acceptance should be promoted. These standards would serve to provide design and evaluation criteria. Standards will not guarantee a standardized control room, which is probably an unrealistic near-term expectation, regardless of the merits of control room standardization. Rather, such standards will stimulate a uniform and systematic concern for human factors in design considerations.

In addition to a comprehensive set of standards, a need is perceived for human factors engineering design guides specific to the needs of the nuclear power industry. Such guides should first address realistic and cost-effective

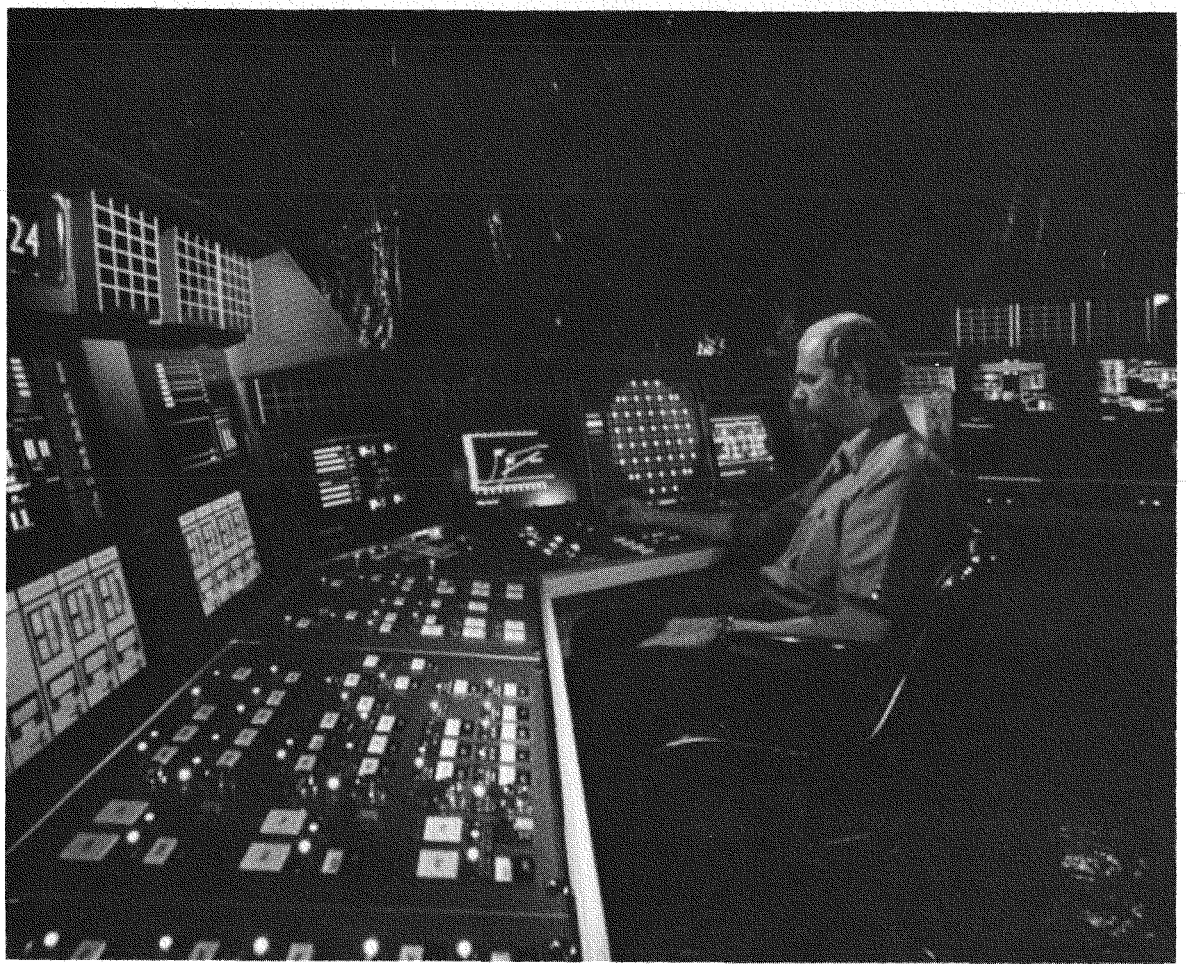


Fig. 1-30. General Electric Nuclenet advanced control-display system.

methods for upgrading present operational control rooms and second, guide the development of future control room designs.

Beyond these efforts, a program of research should be initiated to develop a human factors data base that can be applied to the nuclear industry. Some of the research topics suggested by the work conducted to date include the following:

- Major selected control board panels should be reconfigured in terms of human factors engineering criteria and an evaluation of operator performance should be conducted to compare existing panels with human engineered layouts.
- A definite comparative evaluation should be conducted to determine the advantages of conventional versus advanced, computer-based, control board concepts.
- Candidate warning-annunciator approaches need to be defined and evaluated to provide improved operator-alerting systems and diagnostic aids.
- An investigation should be conducted of decision-aiding techniques, such as fault trees, that might help the operator to identify, integrate, and assess presently scattered bits of information.
- The human factors of the auxiliary operator's role, his interaction with the control room operator, and the man-machine interfaces associated with the auxiliary operator's tasks should be reviewed.
- Nuclear power plant communication systems should be thoroughly investigated to develop recommendations for facilitating normal and emergency control room operator contacts with other plant personnel.
- The ease of maintenance of nuclear power plant hardware systems, the adequacy of maintenance instructions and procedures, and the training and selection methods for maintenance personnel should be evaluated.

Section 2

STUDY BACKGROUND

Human factors engineering, also referred to as human factors or human engineering, started to develop during World War II. The sophisticated and complex military systems being developed showed high failure rates because of inadequate concern for the human component of these man-machine systems. More precise data regarding the abilities and limitations of the human operator were needed so that mutually supportive man-machine interfaces could be designed. The consequences of degraded operator performance were so severe that behavioral scientists, who specialized in the study of human performance, were added to the traditional members of the design team. These early joint efforts of behavioral scientists and engineers produced the field of human factors engineering.

Special laboratories were established to investigate man-machine interface questions. Human engineering standards for the design of a military hardware and facilities evolved from the analyses and research conducted within these laboratories, and have been applied to every major military system developed in the last 30 years.

Human factors standards developed for military systems have since been applied to space operations, where degraded human performance also could not be tolerated. The discipline is now being applied to such diverse areas as automobile design, medical equipment systems, safety of ski equipment, and the design of criminal justice systems. There are now about 3,000 human factors specialists in the U.S., approximately 1,700 represented by the Human Factors Society.

This study explores the human factors of nuclear power plant control rooms and was prompted by the conclusions of earlier investigators. The utility industry has largely escaped the attention of the human factors specialist, and vice versa. Fossil-fuel systems can tolerate less than optimal man-machine interfaces,

and these have produced no public outcry. However, this is not the case with nuclear power systems. Because of the great public concern for the nuclear industry and the importance of nuclear power to our national energy situation, the nuclear industry must demand no less specialized attention to its operator-control room interfaces than is given to those of military and manned space systems.

In 1960 (2), Dickey attempted to alert the utility industry to the value of "human engineering" control panels. In addition to providing some "DOs and DON'Ts" for the control board designer, he said that "taken individually, human-engineering features might seem trivial and hardly worth-while, but together they provide a control panel that makes the reactor-plant operator's job easier and helps him avoid errors and needless shutdowns." Dickey was seeking to design panel arrangements that provided information in a meaningful format. In the late 1960's, Austin, Kanous and Starkweather (1) of the Detroit Edison Company promoted a task force approach to control room planning. This approach, which included operators and specialists in human factors, was applied in the development of the Trenton Channel control center. Emphasis was placed on the information requirements of the operator and control options that would have to be available. Scale models and full-scale mockups were used as design tools and for evaluation by operators, maintenance personnel, plant staff and management. Considerable attention was given to the operator's and maintenance man's needs, as well as their strengths and limitations.

Raudenbush (8,9) conducted a human factors engineering review of the Carolina Power and Light Company's H. B. Robinson Unit 2, Hartsville, S.C. He uncovered a series of human factors engineering deficiencies in the design of the "miniaturized" control board and proposed standards to govern control board layout designs that would assure optimum operator response. Hanauer (5) recommended control room standardization and the use of human engineering principles in control room design. He cited the cost and safety penalties that result from the present lack of control room standardization, and pointed to the savings in simulator costs that would be accrued if control room diversity were minimized. The need for standardization becomes especially important as the industry expands and operators move from one plant to another.

Recently, Swain (21) conducted, for the NRC, a study of the Zion Nuclear Reactor

Plant. His attention was focused on the control room safety panels and their associated procedures. As had his predecessors, he concluded that the design of control room panels and other man-machine interfaces deviate from human engineering standards and "increased the probability of human errors that could contribute to unavailability of safeguards systems." Swain pointed out that standard human factors techniques that routinely optimize the human role in complex military and space systems can also be applied in the nuclear power plant.

Swain (10) also contributed to the WASH-1400 Reactor Safety Study in the area of human reliability. In this analysis human error rates were derived from the following factors: (1) level of presumed psychological stress, (2) human engineering quality of controls and displays, (3) quality of training and practice, (4) quality of written instructions and method of use, (5) coupling of human actions, (6) type of display feedback, and (7) personnel redundancy. This analysis is based on subjective estimates and inferences from data derived in other than nuclear industry contexts. The study points up the need for a substantive data base describing the human element in the nuclear power plant control room.

The human factors attention that has been given to nuclear power plant control room design is inadequate. There is also insufficient information describing the control room operator, his functions, how he is selected, and how well he performs his duties. The American Institutes for Research conducted, for the AEC, a study of the performance of nuclear reactor operators (3). Using the critical incident technique, the study accumulated 1,400 reports of outstanding effective and ineffective job performance operations. From these data, lists of functions and of critical job requirements for operators were produced and a reactor operator performance checklist was developed as a measure of job performance. Using this checklist, 82 supervisors at 10 facilities observed and recorded the performance of 127 operators.

In 1975, the Electric Power Research Institute conducted a workshop on power plant operator selection methods. About 80 persons attended this workshop, most of them utility personnel involved in the selection, training, and supervision of power plant operators. The Conference Proceedings (7) provide a good overview of the operator's role, the existing and proposed standards affecting

operator selection and training, the impact of EEOC requirements on selection procedures, the selection testing programs conducted to date, and areas in need of future research.

This study was undertaken to provide a comprehensive assessment of the human factors of nuclear power plant control rooms. This study is timely because the effectiveness of the operator is becoming a matter of public attention and the man-machine interface is receiving increasing scrutiny from the Nuclear Regulatory Commission. In 1972 the AEC Office of Operations Evaluation evaluated 8 incidents of coolant release at boiling water reactors (4). Based on a review of actions of operating personnel during the incidents, the report concluded: " ...that a standard or guide should be developed by industry, with AEC participation, for control panel and control room design that better addresses the human engineering aspects of reactor operation during abnormal operating occurrences."

In the NRC Standardized Review Plan for new nuclear plants the following question is posed: "Describe how the following responsibilities are delegated and assigned within and from headquarters staff, and identify the functional unit for: (1) development of human engineering design objectives and design phase review of proposed control room layouts, (2) development and implementation of staff recruiting and training programs, (3) development of plant operating procedures, etc."

The NCR Regulatory Guide 1.114 dated February 1976 is concerned with the operator of a nuclear power plant. A quote from this guide is appropriate: "In order for the operator at the controls of a nuclear power plant to be able to carry out these and other responsibilities in a timely fashion, he must give his attention to the condition of the plant at all times. He must be alert in order to ensure that the plant is operating safely and must be capable of taking action to prevent any progress toward a condition that might be unsafe. This is facilitated by control room design and layout in which all controls, instrumentation displays, and alarms required for the safe operation, shutdown, and cooldown of the unit are readily available to the operator in the control room."

Another significant endeavor is to develop a "Guide for the Design of Display

and Control Facilities for Central Control Rooms of Nuclear Generating Stations." This guide is being developed under the auspices of the Power Generation Committee and the Nuclear Power Engineering Committee by a combined Working Group of the Nuclear Power Plant - Control, Protection and Automation Subcommittee and of NPEC SC1.2. This guide, now in draft form, promises a more standardized approach to human factors than has previously been the case.

Section 3

STUDY METHODOLOGY

A multi-pronged technical approach was devised to assess the human factors adequacy of present generation nuclear power plant control rooms. This section of the report describes the methods and tools used to gather the data which are the basis of this report.

SYSTEM FAMILIARIZATION

The Lockheed study team, while well versed in control and display systems for complex underwater, space, and military systems, had little familiarity with nuclear power plant control rooms. This lack of prior involvement provided the study team a degree of objectivity not otherwise possible. However, in order to successfully critique the operational aspects of the control room, some basic knowledge of nuclear systems and utility industry practices was required. The Training Services Division of the NUS Corporation provided for the LMSC team an intensive and specially tailored four-week training program. The systems familiarization program included an overview of the basic categories of nuclear power plants, nuclear and balance of plant subsystems, NRC regulations, operator training programs, quality assurance requirements, characteristics of control room simulators, etc. Formal "classroom" training was supplemented by a one-week familiarization tour of four operational control rooms, a control room simulator, and operator training facilities.

DEVELOPMENT OF THE MEASUREMENT SYSTEM

Methods for investigating the human factors aspects of control rooms were developed or adapted to the specific needs of the study. These approaches were designed to provide a comprehensive and consistent observational framework through which reliable human factors data could be obtained across five different control room simulators and their corresponding operational control rooms. The data-gathering methods employed are described below.

Checklist Guided Observation System

A checklist guided observation system was developed for gathering a comprehensive body of human factors data and to ensure that evaluation points were not overlooked in moving from one evaluation site to another. The checklist, assembled in the format illustrated in Figure 3-1, is 111 pages long and is based largely on MIL-STD-1472A, Human Engineering Design Criteria for Military Systems, Equipment and Facilities. This document embodies most of the design criteria developed for military systems, as well as those extended to space programs. At the present time, comparable human engineering standards for nuclear power systems do not exist. The references provided in Appendix A were also consulted for design criteria not encompassed in the Military Standards. These references are generally unknown within the utility industry and may prove useful to the reader who is interested in delving further into the human factors engineering aspects of hardware design.

The checklist progressed from the general to the specific. For example, a general evaluation point reads as follows: "STANDARDIZATION - are controls, displays, marking, coding, labeling and arrangement schemes uniform for common functions of all equipment?" At the other end of the specificity continium, the checklist includes such items as: "SCALE MARKINGS (METERS) - Do scale graduations progress by 1,2, or 5 units or decimal multiples thereof?"

Major topical areas covered by the checklist include: control-display integration, visual displays, audio warnings and signals, controls, labeling, anthropometry, workspace design requirements, and work environment.

Structured Interviews

The second major approach used to gather human factors data was the structured interview technique. The interview presented 51 questions to control room operators and supervisors, and to instructors associated with nuclear training center control room simulators. The interview covered the following general topics: control room arrangement and environmental factors, manning requirements, control panel design, controls, displays, warning-annunciator system, procedures, training and selection factors, and shift work and overtime effects on performance.

The time taken to administer the interview ranged from 1-1/2 to 5 hours, depending on the depth of response. The average interview required approximately 2-1/2

HUMAN FACTORS ENGINEERING DESIGN CHECKLIST

ITEM

FACILITY_____

CONSOLE(S)/PANEL(S)_____

DEVICE(S)_____

	YES	NO	PHOTO TAKEN	N/A	NEED INFO (SEE NOTE)
42 5.2.2.1.16 Lamp Removal, Method. 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 Lamp Removal, Safety. 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 Indicator Covers. Are legend screen or indicator covers designed to prevent inadvertent interchange? NOTES:_____					
45 5.2.2.1.19 Color Coding. 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 Impending 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:_____					

SHEET____OF____

Fig. 3-1. Sample page of the Checklist Guided Observation System based primarily on MIL-STD-1472A.

hours. In all, 40 operational personnel and 13 trainers were interviewed.

The final questions were reserved for the "Critical Incident" methodology. This technique, which was developed initially for investigating operational problems associated with aircraft pilots, involves the questioning of operators and trainers regarding accidents, or near accidents, and operator errors or near errors. By probing the history of such incidents or near incidents, it was hoped that some meaningful patterns of human factors data would emerge.

A copy of the questionnaire developed for this study is included as Appendix B of this report. The interviewers were successful in establishing rapport with all interviewees with the following basic introduction to the interview:

> "We are doing a study for the Electric Power Research Institute to determine how good present day nuclear power plant control rooms are from an operational standpoint. The purpose of the study is to determine what groundrules should be used in designing control rooms for future generations of nuclear power plants. Perhaps the best source of information in terms of improving control room designs and avoiding the mistakes of the past is to talk directly to the people who have to operate control rooms on a day-to-day basis. That is why we have asked for this interview with you.
>
> "Let's pretend that you are talking with the man who was responsible for the design of your control room. He is about to embark on the design of another generation of control rooms and he wants your frank advice. What guidance would you give him? I'm going to ask you a number of questions to help me design a control station that takes into consideration the needs of the operator for the most effective possible operation of the future control room."

Direct Observation of Operator Behavior

The study team had ample opportunities to observe directly operator behavior in the control room and in simulated control rooms during requalification training programs. Such observations included: operator response to annunciator alarms, ease of reach of controls, the necessity for the operator to leave the primary control area, the impact of nonoperator personnel in the control room, the nature of the interaction between two operators working as a team, etc.

Task Analysis - Procedure Evaluation

This part of the study reviewed in detail one representative task in order to

evaluate how well the control room design and documented procedures met the needs of the operator in the performance of his tasks. Several candidate procedures and task analysis techniques were considered at the pilot study. The selected task was a response to a steam generator tube rupture for PWR plants and a vessel feedwater regulating valve failure for the BWR plant.

Specific elements of the task sequence were obtained by witnessing simulations and by a detailed review of procedures with cognizant operational personnel aided by the NUS representative. The content, chronology, and clarity of written procedures were compared with the documented task sequence. Relevant portions of checklists and instructional material developed earlier for military applications served as aids in this evaluation.

The format selected for the task analysis is known as the Operational Sequence Diagram (OSD). An example of the OSD is shown by Figure 3-2. The advantage of this format is its flexibility in the selection of control room points (columns) and in the capability of logging virtually all relevant and concurrent events, e.g., conversation, physical movement, decision points, panel response, etc. Depending on the problems uncovered, different supplemental tools were used, such as correlation and adjacency diagrams, summary tables of display and control evaluations, and walking or visual path diagrams to evaluate control room layout and panel arrangements.

Analyses of Historical Records of Operational Problems

Another data gathering approach was to investigate the history of operational problems at a given plant. The starting point was the incidents pertaining to a specific plant as reported in Nuclear Power Experience (22). These events were discussed with operational personnel. This investigation related actual operational problems or errors to control room design features, procedures, and training deficiencies.

Physical Measurement

Control rooms were carefully measured and scaled layouts were produced for each plant. These layouts were compared and analyzed for such factors as operational walking distances, viewing distances, arrangement of panels, traffic paths and visual paths. Dimensions and arrangement of furniture and consoles were noted and examined against similar criteria, stressing anthropometric considerations.

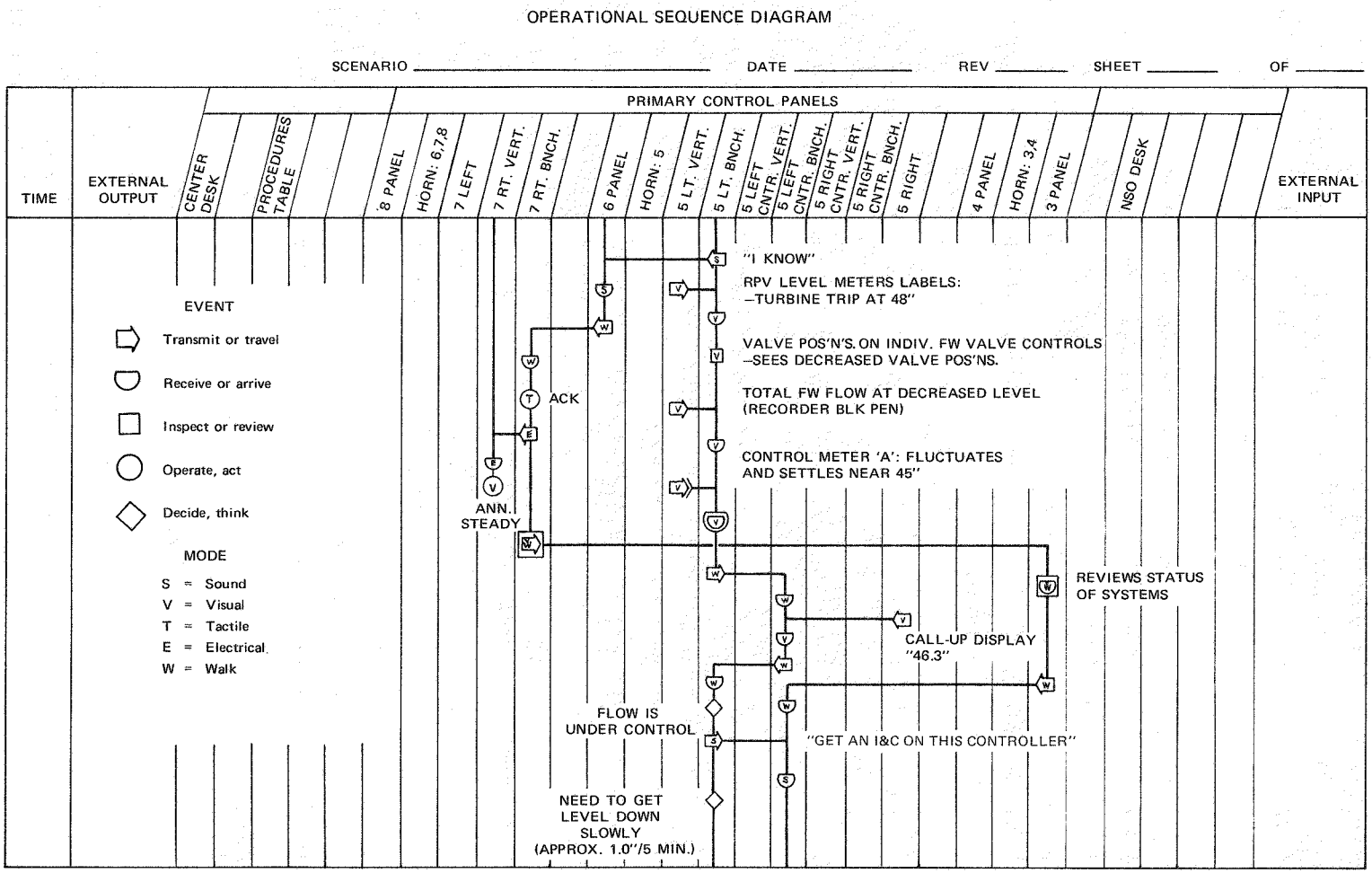


Fig. 3-2. Operation Sequence Diagram (OSD) format

The scaled layouts also provided a reference base for operator interview comments and as a tool in the task analysis.

Other measurements made were detailed dimensions of controls and displays and illumination levels. These were made as an integral part of the checklist described above.

A comprehensive photographic record was made of control rooms, panel elements, and selected control board features. As appropriate, operators and study team members were posed to illustrate specific problems of visual access, control reach, etc. A file of photographs was thus developed for later reference and analysis.

PILOT STUDY

The first of the five simulators and corresponding operational plant visited served as the pilot study site. The pilot test program was conducted to evaluate and "debug" the test and measurement approach described above. The study team conducted the pilot study over a two-week period in early October 1975.

Based on the pilot study data, the measurement tools were refined for application to the main segment of the study. For example, unproductive questions in the initial draft of the structured interview were deleted. Other questions were rephrased when ambiguities surfaced. Selection between alternate formats for the task analyses was made based on the pilot study results. The pilot study data were analyzed and provided assurance that the methods adopted for this study were appropriate and would be productive.

MAIN STUDY

The study team proceeded with the main portion of the study, spending one week for data gathering purposes at four additional simulators and their corresponding operational control rooms. This portion of the study was conducted between November 1975 and February 1976. The study teams visiting each site consisted of two or more LMSC researchers and one NUS nuclear training specialist with extensive operational experience.

In addition to the human factors evaluations of the five present generation control room configurations, the study team attempted to obtain some insights

regarding trends in control room design. Discussions were arranged with advanced design personnel from the following companies: Combustion Engineering, Windsor, Conn.; General Electric, San Jose, CA; Babcock and Wilcox, Lynchburg, VA; Bechtel, San Francisco, CA; and Westinghouse, Pittsburg, PA.

We have investigated general human factors engineering concerns and potential improvement areas, rather than offered specific criticisms of any one plant or design. Therefore, the data in this report is not identified with regard to the specific plants or simulators where observations were made or data was gathered. In the course of this report, the five designs reviewed will be designated "A" through "E." However, these letter designations vary from section to section.

Section 4

CONTROL ROOM DESIGN

This section considers the size and arrangements of control rooms and the impact of these factors on the man-equipment interface. The arrangement of control consoles, both primary and secondary, are reviewed for the five plants visited. The relationship between the control room layout and the required number of operators is examined. Single and multiple-unit control rooms are compared. Also discussed are the integration into the control room complex of such areas as the watch supervisor's station, rest rooms, kitchen facilities, and provisions for plant visitors. Finally, environmental factors are reviewed, including temperature, humidity, ventilation, noise, illumination, and decor.

CONTROL ROOM SIZE

The size and shape of the control room are related to the configuration of the control boards and the distribution of control-display elements with respect to the operator's station. Control room size and shape also affect the distribution of consoles and traffic patterns and should be based on an analysis of operator functions and tasks relating to the hardware required in the room. The variability of sizes and shapes observed suggests that the operator and his equipment were adapted to fit an initial space allocation rather than evolving from a design based on human factors requirements.

Figures 4-1 to 4-10 are sketches and photographs of the five control rooms investigated. These control rooms are designated "A" through "E." A number of measures were taken in an attempt to examine size factors as follows:

- Operational panel area. The area of panels actually containing displays and controls (i.e., unused, blank panel space was not included).
- Maximum viewing distance from desk. The distance from the operator's desk position to the farthest display area of the operating panels.

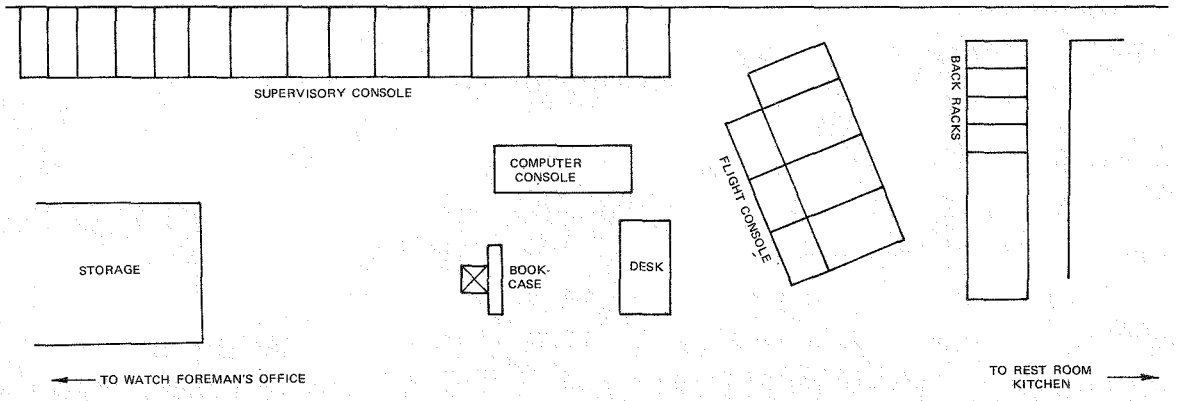


Fig. 4-1. Unit #2 of the Plant A control room. This two-unit control room houses two L-shaped control boards. Each unit is manned by two operators.

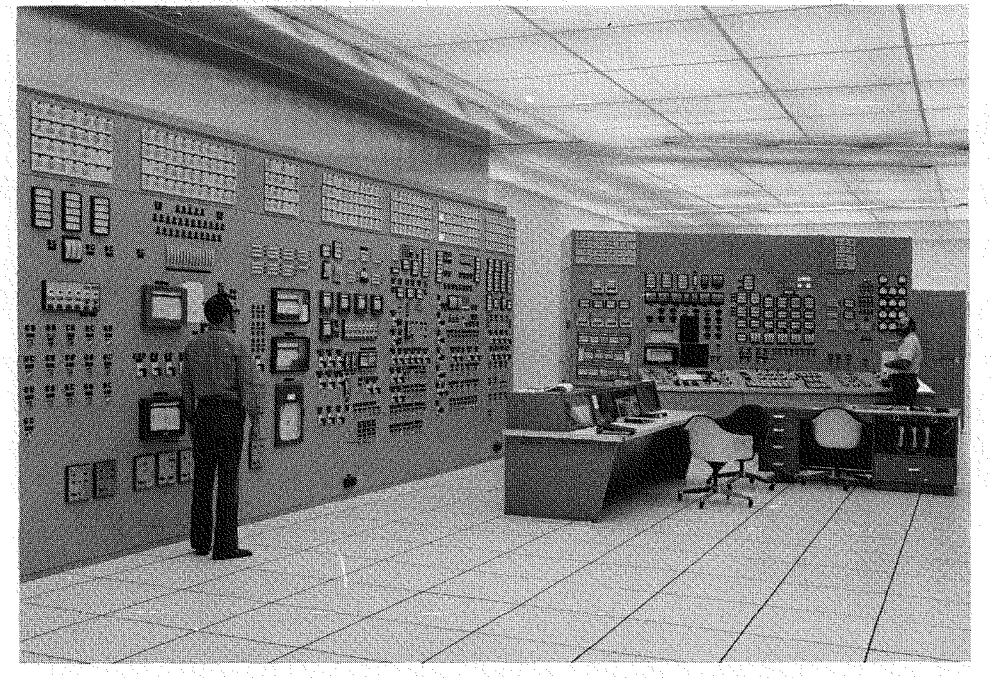


Fig. 4-2. Plant A control room arrangement as reflected in the corresponding simulator. Approximately half of the Supervisory console to the left is shown.

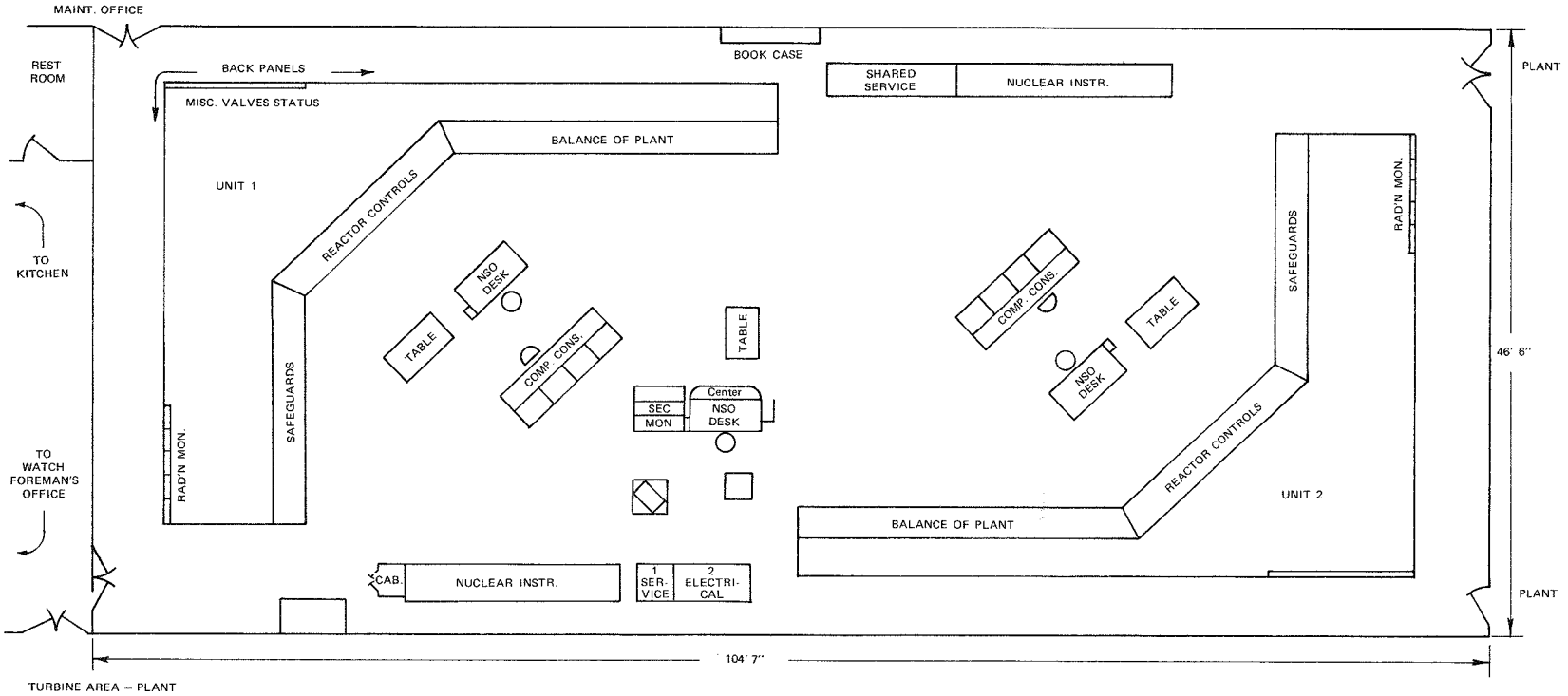


Fig. 4-3. Layout of Plant B control room. This control room houses two wing-shaped control boards. It is manned by one operator at each control board and a center desk operator.

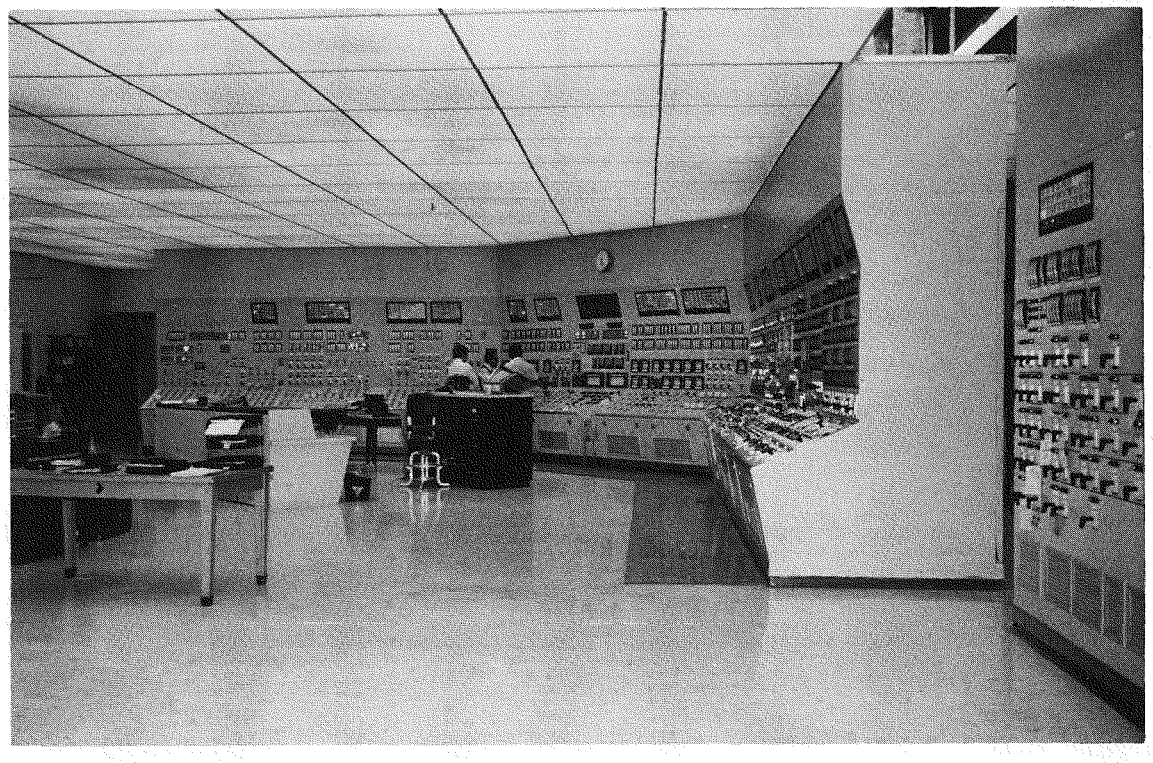


Fig. 4-4. Unit #1 of Plant B control boards.

- Maximum walking distance. The distance between the two most distant control points in the operational area.
- Gross floor area. An approximation was made of the total floor area enclosed by the operational control boards. This describes the area in which the operator must remain while on duty, short of any back-panel trips.
- Open floor area. The gross floor area is partially taken up by bookcases, desks and similar obstructions and furniture. This lost floor space was subtracted from the gross floor area to obtain an "open" floor area.

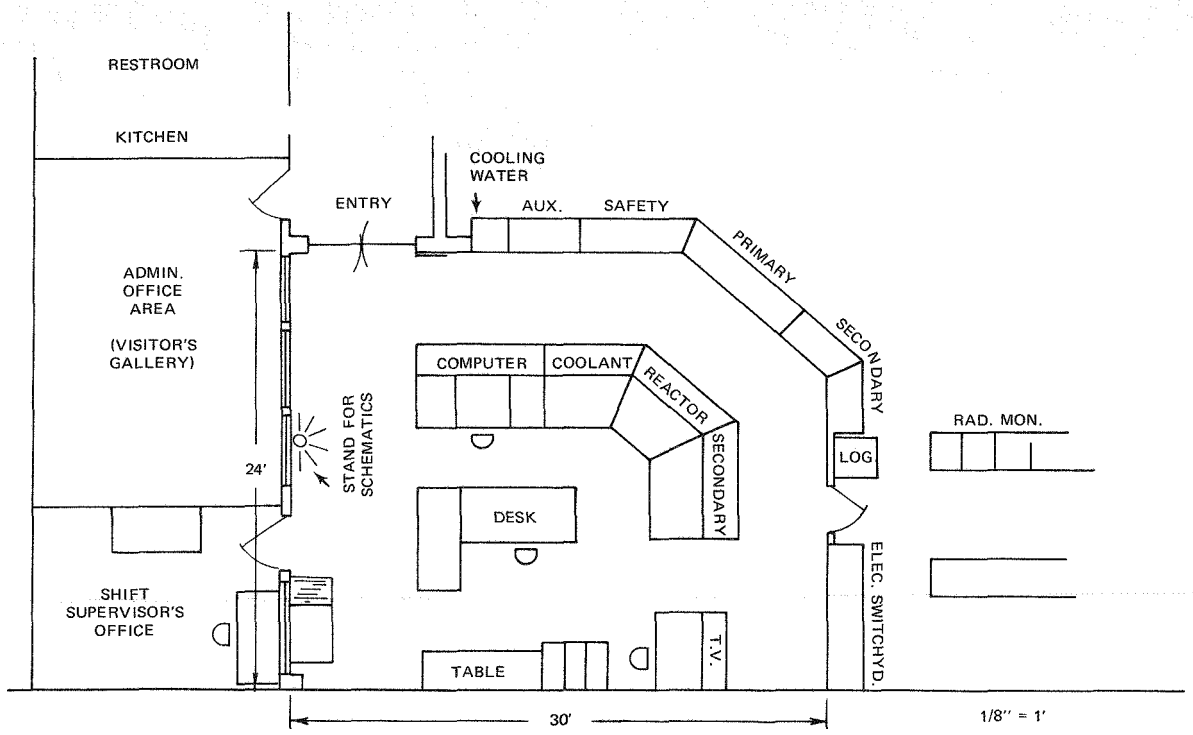


Fig. 4-5. Layout of the Plant C control room. This single unit room has an inner and an outer arrangement of control boards. It is normally operated by two operators. The radiation monitoring equipment to the right is considered an extension to the control room.

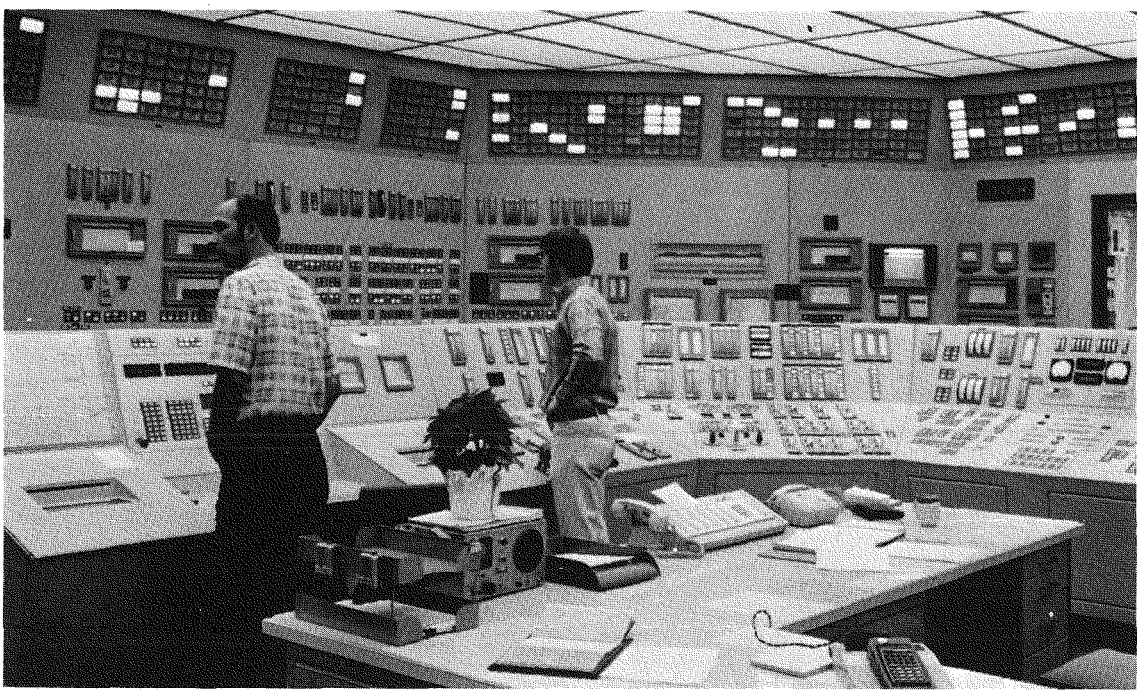


Fig. 4-6. Plant C control room.

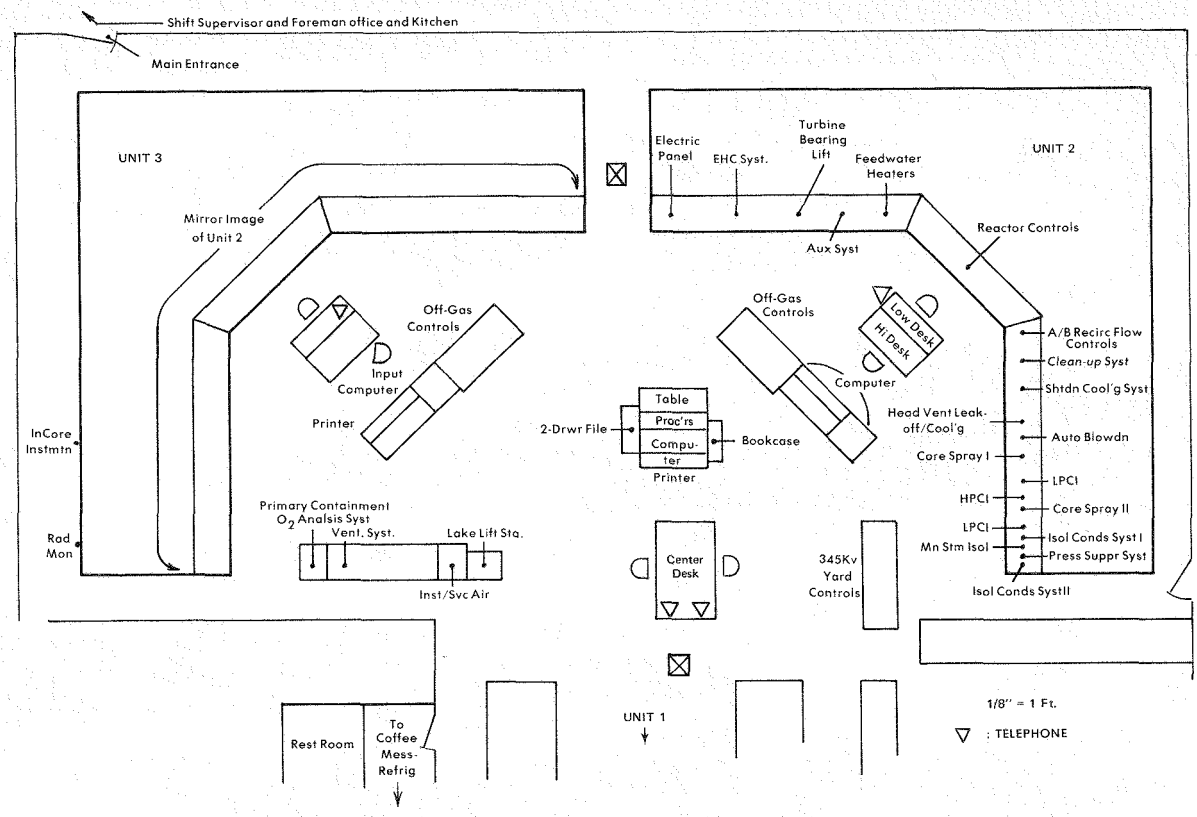


Fig. 4-7. Arrangement of the Plant D control room which houses three generating unit control boards; two wing-shaped and one U-shaped. This room is manned by four operators; one for each unit plus a center desk man.

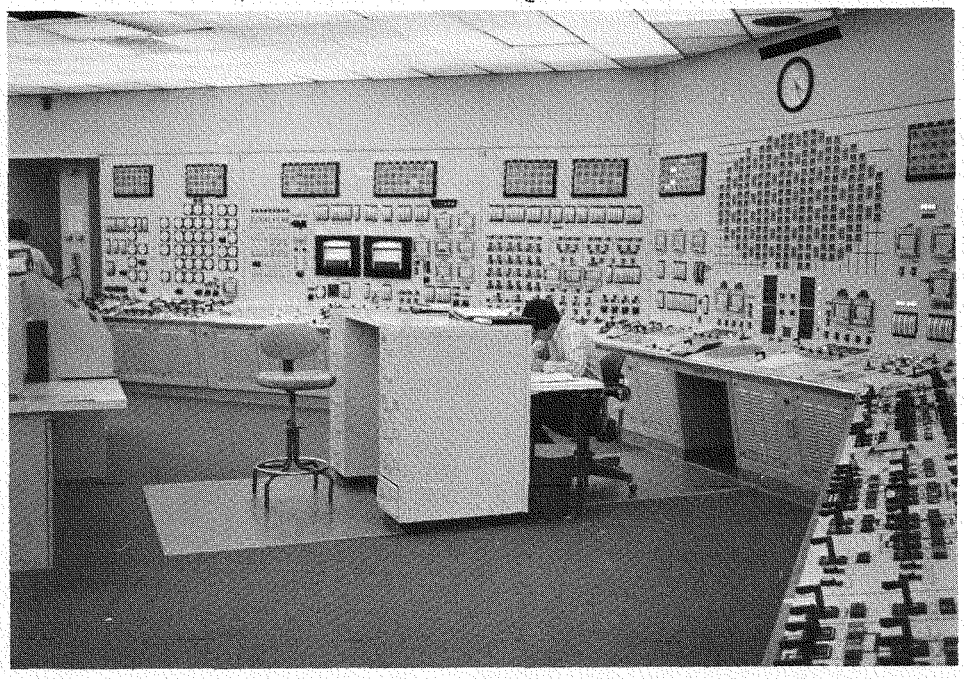


Fig. 4-8. Unit #2 of the three unit Plant D control room.

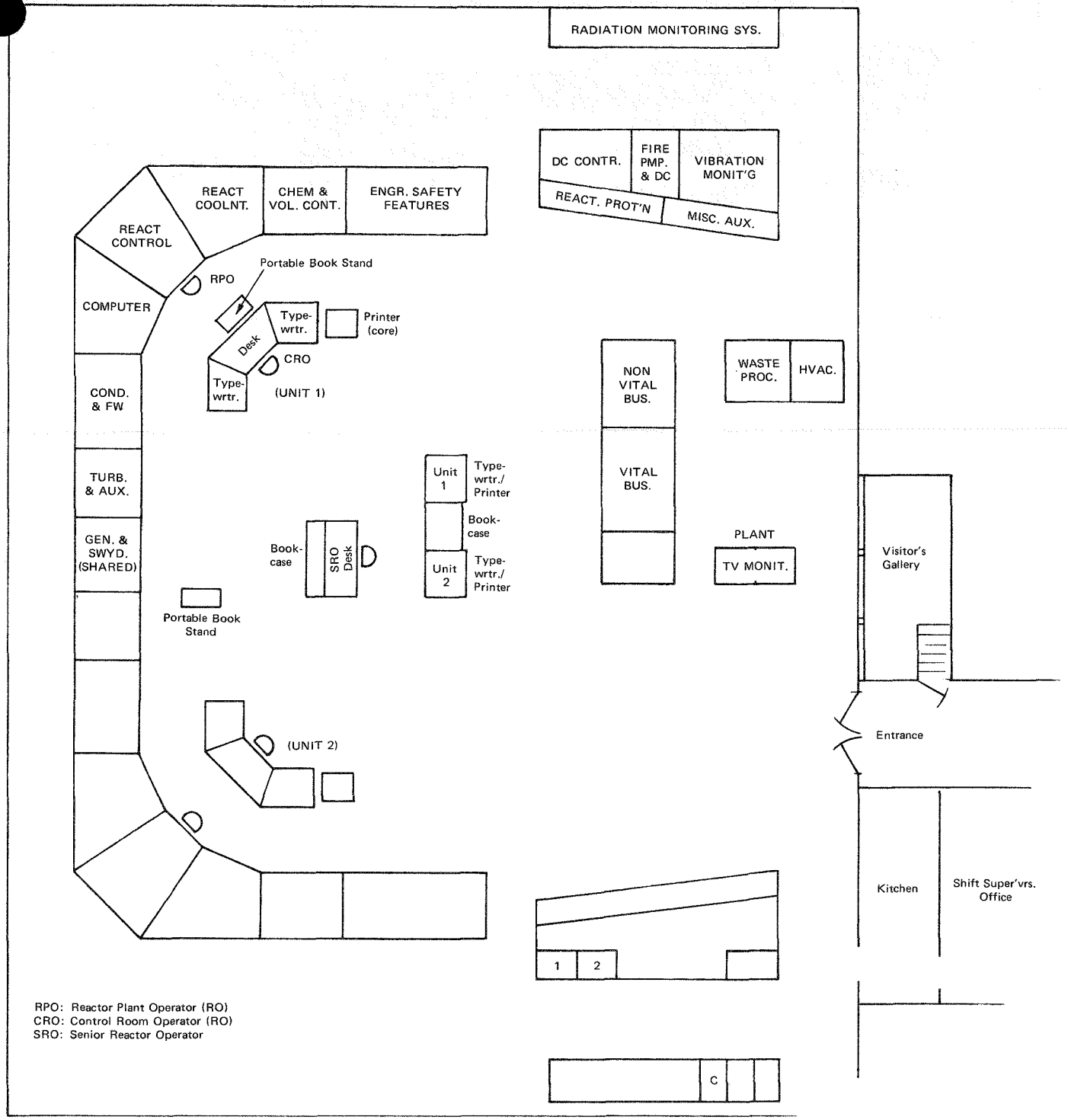


Fig. 4-9. Layout of the control room for Plant E. This room houses two mirror-imaged wing-shaped control boards; one operational and one under construction. It is presently manned by three operators. When Unit #2 is completed, five operators will man this room; two operators for each unit and a centrally located SRO.

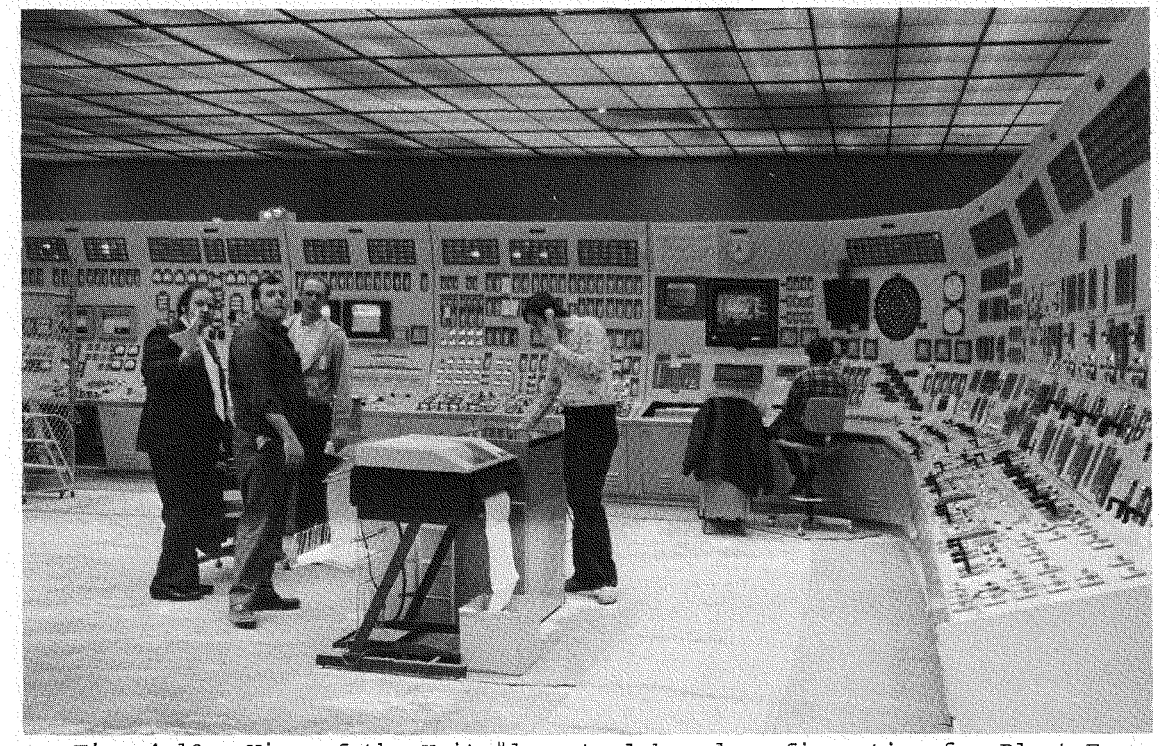


Fig. 4-10. View of the Unit #1 control board configuration for Plant E.

Table 4-1 summarizes the control room measurement data. The five control rooms are ranked from "1" to "5" with "1" representing the smallest and "5" the largest dimension.

Table 4-1

CONTROL ROOM DIMENSIONS

MEASURE	PLANT					RANGE
	A	B	C	D	E	
Operational Panel Area	2	5	1	3	4	318 - 651 ft.^{2}
Maximum Viewing Distance from Desk	5	3	1	2	4	19 - 36 ft.
Maximum Walking Distance	5	3	1	2	4	32 - 57 ft.
Gross Floor Area	3	5	2	1	4	624 - 1184 ft.^{2}
Open Floor Area	3	5	1	2	4	370 - 1061 ft.^{2}

A majority of our sample (58.5%) felt that their control rooms were too large. Some interesting findings emerged from an analysis of the responses of operators on a plant-by-plant basis. Perception of control room size is definitely related to the arrangement of the control board, not simply to the size of the room. If we rank the degree of dissatisfaction with excessive control room size on a plant-by-plant basis, there is a perfect correlation in rankings with two factors provided in Table 4-1: maximum viewing distance from the operator's desk and maximum walking distance from one end of the control board to the other. For example, Plant A, while only the second largest control room in terms of control board area, engendered dissatisfaction from 100% of the interviewees, primarily because of the unwieldy L-shaped configuration. Similarly, Plant B, which was the largest room, ranked in the middle of all five plants in terms of dissatisfaction over excessive size because the wing-shaped boards allow a better operator/control board interface than the L-shaped boards.

A more subtle factor that affects the operator's conception of control room size is the frequency and extent of walking required. This is the result of panel arrangements and locations of panel elements. Ten feet can become a long distance when it must be traversed several times in the performance of one operation. This factor is best described by the response of operators when asked about control room size. Statements frequently alluded to the need for roller skates, too much searching and running, the scattering of panels, and the placement of panels in the backracks instead of out front. These were all offered as elaborations as to why the control room was too large.

The majority of operators indicated that there was excessive traffic in the control room and felt that a large control room "invites" traffic. Obviously, there are other factors to consider such as plant administrative policy and the location of the control room within the plant. But the two largest floor area plants had the greatest number of complaints regarding excessive traffic.

CONTROL BOARD CONFIGURATION

As indicated above, the configuration of the control boards is more important than the absolute size of the control room. Plants A and C vie for the distinction of being least effective in terms of operator interaction. Plant A, an L-shaped, has a 46-foot "supervisory" board and a 15-foot "flight" console. Plant C, the smallest control board, separates functionally related inner primary consoles from rear wall-mounted consoles. The remaining three plants have "winged" arrangements,

symmetrically placed around a centrally located reactor or primary control board and the operator's station. In our view and that of the operators and trainers, this "winged" arrangement minimizes viewing and walking distances.

Four of the plants studied are multi-unit control rooms. Three of them provide a central desk position for a back-up man or supervisor. The configuration is therefore designed to provide visual, acoustic, and walking access to the two or more units from the central desk. The operators complain of any obstructions to a straight-line walking route or visual access between the center desk station and the control boards. Consoles that are added to the control room often constitute such obstructions (see Figure 4-11). As one operator put it: "There are too many obstructions. No matter where you want to go, there's something in the way!"

MANNING AND CONTROL BOARD CONFIGURATION

The configuration of the control boards and the number of operators required are related. This relationship is important because operator salaries and training costs are expensive. In examining manpower requirements, we considered the technical specifications governing plant operation, the usual plant practices in manning the control room, and the attitudes of operators regarding manning required for normal or routine operations as well as special demands imposed by such operations as startup.

The five plants are manned as follows:

Plant A

This two-unit control room houses two L-shaped boards with two operators assigned to each board. The technical specifications require one man per board, but the plant practice is to provide two. The operators interviewed feel that a minimum of two operators is needed to operate each control board during normal operations. During the startup or other off-normal situations, three operators are seen as necessary.

Plant B

This two-unit control room is generally manned by three operators; one per wing-shaped unit plus a center desk operator available to relieve or assist the operators assigned to the two units. This practice coincides with technical specification requirements. The operators feel that this manning level is



Fig. 4-11. Physical obstructions between the center desk operator's station in the foreground and the control boards.

adequate for normal operations. An additional operator is seen as needed for off-normal situations. The ratio of operators to units for normal operation is 1-1/2 men per unit as opposed to the 2 men per unit required at plant A.

Plant C

This single-unit control room generally has two operators available with the exception of occasional back shifts. The control boards are divided into a primary, inner console supplemented by an outer, wall-mounted, secondary board area. Technical specifications require only one operator, but this is seen as inadequate by the operators and plant management so two are generally employed. Casualty mode operations are seen as requiring either two, three, or four operators in the room depending on the casualty or individual opinion on this matter. In any case, there was general agreement that at least two operators are required normally.

Plant D

This control room houses three unit control boards; two wing-shaped and an older U-shaped control board. Technical specifications require four men in the control room at all times, one for each unit plus a man located at the cener desk station. The plant uses this manning level. The operators feel that one operator per unit is normally adequate. However, several feel that a single center desk operator to relieve and assist three units is inadequate, and suggest that two center desk operators would be more appropriate. The operators also feel the need for a fifth man during off normal operations. The ratio of operators to generation units is 1-1/3 men per unit, the most economical ratio of the five plants visited.

Plant E

This two-unit control room has two wing-shaped control boards; one operational and the other in the final stages of construction. Tech specs required one RO at each unit and a centrally placed SRO. The plant practice is to assign two ROs to a unit in a unique fashion. One RO is stationed directly in front of the reactor control panel and the associated CVCS panel (see figure 4-12). The second operator is responsible for all other systems. The operators report that this plant finds it cost-effective to charge one operator with sole responsibility for the reactor control. He is responsible for holding power steady at plus or minus 0.5% by "fine-tuning" the CVCS system and operating with the rods full-out. Automation of this function is planned. With five men in the control room to



Fig. 4-12. At Plant E one operator is stationed at the Reactor Panel to maximize power output.

manage two units, the operators feel that there is sufficient manpower to cope with both normal and emergency operations.

The manning practices described above lead us to conclude that of the alternatives examined the most cost-effective manpower utilization occurs in multi-unit control rooms with wing-shaped control boards. At these plants the ratio of men to units is between 1-1/3 to 1-1/2 for each generation unit. Plant E is an exception, not as a result of configuration, but rather because of a temporary trade-off between additional manpower and higher power output.

The two most unwieldy control boards (Plants A and C) have the worst manpower/unit ratio, two operators per unit despite tech spec requirements of one operator per unit for normal operations. This points up the operator effectiveness and economic importance of control board and control room configuration factors. It also raises an important question as to the basis used in formulating manning tech spec requirements when existing requirements are clearly perceived by the utilities and the operators as insufficient for adequate control room

operations.

The human factors approach to defining manpower requirements for a given system can take two forms. During the conceptual development phase of a given system the designers can start with an assumption or specification that a two-man crew, for example, will be required and then shape a workspace envelope on this basis. The other approach is to define the functions and tasks imposed by a given system and then develop an optimal manning concept based on system requirements, level of automation, available space, etc. Neither of these approaches appears to have been used to establish control room manning requirements or to define technical specifications for control room manning levels.

BACK PANELS

At each of the plants visited, controls and instrumentation were placed in areas outside the primary control room area or outside the operator's line of sight. Such panel areas are called "back panels" as shown in the schematics presented earlier in this section. Some back panels are located directly behind the primary boards, some are in racks in a remote area of the control room, and at one plant there were panels across a corridor in a separate room altogether. Without excpeption, operators at all plants complained that display and control access was required during off-normal and normal operations.

The procedure sample for task analysis at PWRs was the response to a leak or rupture in a steam generator tube during which at least one radiation alarm occurs. A common alarm annunciator alert occurs in the operational area. The operator must go to the back panel area to check the radiation monitor panels to determine which radiation monitor or sensor location has exceeded a set point. Thus the operator must leave the primary operational area. Depending on the plant and specific circumstances, additional radiation alarms and trips may occur. In order to diagnose the problem and also to control the plant, several other displays and controls within the primary area are required. Radiation monitor trend information is useful to the operator, but retrieval of this information takes time. Policies and manning vary across plants, but in all cases there are times during which only one operator is available. NRC Regulatory Guide 1.114 allows an operator to "momentarily" leave the control area to verify alarms as long as he remains within the confines of the control room. Another Regulatory Guide, 1.97, states that accident surveillance

displays "--should be arranged to simplify the operator's surveillance, interpretation, and response determination following an accident signal." The stipulation of the second guide does not appear to be satisfied, despite the permission given by the first, in the area of radiation monitoring.

Speedy, accurate diagnosis and control response are important in any off-normal event but are especially important when release of radiation is concerned. It is understood that a "moderate controllable" leak into the steam generator need not result in reactor trip (scram) if quickly diagnosed and brought under control. A graduated and less costly shutdown can then be accomplished, allowing loop isolation and management options. Any delays caused by the need for an operator to leave the primary control area are inefficient. Figure 4-13 depicts the traffic flow path of an operator responding to the analyzed task at Plant C. The contrast between the well-grouped functions in the primary area and the placement of the radiation monitoring panels is obvious. This represents time lost and time away from the crucial area of operation. Figure 4-14 shows the same task response movements of two operators at another plant. Not only is there more movement in the primary control area, but both operators acknowledge at separate times an alarm at "A," then walk to "B," the radiation monitoring panels. Figure 4-15 shows the same operation with the primary operator assisted by the center desk man. The complex pattern of motion is compounded by the remote placement of the radiation monitoring panels. The radiation monitoring panels are only one example of back-panel problems that divert the operator from his primary sphere of attention and control. Others are discussed later in this report.

OPERATOR STATIONS AND FURNISHINGS

Various support consoles and items of furniture are located in the control rooms. These include desks for the operators, storage facilities for spare parts, file cabinets and shelves, communications gear, computers and associated printout devices, and in one case, a stand to hold plant schematics. The manner in which these items are integrated into the control room can markedly influence the operator's relationship to the control boards. Each plant had a unique arrangement. For example, Figure 4-16 shows an excellent means for displaying plant schematics. This stand permits easy access to the prints and the operators can mark the encased prints with crayon and maintain cognizance of sub-systems under repair. Figure 4-17 shows an operator's desk with built-in provisions for storing

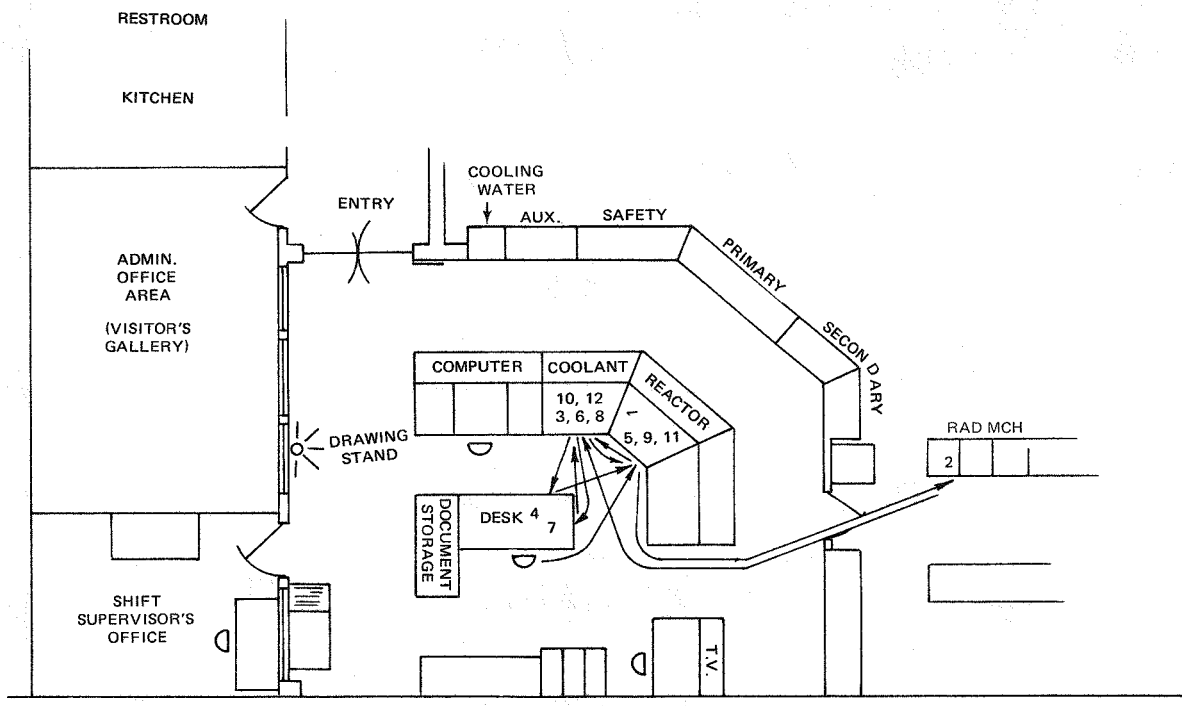


Fig. 4-13. Traffic flow paths for a single operator in responding to a steam generator tube rupture prior to shut-down initiation. The numbers represent the sequence of steps taken.

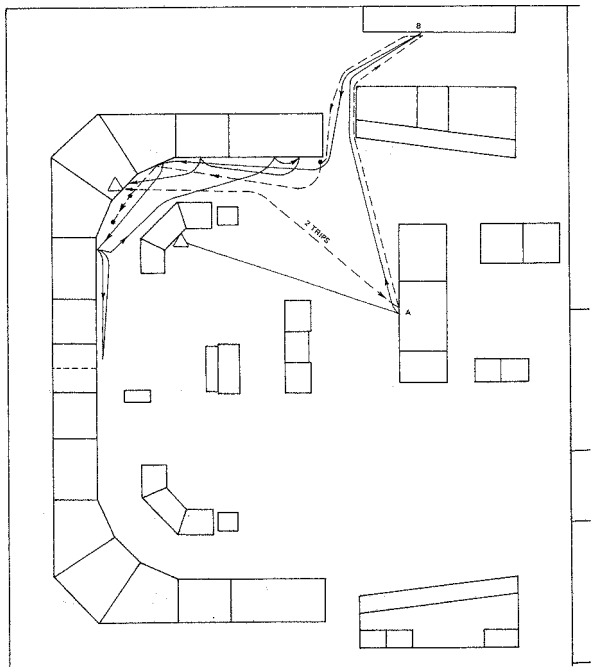


Fig. 4-14. Traffic paths of two operators (one solid line and the other dashed line) in response to a steam generator tube rupture.

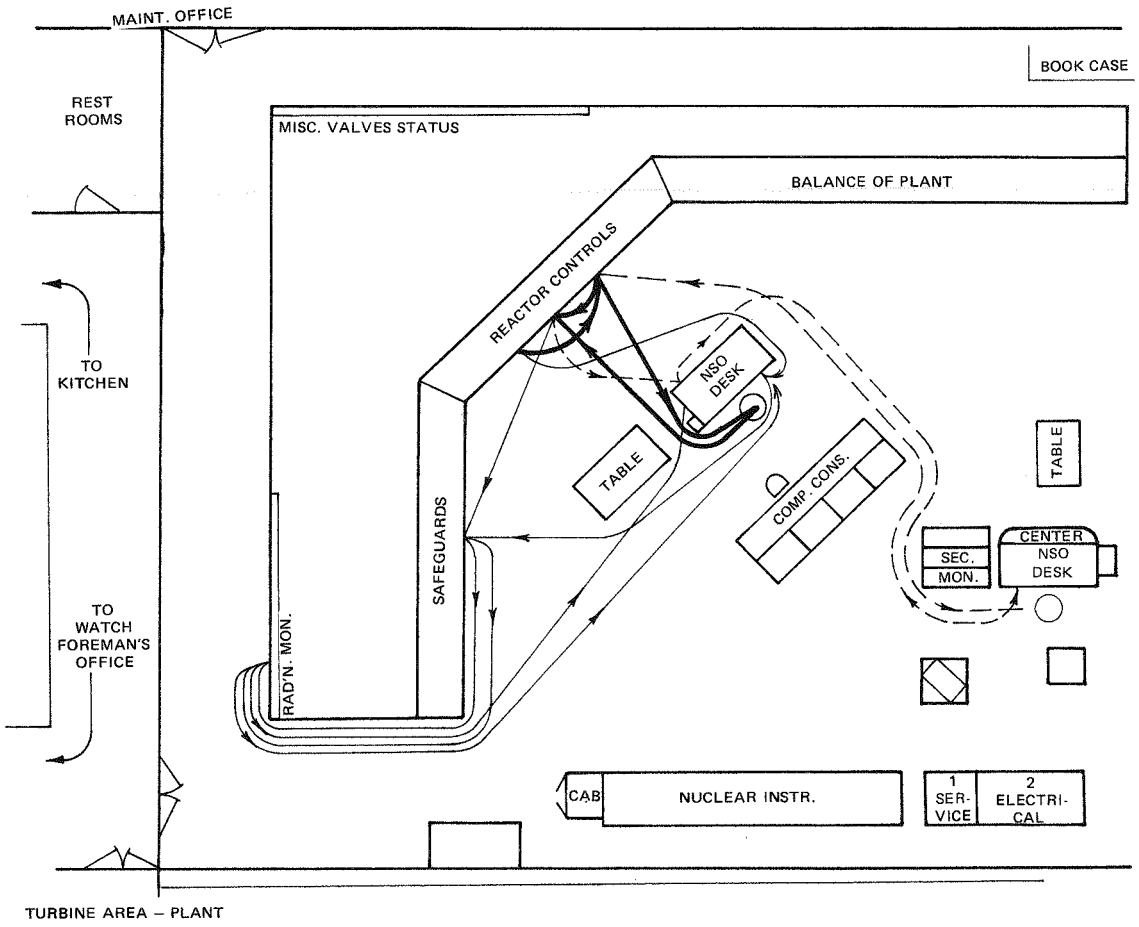


Fig. 4-15. Traffic flow of operators in response to a steam generator tube leak at a third plant. Darkened lines show repeated traverses. Again note the movement away from the primary control board area to the back panels.

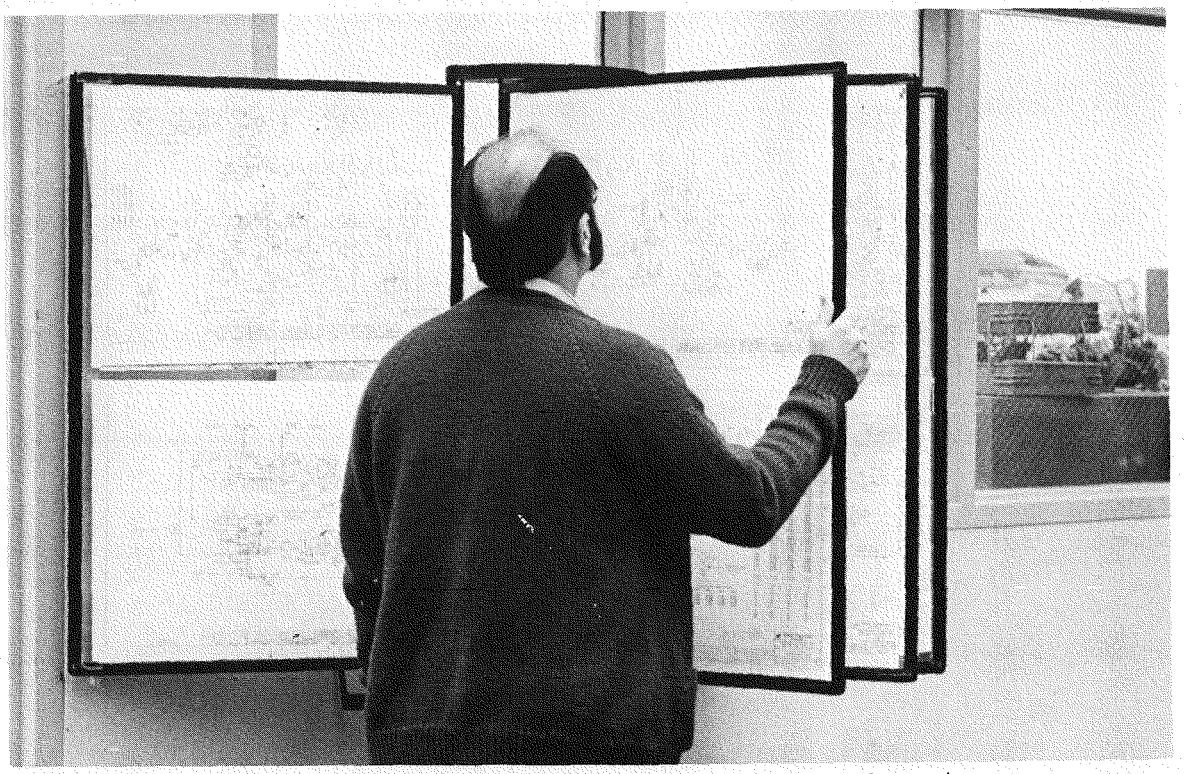


Fig. 4-16. A handy device for displaying plant schematics

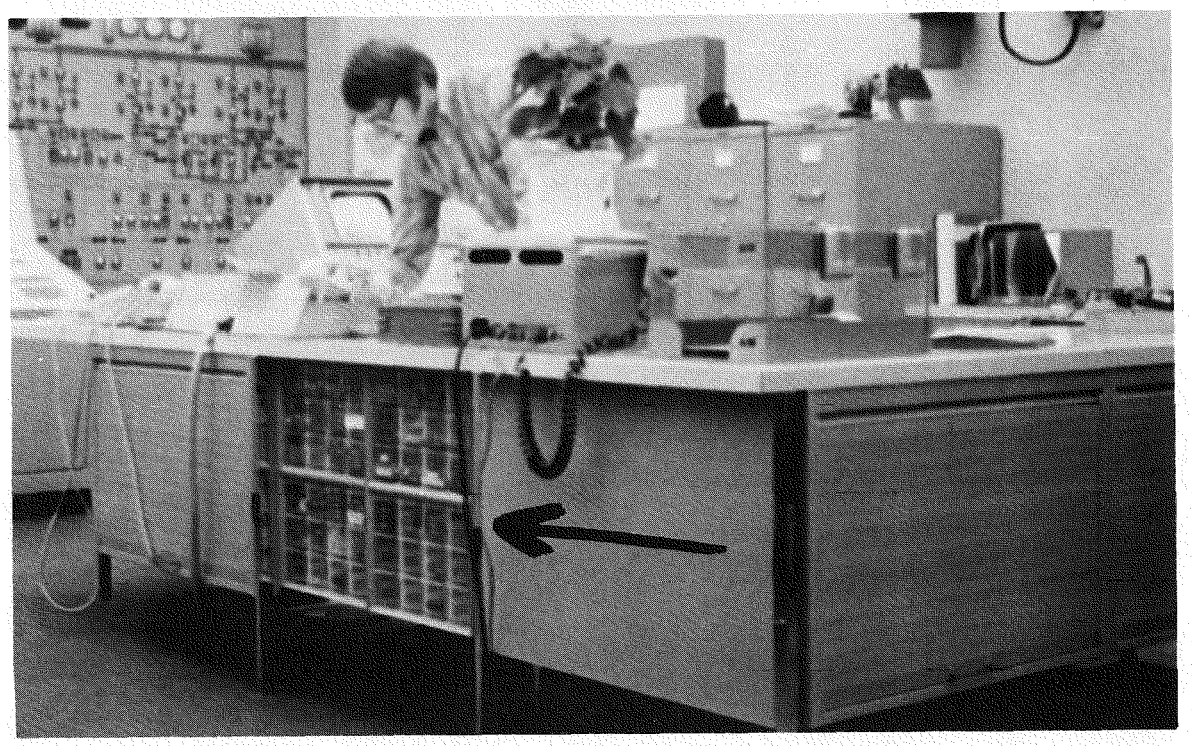


Fig. 4-17. Operator's desk with good storage provisions for spare indicator lamps, etc.

indicator lamps and other spares.

Some problems uncovered with the arrangement of operator stations are revealed by the following operator comments:

- The computer console obstructs freedom of movement to the panels from the operator's chair and also between panel board locations. It further obstructs visibility of lower panel areas from the operator's chair.
- The computer console faces away from the panels. It should be turned around to allow the operator to face panels while he's using it.
- The operator must walk around the desk to gain access to the computer. This is cumbersome and tiring.
- There are two face-to-face desks. The one facing away from the panels has the telephone. We should face the panels but then we can't reach the phone, so we sit by the phone with our backs to the panels.
- We do a lot of paperwork and reading, so we sit at the desk, but then we must walk around it to get to the console, then walk around the console to get to the panel boards. We can't really see the panels to monitor. We can only see alarms from the desk.
- If we face the panels, the desk gets in the way; if we turn the desk around, our backs are to the panels.
- The desk is too high. There's no way to get comfortable on a stool and it's a problem looking over the desk.
- Phone locations are awkward; accessible only from the front of the desk--away from the panels; or very low on the side of the desk, requring stooping to dial. Phone cord lines are a hazard at one location.
- We need someplace at the panels to lay our procedures down. (Procedures were sometimes remote from the panel area, in an enclosed cabinet, or on a centrally located table).

All of the problems noted with the layout of operator stations could have been avoided had mockup evaluations been made during the design phase of the control room development. These problems are by no means insuperable at this time and could easily be corrected with a minimal expenditure of resources.

THE SUPERVISOR'S OFFICE

At times, an operator must call on his supervisor or foreman for immediate assistance. The layout sketches show that in most plants, the watch supervisor's office is remote from the operational control room. This requires the operator to utilize the telephone or page system to call his supervisor. If he is urgently occupied with control tasks, he must forego the call unless someone else can make it for him.

Also, the supervisor may not be immediately available. The supervisor's trip from his office plus the call represent a delay about which operators at four plants complained. The exception to this situation is at Plant C. At this plant, the supervisor's office is adjacent to the control room, separated only by a large window and a usually opened door. With the open door, the supervisor can hear all alarms and voice calls, while otherwise attending to his normal duties. Figure 4-18 is a photograph of this installation. It can be seen that the supervisor is given the option of privacy while still able to monitor control room activities and to respond to any calls for assistance without delay. All operators at this plant expressed strong satisfaction with this design and some cited cases to confirm the advantages of this arrangement.

RESTROOMS

Locations of these facilities are indicated on the layout sketches. There were two prevailing complaints among operators: inadequate number of toilet stalls and lack of an audible page within the restroom. At each of the five plants, there is only one toilet stall. This is a very real problem in that during the resultant delays the control room generally is left without a backup man. In multi-unit plants when a center desk operator is relieving one unit, the other units are also left without a back-up man. Most operators feel that a minimum of two men are required for effective casualty mode operations that may occur at any time. At three of the plants, large groups of non-operator personnel share the restroom during day shifts. As many as 20 or 30 people use toilets originally intended solely for the operators. Delays are inevitable. The problem was avoided at one plant by the issuance of card keys for entry into the locked control room restroom.

The other, perhaps more serious problem, is that at four of the plants, the page cannot be heard or understood in the toilet. At two of these plants, the restroom is very close to the control room, but out of voice call distance. Someone, therefore, must come to the door to summon the operator. With manpower limited and the situation urgent, the problem is obvious. The problem is compounded by the delay in obtaining the assistance of the watch supervisor when his office is remotely located from the control room.

KITCHEN

A lunch break is not scheduled at the plants visited and this apparently is the practice at most, if not all, plants. This means temporary relief at the controls

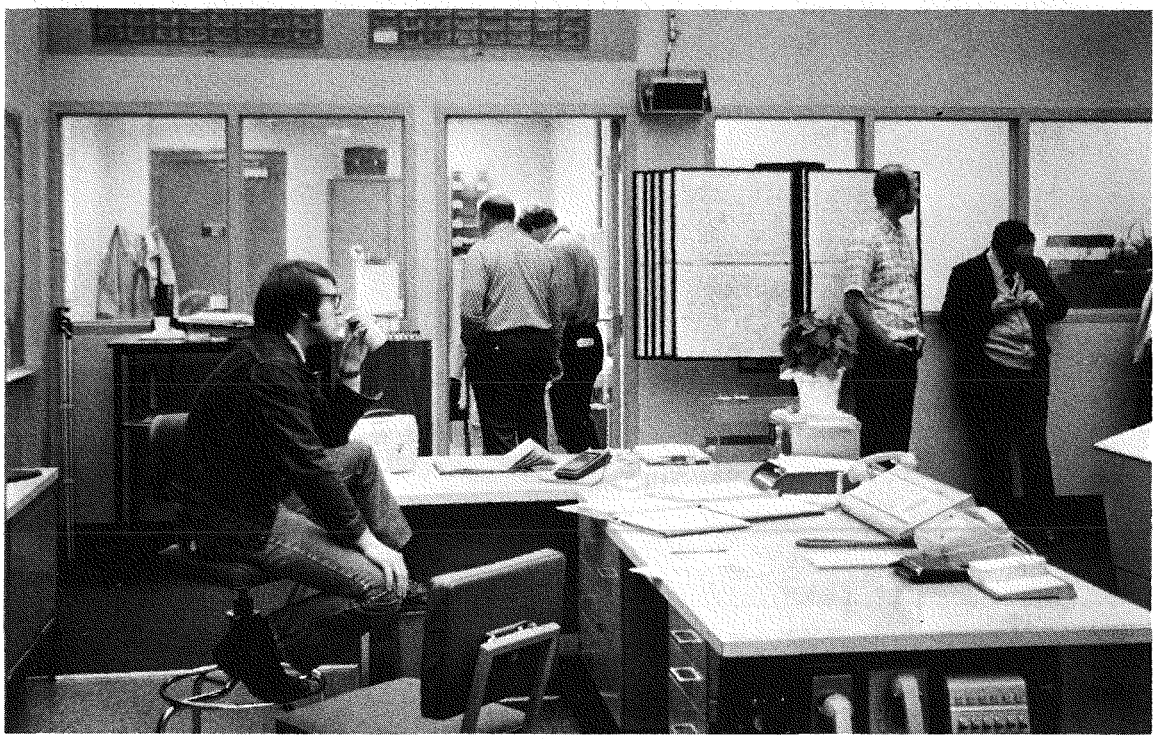


Fig. 4-18. Operator's desk in the foreground and the supervisor's office in the background on the left. The windowed area in the right background was originally intended as a visitor's observation room.

is required for the operator to use the kitchen where an inaudible page was found at most plants. Kitchen provisions and locations varied (see Figures 4-19 and 4-20). The most remote kitchen had an audible page but was possibly one minute away. The closest kitchen was out of normal voice call range and had no page speaker. At this plant an operator noted the need on one occasion to "scream his head off" to be heard by the missing operator. At another plant the kitchen is a lunch room and gathering place for all personnel on the floor and, at peak hours, access even to the refrigerator is difficult. The card key plant again effectively employs this technique for kitchen access, and operators are pleased with the privacy. A microwave oven is installed in that kitchen, purchased by the operators. Such an investment and personalization of the facility is not likely in a plant where virtually anyone will be using it.

VISITOR'S GALLERY

Distractions from out-of-plant visitors was not generally seen as a major problem. However, comments were made at all plants by some operators, indicating this is sometimes a problem. The more prevalent complaint was excessive plant personnel

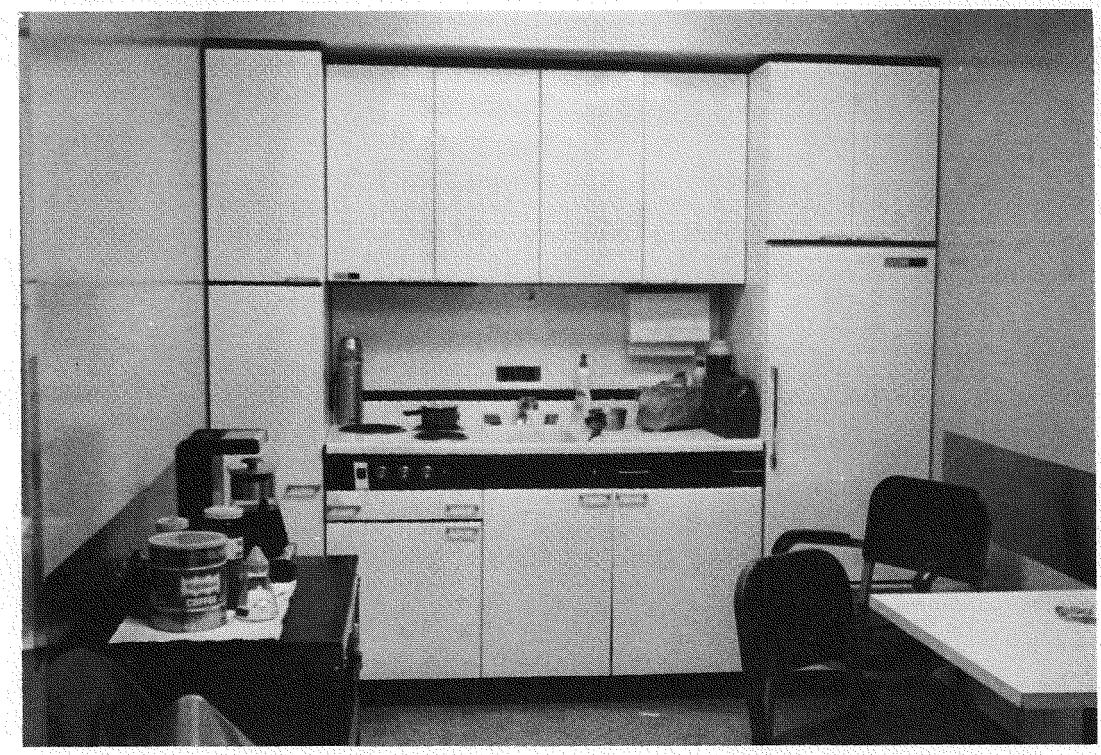


Fig. 4-19. This kitchen was intended for the operators but is used by many nonoperational personnel.

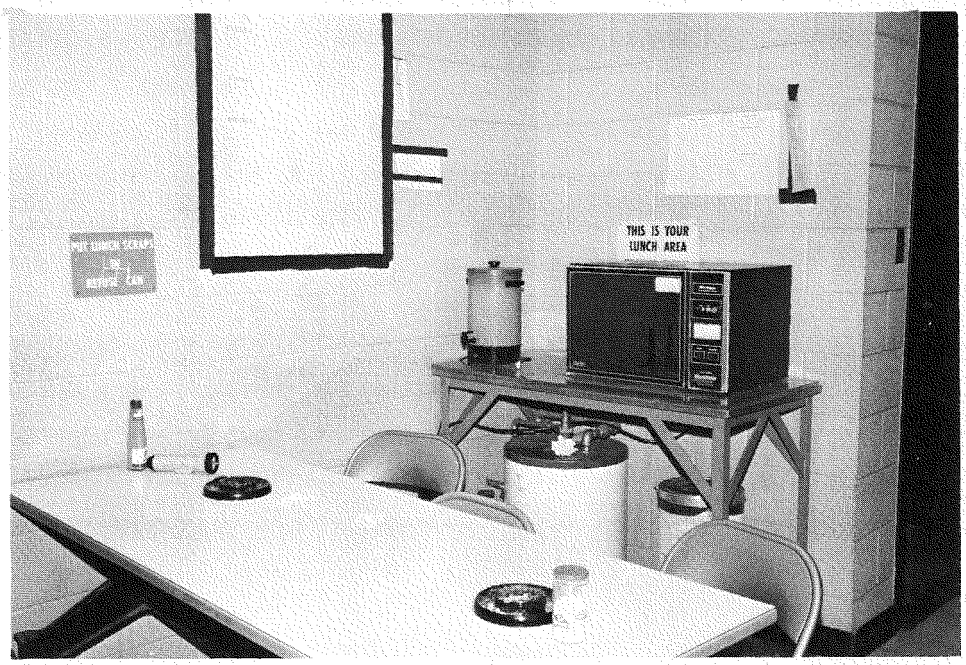


Fig. 4-20. The kitchen is located about 80 ft. from the control room and is available to nonoperational personnel.

traffic. The problem is most acute during major evolutions such as at startup or emergency shutdowns. As one operator put it: "When there is a unit trip we have wall-to-wall people in the control room. Some of them are resetting alarms without the operator being aware of it. We should be separated from the outside by a window."

Some plants have visitors' galleries (see Figure 4-18) but only one is in use. The advantage of a visitor's gallery is both in the avoidance of distractions from visitors and as the means for isolating the operators during critical operations while permitting in-plant observers.

ENVIRONMENTAL FACTORS

Environmental factors are the physical factors that affect the operators physiologically and psychologically, namely, temperature, ventilation, illumination, noise, and decor. Measurements were made of illumination and the study team conducted subjective evaluations of the other factors by means of the interviews with operators and trainers.

Temperature, Humidity, and Ventilation

One-half to 89% of the operators at each plant perceived temperature, humidity, or ventilation problems. Operator opinions can be summarized as follows:

- Adequacy. The most frequent complaint was that air conditioning and heating systems are inadequate; too hot in the summer, too cold in the winter. Cold nights were a frequent complaint. When the generating unit is down at one plant there is no heat and the auxiliary boiler is needed to heat the control room.
- Inadequate Distribution and Control. This too was a common complaint. Attaining comfort in one area of a multi-unit plant often meant discomfort in another. Inevitable morale problems resulted where control was in the "other" area. At one plant the system is shared between the back room electronic equipment and the control area. Because of the priority of the former, operators (and our study team) felt cold, especially at night. At another plant, there was free access to the thermostat and the expected continuous variation caused discomfort to everyone at one time or another.
- Ducting. At one plant an outlet duct is positioned directly over the operator's desk, again, making it too cold at night, though comfortable on a hot day.
- Fresh Air. A complaint heard at two plants was that when wind conditions varied, exhaust fumes from the diesel generator were brought into the control room.
- Low Humidity. This is a problem at one plant that is carpeted; static electricity shocks are common. An additional effect was that the reading on a meter could be altered by merely passing a hand over it.

Complaints in these areas were heard at all plants with surprising frequency. The impact of these factors can be subtle. At worst, they can dull the senses of a tired or bored operator. At the very least, environmental factors can lead to needless frustration and irritation.

Illumination

Illumination was measured at all plants. It was observed that lighting levels are uniformly brighter in the simulators than in the operational control rooms. Reasons for this are discussed below. Figures 4-21 and 4-22 summarize the measured illumination levels and show the relationship to the levels recommended by military standards.

The illuminance distributions were obtained by taking a series of measurements 30 to 40 inches above the floor, at each panel area across the boards and consoles. In Figure 4-21, disconnected boards at any given plant are joined by dashed lines and continuous boards by solid lines. The variance from the recommended band is immediately apparent. The lack of uniform distribution within a given plant is also apparent. The latter variance from illumination and human engineering standards was cited by all operators as a problem except at Plant C, which provides the highest levels of illumination. The human eye is very adaptive and, generally, the higher the absolute levels, the less sensitive it is to differentials in illumination. In other words, despite the measured lack of uniformity, illumination is generally perceived as being uniform across the boards at Plant C by the operators. The fact that some levels are well above those recommended is not judged to be a problem, per se, though other related problems occur. An operator at one of the low-level lighting plants complained that his eyes hurt when he went outside after duty in the darkened control room. The eyes will adapt to low levels of illumination, but will suffer fatigue and strain from continued reading and writing tasks unless the minimum illumination of 50 foot candles (Ftc) is met. To avoid the eye strain and fatigue of frequent eye adjustments between desk and panels and among different panels, illumination should be reasonably consistent across all control room surfaces, and certainly across a continuous control board or console.

Glare and reflection is a problem at all plants and operators lower overhead lighting levels by any means available. This generally causes an overall illumination level that is too low and the reflection problem is not entirely eliminated as illustrated by Figures 4-23 and 4-24. Shadowing is an additional problem caused both by the design of panel elements--inserts and protrusions--and by the

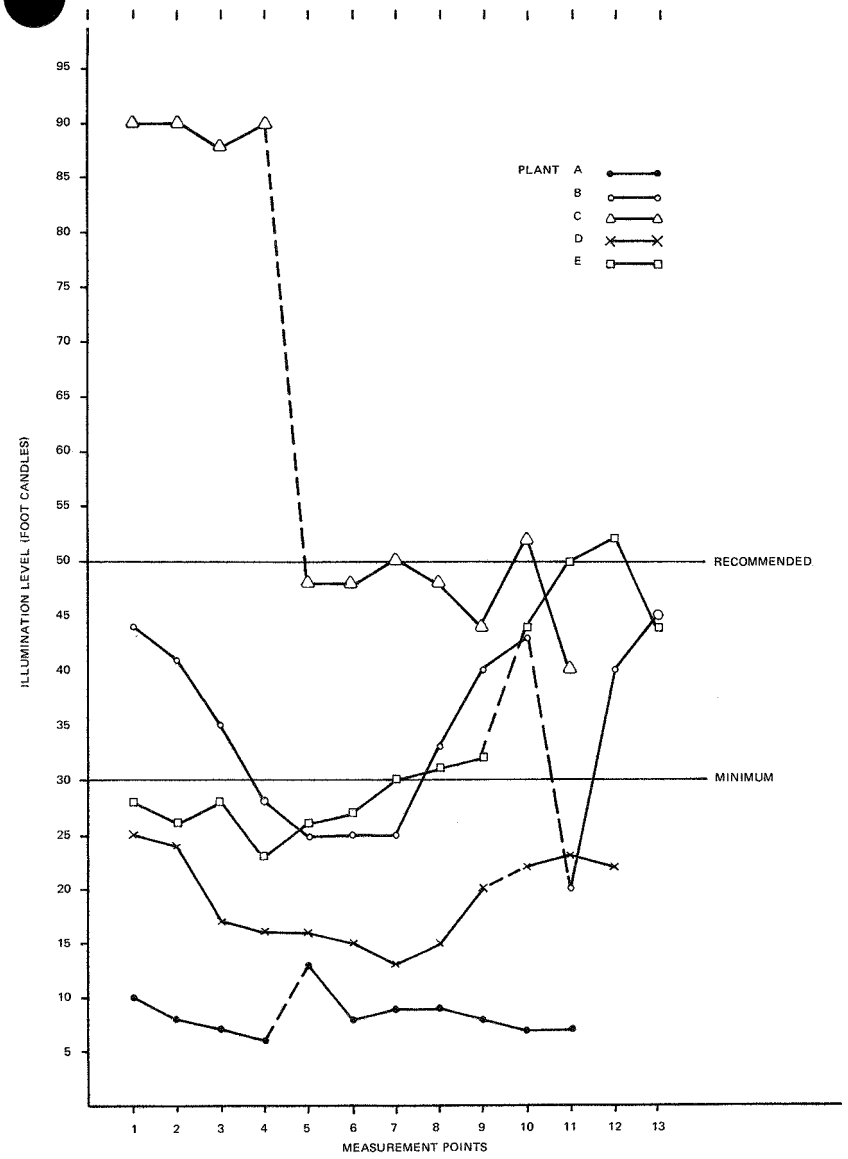


Fig. 4-21. Panel and bench board illumination levels compared to recommended and minimum standards.

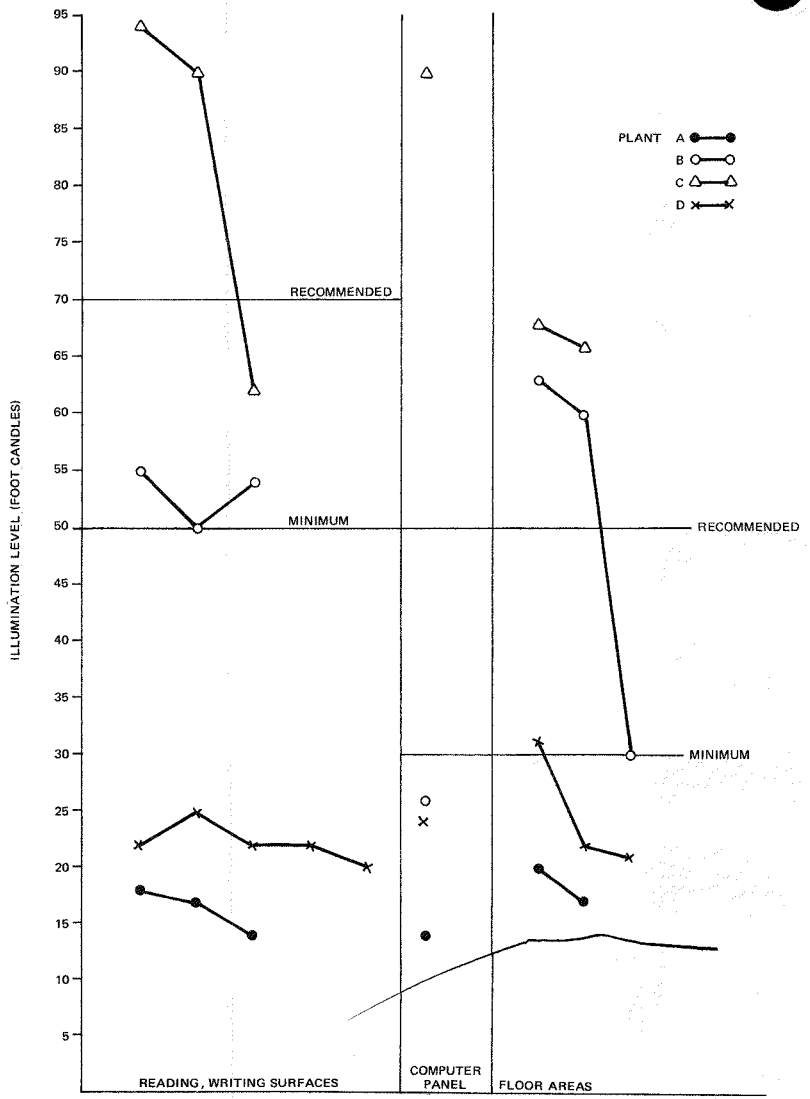


Fig. 22. Illumination levels measured for reading and writing surfaces, computer panels and floor areas.

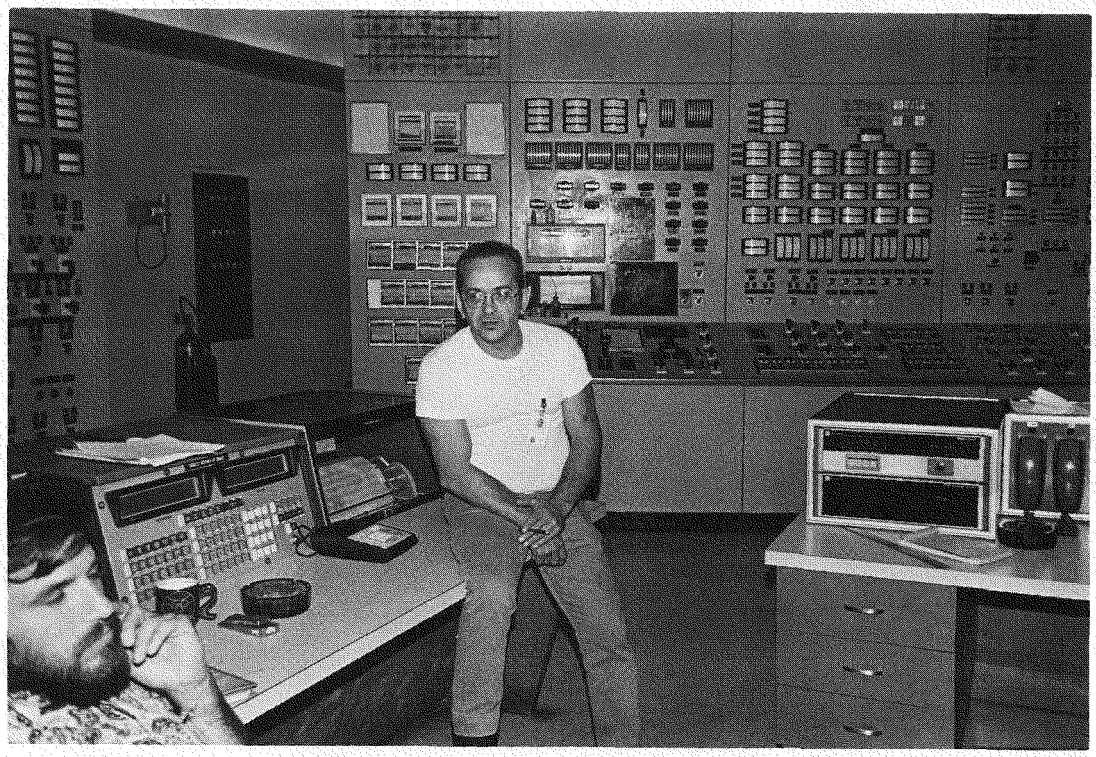


Fig. 4-23. Operational control room which is maintained at too low an illumination level in order to reduce instrument glare and reflections.

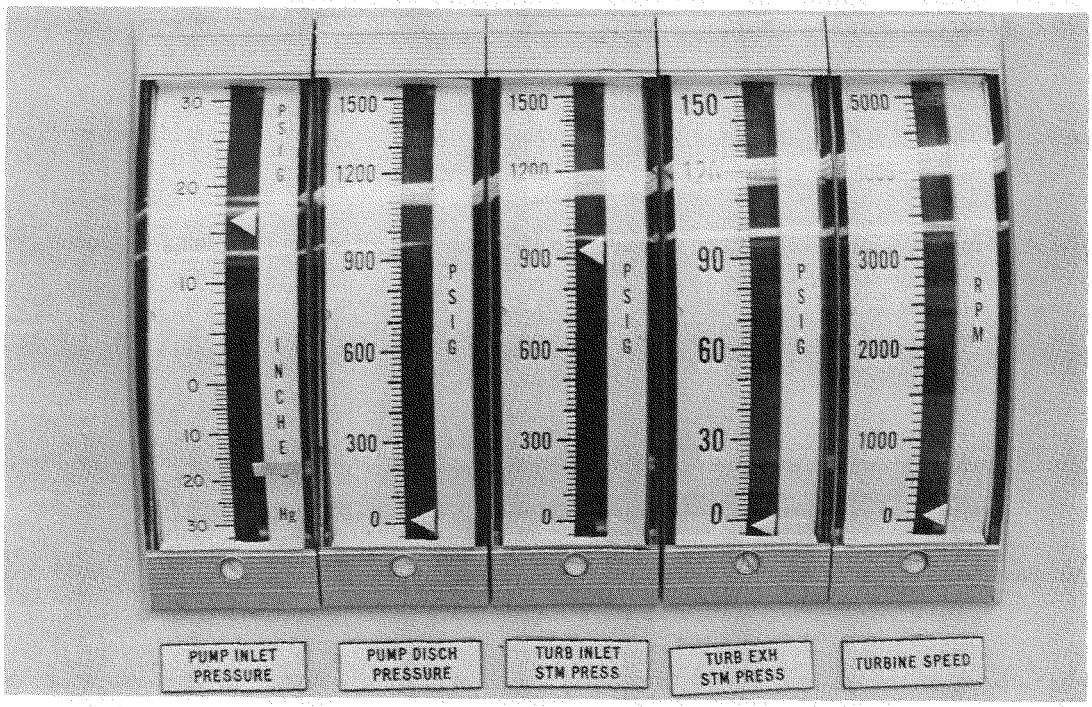


Fig. 4-24. Example of annoying reflections which operators try to avoid by reducing overhead illumination.

placement and characteristics of the luminaires. The closest, most direct and undiffused lights produce the greatest degree of shadowing.

Maintenance of the overhead lights was reported as a problem in that, frequently, lamps are burnt out or missing. Additionally, diffusion panels were sometimes dirty (see Figure 4-25) or damaged.

A uniform and diffused illumination at adequate levels was achieved at only one of the five plants investigated.

NOISE

Operators complained of noise levels in the control rooms of all plants, though for different causes:

- Excessive Personnel. This factor was cited at all plants as an irritating source of noise. Technicians, auxiliary operators, and others tend to congregate in the control room from time to time. Operators generally find it difficult to ask these visitors to leave, despite the unwanted distractions.
- Equipment Operation. Computer typewriters and printers, air conditioners, and ventilation systems, as well as the combined effects of telephones and alarms in multiple-unit plants were variously

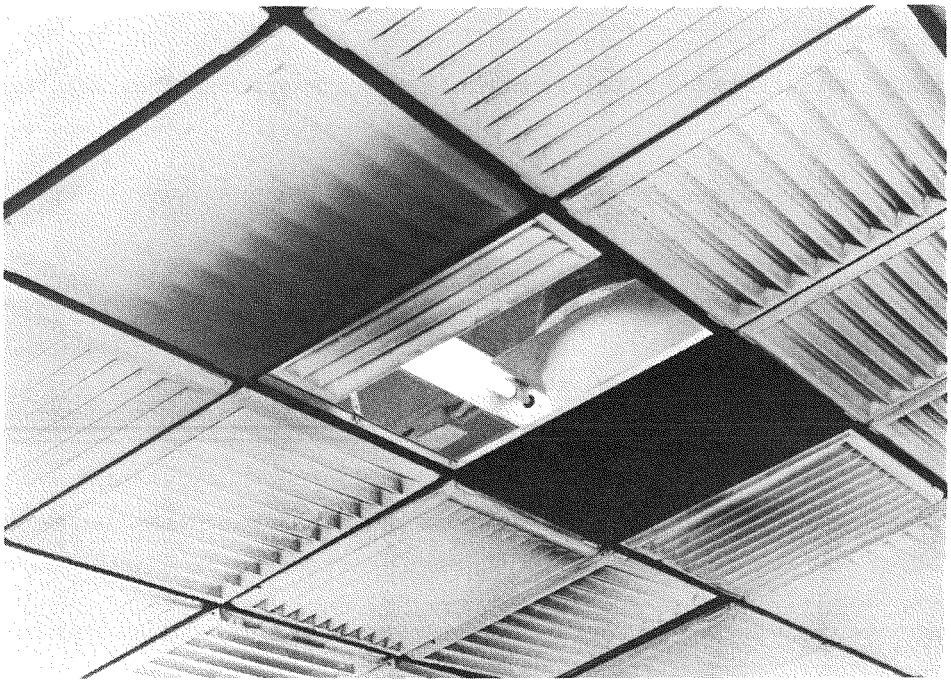


Fig. 4-25. Dirt collects on overhead translucent panels and blocks illumination. Better maintenance is needed.

cited. The ventilation system at one plant was so noisy that loud shouting was necessary for an operator to be heard by the man at the center desk.

- Plant Equipment Drone. This was cited at two plants and was produced by turbine and generator. It was very annoying when certain doors were open. At one plant carpeting helped dampen the noise.

Unless levels are at extremes, the effects of noise are difficult to quantify. The fact that operational personnel are expressing complaints in this area seems sufficient indication of a general problem. Carpeting and closed-door policies offer easy partial or total solutions to the problem. In cases where carpeting had recently been installed, the operators were quick to point out how much the situation had been improved.

Control Room Decor and Upkeep

Decor refers primarily to the "pleasantness" of the work space envelope provided to the operator. This aspect of control room design has an impact on operator performance, although it would be difficult for us to provide a quantitative assessment. However, considering the hours that the operator spends in the control room and the confining aspects of the job (see Section 18) we feel the utilities should pay special attention to this factor. Military and space experience has shown that equipments and facilities designed with aesthetic considerations in mind are likely to earn the respect and care of user personnel. The study team generally found the decor of control rooms sterile and unimaginative. The utilities might profitably experiment with graphics, murals, coordinated color schemes, etc., in providing a more stimulating control room environment.

Plant personnel were asked for their comments in this regard. With the exception of one plant, control rooms were variously described in such terms as bland, drab, dingy, and dull. Those that had carpeting liked it; those without, wanted it. Criticisms included uncomfortable chairs, carpet cleaning problems, and lack of adequate locker or rain gear storage space. At the plant which was the exception, operators were generally pleased with the light blue panels and walls and dark red carpeting. (Carpeting also relieves the fatigue of standing and walking on hard floors for prolonged periods). It may be significant that illumination was bright at this plant. It may not be entirely coincidental that morale at this plant was perceived to be highest.

The maintenance of clean console panels was mentioned several times because raised devices act as dirt catchers. Raised plastic "flow lines" were cited as troublesome.

A special problem associated with a BWR plant carpeting was the contamination that entered the control room (see Figures 4-26 and 4-27). Such contaminated areas sometimes resisted cleaning attempts and sections of the carpet had to be cut out and replaced. In this instance, carpeting pre-cut into uniform squares might prove more practical.

SUMMARY REMARKS

Nuclear power plant control rooms are much larger than those used for aerospace applications. The majority of operators prefer smaller control rooms that are more easily manageable in terms of visual span and the distances to be traversed. Furthermore, the operators prefer to have all relevant controls and instruments within their primary control room area rather than having to divert their attention to back racks or remote areas of the control room. The configuration of the control boards influences the operator's perception of control room size and the number of operators required to effectively man the control room.

In addition to the layout of the control room, this section reviewed the relationship of the supervisor's office to the control room. It was concluded that the supervisor's office should be integrated with the control room so that immediate interaction between supervisor and subordinates can occur during emergencies. Also the designs of restroom, kitchen, and visitor facilities can be improved to allow more effective operations. Kitchens and toilets should be reserved for the exclusive use of the operators.

Examination of control room environments revealed a surprising number of complaints concerning such mundane factors as temperature and ventilation. Low control room illumination was a problem at several of the plants studied and this had a negative impact on the readability of meters and other instruments. Finally, the utilities should investigate techniques for upgrading the decor of drab and dingy control rooms.

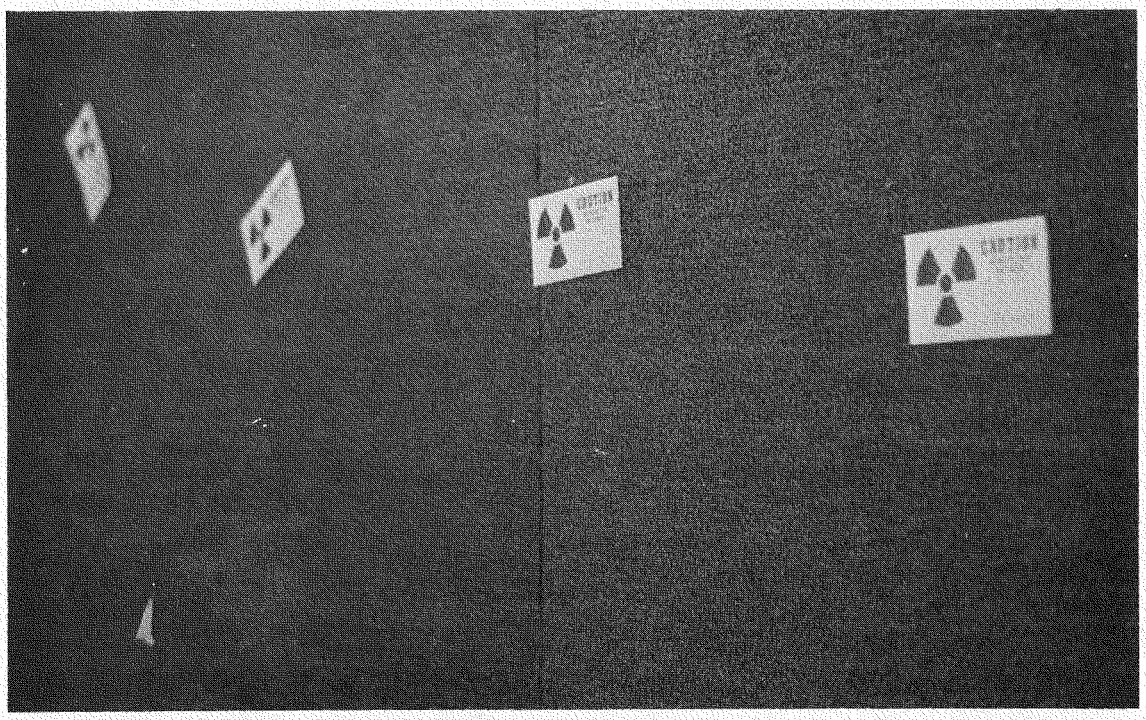


Fig. 4-26. Carpeting in a BWR control room picks up radioactivity.

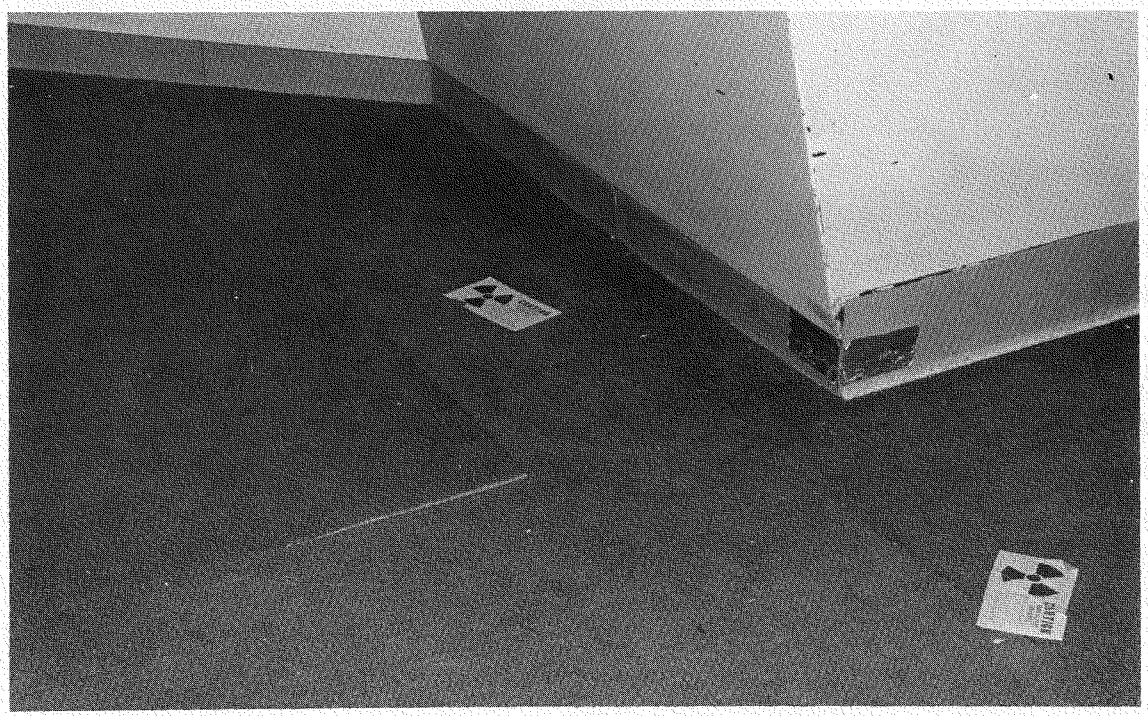


Fig. 4-27. Segments of carpeting that can not be decontaminated are cut out and replaced.

Section 5

CONTROL BOARD DESIGN

This section reviews the human factors of control board design. The section presents an overview of human factors methodology typically applied to military and space applications. The five control boards investigated are evaluated in terms of size, shape, and adherence to human factors principles of panel layout design. The preferences of operators are discussed with regard to the sufficiency of instrumentation and panel arrangements that are easiest to operate and master. One subsection is devoted to the undesirability of mirror-imaging control boards in multi-unit control rooms.

Modifications that operators have made to the control boards over the years are examined particularly as they shed light on problems with the original designs of the boards. Also discussed are the modifications and additions to the control boards necessitated by changing system requirements and those which should be instituted to correct some of the problems observed. The section concludes with a review of operator experience with the control room computer and a brief examination of in-plant consoles outside the main control room.

HUMAN FACTORS METHODOLOGY IN CONTROL BOARD DESIGN

The classical human factors engineering approach to control board design requires the following key steps:

- Manning Concept. Establish the operator's role in the system. Conduct analyses and trade-off studies to determine the best allocation of functions either to the operator or to automated systems. Based on these analyses, establish the number, types, and skill level of operators required to operate the system effectively.
- Task Analyses. Based on an iterative series of tasks analyses in which the operator's role is explored in detail with respect to hardware elements, establish the informational requirements of the operator and the control options that should be made available to him.
- Display Requirements. As the informational needs of the operator are defined, consider the alternate modes of presenting this information and develop an information display concept. Consider the

needs for an effective caution-warning system, color coding of displays, primary versus secondary categories of information, and the division of information among the various members of the operational team.

- Control Requirements. The functions and task analyses will reveal the control options available to the operator. Basic decisions will be made regarding the optimal division of remote control responsibility from the control room or manual control by means of auxiliary operators in the plant. Also response time requirements will dictate whether automated system response is required or whether manual operator response will be the primary control mode. As these requirements are defined, the number and characteristics of specific control elements necessary for the operator to manage the system will be identified.

- Control Board Design. Based on the manning concept, the division of responsibilities among the operators, the magnitude of required control and display elements, and required operator response characteristics, a basic control board concept can be developed. This concept will define the arrangement of major panels in the control room, those relegated to other plant locations, and the configuration of the control-boards--vertical panels, benchboards, wrap-around console arrangements, etc.

- Facility Design. As the control board design needs are defined, the facility, (the control room that will house the control boards), can be defined. This effort will consider illumination requirements, traffic patterns, arrangement of operator and supervisor stations, communication needs, maintenance access requirements, anthropometric requirements, and provision for visitors.

- Detailed Layout of Control Boards. Given a general control board configuration and having established the control and display needs of the operator, the detailed layout of major panels can proceed. At this point a selection between major layout principles must be made. The emphasis can be placed on graphic, pictorial, or mimic board arrangements, or the panel layout can stress clearly identifiable functional groupings of related control-display elements, or the layout can be based on placing critical controls and displays in primary control board visual and reach areas, while delegating secondary control-display elements to less favored positions. The layout can also stress frequency of control-display use, and finally the panel can be arranged, when appropriate, to reflect a predetermined sequence of operations. These layout approaches are not mutually exclusive and generally a mix of them is employed.

- Mockups. As a panel layout design concept evolves, it becomes important to develop full-scale mockups of the control board. These mockups are indispensable in ensuring an integrated design approach and in permitting human factors evaluations of man-machine interfaces before any metal is cut. At this point, representative operators help evaluate the design. The mockup should be designed to allow trial-and-error reconfigurations of control panels so that competing candidate approaches can be evaluated. The operators should be used to conduct mock operations of normal and emergency tasks to ensure that the arrangement permits effective operations.

- Simulation. Where advanced and unproven control-display concepts are being considered, simulation studies should be undertaken to evaluate man-machine interfaces. Dynamic simulation is costly, but can be highly cost-effective in the long run.

This approach assumes that control room designs should be systematically evolved on the basis of the abilities, limitations, and needs of the operator. The reverse approach is to build a control room and then integrate the operator into it on an after-the-fact basis. This latter approach assumes that the "good" operator is infinitely adaptable. This section will present considerable evidence to support the view that the latter, rather than the former, approach has been historically adopted in the development of nuclear power plant control rooms.

CONTROL BOARD SIZE

Those whose primary experience has been with control boards for aircraft, space vehicles, or missile checkout equipment are amazed at the size of nuclear power plant control boards. These vast expanses of control board (Fig. 5-1) are not due necessarily to the number of elements accommodated on the control boards, but rather to the size of these elements, panel design practices, and the spacing of elements. Space is simply not at a premium in the nuclear power plant as it is in a space vehicle, and designers have not been constrained to limit the size of control boards. One wonders how big a Boeing 747 cockpit would be if the nuclear power plant principles of panel design had been followed.

Why is the size and configuration of the boards of importance to operator effectiveness? The size of the boards is related to the span of the individual operator's control, his limits of visual access, and his ability to integrate many discrete indications into a coherent picture of plant status during normal and emergency modes of operation. The size of the boards can make the difference between a one-man versus two- or three-man control board operation. The relationship between control board configuration and manning was discussed in Section 4 above. Assuming a forty year life span for the control room and a salary of $20,000 per year for an extra operator, added cost is in the neighborhood of $800,000.00. If we add initial training costs for licensing, requalification training costs, fringe benefits, personnel turnover, etc., this cost for an extra operator easily exceeds one million dollars.

Aside from the cost of extra operators, operational personnel generally prefer more compact control rooms. They feel a need to monitor the entire system from one central location.

Separation of related subpanels requires excessive searching and running about, especially during startup, shutdown, and casualty modes. Some of the design practices that have created large control boards are illustrated in Figures 5-2 to 5-9.

First, the size of selected panel elements is a major contributor to the problem. The most common grouping observed in three of the five plants visited is a pistol grip SBM control with two, and sometimes three, associated indicator lights, as shown in Figure 5-2. These arrangements consume many times the space of alternate arrangements that employ switch-lights or simple indicators in association with toggle switches, as shown in Figure 5-3. Compare the options presented in Figure 5-3 with the size of elements found in control board configurations represented by Figure 5-4.

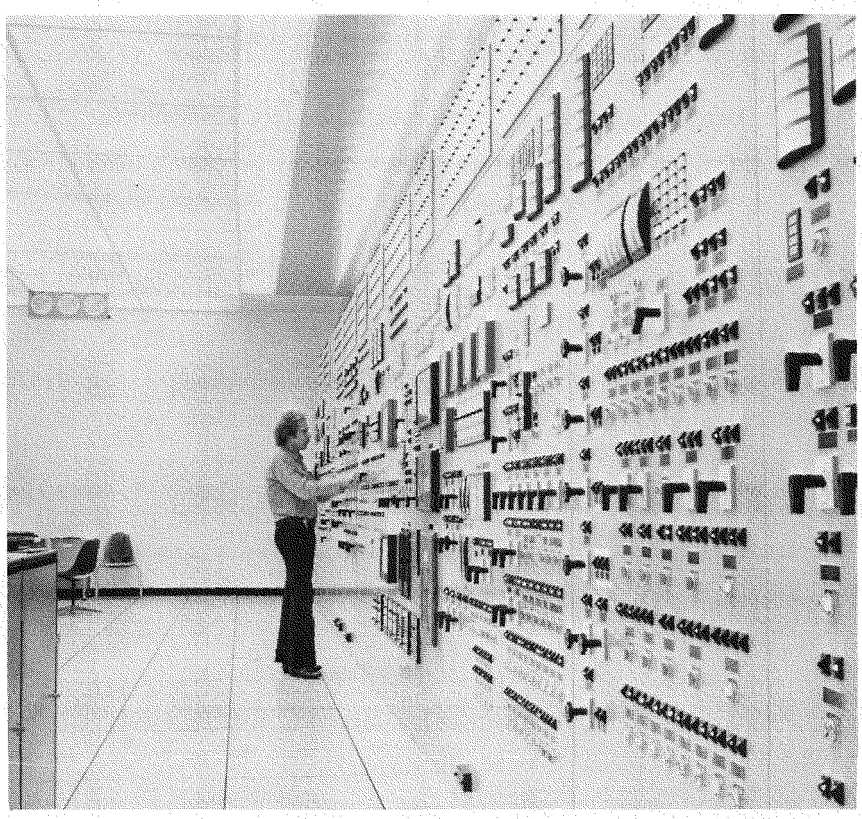


Fig. 5-1. Large expanse of control board, 46 feet wide.



Fig. 5-2. Use of many large pistol grip SBM controls associated with indicator lights requires large control boards.

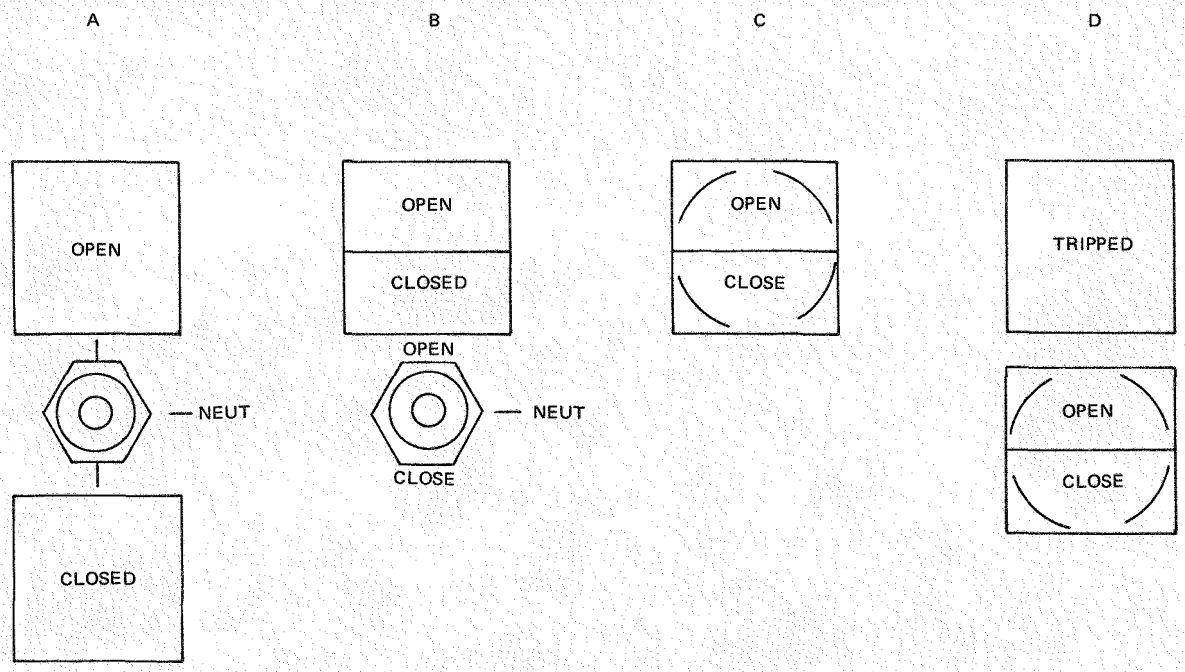


Fig. 5-3. Four space-saving control and display arrangements. A consists of two indicators and a three-position toggle switch. B shows a split-half four lamp indicator and an associated toggle switch. C provides a two-option, switch-light arrangement. D shows a switch-light in association with a TRIPPED indicator. Compare these arrangements with Fig. 5-4.

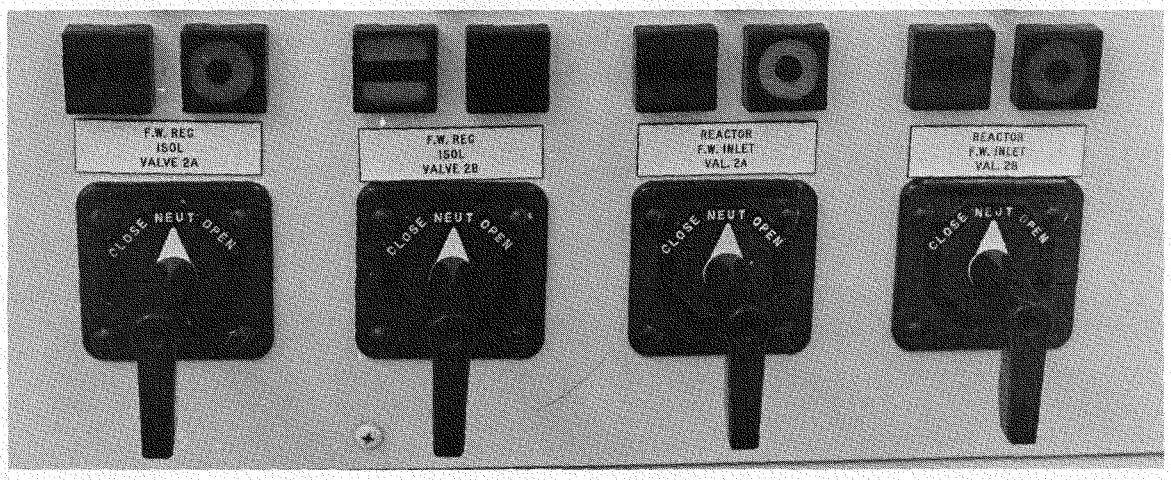


Fig. 5-4. Compare this typical grouping with the space-saving arrangements shown in Fig. 5-3.

In some plants the panel has three to five meters, each meter displaying the same parameter and each display from a different sensor. Other plants save space by providing one meter with a selector switch so that the same information is available to the operator but not displayed simultaneously. Figures 5-5 and 5-6 show the space-saving possibilities. Figure 5-5 shows multiple meters for different channels associated with the same parameter. Figure 5-6 shows a compact arrangement of meters with double scales and switch-lights which select the channel to be read on the meters. Overlooking for the moment some human factors problems associated with the scaling of these meters, it is apparent that the arrangement shown in Figure 5-6 uses only a fraction of the panel space taken by that in Figure 5-5, and poses what may be an acceptable operational task of switching the meters to alternate channels.

A third example of wasted space is shown in Figure 5-7. One entire 28-inch wide panel extending from floor to ceiling is devoted to a temperature monitoring function. This device cycles sequentially through an array of temperature monitoring points. A red light tells the operator which point is being monitored at any given time and the circular display at the top of this panel provides temperature readings. When the temperature limit of any given point is exceeded, the panel generates an alarm. This is the least used panel and the operators store an access ladder for replacing annunciator lamps in front of it. This entire panel could be replaced with several small projection indicators to display the parameter being measured, a temperature meter, and a warning indicator to alert the operator to temperature deviations.

Finally, Figures 5-8 and 5-9 show that the spacing of panel elements is excessive. The choice of unnecessarily large components, coupled with the wasted space between them, largely accounts for the huge control boards in nuclear power plant control rooms.

These space consuming design practices prevent consideration of sit-down consoles with the control panels wrapped around the operator(s) which are more typical of military control rooms. In four of the five control rooms visited, the control boards could have been designed to use from one-third to one-quarter, or less, of the panel space presently used. The need to conserve space has simply not been perceived as an important consideration in terms of operational effectiveness. The lack of space conservation has also necessitated the use of back racks and remote areas of the control room for instrumentation and controls that require the operator to leave his primary control board area.

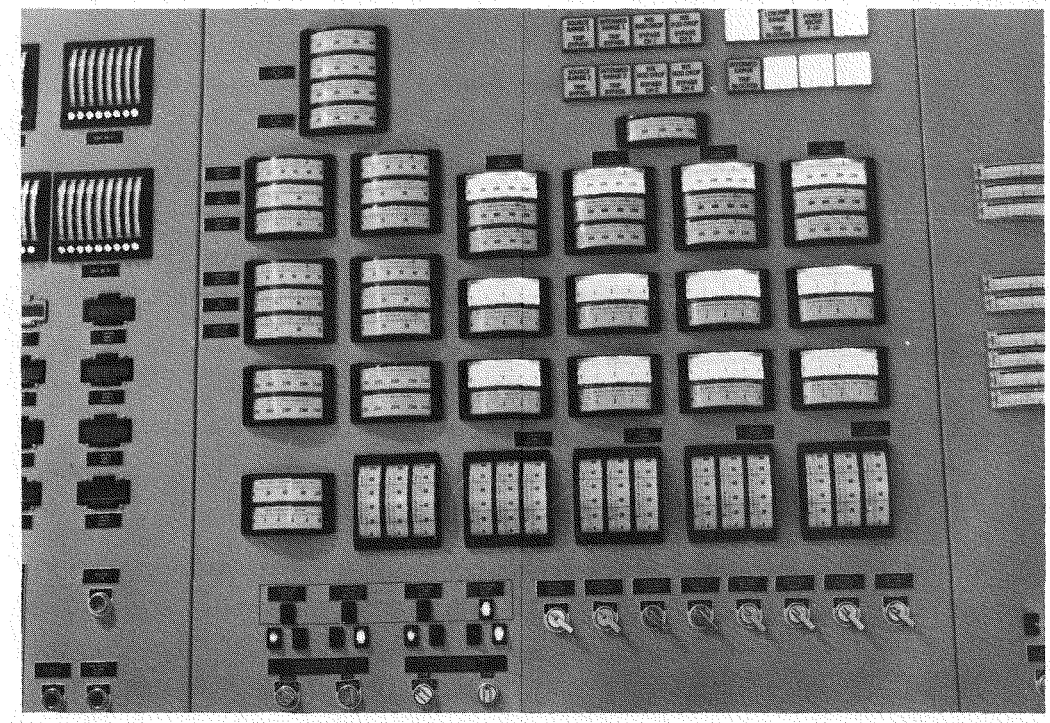


Fig. 5-5. Multiple meters are used to display the same parameter as measured by different sensors.

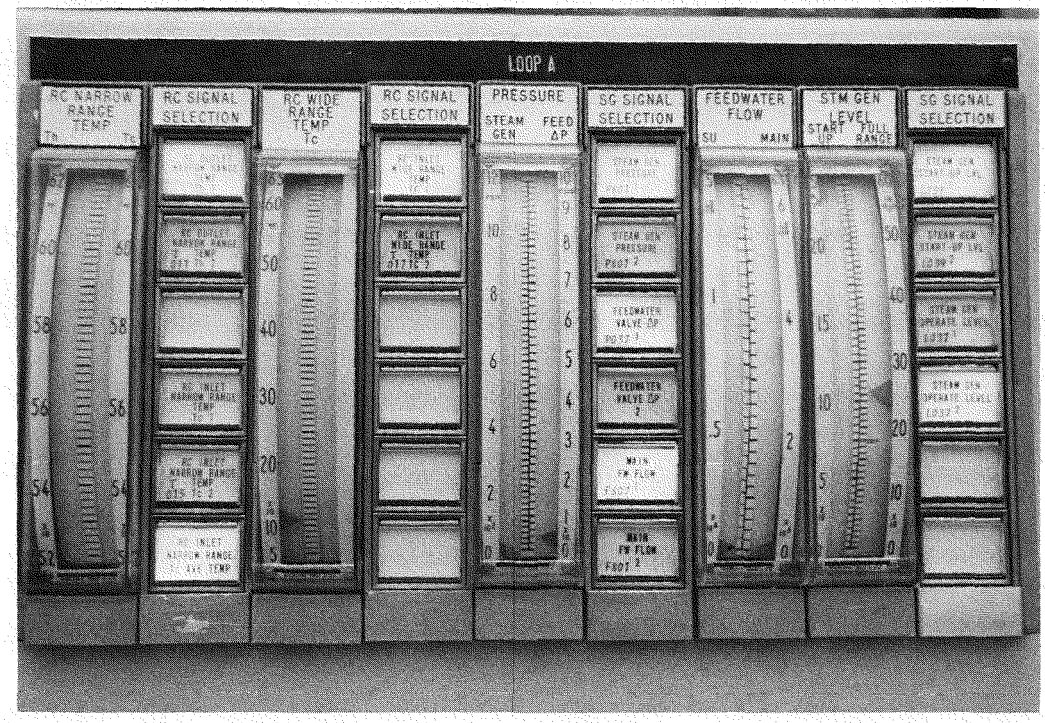


Fig. 5-6. More compact design compared to Fig. 5-5 achieved by using one meter and channel select switches.

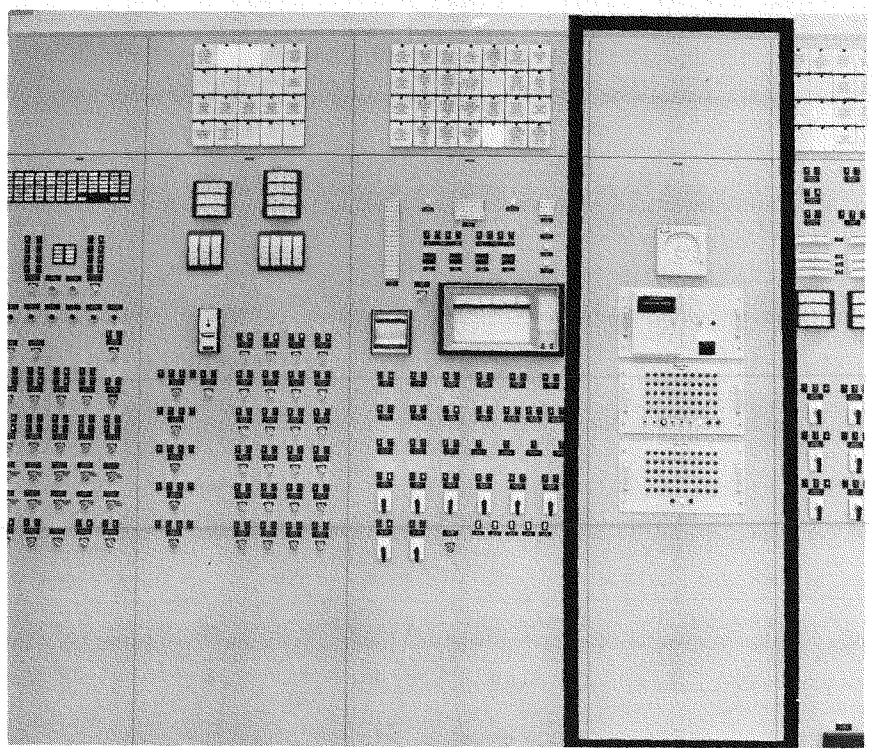


Fig. 5-7. An entire 28 in. wide panel is devoted to a secondary display which could have been replaced with a meter, several projection indicators, and warning lights.

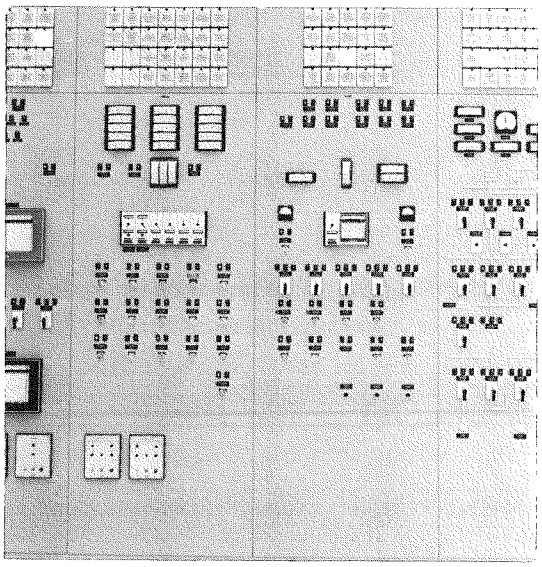


Fig. 5-8. The spacing between panel elements is wasteful.

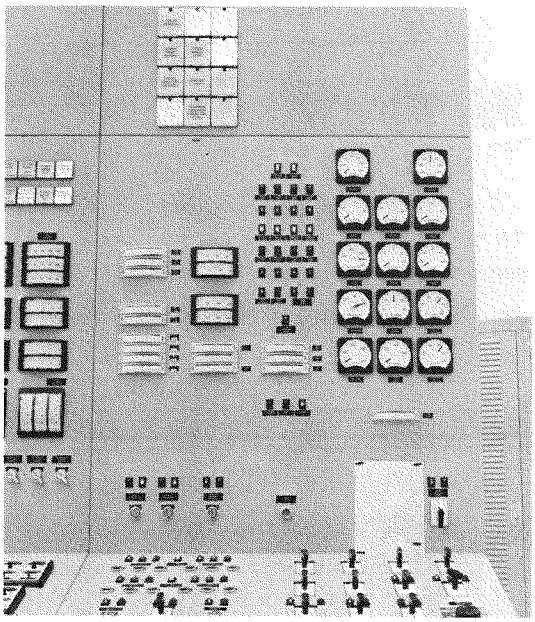


Fig. 5-9. The use of smaller control-display elements and the elimination of wasted space could reduce the size of these panels considerably.

ARRANGEMENT OF MAJOR PANELS

Expansive control boards exaggerate problems by separating functionally related control-display elements that must be operated and observed simultaneously or in close sequence. If all the control panels were within arm's reach of the operator and all displays within the visual access envelope, we would not have observed the operator actuating a control on one segment of the board and having to look for an associated display thirty or forty paces away. Operators were asked the following question: "Have the control panels in your control room been organized in an arrangement that is logical for normal and emergency operations? If not, how could the layout of panels be improved?" The responses of the operators and the results of the task analysis reveal numerous instances where the existing arrangement was creating serious problems for the operator. Figures 5-10 to 5-13 illustrate cases where functionally related control board elements were widely separated and demanded a two-man operation. The following quotes from operators also indicate problems of dissociated controls and displays.

- The feedwater system and displays are separated between the flight and supervisory consoles.
- The turbine controls and displays are dissociated and could have been grouped more logically so that it doesn't take two people to operate them.
- The steam generator level indications for wide and narrow ranges are unnecessarily divided between the flight and supervisory panels.
- The CVCS and auxiliary cooling panels should be located with the reactor coolant pump panel.
- The separation of major panels between the primary inner panel area and the vertical wall area in back is a problem during casualty modes.

The separation referred to in the quote immediately above is seen as that plant's major cause for a normal two-man versus one-man operational situation (even though Technical Specifications only call for one-man control room operation). The safeguards panel is located on the back wall and the reactor control panel is located on the primary panel (see Figure 5-13). With one man on duty, the operator is required to leave the Reactor Panel to operate the Safeguards Panel, as was discussed in the preceding section.

As noted in Section 4, the operators often complained of having to leave the primary control panels to read instruments or make control adjustments in back-rack areas or areas within the control room which were considerably removed from the operator's station. The Radiation Monitoring equipment was relegated to a



Fig. 5-10. The feedwater isolation valve controls are separated from the feedwater regulating valves as shown by the position of the two men in this photo.

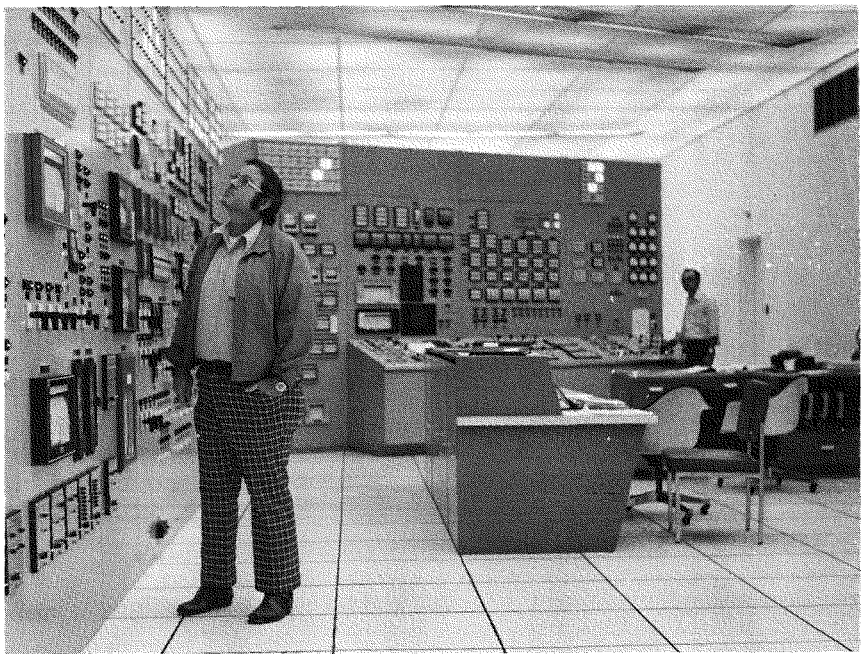


Fig. 5-11. Primary turbine controls are located on the console to the right. Turbine speed is monitored at a position assumed by the man on the left about thirty-five feet away.

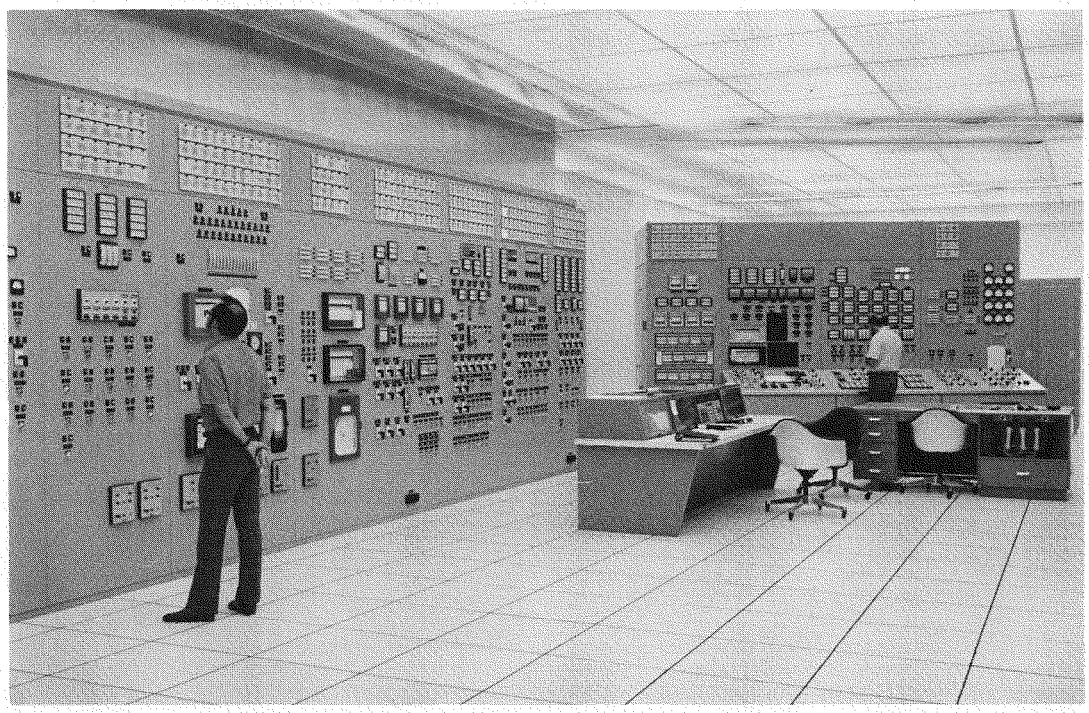


Fig. 5-12. CVCS controls are placed on the main "Flight" console to the right. Most CVCS alarms are located on the supervisory panel at the position assumed by the second man to the left.

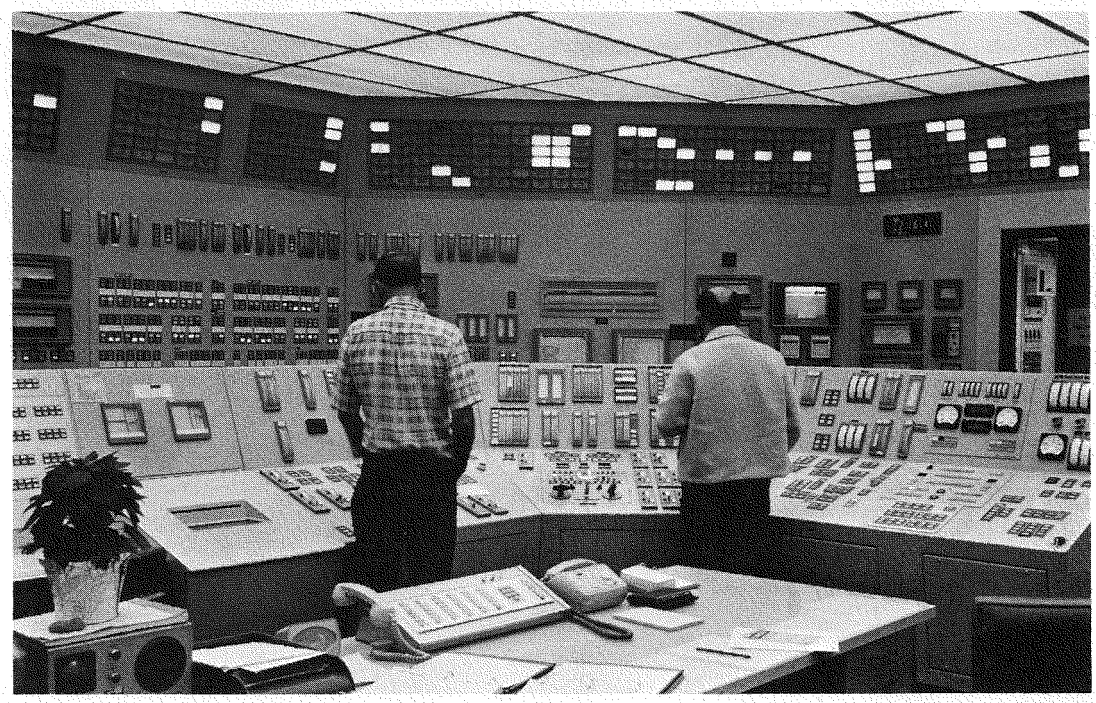


Fig. 5-13. The safeguards panel is mounted on the rear wall to the left. The reactor panel is in the primary inner tier of consoles. The single operator must be in two places at once in an emergency.

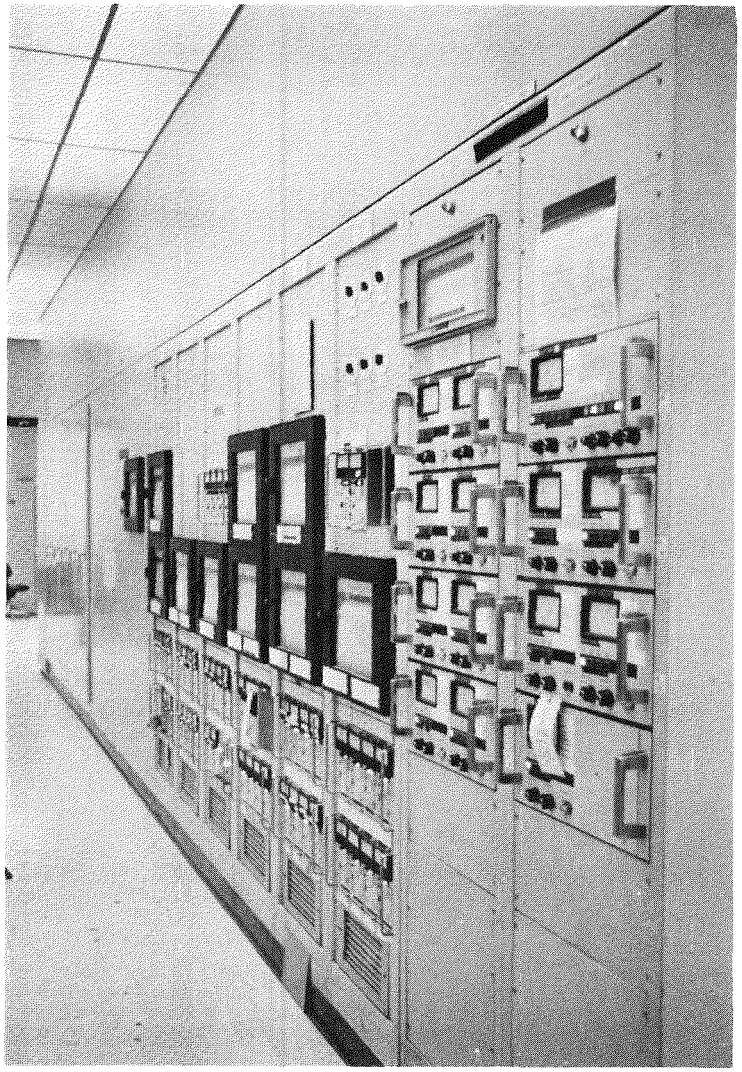


Fig. 5-14. Typical distribution of control panels in the back panel area of a control room.

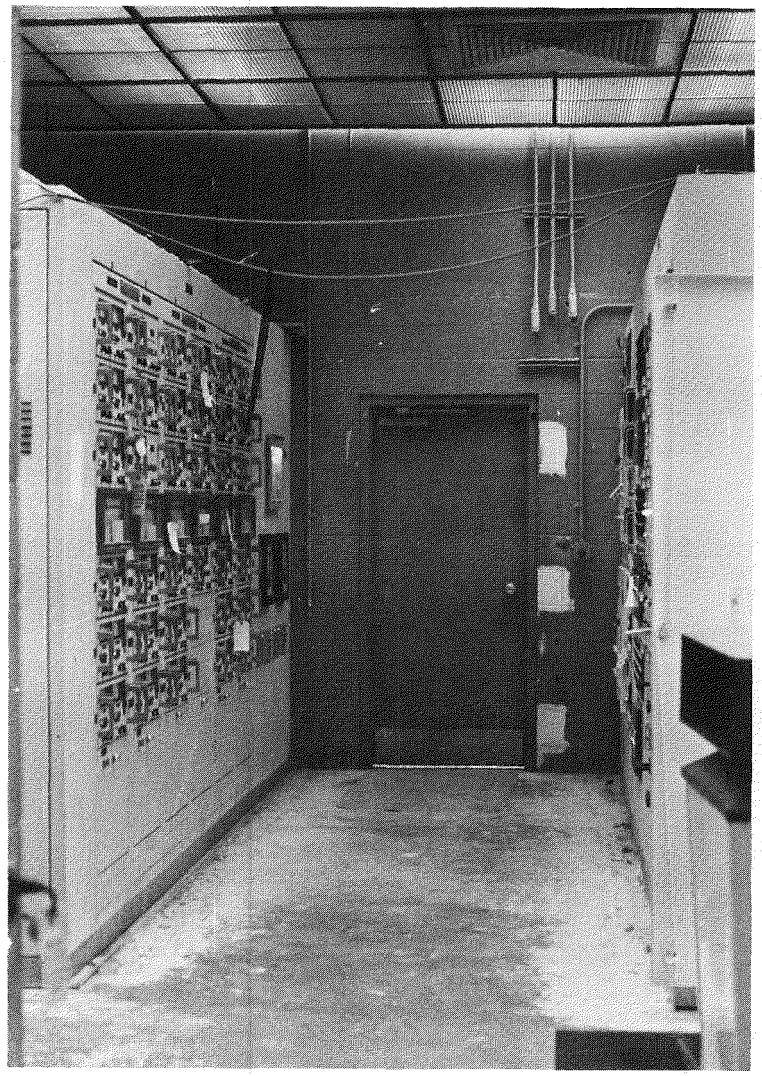


Fig. 5-15. Panels located in a remote corner of control room require the operator to leave the primary panel.

secondary and remote panel area in all five plants visited. Figures 5-14 and 5-15 show some of the back rack and remote control room locations to which the operators must go, either on a routine basis or when an alarm directs their attention to the panels involved.

In reviewing the arrangment of specific major panels to each other, the only consistency observed was that the reactor control panel was given a central location in four of the five plants. For example, the control room layouts presented in the preceding section reveal that the safeguards panel has a different relationship to the reactor control panel in each of the plants visited. Similarly, the turbine-generator and the chemical volume and control systems are not consistently related to each other or the reactor control panel. One might assume on an a priori basis that there is one best way of organizing the relationship of major panels to each other on the basis of the required operator interaction with them. The writers are not aware of any formal or comprehensive functions and task analyses that were conducted to establish the optimum arrangement of major panels to facilitate the operator-control board interaction for both normal and emergency operation modes.

PANEL LAYOUTS

Human engineering principles of panel layout are simple to describe and rarely generate arguments regarding their validity. However, faithful observation of these principles is rare unless a member of the design team assumes or is given the responsibility to see that they are uniformly applied.

Where the operator observes events and selects control options in a fixed sequence of operations, panels lend themselves to sequential layouts of control-display elements. Missile launch panels generally take this form. Sequential layouts from left-to-right or top-to-bottom are helpful in ensuring that all operational actions are made in the proper order. However, few nuclear power control-panels require a fixed order of events, so this approach should not be employed as the central design principle.

Other panels lend themselves to a pictorial or graphic approach. These arrangements are called mimic panels since they mimic the arrangement or interrelations of system elements. Mimic panels are often used to display petrochemical processes where they give the operator some understanding of the entire system so displayed. The disadvantages of mimic panels are that they tend to require

more panel space and it is not easy to modify them if the relationships initially shown are changed.

Some panel designs are based on the principle of importance. The operator has a primary viewing core around his line of sight and an optimal reach envelope. Groups of displays and controls are sorted according to primary and secondary functions and optimize the placement of primary elements.

Another panel layout principle is based on the frequency of use of the control-display element or groups of elements. The subpanels used most often are given preferred locations and favor right-hand operation so that most operators are accommodated.

The most common panel layout practice is to provide clearly distinguishable functional groupings of panel elements according to systems and subsystems. These groups of related elements clearly stand out from each other by using proper labeling, lines of demarcation, spacing, and variously shaded panel areas.

These panel layout principles are not mutually exclusive. For example, we could design a panel with clear functional groups of panel elements or subpanels, with the subpanels arranged on the basis of importance or frequency of use, and still consider right-hand versus left-hand operation of controls.

The five control rooms have used a mixture of practices, many which do not follow human engineering guidelines. All five plants provide a mimic arrangement for the electrical distribution panel. Two applied the mimic panel approach to major panels other than the electrical distribution system. Most controls have been placed on the benchboard segment of the console, quantitative displays on the vertical panel segment directly above the benchboard, and the great majority of qualitative displays, i.e., the annunciator alarms, in a horizontal band across the top of the consoles. Figures 5-16 and 5-17 show this general arrangment found in four of the plants visited. The major problem is that the arrangement does not group related elements into meaningful and clearly identifiable subpanels. The operator must scan the three zones and mentally reconstruct the relation among the annunciator lights, the related quantitative displays (meters, chart recorders, and computer-associated read-outs), and the relevant controls. The control boards fail to make these relations clear and unmistakable. To make matters worse, some of the annunciator lights, related quantitative displays, and associated

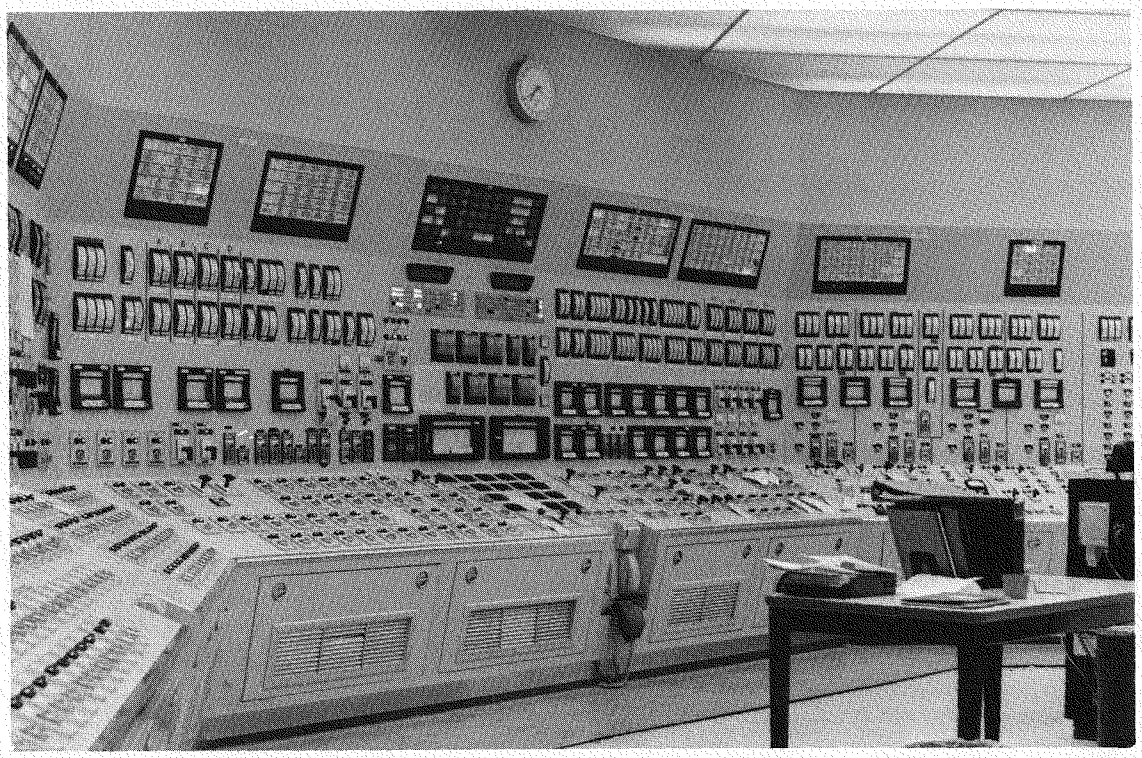


Fig. 5-16. Controls are placed on the benchboard or just above, quantitative displays are placed on the vertical segment of the boards, and qualitative annunciator displays are placed in the uppermost segment of the boards.

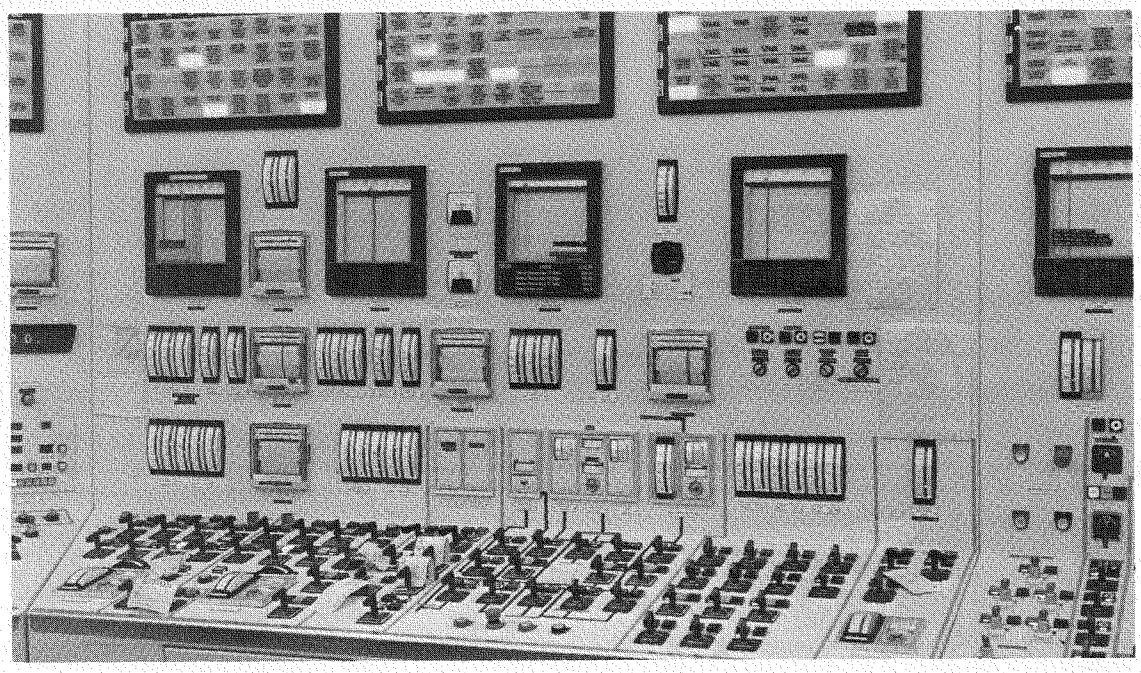


Fig. 5-17. Another example of the layout practice described in Fig. 5-16. Functional grouping of related control-display elements is hindered by this approach.

controls are not lined up in one vertical plane. For this reason, operator trainees have been reported tying strings between related control-display elements in preparation for a license examintion. If the panel relationships were clear through design, the strings and other memory cues would not be necessary.

The operators were questioned regarding the adequacy of control panel layouts within their control board. The following sample comments support the criticisms made above.

- The safeguard panel should be laid out logically with proper separation of subsystems.
- Related valve controls are not necessarily near each other, especially the CVCS System.
- The CVCS layout separates controls from indicators.
- The arrangement of feedwater pump controls is illogical. The master controller should be closer to the individual pump controllers.
- There wasn't much thought or logic applied to some alarms, e.g., on engineered safeguards features. The pressurizer annunciators were not grouped together. The feedwater control panel is grouped logically but it's hard to tell the groups apart.
- For the most part the layout is logical. However, on the feedwater panel there are so many controls and instruments that you have to watch yourself. I have caught myself activating the auxiliary pump when I wanted the main pump.
- Add-ons to the panels have mixed things up.
- The turbine speed is on one panel and the breakers are on another panel--which makes this a two-man operation.
- Feedwater system controls should all be in the same area.
- Nuclear instrumentation is split into two different areas.
- The electrical panel is very badly laid out. We have made four switching errors. You need a road map to tell you where you're at.
- Some panels are so complicated that you have to get the prints out to understand them, e.g., HPSI.
- The pressurizer level readout is about twelve feet down the board from the controls.
- There is no separation between letdown, charging, and excess letdown control and displays. The makeup boron injection tank and the RCP seal valve controls are all mixed together.
- The grouping of controls is good but we need distinguishing characteristics between groups.
- The original layout was good and logical. Back-fits to the panels have caused loss of good grouping, for example, the feedwater controls.

OPERATOR MODIFICATIONS TO CONTROL PANELS

When allowed to do so, the operators have attempted to rectify the lack of clearly defined functional groups of controls and displays by using tape to mark logical groups or to superimpose mimic lines that show the relationship between panel elements. In some cases, they have resorted to more distinctive labeling to isolate a given group of panel elements. Some of these efforts to simplify the understanding and operation of the control boards have been frustrated by plant management because of a concern for configuration control and cosmetic factors which outweighed the concern for, or understanding of, the factors that contribute to operator effectiveness.

Let us examine some cases in which the operators have attempted to clarify panel relationships. Usually, a comparison between the simulator and the corresponding operational control room panel shows the difference between the panel as originally designed and installed and the result of operator modifications. Figures 5-18 to 5-21 show four such efforts at one plant. Figure 5-18 shows the addition of three vertical tapes to distinguish four columns of meters, each column pertaining to a different steam generator. The operators have also added dymo labels to identify each meter. Unfortunately, the associated selector switches below the meters were not arranged in a manner that allowed them to be grouped with their associated steam generators.

Figures 5-19 shows the addition of label bars that attempt to tie together related groups of controls. Note that the summary label size is larger and readily distinguishable from the markings that identify individual components. Figure 5-20 shows an attempt to relate a series of controls with tape. Without this tape, the relationship between these controls would not be apparent. Similarly, Figures 5-21 provides a crude attempt to superimpose mimic panel interrelation on a panel that was not designed with this principle in mind.

Operator attempts to functionally group panel elements at a second plant are shown in Figures 5-22 to 5-25. Figure 5-22 shows how tape was used to group the displays and controls associated with the steam generators. Figures 5-23 shows a comparable attempt to label and separate four sets of related meters. Figures 5-24 and 5-25 show two cases where the layout of the panel elements was illogical and where the operators provided some cues to prevent errors.

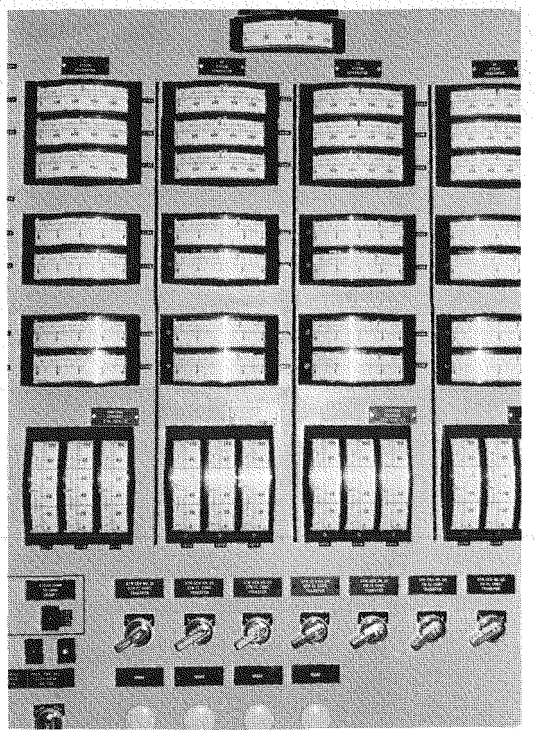


Fig. 5-18. Attempt by operators to functionally isolate meters pertaining to the four steam generators.

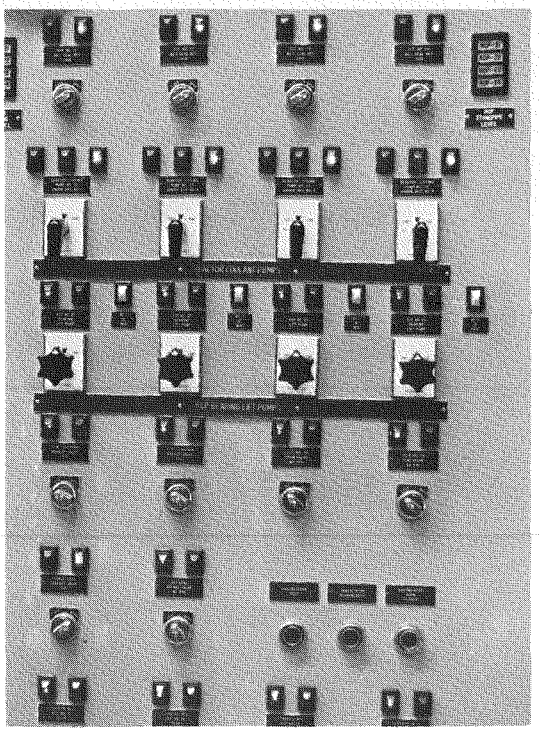


Fig. 5-19. Horizontal label strips have been added to the panel to achieve a grouping of reactor coolant pump controls.

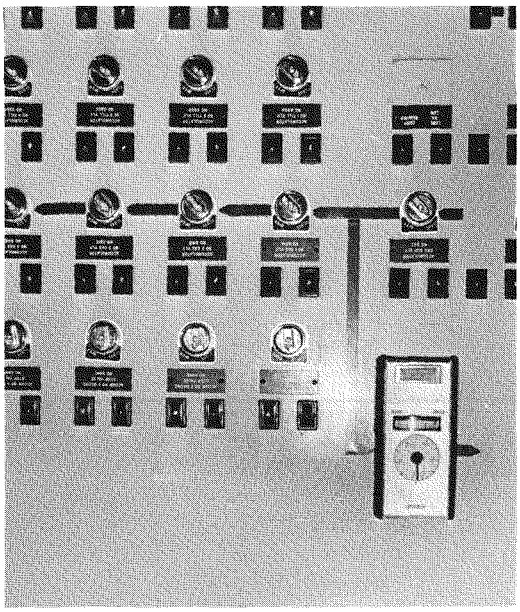


Fig. 5-20. Tape has been added to the panel by operators to functionally relate associated controls.

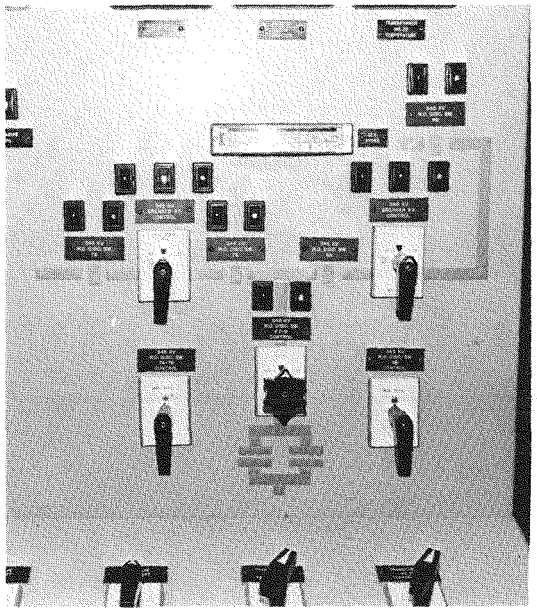


Fig. 5-21. Operators have improvised a mimic arrangement on a segment of the panel.

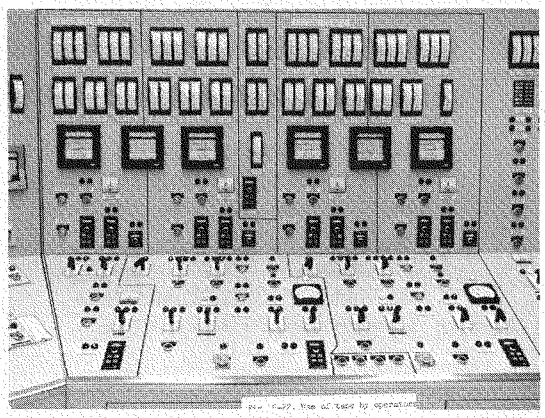


Fig. 5-22. Use of tape by operators to achieve functional separation of related panels.

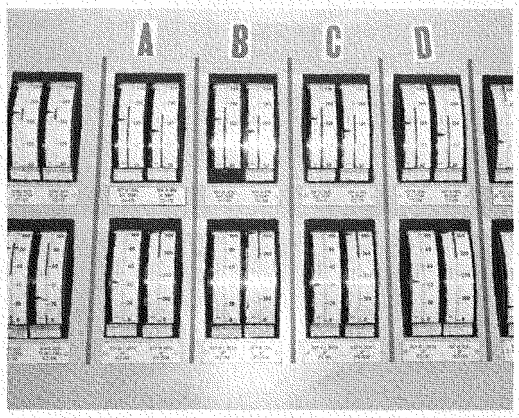


Fig. 23. Addition of letter designations and tapes to isolate four meter groupings from other panel elements.

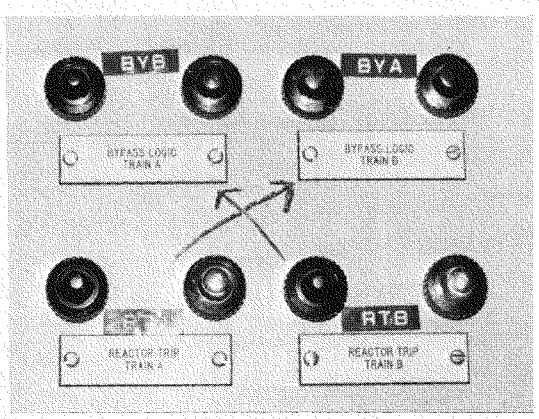


Fig. 5-24. Operator improvised cue to alert himself and others to an illogical grouping.

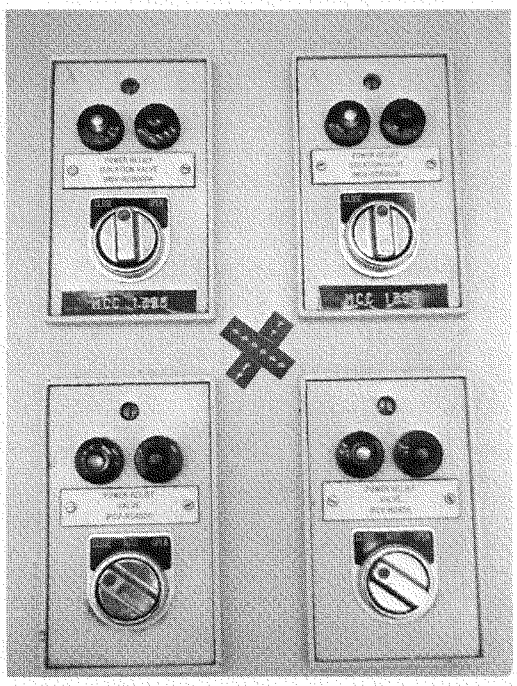


Fig. 5-25. Another case where the relationship of panel elements is incorrect.

At a third plant, the operators were discouraged from adding tape to their boards. As Figure 5-26 reveals, the safeguards panel is an undifferentiated mass of indicator switch lights. Figure 5-27 shows the same panel in the corresponding simulator. This was an exception to the general rule that the control boards in operational control rooms were better defined into functional groups than in the simulators.

At a fourth plant, the same problems were uncovered. Examine Figures 5-28 and 5-29 which compare the same panel in the simulator and the operational control room. Note the difference which the lines of tape make in helping the operator to sort the nine relevant groups of control panel elements. The functional grouping would have been even more effective had the designer provided descriptive labels to identify each block and used better spacing between each block of elements. Figures 5-30 and 5-31 show how the operators struggled to force a mimic design approach on a layout of control-display elements that was not designed with this rationale. This attempt to functionally relate the control panels extended to most of the panels in the control room.

At the fifth plant investigated, the operators were "spoiled" by a heavy emphasis on mimic panel design throughout the control room, as shown in Figure 5-32. This was the only plant to mimic the safeguards and CVCS panels. The operators at this plant complained vigorously about one exception in the lack of evident panel logic associated with the amorphous and confusing layout of the condensate and feedwater panel shown in Figure 5-33. The trainers observed that this was the most difficult panel to teach trainees.

These examples, which were drawn from all five plants, are a small fraction of the cases observed. They show instances where attempts were made to tie together panel elements when these elements were in the same general area. There was nothing for the operator to do to clarify interrelationships when associated controls and displays were separated by distances of 12 to 40 feet on the control boards as discussed earlier in this section.

OPERATOR PANEL LAYOUT PREFERENCES

Given a choice, the operators, almost to a man, opt for greater or exclusive use of mimic panel design. An overwhelming 90 percent of the operators favored mimic arrangements. The advantages attributed to these panels are summarized by the following responses:

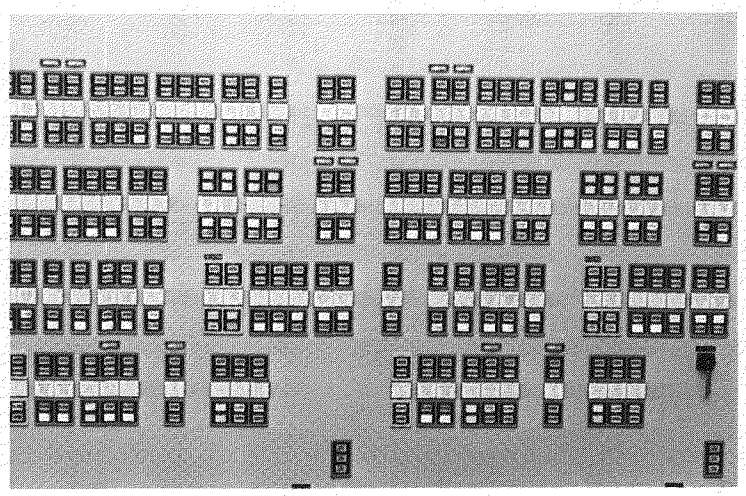


Fig. 5-26. Undifferentiated grouping of safeguards panel elements. Operators at this plant are not allowed to tape their boards to clarify panel relationships.

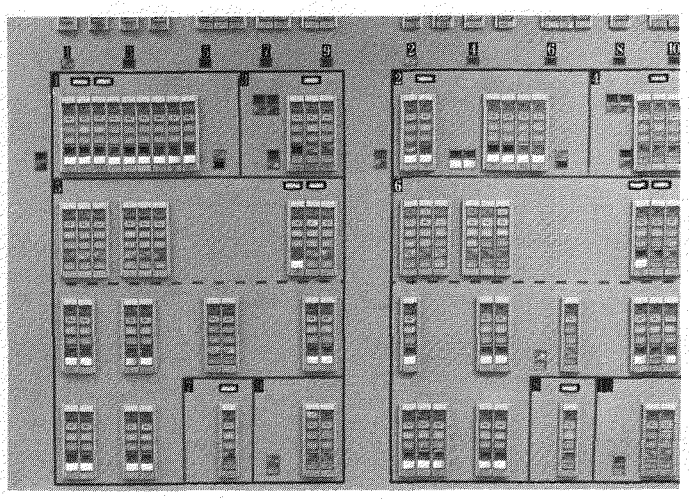


Fig. 5-27. Same panel shown in Fig. 5-26 as configured at the corresponding simulator.

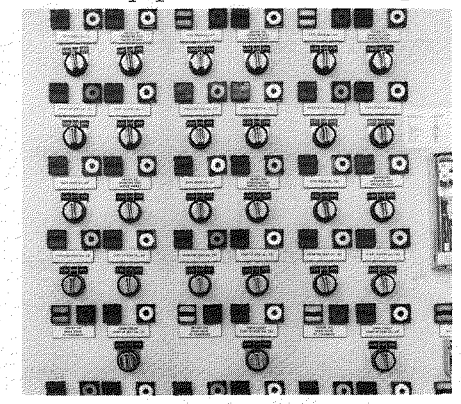


Fig. 5-28. Mass of unsegregated lights and switches found in the simulator.

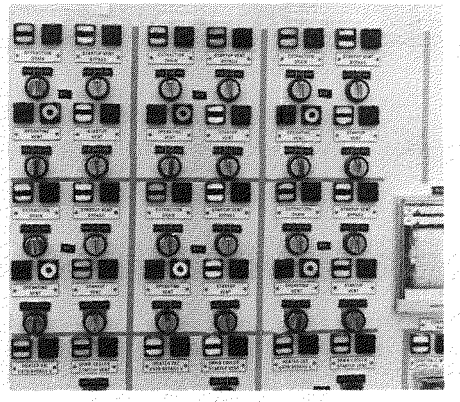


Fig. 5-29. Operators have added tape and labels to the initial design as shown in Fig. 5-28 to clarify panel relationships.

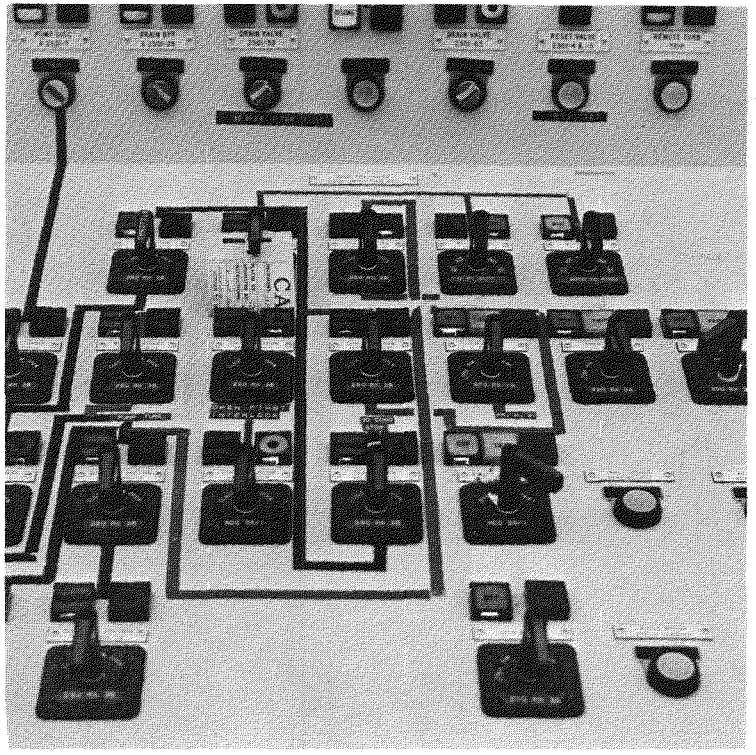


Fig. 5-30. By use of tape, the operators attempt to achieve a mimic panel arrangement.

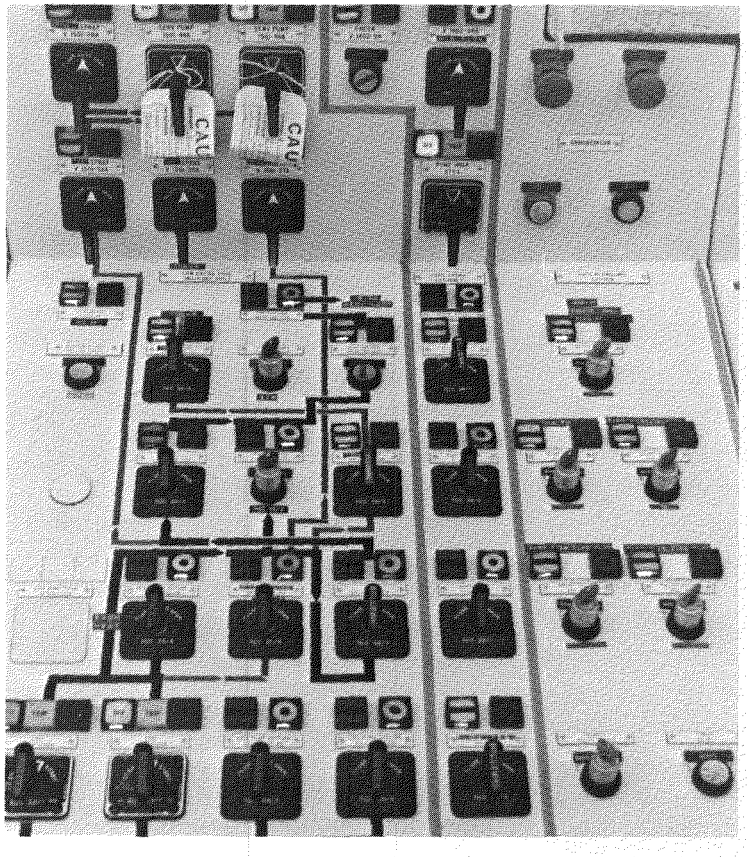


Fig. 5-31. Another attempt to superimpose mimic lines on a panel layout not designed with this rationale.

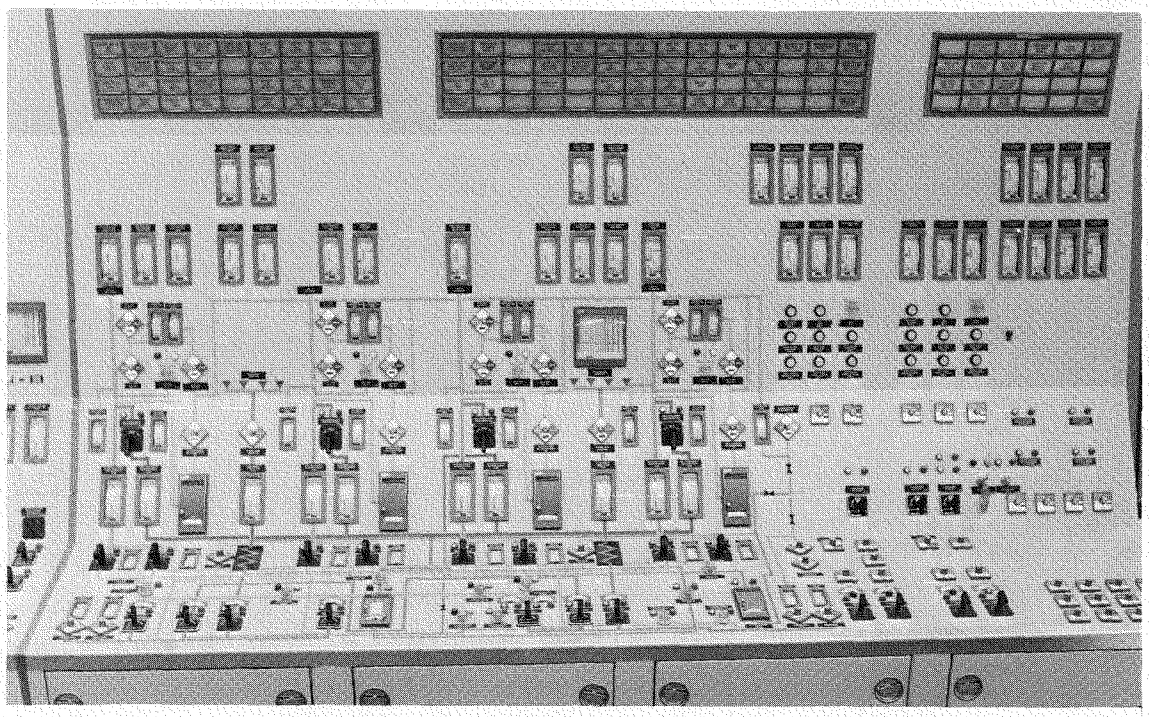


Fig. 5-32. One of the five plants placed a greater emphasis on mimic panel arrangement than the others.

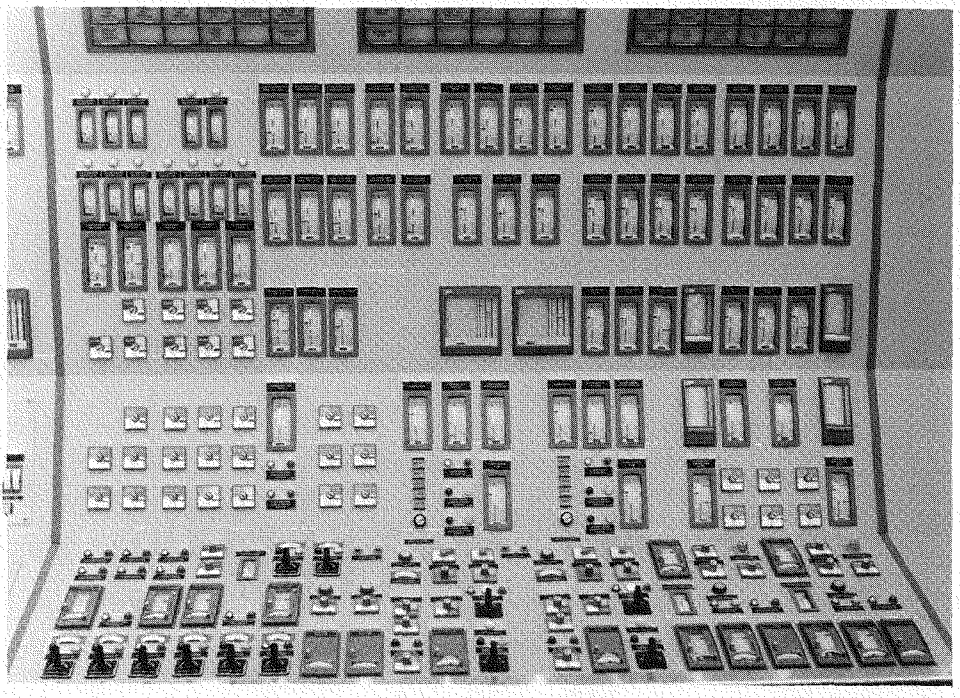


Fig. 5-33. The exception to mimic panel arrangements used extensively at one plant drew strong complaints from operators.

- Mimic panels are great! It is easier to monitor them at a glance. When a valve should be open, the lights tell you immediately if the situation is wrong. The mimic panel refreshes your memory.
- I favor mimic panel layouts. During times of stress, you can easily troubleshoot from the mimic panel. With other panels, in a panic--a hurried situation--you cannot always find that valve, even though you know it is there.
- We could definitely use more mimics. It makes all the difference in the world when you get confused!

A few operators (10 percent) were negative or neutral with regard to mimic panel designs. One felt that mimic panels oversimplified the situation and an operator could get lax if this panel arrangement were employed extensively. Another felt that mimic panels require too much space.

The trainers were favorably disposed toward mimic panels in the same proportions as the operators. They indicated that mimic arrangements were a big help in teaching students to operate the panels. One felt that mimic panels were important for students and new operators, but of less value to experienced operators.

The panels most often recommended for mimicking were the CVCS and Safeguards panels. As was mentioned earlier, only one plant had arranged these panels in a pictorial or graphic format.

The operator's desire for more extensive use of mimic panel arrangements can be interpreted as evidence that control boards often fail to clearly depict system relationships, and thus generate unnecessary confusion, retard diagnosis of system abnormalities, and place an unwarranted and expensive burden on both the trainers and trainees. The multi-unit control rooms with an older board in the midst of more modern control boards show a trend away from the use of large mimic panels (see Figures 5-34 and 5-35). Operators who have experienced the old and the new regret the disappearance of these large mimic boards and feel that economic pressures have caused this trend. Designers, on the other hand, point out that mimic arrangements should be avoided because of the space they consume and the difficulty of modifying them. In fact, the control board which made the most extensive use of mimic arrangements, such as shown in Figure 5-32, was the second largest control board investigated. However, it is felt that mimic panel designs could be miniaturized by using smaller panel components and placing greater emphasis on panel space conservation.

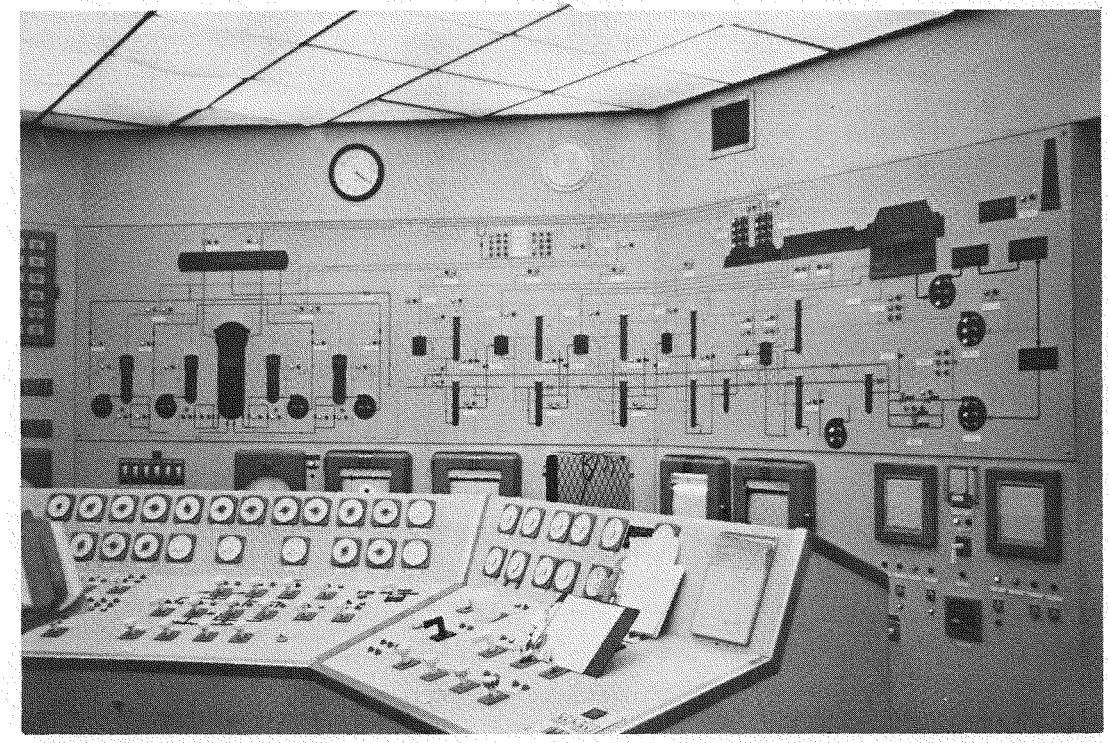


Fig. 5-34. Large mimic panel in the oldest unit of a three-unit control room.

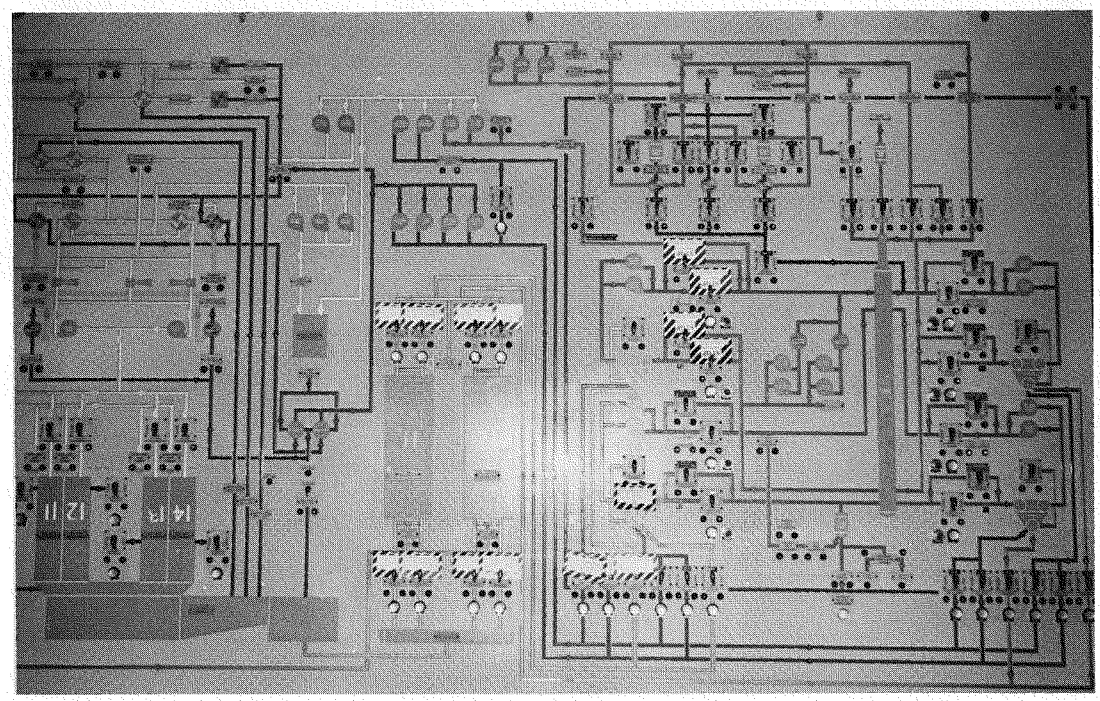


Fig. 5-35. Large mimic panel in the older unit of a two-unit control room.

As systems become more complex, we anticipate that the trend away from large mimic panels will continue. Two answers to the problem seem plausible. In the case of new control rooms that provide many discrete, dedicated control-display elements, better designs will be required to provide clearly distinguishable, functionally-grouped sub-panels, panels, and control boards. However, in our judgment, the advanced control boards based on computer-generated CRT graphic display formats may yield the best operator insights into system relationships. At the same time, they use a minimum of control room space, thereby placing all necessary control-display elements within easy reach of one or two operators. More will be said about advanced control room concepts in Section 20.

MIRROR IMAGING

Of the human factors discrepancies observed, the practice of mirror-imaging control boards in multi-unit control rooms is at the top of the list. With mirror imaging, two side-by-side control boards are laid out symmetrically so that one is a complete, or almost complete, reversal of the other. Figures 5-36 to 5-41 illustrate mirror imaging design practices that were observed at two plants investigated.

Mirror imaging violates the principle of positive transfer of training. The operator is trained intensively to react on the simulator to one set of visual stimuli in a given configuration and one set of controls oriented in one specific arrangement. When he is licensed to operate in the control room he is confronted with two patterns of controls and displays, one of which is the reverse of all his prior training and contradicts all his response expectations. This is what human factors engineers call negative transfer of training; i.e., the operator must "unlearn" something before he can learn to respond to the new stimuli. To show the seriousness of this problem for the operators, let's use an analogy. Suppose we have two identical stick-shift automobiles in the garage, except that the shift positions on one are the reverse of the other. The dashboard displays are similarly reversed. It takes little imagination to see what might happen under adverse driving conditions.

In our analogy, the situation would not pose a problem if the husband consistently drives one car and his wife consistently drives the other. However, in our control room situation, the operators are rotated from day-to-day between the two mirrored boards. When the operator returns from four days off and starts his first graveyard shift before having adapted to a new sleep schedule, he may



Fig. 5-36. Compare this photo with 5-37 and examine the mirrored relationship of the two units.

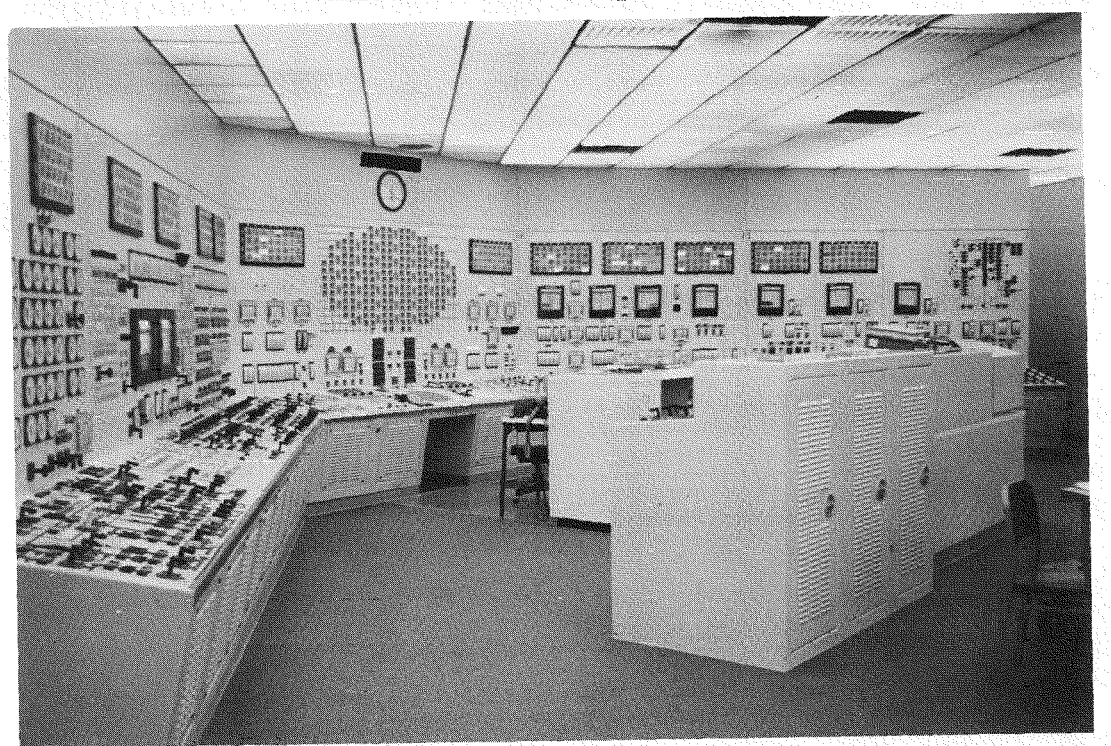


Fig. 5-37. Mirrored control board compared with Fig. 5-36.

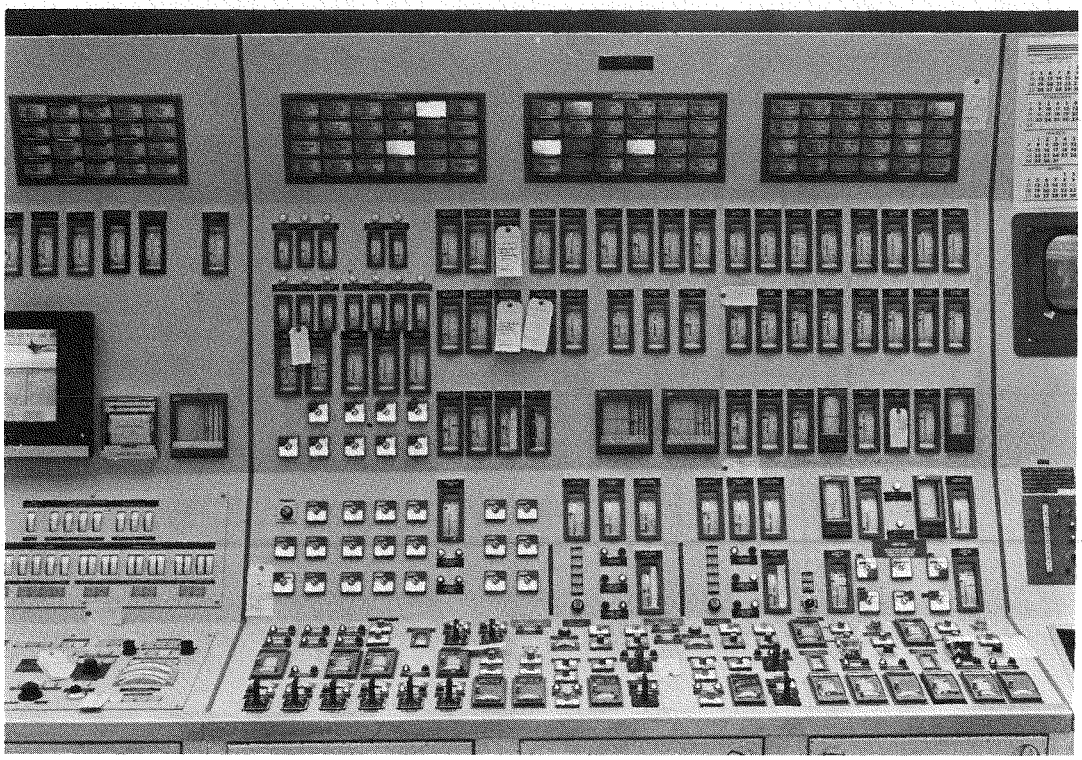


Fig. 5-38. Compare this photo with 5-39 and note mirror imaged arrangement of panel elements.

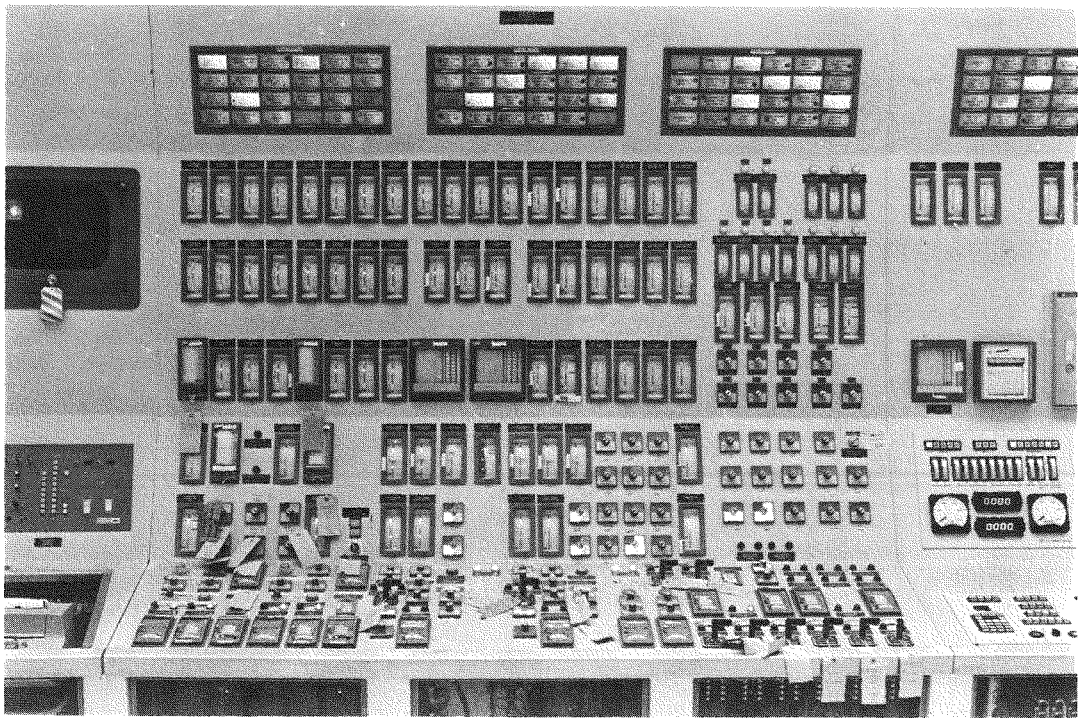


Fig. 5-39. Mirrored version of Fig. 5-38 presently under construction.

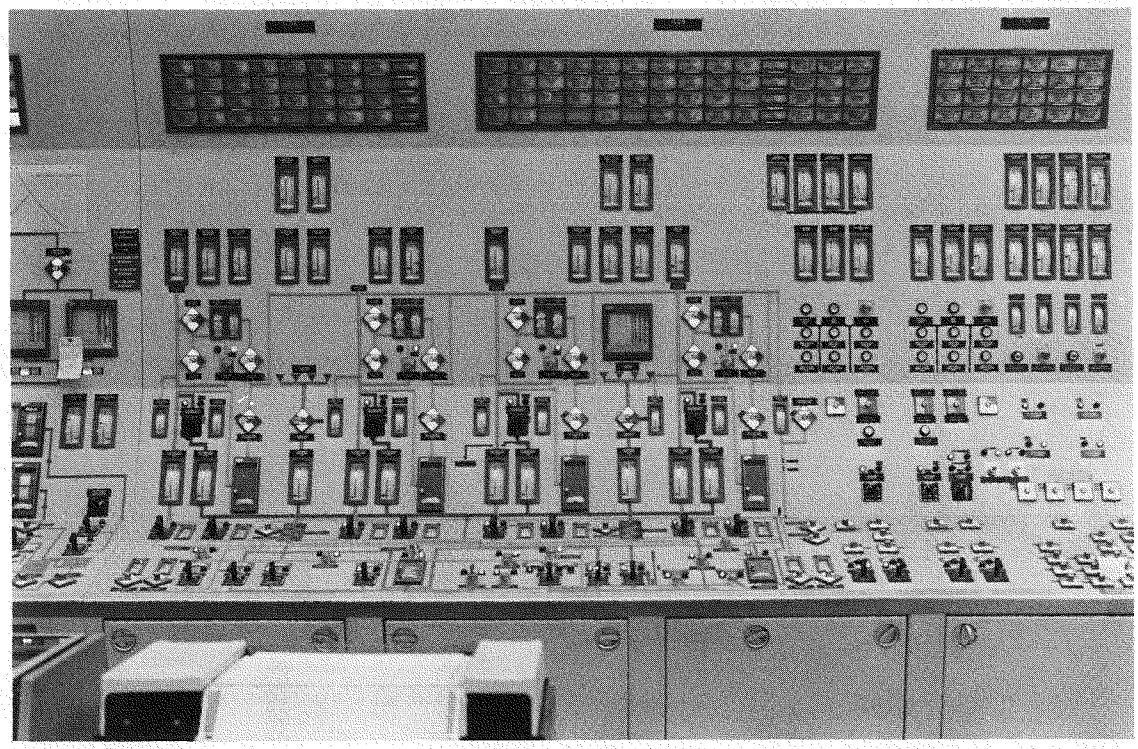


Fig. 5-40. Compare this mimic arrangement with Fig. 5-41 and observe mirrored arrangement.

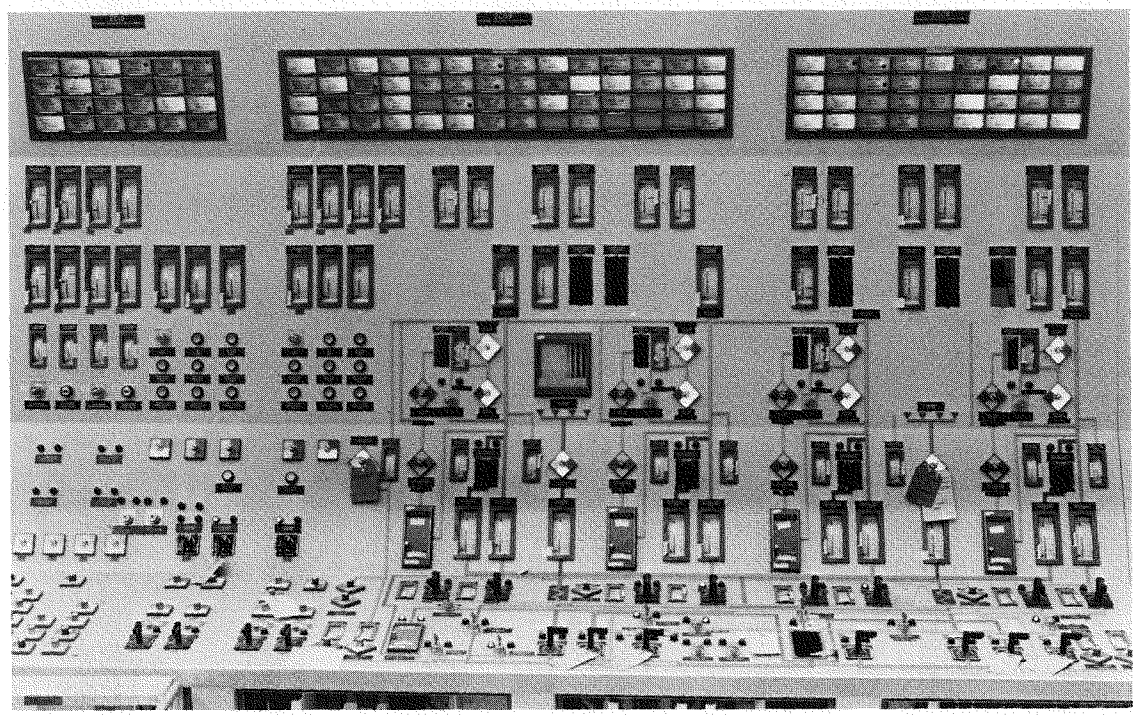


Fig. 5-41. Mirrored version of Fig. 5-40 presently under construction.

be confronted with a sudden emergency and may be completely disoriented for some seconds about which half of the mirrored control boards he is dealing. Comments by the operators are enlightening. At one of the two plants where the boards were mirror imaged, the operators had lived with these boards a number of years. At the second plant, the mirrored half of the boards was still under construction and the operator's comments were anticipatory. Here is what experienced operators had to say:

- Mirror image is lousy! You find yourself getting up and turning the wrong way.
- Units #2 and #3 are mirrored. That's bad news! You get used to one orientation and then get confused--especially when you are new and have just spent 90 days training on the simulator.
- Mirror imaging is a problem because of the simulator being like Unit #2. I still find myself hesitating--the first outs, trip alarms are on opposite sides. This causes delays in responding. I would prefer identical rather than mirror-image layouts.
- Mirror imaging is a problem for the first three weeks. Now it isn't a problem.

The operators who were about to operate a mirror imaged control board that was under construction had the following to say:

- There will be problems with mirror imaging--everyone agrees. You automatically head in the wrong direction.
- It's terrible to have to operate Unit #2 after #1. We complained about it but the decisions were made before we were hired. It's going to be hell to operate. We've already made mistakes. You have to keep your right hand in your pocket and then it's not so bad.
- Mirror imaging wouldn't be so bad if they had located the panels as they are but didn't change the arrangement within each panel.

The operators also pointed to inconsistencies in mirror imaging--cases where complete mirroring had not been followed. The arrangement of specific annunciators within the annunciator warning panels is a good example. In one plant, although the two control boards were mirror images, the annunciators were maintained in the same arrangement for both units. This arrangement was used so that common procedural references could be used for both sets of annunciators. At another plant with mirror imaged control boards, the annunciators were also mirrored. In this case, the designers simply reversed the location code on the annunciator panels so that the one set of procedures was common to both sets of annunciators.

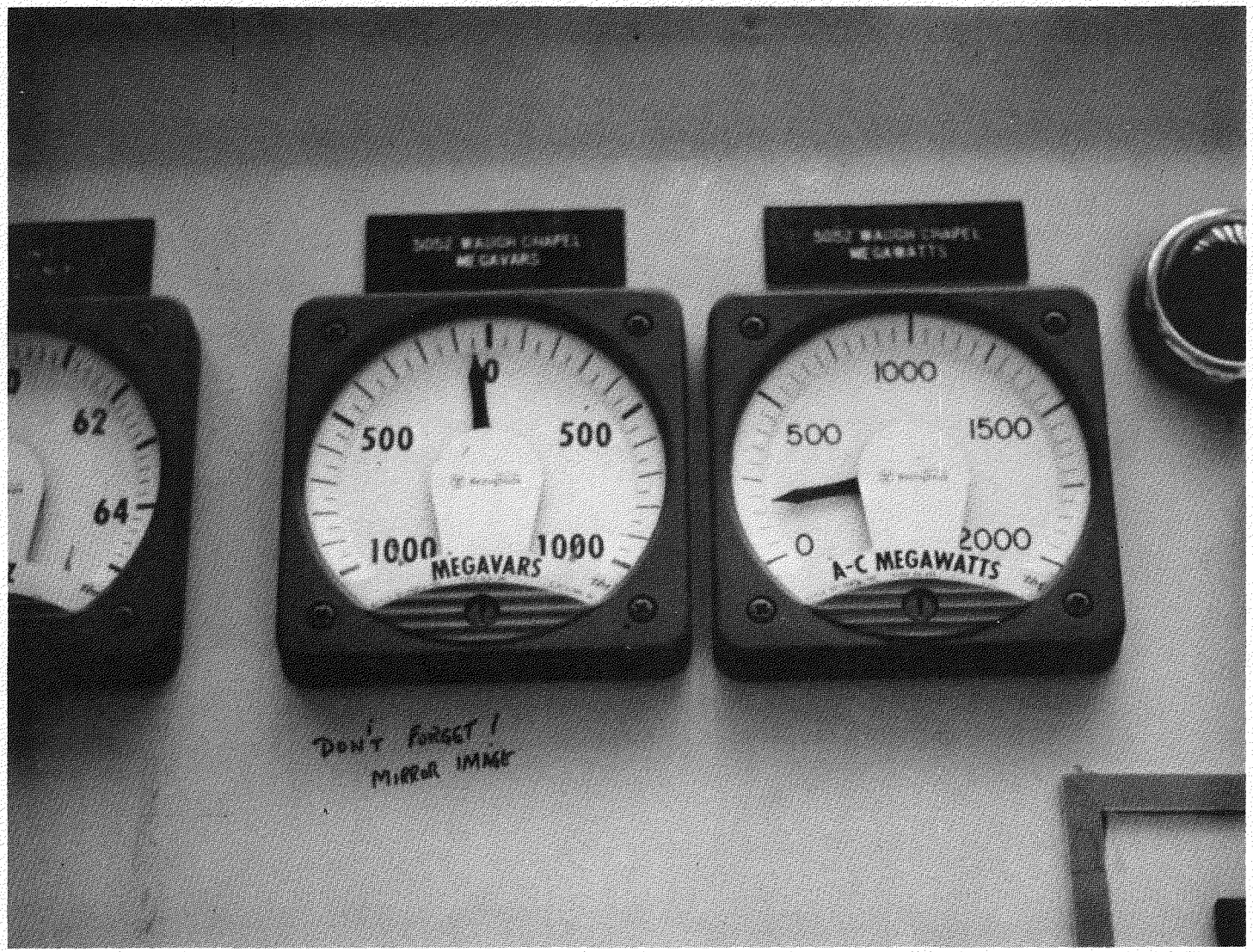


Fig. 5-42. Note the cue the operators have scribbled on the panel to indicate the starting point for the mirrored arrangement.

Why have the utilities opted in many cases for mirror imaged control boards? Two primary reasons have been offered. The most common is that the mirror imaging is aesthetically pleasing. The more plausible explanation heard is that considerable economies are effected due to architectural considerations and the ability to cut identical cable lengths for two-unit control boards.

In our judgment, any economies resulting from mirror imaging are not justified considering the penalties exacted in potential operational degradations. We strongly recommend that this design practice be abandoned. The plants that already have mirror-imaged control rooms should strongly consider two measures to alleviate the situation. First, operational crews should be committed to one or the other mirrored half of the boards, and not be allowed to alternate between the two. Second, the distinction between the two mirrored units should be heightened to the greatest extent possible, especially if the first measure is not feasible. This can be done by using two color schemes to differentiate the two units--the board surface areas, the operator stations, and the carpeting. At present, the operator is left to his own devices to show where mirror imaging begins, as is shown in Figure 5-42.

TOO MANY OR TOO FEW INSTRUMENTS

Upon entering the nuclear power plant control room, the study team's first impression was one of bewilderment at the vast array of controls and displays presented to the operator. An "educated" guess was that the operator was being overloaded with redundant and superfluous instrumentation, perhaps to serve the engineers' interests for system data, rather than to provide the operator the minimum and simplest control boards for effective system management.

Accordingly, two questions were put to the operators bearing on this issue: "Does your control room include more instrumentation, controls, and displays than are really needed for you to do an effective job?" And, "Does your control room lack important instrumentation, controls, and displays which would help you do a more effective job?"

Much to the surprise of the study team, the overwhelming sentiment of the operators--more than 90 percent--was that their control boards lacked essential or important instrumentation rather than there being a large percentage of superfluous instruments and controls. Only 25 percent of the operators were able to point to unnecessary instrumentation--and most of these comments came from one of the five plants investigated. The perceived lack of control board instrumentation fell into

several categories of omissions. In some cases the operators felt that important control functions had been relegated improperly to auxiliary operators outside the control room and that this prevented effective management of the system. In other cases, important instruments or display parameters were seen as simply not available anywhere in the plant. Some operators pointed to recorders that were overloaded (see Section 11) in the interest of economy. These operators felt strongly that additional recorders were required in lieu of illegible recorders with overly long cycle times. A few mentioned instruments that did not function properly, causing them to do without important data. Finally, many pointed to the lack of important instrumentation within the operator's primary sphere of operation and the placement of such displays and controls in back panels or remote areas of the control room.

Some of the instruments, controls, and displays the operators at one of the five plants saw as lacking in their control rooms are as follows:

- Turbine lube oil temperature is given by the computer but we need a separate display.
- Delta P indicator displaying the difference between steam and feedwater pressures is needed.
- RCP seal water injection flow indication is lacking.
- Boric acid system status display is required.
- Excess letdown flow indication is needed.
- We need controls for reactor cooling drain tank. We have to call on the auxiliary operator.
- More readily accessible radiation monitoring information is required.
- More specific annunciator alarms are needed. For example, one alarm window comes in on HIGH/LOW Level or Pressure. Four separate indications are needed in such cases.
- Need speed indication on positive displacement charging pump.
- The containment isolation valves and ventilation systems should be located on the front of the control boards.
- Need more specific alarms for the Stator Water Panel and the Hydrogen Panel. When we get a general alarm, we must call the auxiliary operator to a local panel and time is lost.
- We need a CRT for more computer readouts.
- We need more information displayed on recorders instead of meters so that trends can be monitored.
- We should have dual ranges on variables which vary widely such as feedwater flow, steam flow, etc.

The writers are not qualified to judge the merits of each perceived lack of instrumentation. However, there is apparently a wide variation from plant to plant as to

the specific parameters displayed, the means of display, and the importance assigned to these parameters in terms of location in primary or secondary control room areas. This wide variation suggests that no comprehensive or generally agreed upon list of major display parameters and associated control options has been developed on the basis of systematic functions and task analyses of the operator's role in the control room. Such analyses should be conducted to guide the development of future control rooms.

A major issue that emerges from discussions with operators is the division of control and display functions placed in the control room and those placed locally in the plant under the surveillance of auxiliary operators. The control room operator typically feels that he should have direct access to information and direct control of system events. To the greatest extent possible, he wants to minimize reliance on auxiliary operators, especially when a casualty or emergency is developing. At some plants only one auxiliary operator is available to the control room operator and, at the other extreme, five auxiliary operators are required at another plant. This variation in manning levels to support the control room operator suggests that an optimal balance between control room functions and in-plant functions has not been developed or applied throughout the industry. The cost of one versus five auxiliary operators is significant and it may be more cost-effective, as well as efficient, to provide more comprehensive and direct control from the main unit control room. This question also needs to be answered on the basis of functions and task analyses to establish the optimal work load distribution between control room and auxiliary operators.

ROD MONITORING DISPLAYS

The rod or core monitoring displays are generally the central focus of the control boards. As such, we will single out these displays to point out the variability of display design approaches. The five display configurations observed are shown in Figures 5-43 to 5-48.

The design shown in Figure 5-43 provides a series of meters with scales ranging from 0 to 144 inches to describe the excursion of the rods. When the rods are fully inserted, red lights are illuminated at the base of the meters. Associated with these meters are a series of counters that show the movement of groups of rods. Surprisingly, the counters show numbers of steps from 0 to 230, each step representing a movement of 5/8 of an inch. Therefore, the operator must convert steps into inches by multiplying the counter number by 5/8ths, an unnecessary

chore that could produce arithmetic errors. Furthermore, the counters are not organized with respect to their related meters as might easily have been done if the chart recorders and the black placards had been oriented differently. The row of red lights at the base of the meters provides an effective cue that all the rods have been inserted. However, indicators with two bulbs, or a two-color indicator (rod-out and rod-in), should have been used because an expended bulb could falsely indicate a rod-out condition.

Figure 5-44 shows a comparable arrangement of meters and associated counters. In this case, the counters are placed on the benchboard segment of the console. The counters and meters read in the same units--more reasonable comparison tasks for the operator. In this design, the need for a core map on the panel was not considered essential.

The third display of this type is shown in Figure 5-45. In this arrangement rods-in and rods-out indicator lights are aligned so that there can be no mistaking the absence of one or several lights from a straight line of indicators. Rod position meters are integrated into this display, but the counters observed at the first two plants are lacking. This display, which is ordinarily associated with the reactor control panel, is on a back wall, remote from the reactor control panel (see Figure 5-46). The operator stationed at the primary controls cannot read the markings on this panel.

Figure 5-47 shows a bewildering matrix of indicators used on the core display at the fourth plant. These indicators reflect the geographic arrangement of the core elements, usually a good idea. However, trying to discern an absent rod-in or rod-out indicator in this morass is markedly more difficult that noting the appearance or lack of one light in a straight line array in the three earlier cases.

The fifth rod display (see Figure 5-48) is similar in concept to the one above, but it is not nearly as busy and confusing. The designers did not force as much data into this display. Location cues are also available. However, again, it is harder for the operator to spot deviations than in the straight line indicator displays described above. One trainer described this core monitor display as useless. He pointed out that the pattern of lights on this display "do not hit you in the face." In his view, an associated METRASCOPE display on an adjacent panel told the operator all he needed to know.

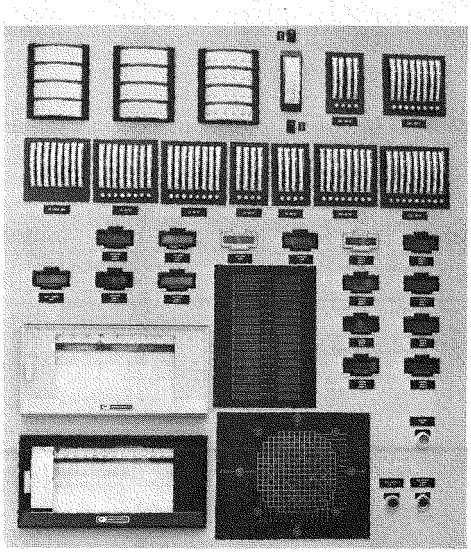


Fig. 5-43. The core monitoring displays at Plant A include meters and counters for rod positions, rod bottom lights, and a core map.

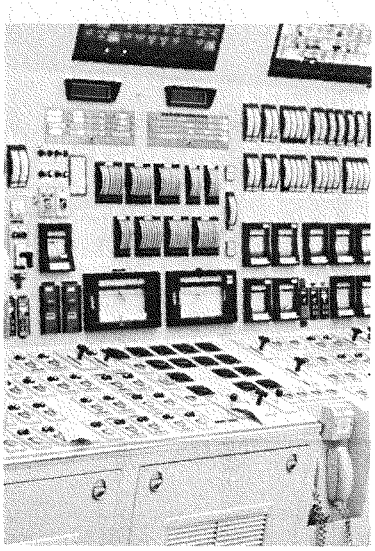


Fig. 5-44. A comparable arrangement to Fig. 5-43 is shown with counters placed on the benchboard in this case.

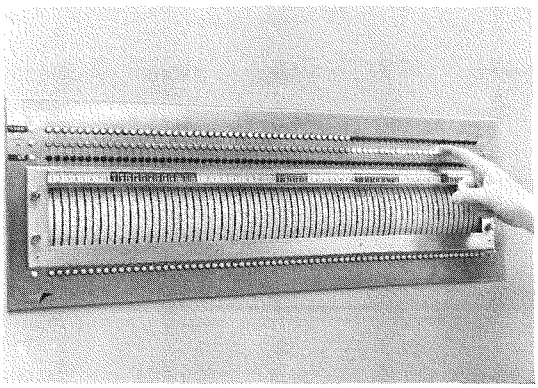


Fig. 5-45. Straight line alignment of rods full-in or full-out provide good cues of deviations.

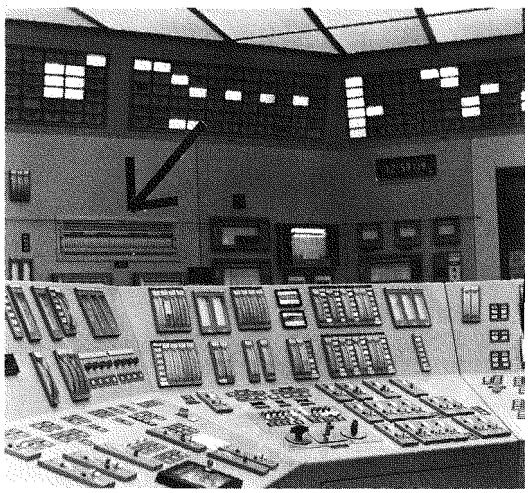


Fig. 5-46. The rod monitor display shown in Fig. 5-45 is poorly placed with respect to the reactor control panel in the foreground.

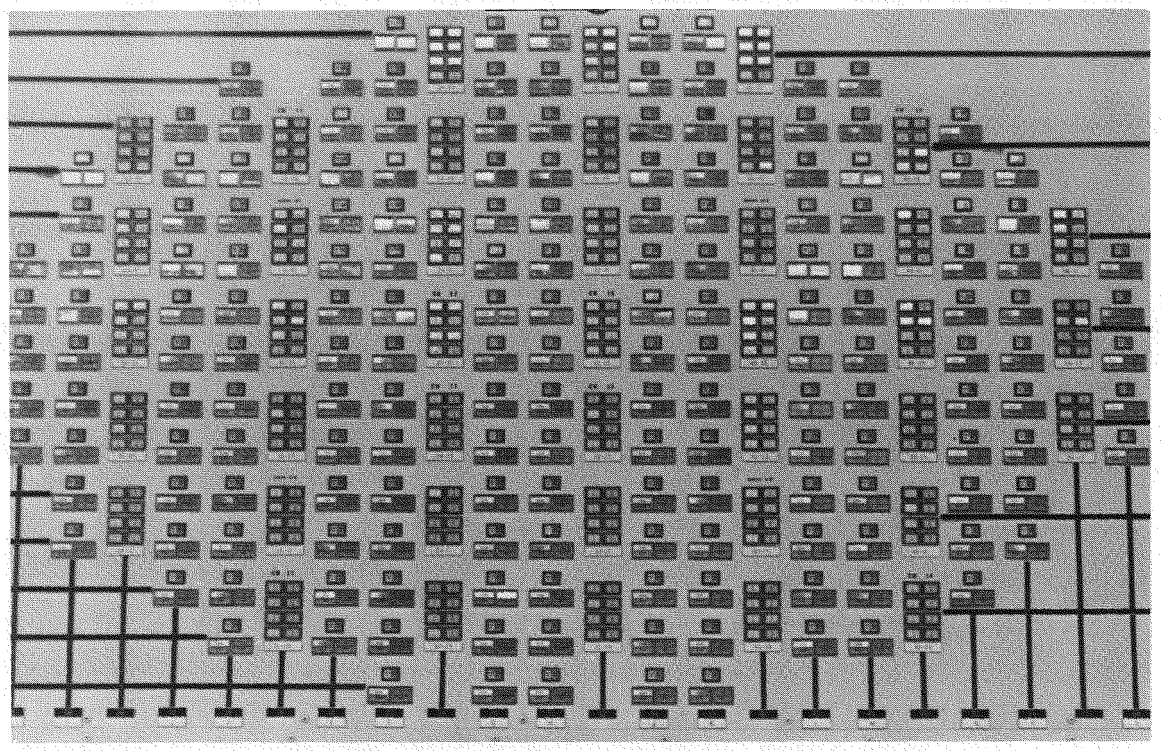


Fig. 5-47. Most elaborate of the core monitor displays. Exceptions are hard to spot.

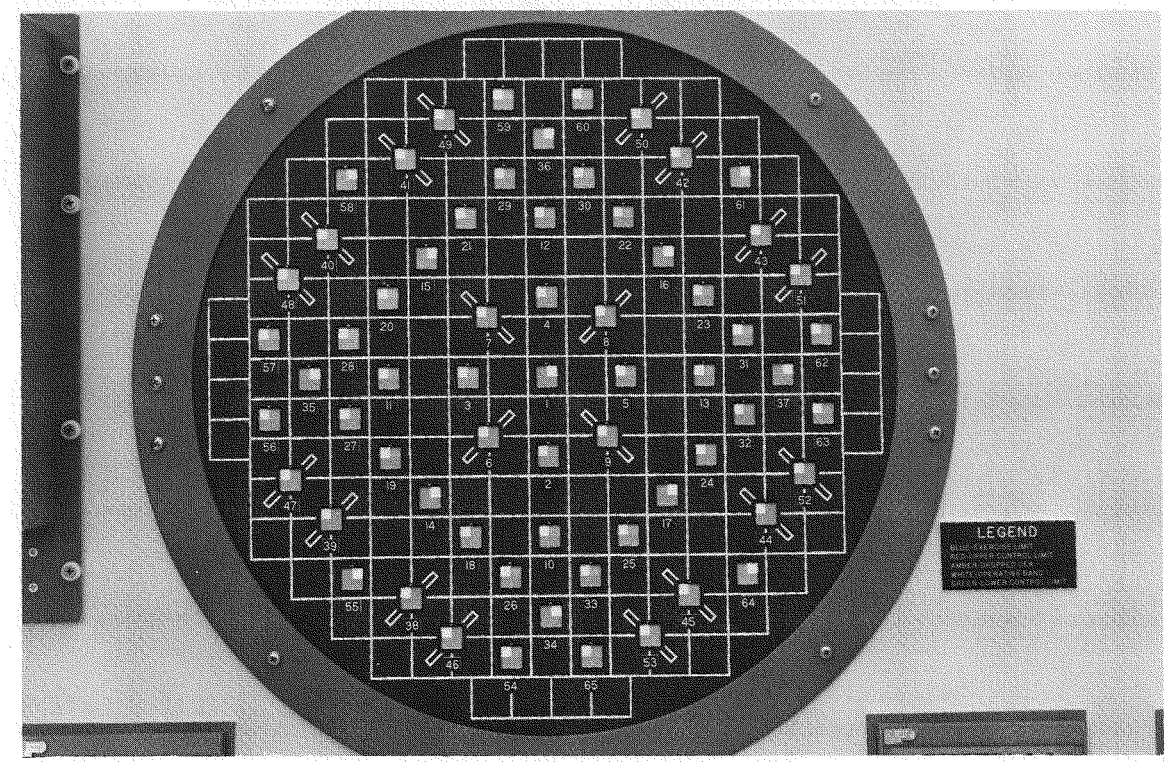


Fig. 5-48. While not as complicated as Fig. 5-47, deviations are also hard to spot on this array.

Hard data are lacking on the relative effectiveness of the five display configurations. It is evident that different designers perceived different information needs for the operators. The validity of their assumptions can only be derived through human factors research designed to provide quantitive error rates associated with competing design concepts.

CONTROL BOARD ADDITIONS AND MODIFICATIONS

The life of a nuclear power plant is usually said to be forty years. It would be unreasonable to expect that the control room would remain unmodified during the entire life of the plant. In fact, it was apparent that the control rooms observed had undergone extensive modifications after a few years of operation (see Figures 5-49 and 5-50). If we project these trends over forty years, it seems likely that today's control room will be unrecognizable. Our concerns with control board or control room modifications, from the human factors standpoint, are three-fold. First, because additions to control boards are almost inevitable as new requirements are generated, the control board design and the control room layout must allow for orderly growth. Second, as these additions or modifications are made, they must not compromise the established human factors principles of design and thereby degrade the man-machine interface. Third, when operational experience indicates persistent human factors problems with a given panel, subconsole or annunciator array, modifications should be planned and installed during scheduled down-times such as refueling. Let us examine these three points in greater depth.

There is often not enough clear space on the control boards to accommodate additional control panels. Additional consoles then impede traffic patterns and visual access between the center desk operator's station and the unit operator's station as shown in Figure 5-51. In other cases, the requirements for additional instruments and controls are met by placing instruments on back panels, outside anthropometric limits on the control boards, or in remote corners of the control room that take the operator away from his primary control board areas of responsibility. In one case, (see Figure 5-52), additional panels were added at the left extremity of the long board, far from the main "flight" console to the right. Sufficient spare board room could have been reserved for growth by using the space conservation techniques described earlier. It would be difficult to estimate what would be a reasonable initial space allowance, but a 20-25% growth factor can serve as an educated guess.

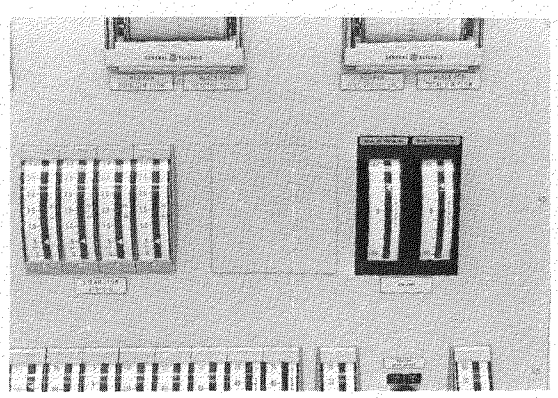


Fig. 5-49. Example of control board modification. Note the panel patch where displays have been removed.

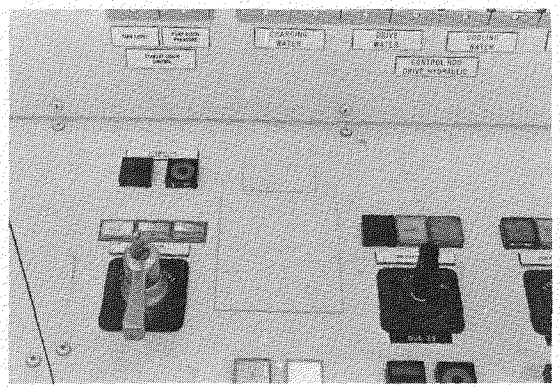


Fig. 5-50. Another area of the control board showing patch-up marks.



Fig. 5-51. The requirement for additional consoles limits traffic accesses.

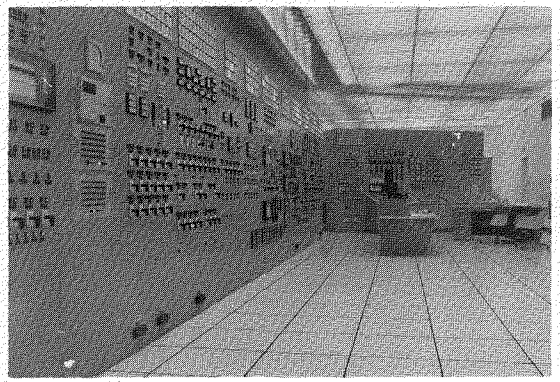


Fig. 5-52. As additional panel space is needed the long board to the left is extended further.

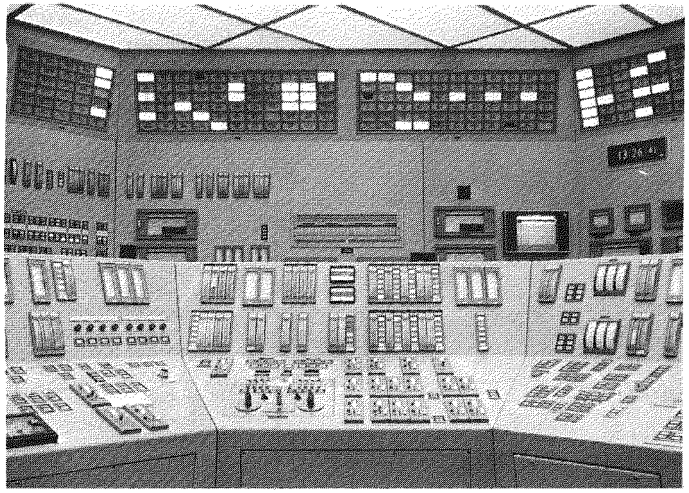


Fig. 5-53. Feedwater controls that were initially grouped in one location on the primary console in the foreground are now spread out illogically.

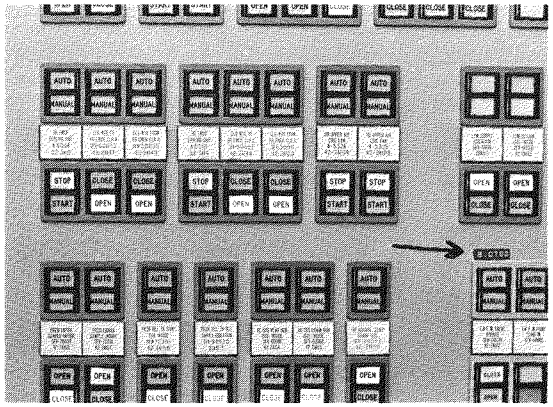


Fig. 5-54. The groups of "A" and "B" segments of the Safeguards panel are not entirely consistent. Note "B" element in the middle of the "A" segment.

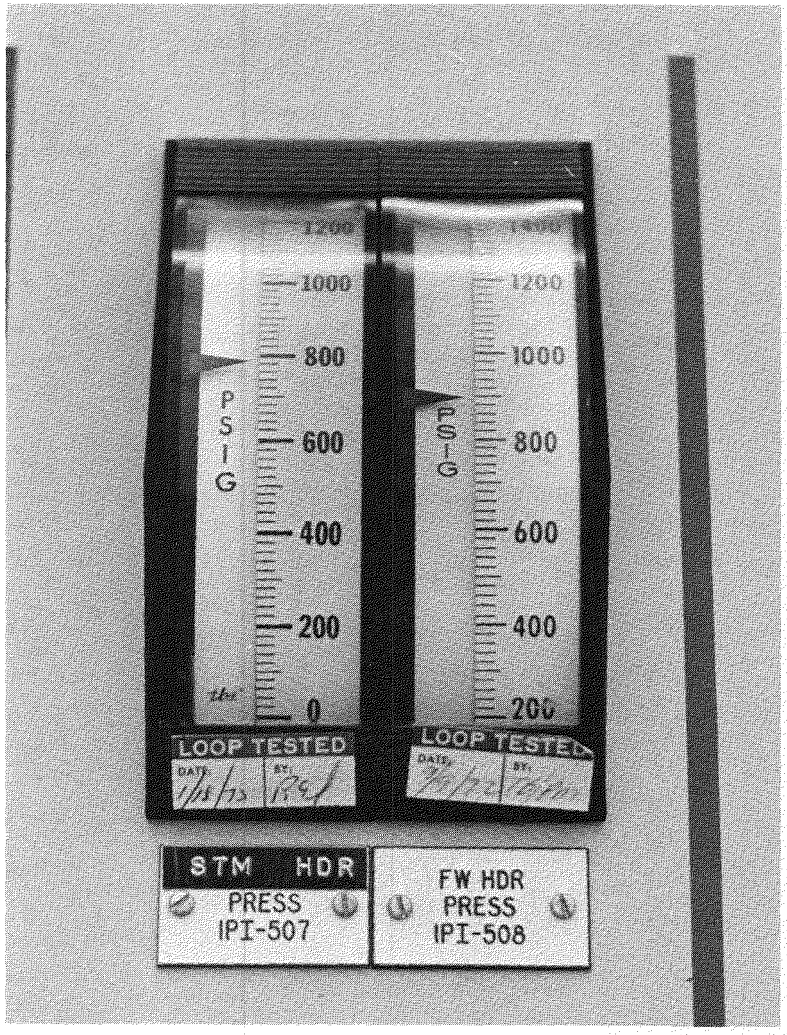


Fig. 5-55. The two meters must be compared directly but different scales are provided.

Our second point is that modifications to panel designs should not violate human factors principles. In some cases the initial logic of the panel layout was violated as modifications became necessary. For example, in the layout of the primary panels shown in the foreground in Figure 5-53, the feedwater controls were located on the right hand console segment. Later, the panels were back-fitted with some feedwater controls on the console segment left of the center panels. This illogically separates functionally related controls for feedwater pumps and feedwater valves. The operators complained about this awkward arrangement.

In the same control room, the safeguards panel is functionally grouped into an "A" segment to the left and a "B" panel to the right. However, a "B" element has found its way into the "A" panel as shown in Figure 5-54, and an "A" element is now in the "B" panel. These exceptions compromise the initial logic of the panel layout and should be corrected at the first opportunity.

The third problem here is that some operational problems remain unremedied after they are discovered. There seems to be a significant amount of inertia or unresponsiveness to operator needs or pleas for changes. Whenever the study team uncovered a human factors problem that was blatant, the inevitable question put to the operator was, "Why hasn't this problem been fixed?" The operators often shrugged their shoulders and could not explain why their appeals for modifications went unheeded. For example, the feedwater header pressure and the steam water pressure indicators shown in Figure 5-55 must be compared directly by the operator. Yet the meter scales do not match. The difference in the two pressures is a matter of operational importance and, in fact, a differential pressure meter might be most appropriate. The operators claim that they have been trying to have this changed for four years. In some cases, cost is a consideration. In other cases, channels of effective communications between management and the operators are lacking. Some felt that certain inexpensive changes, which everyone agreed would be improvements, required so much paperwork and formal requests for NRC approval that they were more trouble than their worth. By way of contrast, one plant visited had a program that offered incentives of up to $1000 for operator suggestions.

Human factors problems are sometimes carried over to a second control board when a generating unit is added to the plant. Figure 5-56 shows the incorporation of a supplementary item in an operational control console. This appears to be a temporary expedient. However the same supplementary unit is used in a second control

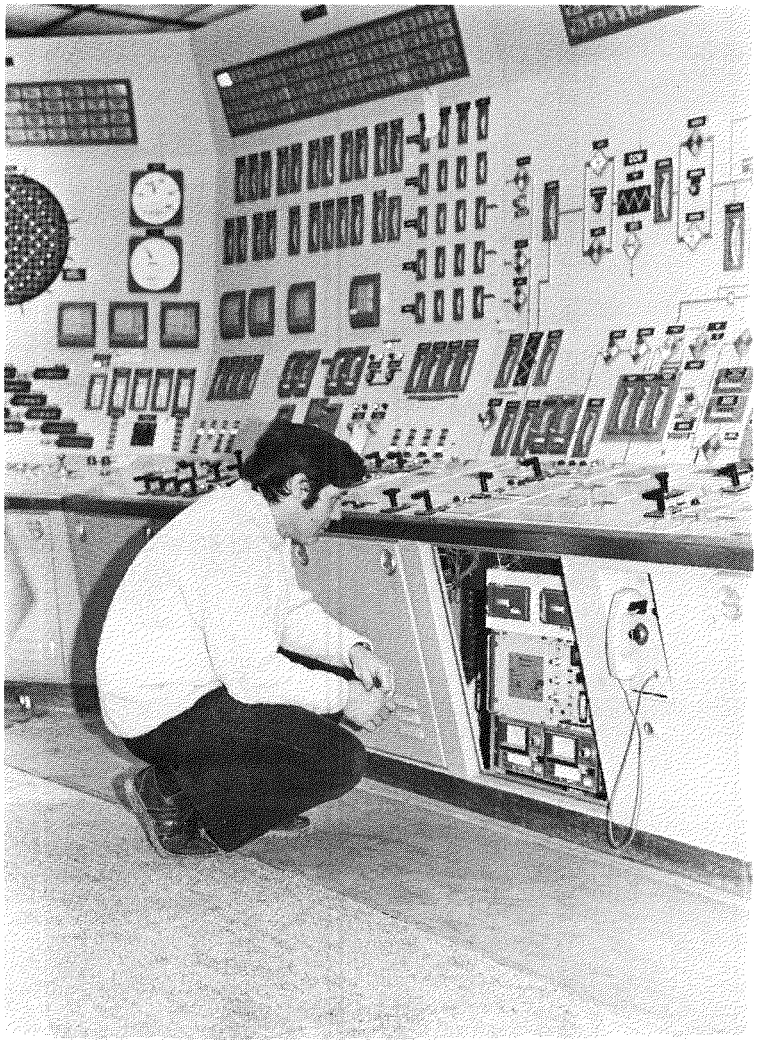


Fig. 5-56. Note what appears to be a temporary location for an additional panel under the benchboard.



Fig. 5-57. The "temporary" panel addition is being carried over to the second unit under construction. While the two control boards are mirror imaged, these under the bench panels are not mirrored.

board under construction. The second control board is a mirror image of the first one, with the exception of the layout of the added rack below the benchboard (see Figure 5-57).

The utilities must take advantage of refueling periods to make required modifications of the control boards, just as they use such periods to overhaul major equipment. This is a matter of establishing new priorities and considering the importance of human factors in minimizing the probability of costly operator errors. One of the plants visited is thinking along these lines and a particularly troublesome panel has been redesigned. At the first opportunity, the new panel will be assembled and installed.

THE COMPUTER

Each of the five control rooms investigated had its own computer. Computers are used to track a variety of plant parameters, perform complex calculations such as flux mapping, gather historical trend data, provide automatic logging of events, and present alarms to the operators. All of the plants had print-out typewriters associated with their computers (see Figures 5-58 and 5-59). There was wide variability in the nature of readout devices associated with computer output. Only one of the plants visited had a CRT readout of parameters (see Figure 5-60). Others had digital readouts, meters, or chart recorders that could display computer generated readouts at the discretion of the operator. Computers are generally regarded as a supplement to the dedicated, hard-wired control boards rather than as serving as the primary focus of the operator's attention.

Operators and trainers were asked to describe the functions served by the computer, to comment on the usefulness and reliability of the computer, and to indicate desirable changes or additions in computer usage. These questions brought a varied response from the five plants visited.

The major problem that emerged was the unreliability of the computers. This was a major concern of the operators in four of the plants. The operators in the fifth plant were satisfied with the reliability and availability of their computer compared to what they had heard was the case at the other plants. The second major problem was insufficient training in computer use. For example, the computer at one simulator training center was not included as part of the simulated control room. Even when the control room simulator includes a computer, the operators apparently do not receive extensive training in the operation, programming, or

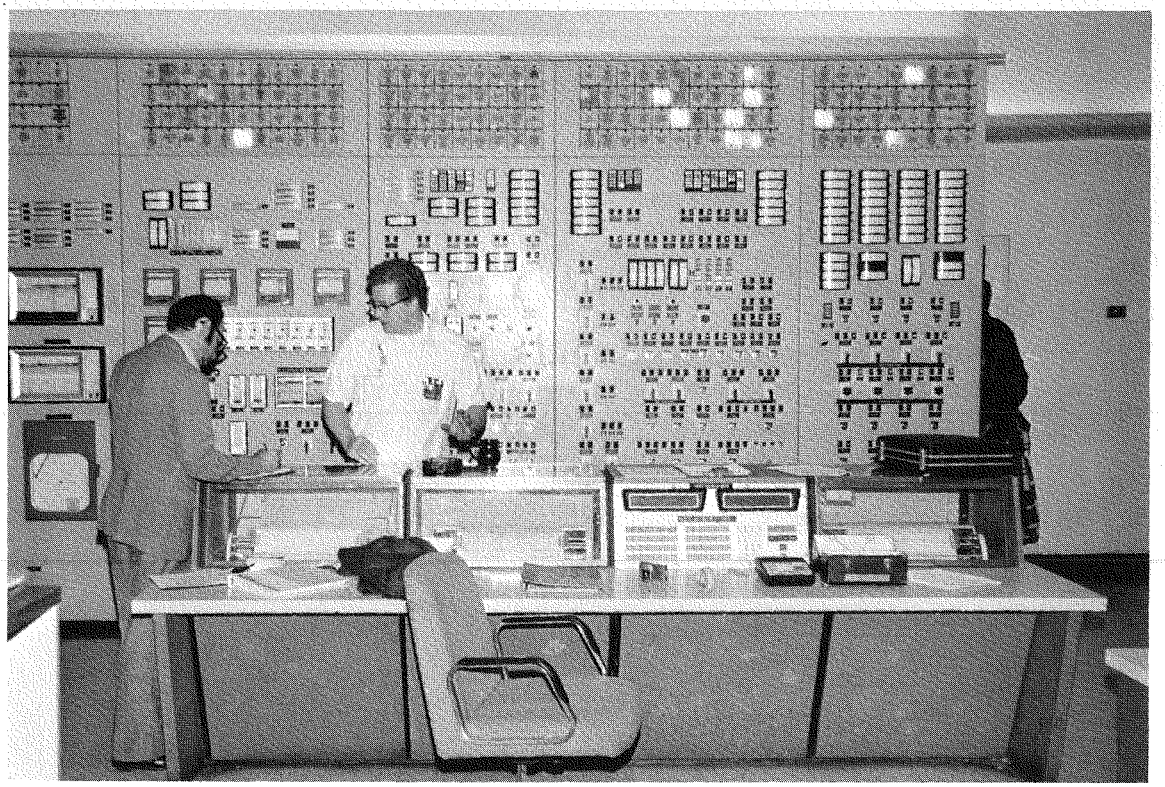


Fig. 5-58. Computer console and printout at one plant.

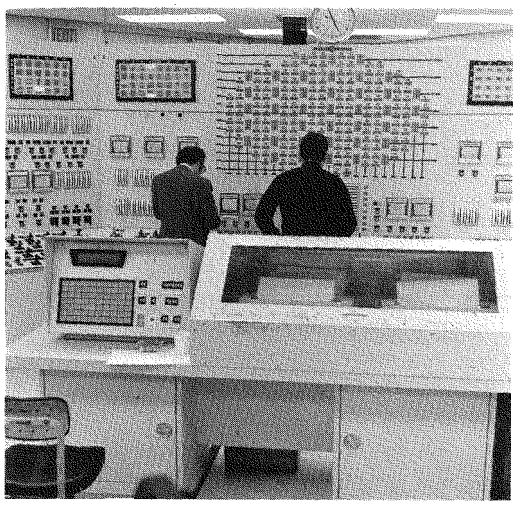


Fig. 5-59. Computer control console to the left with typewriters to the right.



Fig. 5-60. One plant had a CRT display of computer readouts in addition to typewriters.

general capabilities of the computer. Most of the operators' knowledge of computer use is derived from on-the-job training and experience. This is unstructured and varies from plant to plant and individual to individual.

These factors have produced much of the operators' general distrust of computers. There is an accompanying sense of frustration; reliable computers are generally perceived as labor saving devices, and the operator would generally assign more, rather than fewer, functions to the computer. As will be discussed later, negative operator experiences with present computers have colored their views and expectations of advanced control room design concepts based primarily on computer systems.

Representative comments from the operators reveal specific and general problems associated with computers:

- The computer gets bogged down and it may take half an hour for an answer. We should have a line printer to obtain a faster printout.
- The computer needs a more reliable power supply.
- We should have a backup computer in cases where the primary unit fails.
- We should have CRT readouts for our computer.
- I would prefer pushbuttons to the thumbwheels which are provided for inputting to the computer.
- The audible alarms that the computer generates have been disconnected because of loudness and the frequency of false alarms. You can't believe 99% of them!
- Operators do not keep up on how to do calculations in case the computer is out of service.
- I would like more information as to what it (the computer) will do and how to do it.
- Computer repairmen only work days. If it breaks at night or on a weekend - - - -.
- The computer is a good aid but you shouldn't rely on it. It is not dependable since it fails often. It gives erroneous alarms and data when operating at max or min end of the range. It keeps coming in with bad output. The alarms are distracting and "cry wolf" symptoms develop. I have disconnected the alarms in the past.
- During start-up most computers malfunction and from then on the operators distrust it.
- The computer alarm is weird so it was unplugged. We get a visual alarm. Some computer-generated alarms are unreliable so the operator ignores them. You can't believe 99% of alarms. I would settle for 75% accuracy. If you believe every alarm you would have a guy (auxiliary operator) running all over the plant. They get real mad at you and there are hard feelings. I've been in his shoes.

- I trust computers but not programmers!

Nevertheless, the operators felt their computers could be used to greater advantage in performing additional functions:

- We could and should use the computer to handle in-core monitoring.
- Management does not rely on the computer. The operators are asked to take readings that the computer could handle.
- The computer should provide some secondary plant readouts.
- The computer should include rate alarms or rate of change of processes. This computer does not look at enough variables.
- We have the ability to allow the computer to move rods but the administration will not use this due to peaking factors, fuel density, and other NRC regulations.
- The computer requires a CRT readout which provides emergency procedures.
- We could use more trend recorders hooked to the computer to produce readouts.
- The computer should be programmed to calculate estimated critical rod positions and do shut-down margin calculations.

There was sufficient variability from plant to plant in the functions assigned to computers, computer printout and readout devices, and the attitudes and expectations of operators to suggest that an optimum operator-computer interface has not been developed. It seems clear that the computer, when placed in the hands of a well-trained operator, could be of tremendous value in control room operations. However, the responses from operators suggest that a separate and more detailed study should be made to specifically explore the operator-computer interface.

IN-PLANT CONTROL PANELS

While this study concentrated almost exclusively on the main control rooms of each nuclear power plant visited, the study team was able to examine, in a cursory fashion, control panels remotely located from the main control room. These remote panels served such functions as water demineralization, emergency shutdown in the event that the control room became uninhabitable, and monitoring of radiation waste processing. Brief walk-throughs of the plants showed that these remote panels deserved human factors attention to an even greater extent than the main control rooms. In fact, it would appear that the main control room tends to be treated as the showplace of the plant--a place where the plant superintendent can parade visitors with pride. By way of contrast, some of the in-plant panels were located in such cramped quarters that it was sometimes not possible to obtain photographs.

In general, not much thought was given to providing adequate illumination to these remote panels, and labeling practices could best be described as primitive. Often anthropometric guidelines were totally ignored, and if these panels were grouped according to functional relationships, it was not readily apparent. A sample of photographs taken during these plant walk-throughs (see Figures 5-61 to 5-69) speaks more eloquently than words. In discussing these panels with senior operational personnel who guided us through the plants, it became obvious that operational problems are not uncommon with these panels. Also the men who operate these panels are not as rigorously selected nor as highly qualified by training as control room operators.

There were exceptions to the foregoing. Perhaps the best example of a well-designed mimic board was observed, not in an operational control room, but rather, in a remote plant location. As Figures 5-70 and 5-71 reveal, the elaborate mimic board integrates chart recorders, controls, meters, indicators, and color coded flow lines in a manner which would ease the task of any operator. Plant personnel indicated, with understandable pride, that special pains and expense had been expended in acquiring this panel, but in their view the effort had paid off, considering operational difficulties encountered with other panels.

MISCELLANEOUS

While admittedly a relatively small point, one of the human factors evaluation criteria addresses itself to the clutter introduced by vendor logos and identifying placards. Such additions to the boards take up valuable space, provide needless distractions, and serve no useful operational function. Figure 5-72 is one of many examples of needless and inappropriate advertising in the control room.

A second problem that fits in the miscellaneous category is depicted in Fig. 5-73. The console shown provides closed circuit TV views of various plant locations of interest to the control room operator. The operator must remember to reposition the TV camera view every 15 minutes or so in order not to burn an image on the vidicon tube. The operator cannot be counted on to remember to do this when he is pressed by other, and more important, concerns. Perhaps a timer and flashing light might be in order.

SUMMARY REMARKS

In this section we have reviewed control board designs as observed at five nuclear power plant control rooms. The major problems observed were: (1) excessively large



Fig. 5-61. Operator must monitor gauges placed about 12 feet above floor level.

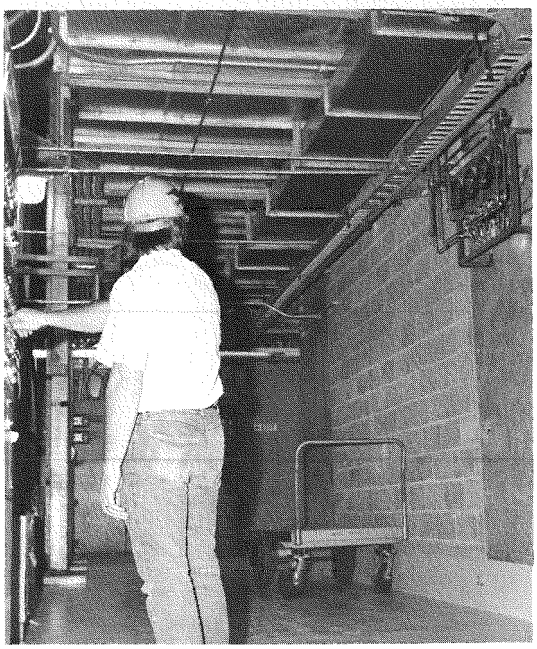


Fig. 5-62. The operator must monitor gauges placed across an aisleway while operating the control console shown.

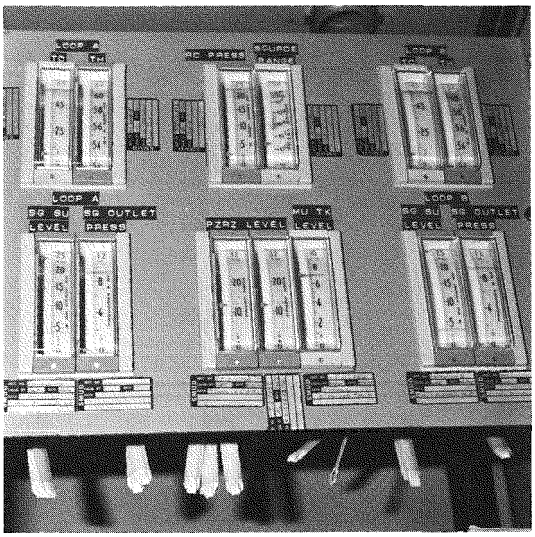


Fig. 5-63. Emergency plant shutdown panel to be used in the event the control room is not habitable.

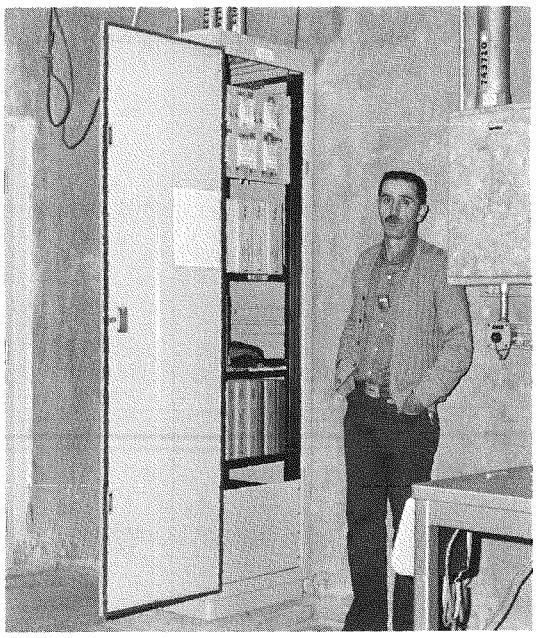


Fig. 5-64. Note the placement of the emergency panel shown in Fig. 5-63. There is no apparent reason for its high placement.

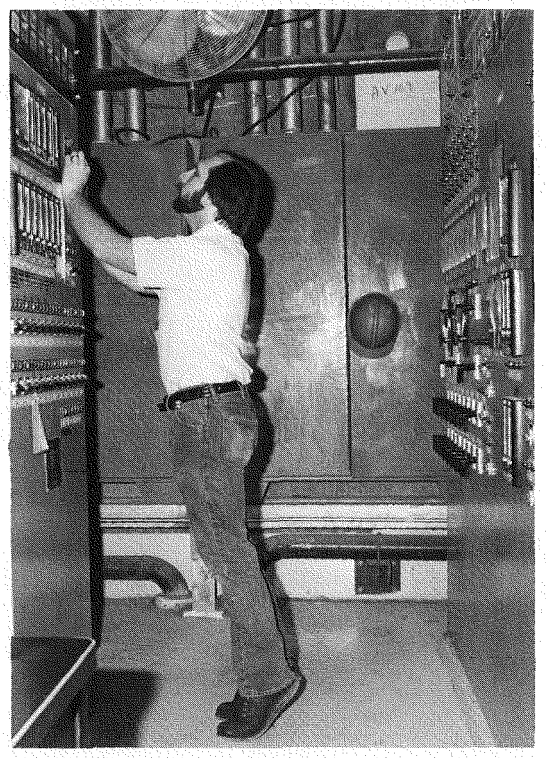


Fig. 5-65. Operator standing on tip toes has trouble aligning his eye to a special optical display.



Fig. 5-66. Illumination of remote panels is undiffused and very uneven.

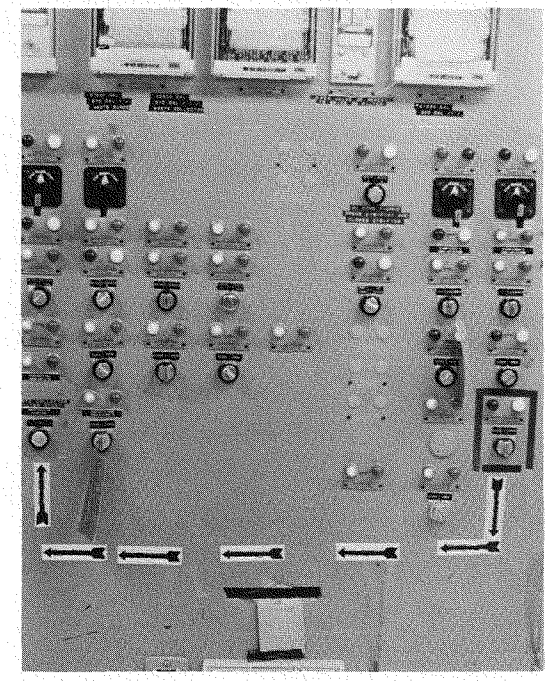


Fig. 5-67. After repeated errors, the relationship between two related controls was clarified by arrows.

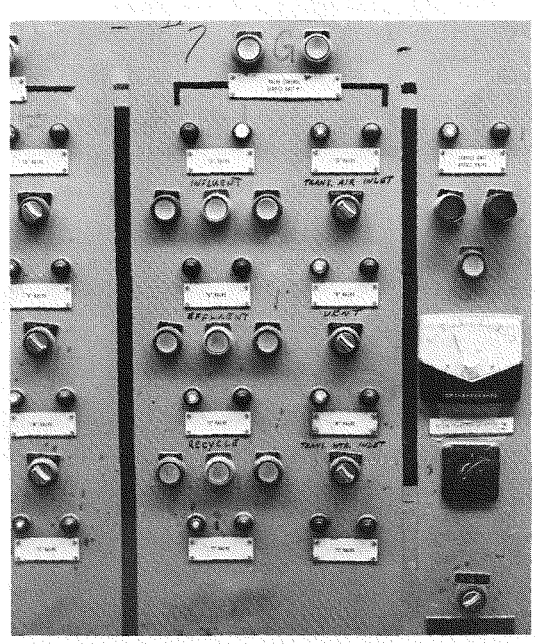


Fig. 5-68. Labeling of remote panels is rather primitive.

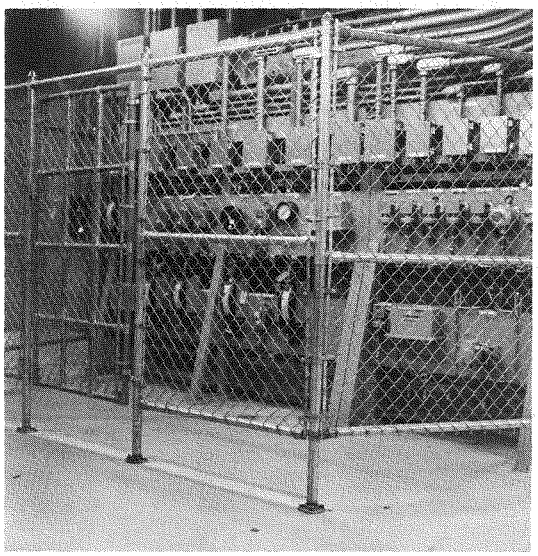


Fig. 5-69. Access to remote controls is sometimes limited due to security precautions. This slows down auxiliary operators.



Fig. 5-70. Example of a well laid out mimic board in a remote plant location.



Fig. 5-71. Another view of the mimic board shown in Fig. 5-70.

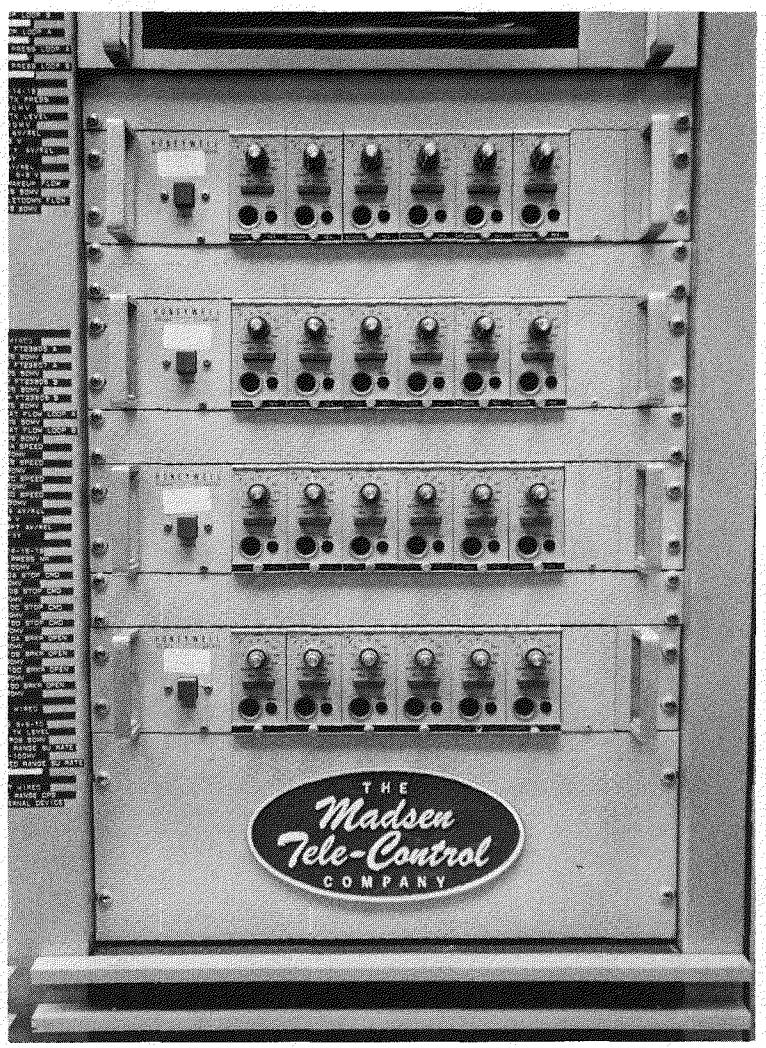


Fig. 5-72. Large vendor logos add clutter to the control room and serve no useful purpose.



Fig. 5-73. The operator must remember to reposition the TV cameras every 15 minutes or so.

control boards that require too great a visual and control span for the operator, (2) mirror-imaged control boards that grossly violate human factors principles of transfer of training and preclude consistency of operator response patterns, and (3) a general lack of clearly demarcated functional groups of panel elements into major systems and subsystems.

While this report is intended to provide a critique of control rooms rather than serve as a design guide, it might be appropriate to suggest the outline of an alternative design approach to the man-machine interface. The present control board designs require the operator to assimilate too many discrete and widely scattered bits of information. The relations among items of displayed information and associated control options are not clearly portrayed by the panels. This is basically why mimic panel arrangements are held in such high regard by operators and trainers.

These problems result from the size of the boards and, in some cases, from the basic configuration of the boards with respect to the operator's station. The huge boards have encouraged designers to split into separate zones the qualitative displays (the annunciator alarms), the quantitative displays (meters, chart recorders, counters), and the controls. By the use of panel space conservation techniques--smaller components and space-saving design practices--the control boards could be reduced to a size and configuration that would render all areas of the boards within the visual envelope and within easy reach of the operator. There would then be no need to separate controls from their associated qualitative and quantitative displays. This would further lead to clearly defined and demarcated functional groups into subpanels and major panels or a greater use of mimic arrangements. In place of the hundreds of annunciator windows now ringing the upper tier of the control room, a fraction of such indicators would be employed simply to key the operator's attention to the panel containing the information and control options of immediate concern to him. For example, one annunciator window might read TURBINE and it would serve as a summary alarm for the dozens of possible turbine problems or conditions requiring the operator's attention. This alarm would be situated directly above the turbine panel. For specific information regarding the nature of the turbine problem, the operator would have available qualitative alarms and quantitative displays clearly integrated with the controls either on a major turbine panel unambiguously separated into turbine subsystems or on a comprehensive mimic of the turbine system. The specific control and display elements provided, as well as the arrangement of subpanels and major panels, would

be based on functions and task analyses and verified by means of mockup evaluation exercises. A consistent color code for indicators along with coded auditory warnings would immediately alert the operator to marginal and dangerous conditions pertaining to each subsystem.

Such approaches have proven successful in hundreds of military, space, and commercial aviation designs. The need for human engineered control consoles is no less acute in nuclear power plants.

Finally, although not observed, nor especially sought out, as a source of human factors problems in the plants visited, there is some concern that future compliance with NRC Regulatory Guide 1.75--Physical Independence of Electrical Systems--may lead to problems of dissociated panel layouts. This Regulatory Guide requires physical separation of redundant components to maintain their independence. This safety provision may lead to awkward non-human engineered operational situations if separation is achieved by extended physical separation of related panel components. On the other hand, functionally grouped panel layouts may still be achieved, while complying with the guide, by use of suitable behind the panel barriers to separate adjacent components. The full implications of Guide 1.75 need to be explored further in light of human factors engineering implications.

Section 6

ANTRHOPOMETRICS

A major human factors engineering concern is the degree to which equipment systems match the physical dimensions of the men and women who operate these systems. In other words, how readily can an operator reach controls, are displays placed where they can be read accurately, and have chairs, operator stations, or equipment accesses been sized to accommodate the range of operator dimensions? Anthropometric, or body dimensions, data describing the nuclear power plant operator are lacking. Consequently, evaluations of present generation control rooms in terms of anthropometric criteria are based on data pertaining to military personnel as provided in MIL-STD-1472A. In order to obtain an indication of the applicability of military anthropometrics relative to the nuclear power plant operator, height, weight, and age data were accumulated on our interview sample of operational personnel. Operators were also asked to comment on the placement of controls and displays with respect to arm reach and visual access. This section provides an assessment of present generation control room designs in terms of anthropometric factors.

OPERATOR DIMENSIONS

Human factors engineering specialists attempt to influence equipment dimensions to insure that at least 90 percent of the user population can easily operate and maintain the equipment. The design range, according to Military Standards, includes at least the 5th to 95th percentiles for design-critical body dimensions. The 5th percentile for a particular dimension is a value such that 5 percent of the personnel are smaller than the value expressed and 95 percent of the personnel are larger. The 95th percentile for a particular dimension is a value such that 95 percent of the personnel are smaller than the value expressed and 5 percent of the personnel are larger.

Forty operational personnel were asked to state their height, weight, and age. The data are presented in Table 6-1 along with comparable military data. The operational personnel ranged in height from 65 to 75 inches, with an average of 70.7 inches. The weights ranged from 140 lbs. to 230 lbs., with an average of 182 lbs. Ages ranged from 22 years to 49 years. The average age was 34.3 years.

Table 6-1

ANTHROPOMETRIC DATA FOR NUCLEAR POWER PLANT OPERATION PERSONNEL COMPARED TO MILITARY POPULATIONS

	5th Percentile			95th Percentile		
	Army	Air Force	Utility Operators	Army	Air Force	Utility Operators
Stature (Inches)	64.5	65.9	67.0	73.1	73.9	74.4
Age (Years)	18.6	22.4	22.0	31.5	42.4	46.7
Weight (Pounds)	126.3	140.0	140.6	201.9	211.0	223.4

Since only a small fraction of the total national operational population was tapped, there is some question as to how representative the data may be. If these figures are a true reflection of the total population, nuclear plant operational staffs are slightly taller, older, and heavier than military male populations. A more thorough picture of nuclear power plant operator anthropometric data should be developed to aid design personnel.

CONTROL BOARD COMPATIBILITY WITH ANTHROPOMETRIC RANGES

In order to accommodate 90 percent of user personnel, military standards require that visual displays mounted on vertical panels and used in normal equipment operation shall be placed in an area between 41 inches and 74 inches above the standing surface. Special displays that must be read precisely and frequently should be placed in an area between 50 inches and 69 inches above the standing surface. The upper limit for normal control placement is the same as for displays, 74 inches. The lower limit is less stringent, 34 inches above the floor. Special controls that require precise or frequent operation and emergency controls should be located in an area between 34 and 57 inches above the standing surface and no further than 22 inches laterally from the centerline of a stationary operator.

At each of the simulator sites visited, measurements were made to determine the degree to which present generation control room designs meet anthropometric

standards. As the photodocumentary evidence will make evident, the control rooms, with one exception, have serious mismatches between the range of operator dimensions and the placement of controls and displays. This disparity is often aggravated by the characteristics of the particular display unit which is positioned beyond normal visual access, e.g., curved meter faces placed more than 74 inches above the standing surface.

Figures 6-1 to 6-6 show the anthropometric limits for normal visual access superimposed on the vertical control boards of one control room design. It is readily apparent that these limits are widely exceeded. The subject shown in Figures 6-1 and 6-2 is 5 feet 6 inches and represents about the 5th percentile operator. Figures 6-5 and 6-6 show a 95th percentile subject and the positions that he must assume to read the displays placed below his normal visual access limits.

At a second plant, see Figures 6-7 to 6-8, it was found that an entire horizontal band of meters running the course of the main control boards was above the range of acceptable anthropometric limits to accommodate 90 percent of operational personnel. Peripheral consoles, see Figures 6-9 and 6-10, offered similar problems. The shorter trainees at this simulator resorted to the small step-ladder shown in Figure 6-10 to make readings and manipulate controls.

At a third plant an entire band of meters was placed too high to allow visual access without the use of a foot stool that was left in the area for this purpose (see Figures 6-11 and 6-12). In the same control room, the radiation monitoring equipment violated anthropometric criteria at both the high and low limits as can be seen in Figures 6-13 and 6-14. An elaborate step ladder with safety treads and hand rails was available for use in conjunction with these panels (see Figure 6-15). The operator in these photographs is 67.5 inches tall.

At a fourth control room shown in Figures 6-16 to 6-19, most displays, with the exception of the annunciators and half the core monitor display, were kept within visual access limits. While the main control boards in this plant were within anthropometric limits, peripheral panels such as those shown in Figures 6-18 and 6-19 were outside the recommended limits for visual access.

The fifth control room followed the pattern set by the first three discussed above. One entire horizontal band of meters was above visual access limits as shown in Figures 6-20 and 6-21. Peripheral panels revealed even more extreme anthropometric discrepancies as shown in Figures 6-22 and 6-23.

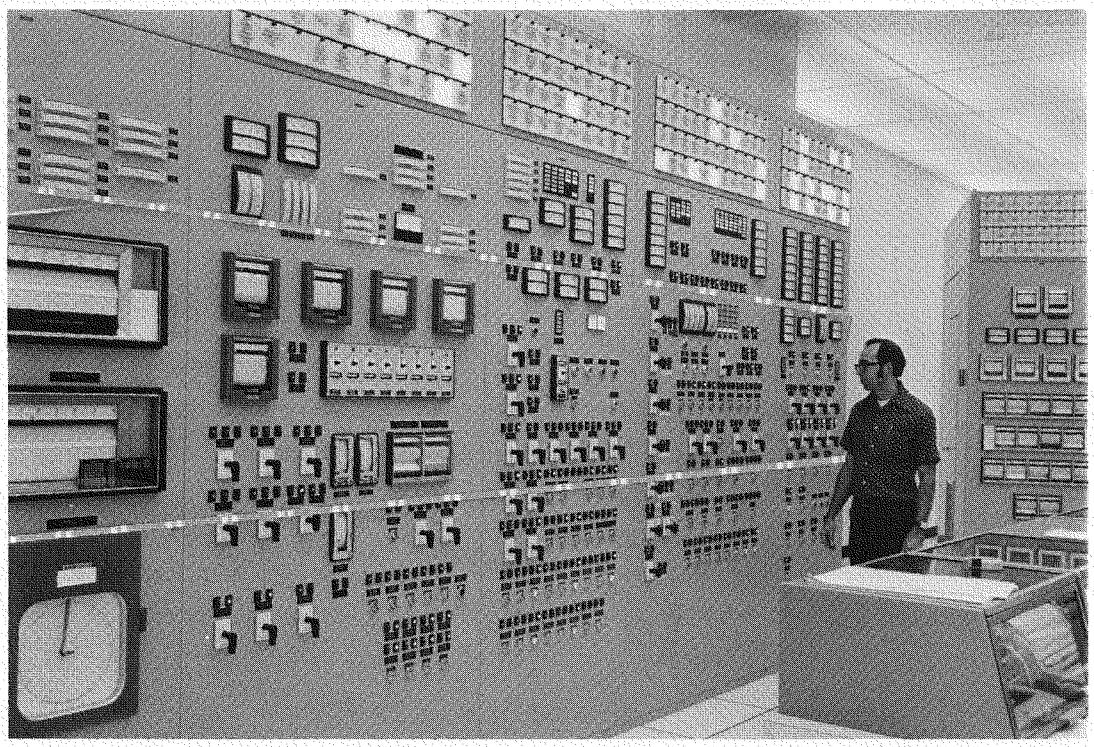


Fig 6-1. The broken lines indicate anthropometric limits for placement of control-display elements for visual access.

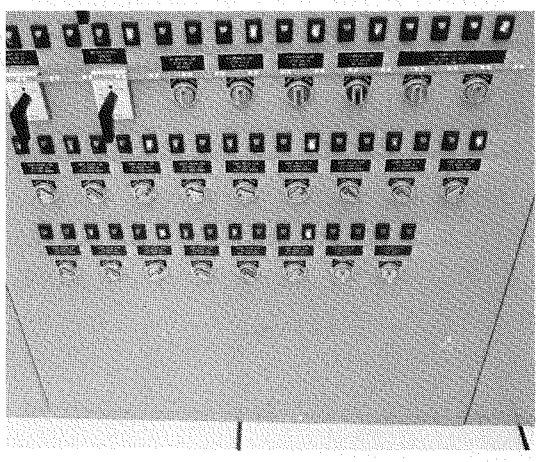


Fig. 6-2. Another view of the control-display elements placed above and below anthropometric limits.

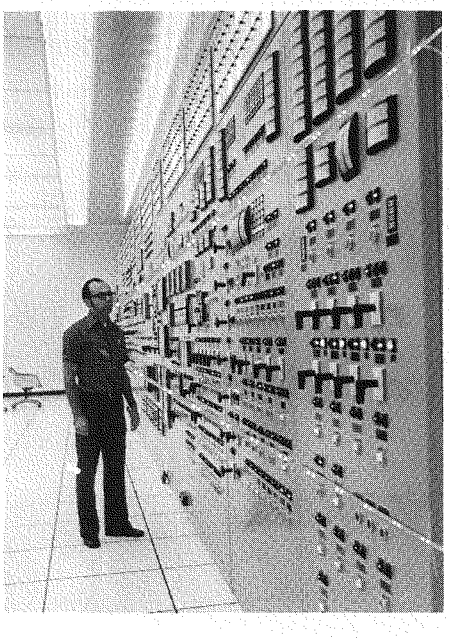


Fig. 6-3. Example of panel elements located too far down the vertical board as seen from the operator's eye view.

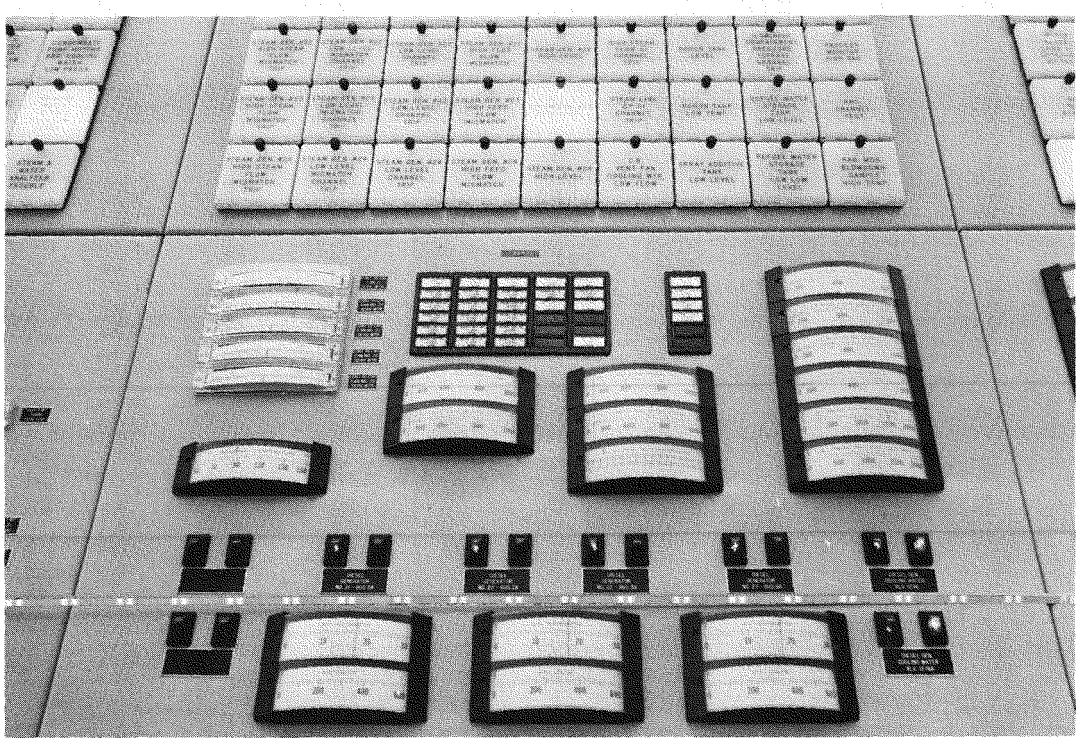


Fig. 6-4. Eye view of short operator in monitoring displays placed above anthropometric limits.

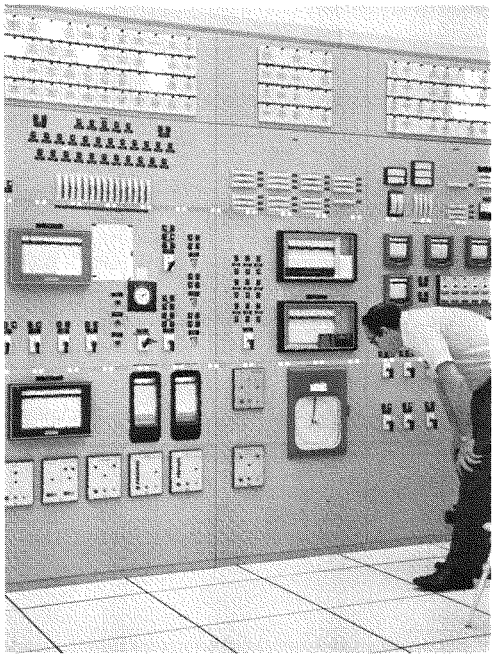


Fig. 6-5. 95th percentile operator viewing display placed below anthropometric limit.



Fig. 6-6. 95th percentile operator stooping to read chart recorder clearly placed too low on the boards.

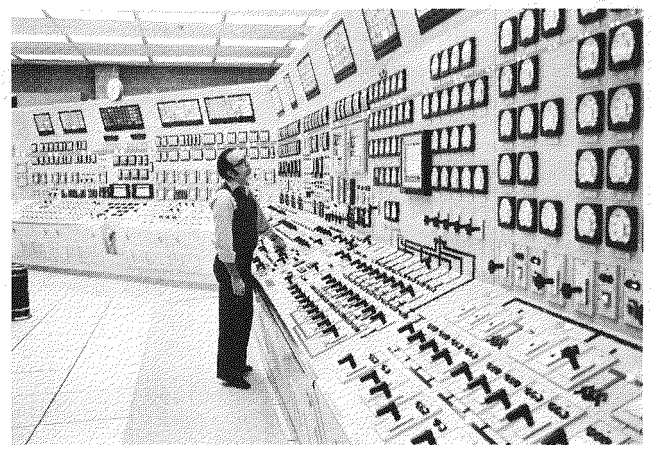


Fig. 6-7. One band of meters across the entire length of the control boards is placed too high for the smaller operator.

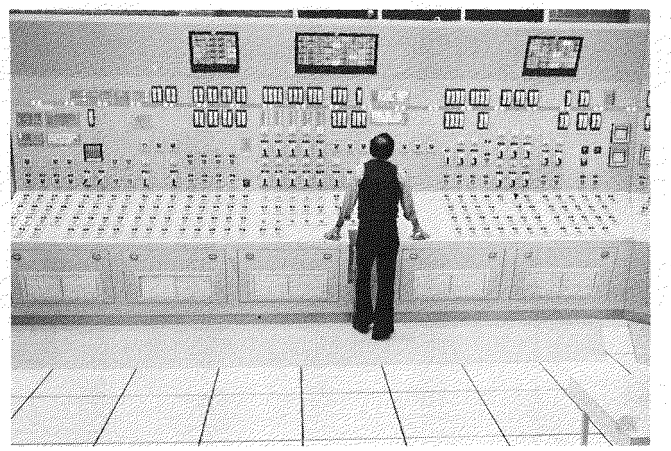


Fig. 6-8. Safeguards related displays placed above anthropometric limits.

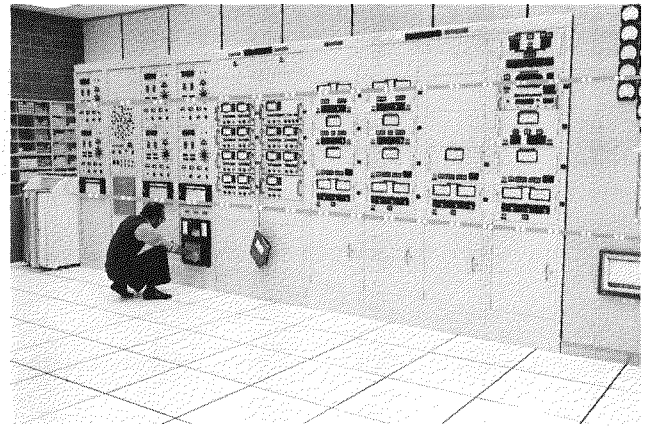


Fig. 6-9. Controls on peripheral panels placed too low.

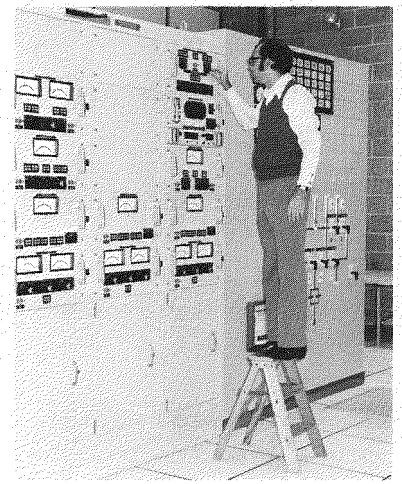


Fig. 6-10. A stool was observed in use by trainees in the operation of panels placed too high. The stool offers a precarious perch.

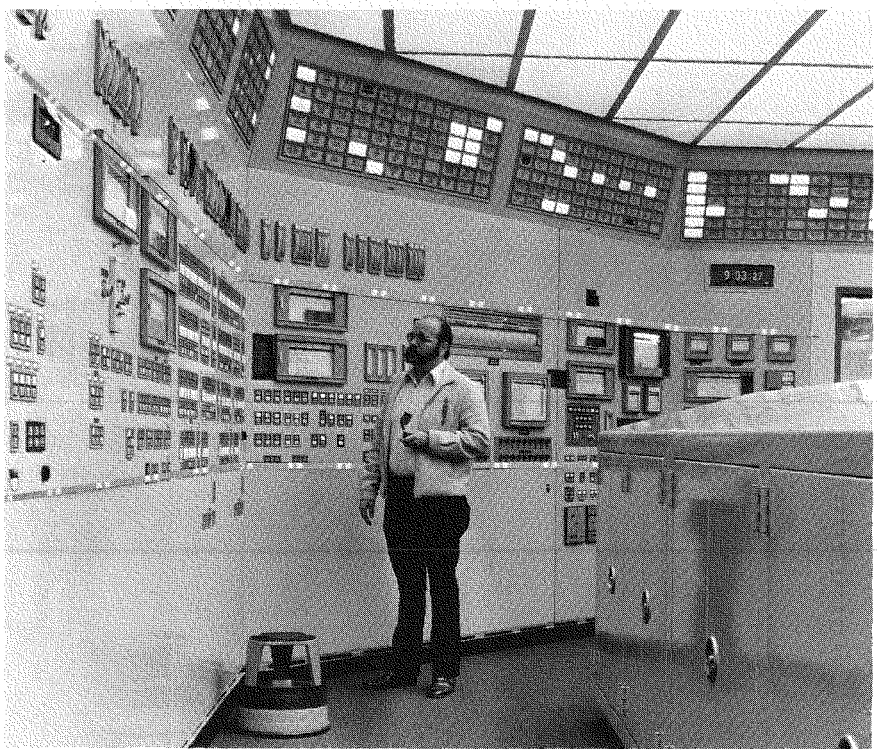


Fig. 6-11. At another plant visited a stool is left in the aisle for visual access to meters placed too high.

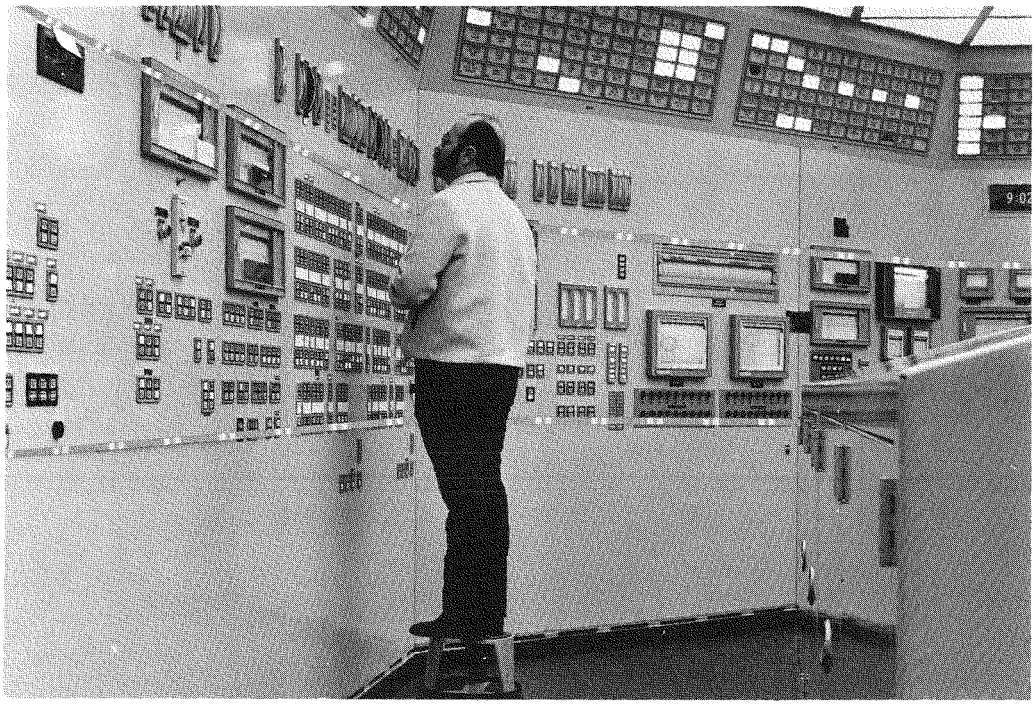


Fig. 6-12. Use of stool to view poorly placed meters.

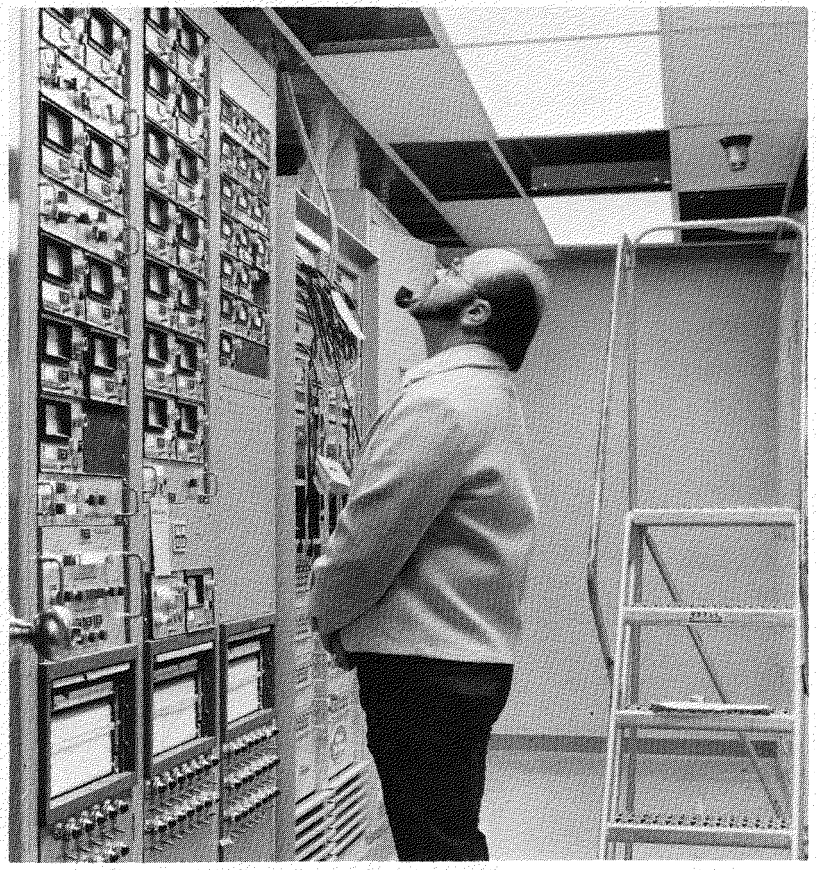


Fig. 6-13. Radiation Monitoring console with panels placed too high for normal viewing.



Fig. 6-14. Radiation Monitoring Console with a chart recorder placed too low for normal viewing.

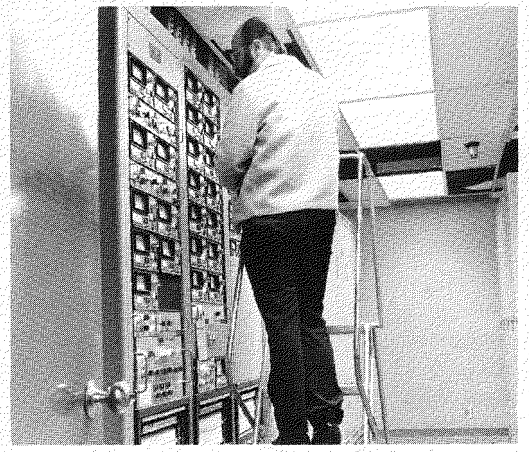


Fig. 6-15. Elaborate step ladder available for operation of Radiation Monitoring panels placed too high.

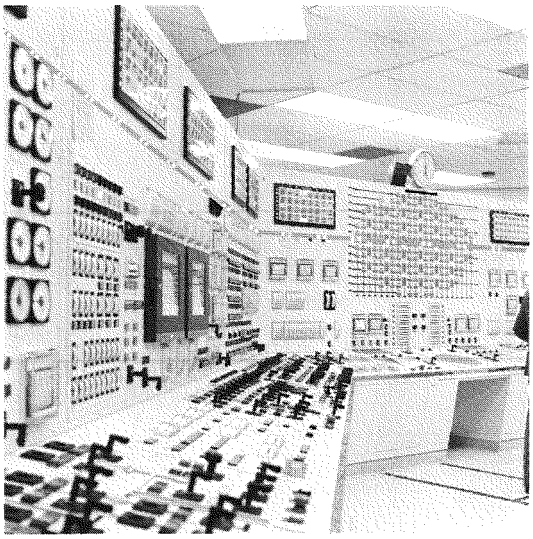


Fig. 6-16. This Control Board has maintained panel elements within anthropometric limits.

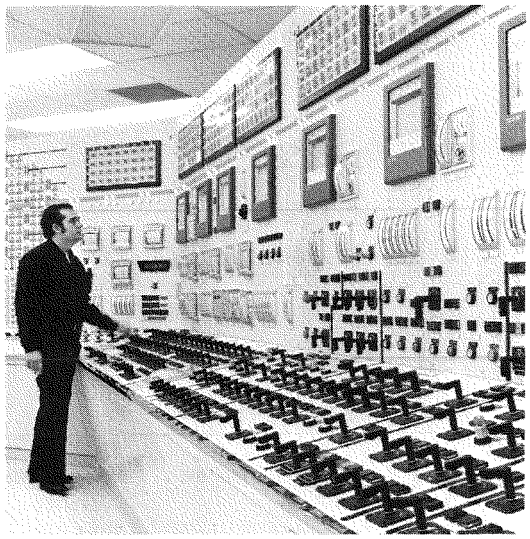


Fig. 6-17. Another view of a control board where the displays were kept within anthropometric limits.

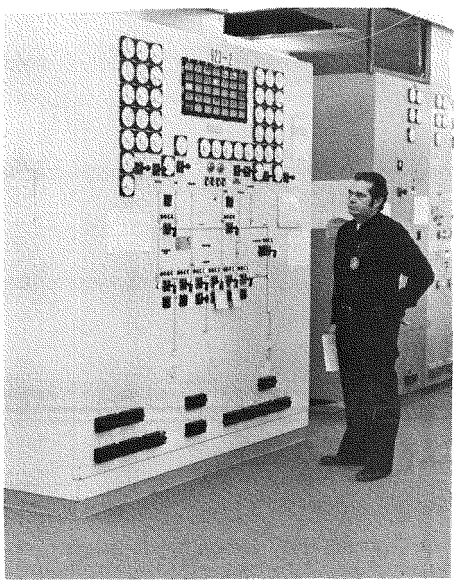


Fig. 6-18. Although the control boards in this plant were within limits, peripheral consoles violated anthropometric limits for display placement.



Fig. 6-19. As in the preceeding figure, peripheral consoles place displays too low for the standing operator.

A problem unique to this control room was the extensive use of mirrored meters designed to avoid parallax errors (see Figure 6-24). The operator is required to visually line up the pointer with its reflection until the reflection is no longer visible. Because of the curved surface of the vertical mirrored scale, the operator must kneel to read the meters on the lower portions of the panels (Figure 6-25). Those meters at the upper limits of the panel require the operators to fetch the step ladder. The operators suggested that this problem would not have existed if meters had been oriented horizontally.

OPERATOR STATIONS

While the primary focus of anthropometric concern was the relationship between the operator and his interactions with the control boards, some attention was devoted to an examination of the operator stations in the control room. Factors examined included the height of desk surfaces and knee room provided for the seated operator.

Human factor standards for desk surface height for the seated operator (see Figure 6-26) require a height of between 26 and 30 inches to accommodate 90 percent of the operator population. The operators' desks at four of the plants were within the prescribed anthropometric limits. At the fifth plant, a sit/stand type desk arrangement was provided as shown in Figure 6-27. For this type of station, the desk surface height should be between 36 to 38 inches. The desk surface height shown in Figure 6-27 was 43 inches, five inches in excess of recommended dimensions. At another plant the center desk operator's desk height was 39.5 inches (see Figure 6-28).

A minimum of 25 inches above the floor surface and below the desk surface should be allowed for the seated operator. The operator desks at each of the plants visited met this requirement.

OPERATOR COMMENTS

The structured interview contained two questions relating to anthropometric concerns. The first asked: "Are important displays generally placed where they can be read easily?" The second question was as follows: "Are important controls generally placed where they can be reached with ease?"

The responses of the operators bear out the observations made through an application of the human factors anthropometric criteria described above. With regard to displays, the following comments are representative:

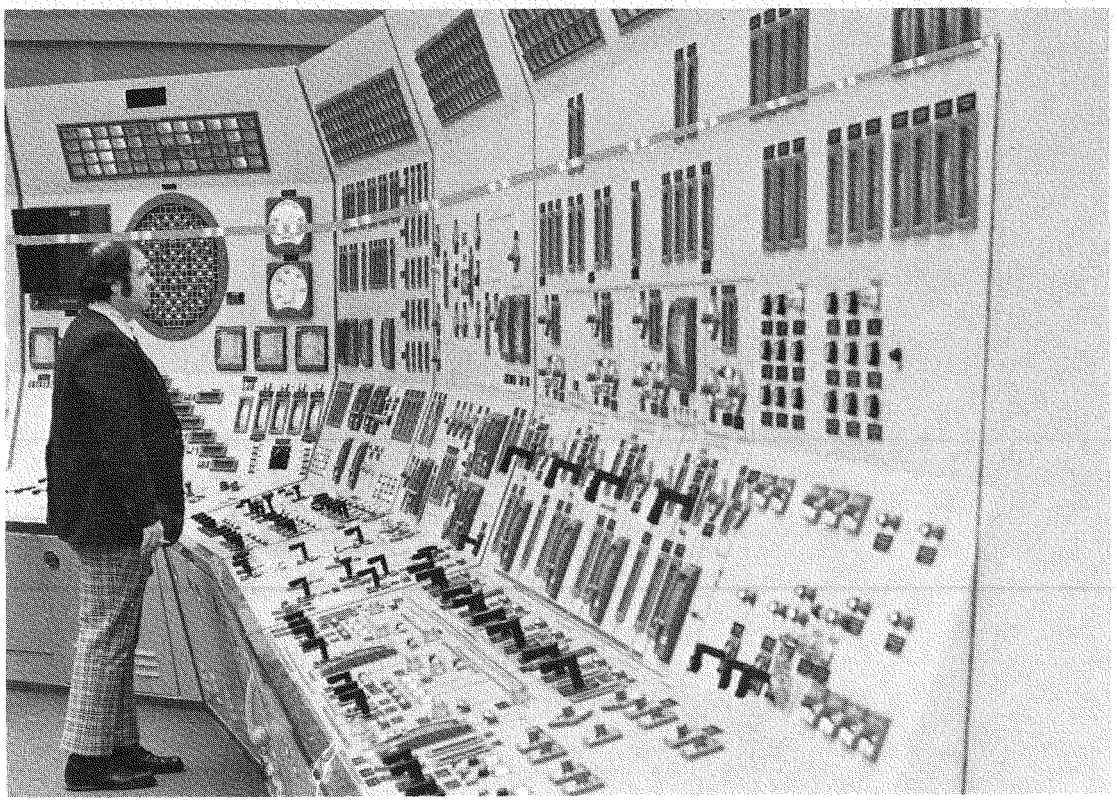


Fig. 6-20. The fifth control board reviewed, as in three other cases, placed a band of meters too high.

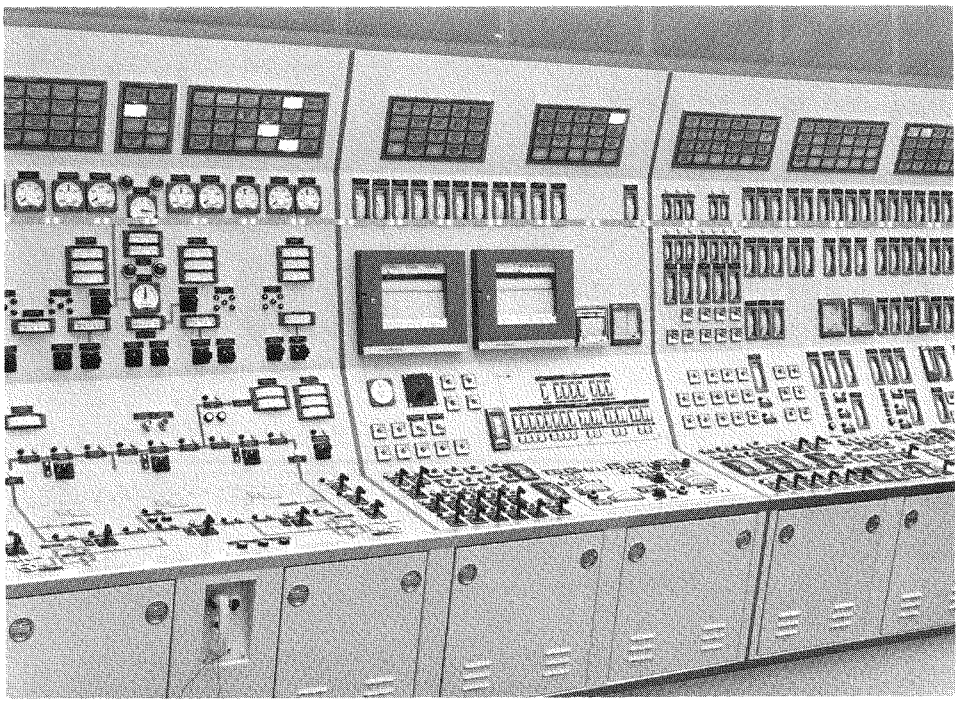


Fig. 6-21. Another view of the control board shown in Fig. 6-20.

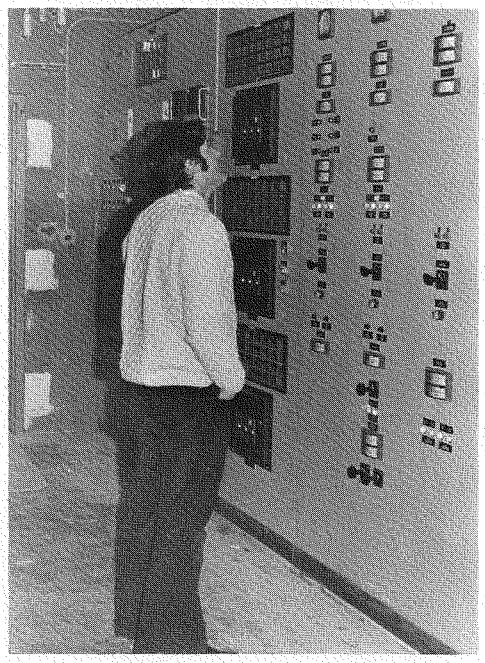


Fig. 6-22. Peripheral consoles in the fifth plant studied violated anthropometric limits more severly than the main control boards.

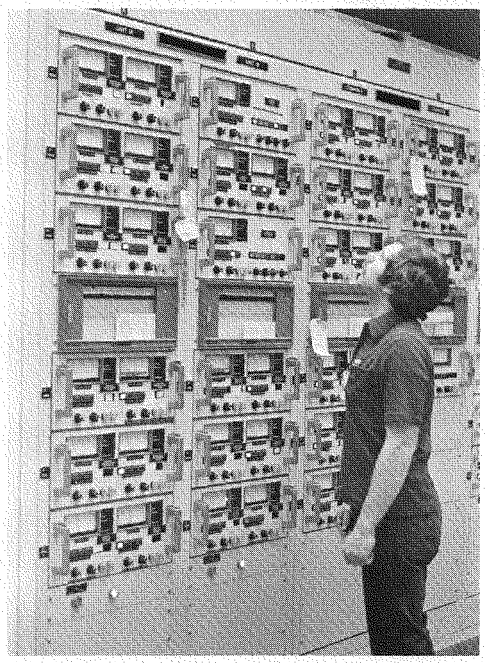


Fig. 6-23. Radiation Monitoring panels placed too high.

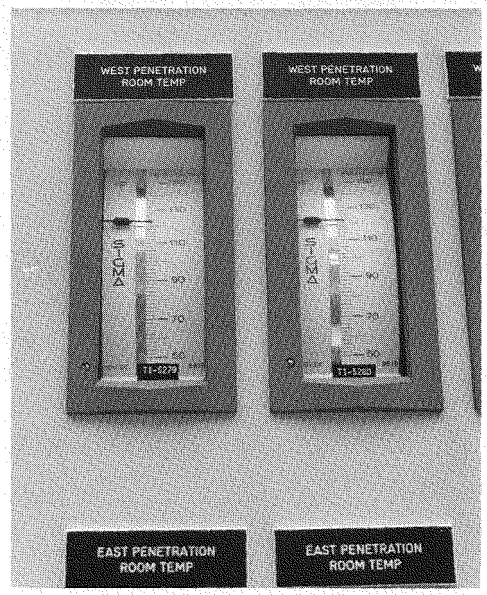


Fig. 6-24. Meters with mirrored scale designed to help avoid parallax problems. The operator lines up the pointer with its shadow until the reflection is not visible.



Fig. 6-25. Position which the operator must assume to avoid parallax with the meters shown in Fig. 6-24.

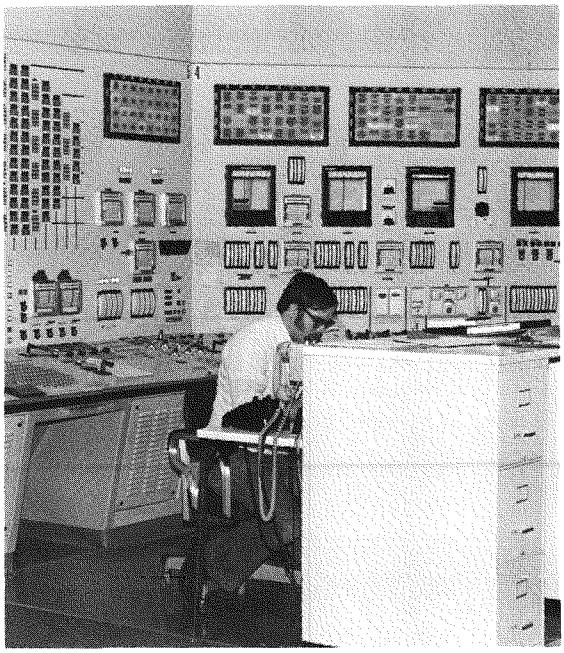


Fig. 6-26. Dimensions for operators' desks were satisfactory in four of the five plants investigated.



Fig. 6-27. A sit/stand type desk with the writing surface slightly too high.

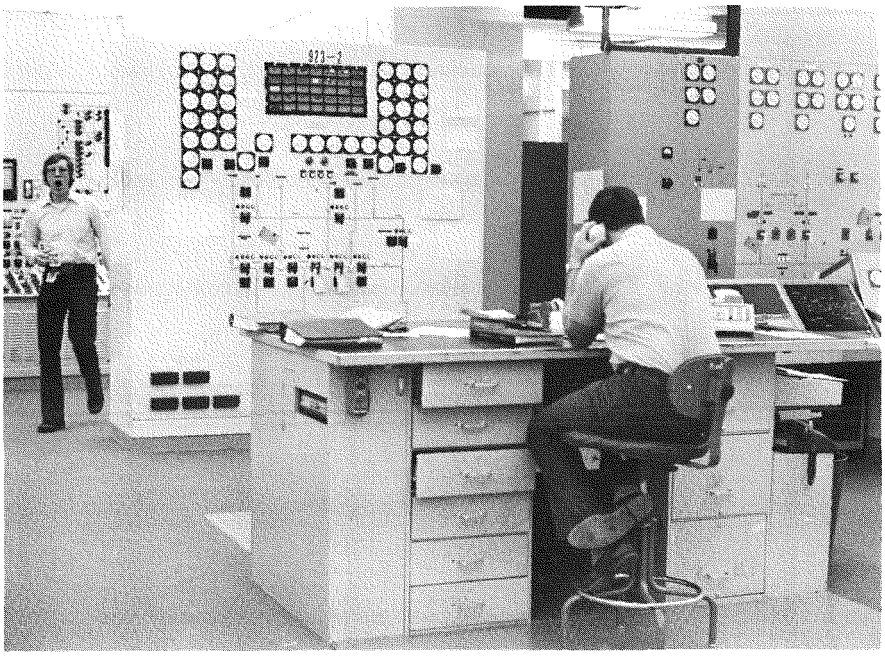


Fig. 6-28. Center Desk operator's station with desk surface slightly too high.

- The chart records are poorly placed in some cases, too high or too low.
- Some gauges are too small to see from any distance.
- The ladder in the control room gets in the way of displays.
- The top row of meters is difficult to read, particularly when they are read in the upper part of the scale.
- There are parallax problems on meters, particularly those located high on the panel.
- We need a stool to read the top row of meters.
- Several displays are too low to read easily on the OFF-GAS Panel. These were add-ons.
- The curved scale mirrored meters are a problem. They did not consider the operator! I am six foot tall and sometimes I have to stand on a foot stool. Some of our operators are real short.

The operators were considerably less dissatisfied with the placement of controls in terms of reach from an operating position directly in front of the control boards. The main complaint here was with the placement of related controls in widely separated areas or in areas remote from the primary control boards such as the backracks.

SUMMARY REMARKS

In many instances, control rooms are not tailored to accommodate the range of operator dimensions. As more females become part of the operator population, anthropometric limits will become more stringent. More comprehensive anthropometric data should be developed to describe the operator population and this data should be made available to control room designers. Until then, military standards should be used to guide control room designers in developing "human engineered" control rooms. Techniques for control board space conservation would preclude the necessity of placing controls and displays outside the recommended anthropometric limits The utilities should also avoid the temptation to place add-on instrumentation in awkward operational locations that violate anthropometric standards and complicate the operators' tasks, thereby inviting operation errors.

Section 7

CONTROLS

This section examines the design of the controls of the five nuclear power plants studied. We will consider appropriateness of specific controls according to their functions, the ease with which the operator can operate the controls, and such factors as spacing, parallax, control size in relation to panel space, and human factors considerations associated with specific types of controls. The most common controls are selector switches, pushbuttons, rotary knobs, thumbwheels, levers, toggle switches, and switch lights. This section concludes with a consideration of automatic versus manual system control.

CONTROL SELECTION

Different types of controls are suited to specific functions. For example, a toggle switch is best suited to allow selection between two options, e.g., on/off. At most, the toggle switch can be used to allow a choice between three options, e.g., auto/off/manual. A rotary selector switch is appropriate for three or more control options, up to twelve options. When necessary, 24 positions can be assigned to a selector switch.

A major problem observed in four of the five control rooms examined is the inappropriate use of large cumbersome selector switches for functions that a much smaller toggle switch or switch-light could serve as well. The vast majority of relatively large SBM pistol grip switches shown in Figure 7-1 are for two or three option operational modes. The use of these relatively large controls in place of toggles or other smaller switches, better suited to two or three switch options, affects the overall control board design. As discussed in Section 5, the size of the individual controls selected determines the control panel size. As the size of each control panel grows, we frustrate the general desire of operators to have more compact control boards where all display and control elements are within easy reach and in view. The choice of massive (see Figures 7-2, 7-3) controls is often a matter of tradition and subjective preference, and is not based on effective or reliable control operation.

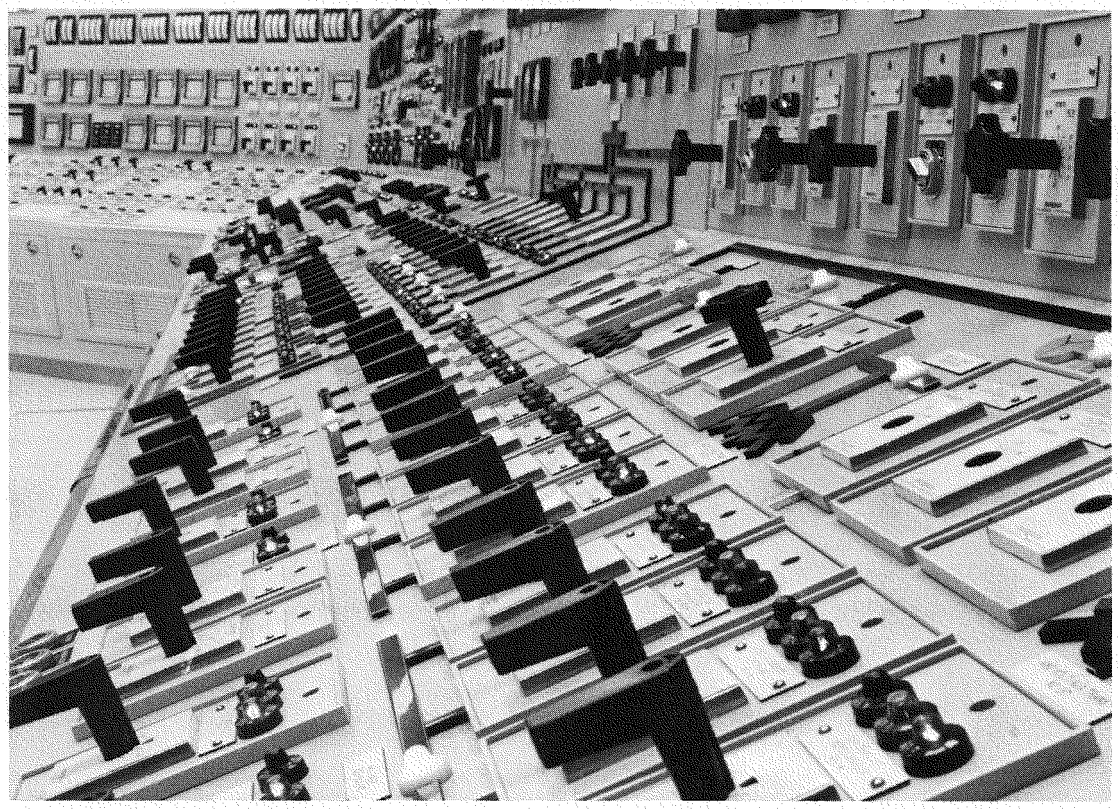


Fig. 7-1. Typical array of relatively large SBM switches with two or three switch options on each control.

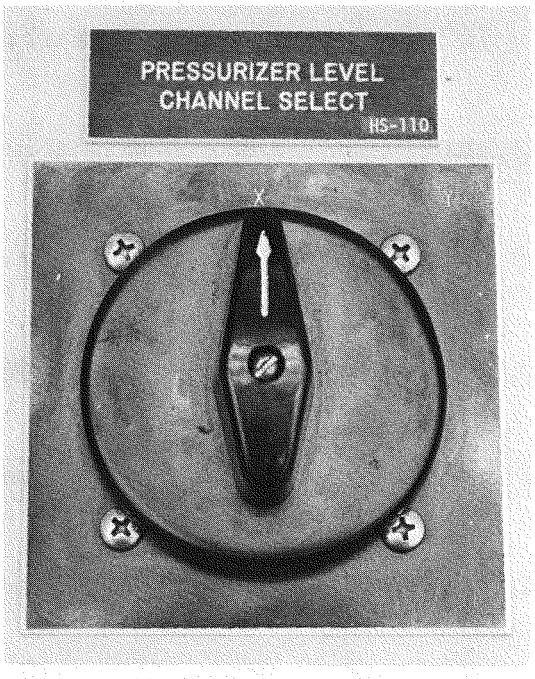


Fig. 7-2. A large selector switch used for selection between X and Y Pressurizer Level Channel Select.

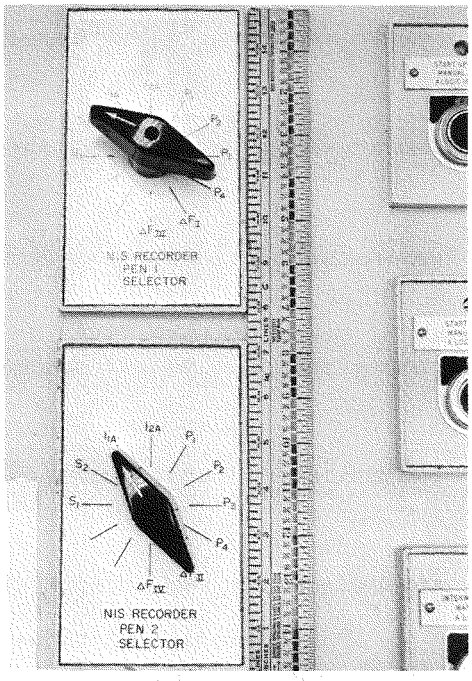


Fig. 7-3. Note the amount of panel space consumed by these two selector switches.

CONTROL ACTUATION FORCE

In evaluating control design we must consider the force that the operator must apply to actuate it. If this force is too great, operation is cumbersome; if too small, the control can easily be activated accidentally. For example, the minimum/maximum recommended resistance values for a rotary selector switch are respectively 1.0 inch-pound and 6.0 inch-pounds.

Measurements were made of the force required to activate representative controls at each of the simulators (see Figures 7-4 and 7-5). Force requirements for controls generally were found to be within the limits specified by human engineering standards. A few exceptions were noted. One pistol grip handle control required a pull-to-lock force of 13 pounds and a push-to-unlock force of 15 pounds. This control was located 75 inches above the floor level and manipulation of it was awkward for the shorter operators.

Another problem occurred with selector switches that are spring loaded to a center position. These switches require the operator to hold the selector knob in the right-of-center or left-of-center position until the system responds to the control actuation. The spring resistance coupled with a small control gripping surface presents problems for the operator. To solve this problem, a special device was slipped over the control to provide a greater mechanical advantage in actuating the selector switches shown in Figures 7-6 and 7-7. This problem occurred at only one of the five plants. We are not recommending the use of such expedients, but rather, pointing up the need for consideration of control force requirements during the initial design phase.

CONTROL POINTERS

Rotary selector switches generally contain a movable pointer knob referenced to stationary alphanumeric labels that describe the control options. The shape of the knob and its relationship to the associated option markings is important in avoiding the selection of incorrect operational modes. It may seem obvious that the pointing end of an oblong control knob should be clearly differentiated from the non-pointing end. It is also wise to avoid positioning control option designations 180 degrees apart from each other. These points are illustrated in Figure 7-8. The white engraved arrow in this perfectly symmetrical selector knob is designed to differentiate the pointing end from the non-pointing end. However, such engraved markings become obscured over time and use with dirt and grease. Second, it is possible for the operator to place his hand over the control in



Fig. 7-4. Measurement of control activiation force requirements.

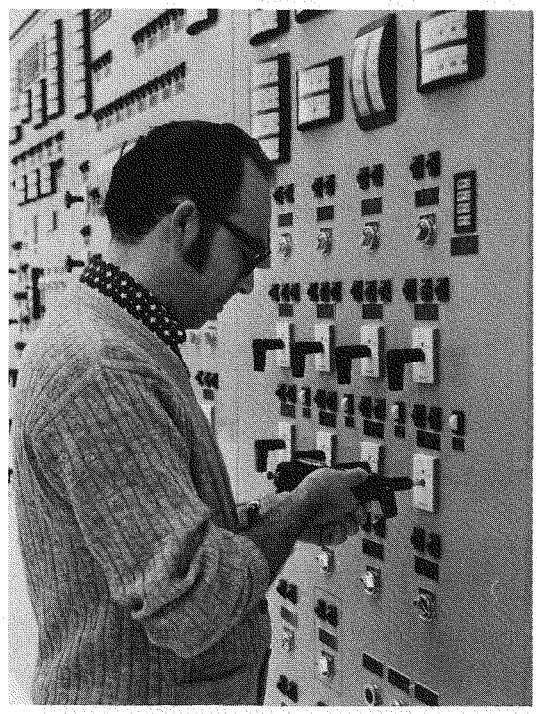


Fig. 7-5. Measurement of control resistance.

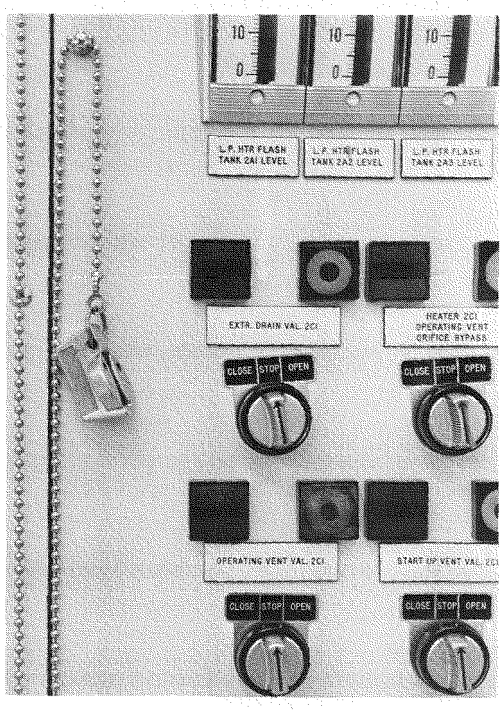


Fig. 7-6. Device used to overcome control resistance chained to the control board.

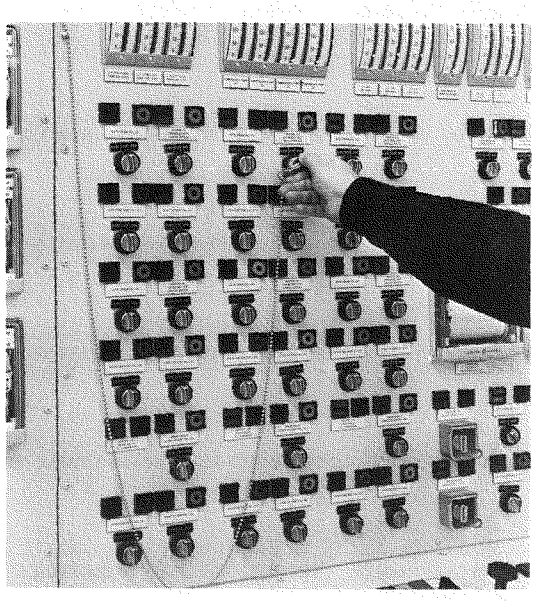


Fig. 7-7. Use of the device shown in Fig. 7-6 for difficult to hold controls.

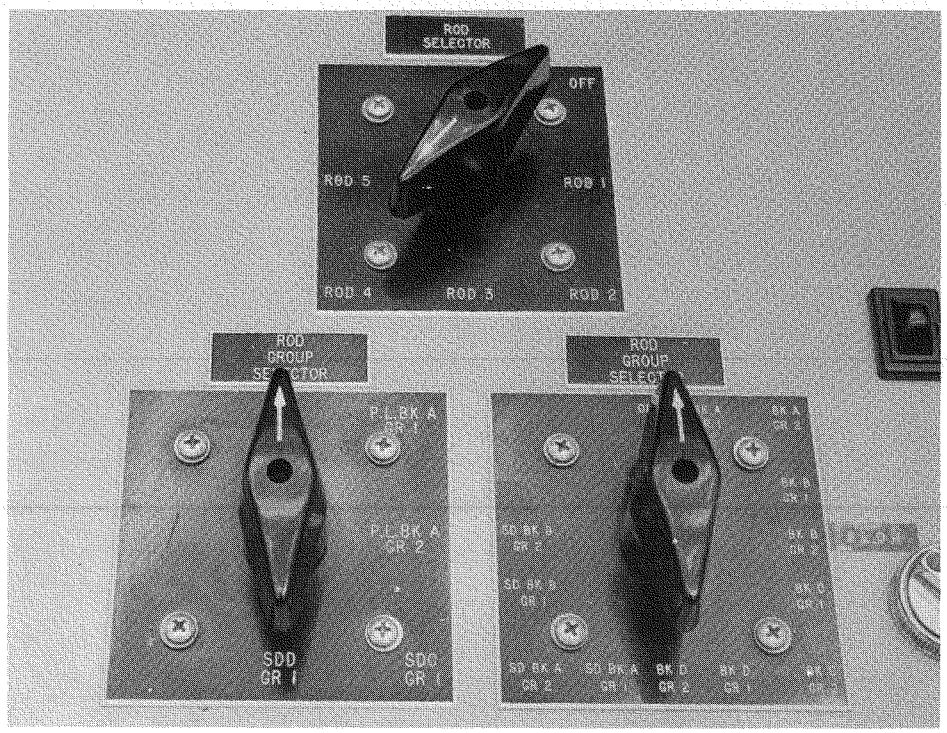


Fig. 7-8. Control knobs with symmetrical point and non-pointing ends. Switch options are placed 180 degrees apart.

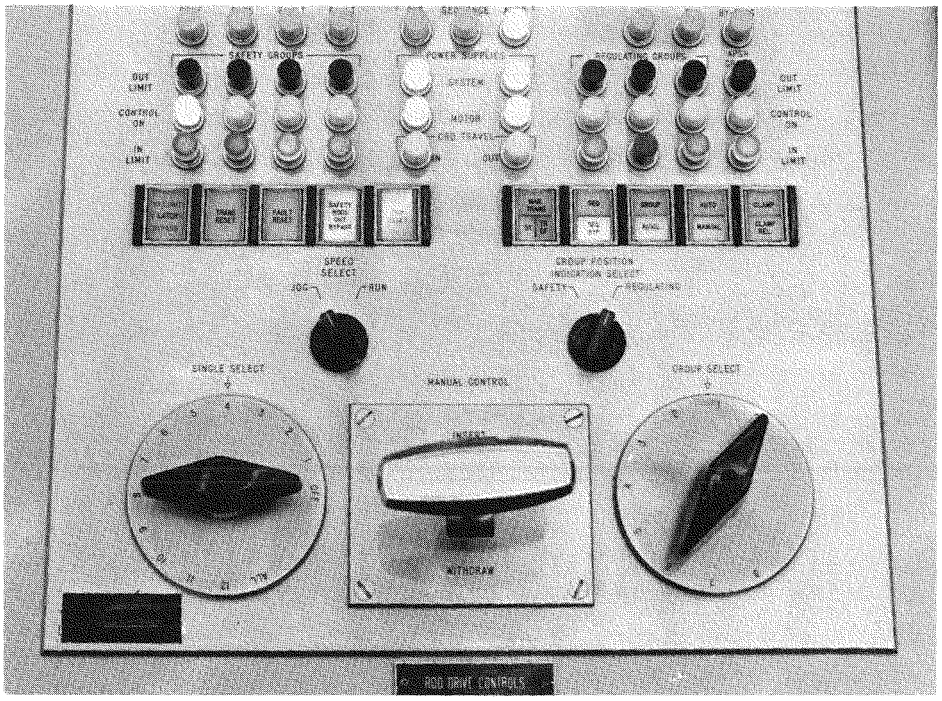


Fig. 7-9. Knobs with nonfunctional and confusing pointing ends. The small arrows on the panel designate the selections.

anticipation of changing its setting and thereby obscure the arrow. Also note that the positions of control option designations are 180 degrees apart on all three selector switches. We might note, parenthetically, that it would have been a good idea to orient the "OFF" position on all three related switches shown in Figure 7-8 at the 12 o'clock position instead of having the bottom two switches at 12 o'clock and the top one at the 1:30 position. This would have given the operator an additional cue when checking the status of these related knobs.

Figure 7-9 shows two large selectors with option markings located on a plate that rotates with the knob. These selector switches are part of the rod panel controls located on the reactor control console. A stationary reference arrow on the panel is used to designate the selected control option associated with each switch. The shape of this knob is inappropriate; it is pointed at both ends and gives the semblance of a pointer knob. The stationary small fixed reference arrows are not very prominent by comparison. A round, nonpointing fluted or knurled knob with a more prominent stationary reference arrow would be more effective in promoting error-free operation of these controls.

A much more commonly observed problem is caused by parallax errors between pointer knobs and control option markings. The control handles are often so large and project so markedly from the control boards that it is difficult to relate the pointing feature of the knob with the markings that are several inches removed on the board. Several photographs illustrate this point. Figures 7-10 to 7-13 shown the offset distance between the control handle and the markings. The slightly tapered shaft of the control points to the option being selected. More often than not, depending on how the control is oriented with respect to the operator's position, the tapered edge of the shaft is not visible because of the size of the control handle. The operator must move his head in search of the pointer. For example, the control shown in Figure 7-10, when viewed directly, provides no cue as to whether the tapered edge is to the right, top, bottom or left of the shaft. Some star shaped control knobs of this type have a filled in white arrow to orient the operator to the position of the tapered pointer edge of the shaft.

In some instances, the problem described above is partially avoided by means of prominent, contrasting pointers located at the base of the control shaft as shown in Figure 7-14. This arrangement does not avoid the problem of the large control obscuring the option markings.

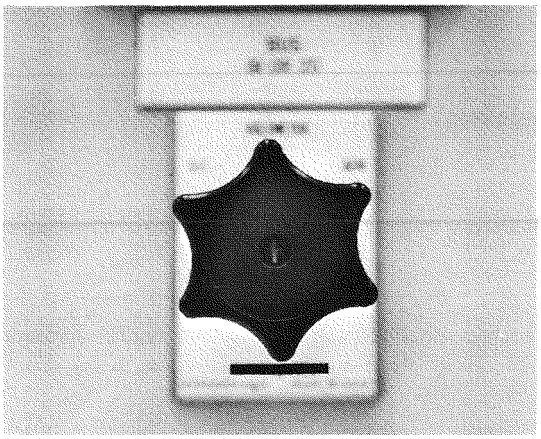


Fig. 7-10. Head-on view of control with the control select feature not visible.

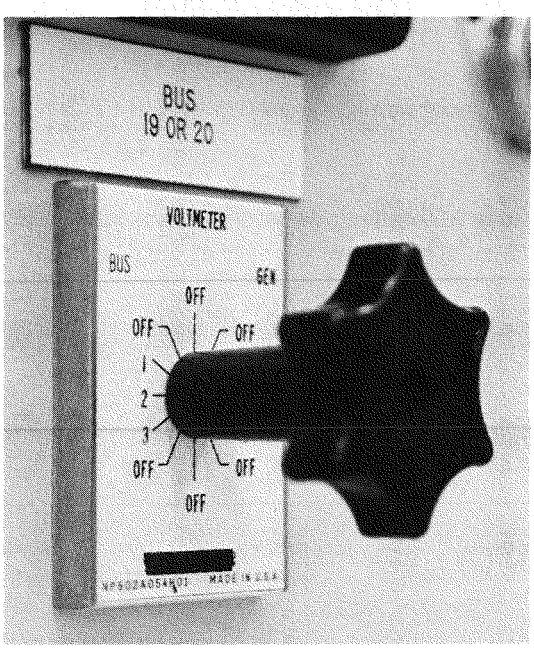


Fig. 7-11. Side view of the control shown in Fig. 7-10 with the control select feature not visible.

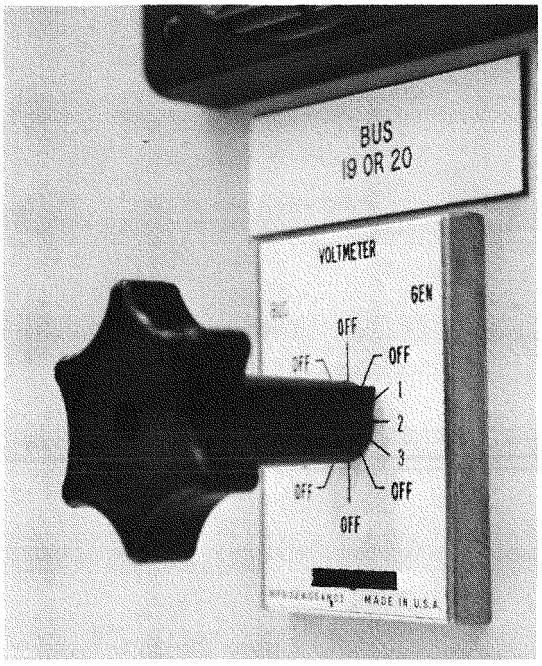


Fig. 7-12. Right-hand view of the control shown in Fig. 7-10 with the tapered edge pointing to the option selected.

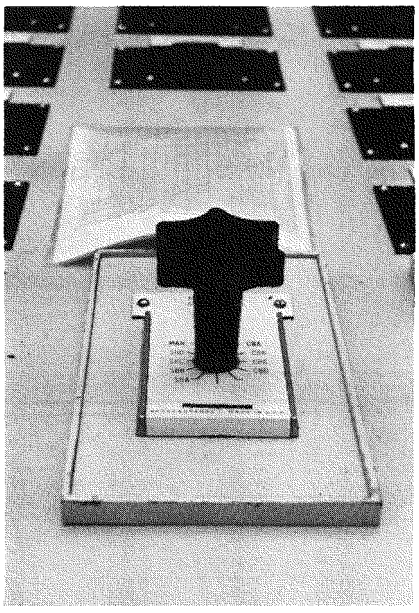


Fig. 7-13. Tapered pointing edge of control shaft difficult to see on benchboard mounted controls.

To further complicate matters, in one plant, those pistol grip handles located at the edge of the bench board panels, as shown in Figure 7-15, are removed from their shafts and inverted to prevent accidental activation. In these cases the nonpointing ends of the control now become the pointing ends and the tapered shafts do not relate to the option markings for this row of controls.

In summary, pointer knobs that lie flush with the control board and provide clearly distinguishable pointing features are much more desirable from the human factors standpoint than those illustrated above.

CLARITY OF CONTROL OPERATION

The mode in which a given control is to be operated should be readily apparent to the operator without his having to memorize the special idiosyncrasies of a host of special cases. In most cases the configuration of a given control and its associated markings make the correct operation of the control clear to the operator and even to the casual observer. Some problems were noted with controls that were unclear in their operation. Several examples that we will present below may indicate the need for a detailed review of the control boards to ensure the clarity of operation of each control.

Figure 7-16 shows the use of indicator lights and switch-lights on the safeguards panel. There is no differentiation in appearance between the simple indicators and the indicators that can be depressed for switching purposes. This problem is pointed out in Section 13, which deals with coding techniques. To add to the confusion, some switch-lights are pressed once and the switching takes place. Others require the operator to hold the switch for several seconds before the system responds. Again, the panel does not alert the operator to this special requirement. Consequently, the operator presses the switch-light, (located on a back wall), and then runs around to attend to matters on the primary control panel located in the center of the control room (see Figure 7-17). The operator's assumption that he has activated the switch-light is often incorrect and he is bewildered by the lack of system response. Some added labeling is required to indicate to the operator that he must depress the switch long enough for the desired system response to take place.

Figure 7-18 shows a mixture of switches that are identical in appearance except for their labeling. The bottom row of switches in Figure 7-18 shows four switches labeled CLOSE in the center of the label plate, with the control knob pointing to the left. The fifth switch in this line up reads CLOSE/OPEN. In what way are the

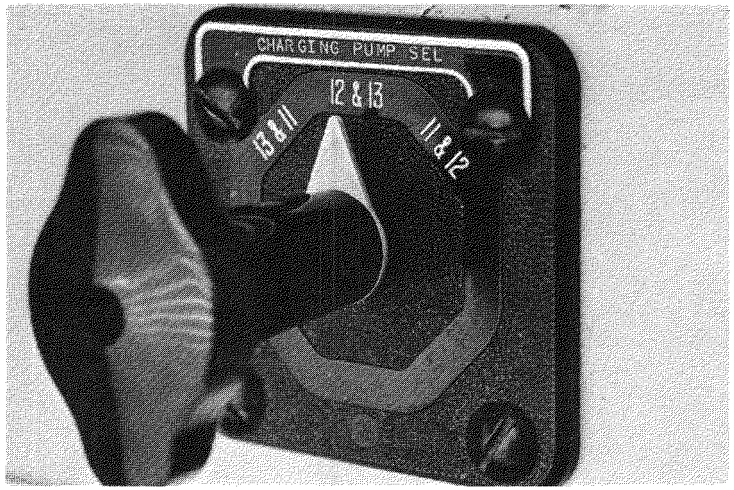


Fig. 7-14. White contrasting arrow located at the base of a large projecting control facilitates option selection.

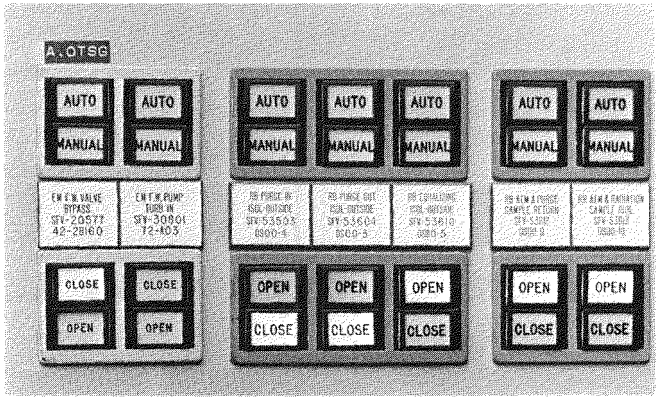


Fig. 7-16. No differentiation between indicator lights and switch-lights.

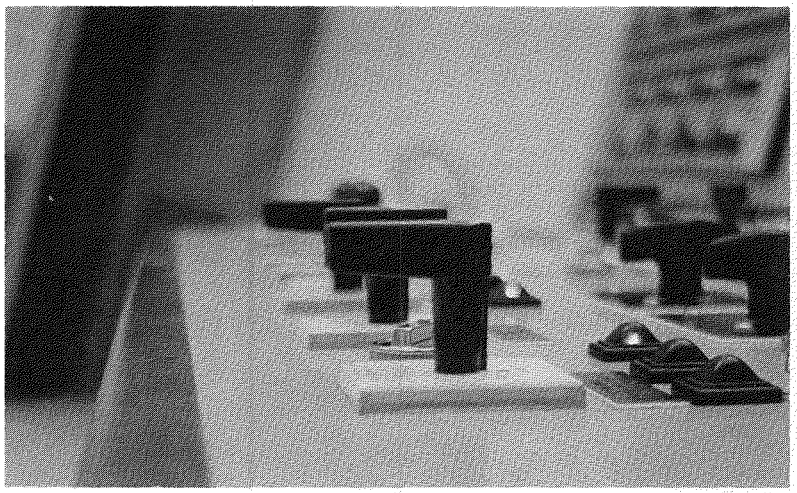


Fig. 7-15. Controls located near the edge of the benchboard are especially vulnerable. At one plant (not shown) these controls were mounted upside-down to reduce their vulnerability. The upside-down mounting made the operation of the controls awkward.

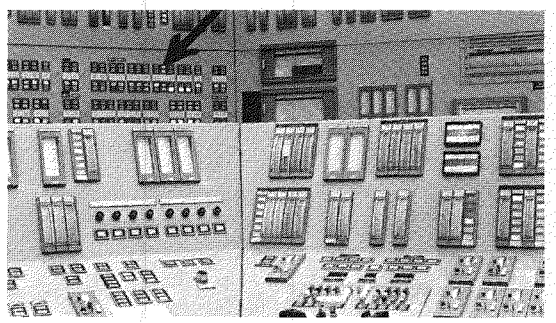


Fig. 7-17. Operator actuates the switch-lights on back wall panels (see arrow) and then turns his attention to the primary consoles in the foreground.

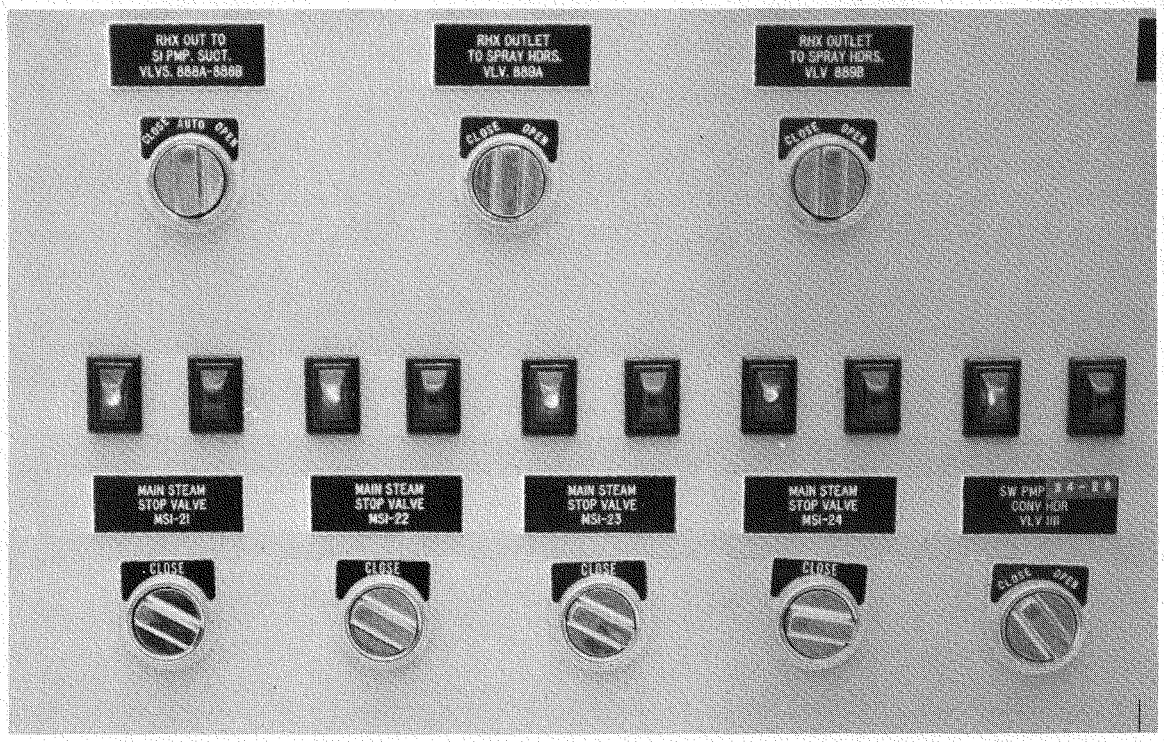


Fig. 7-18. Labeling of these controls is inconsistent and operation is unclear.

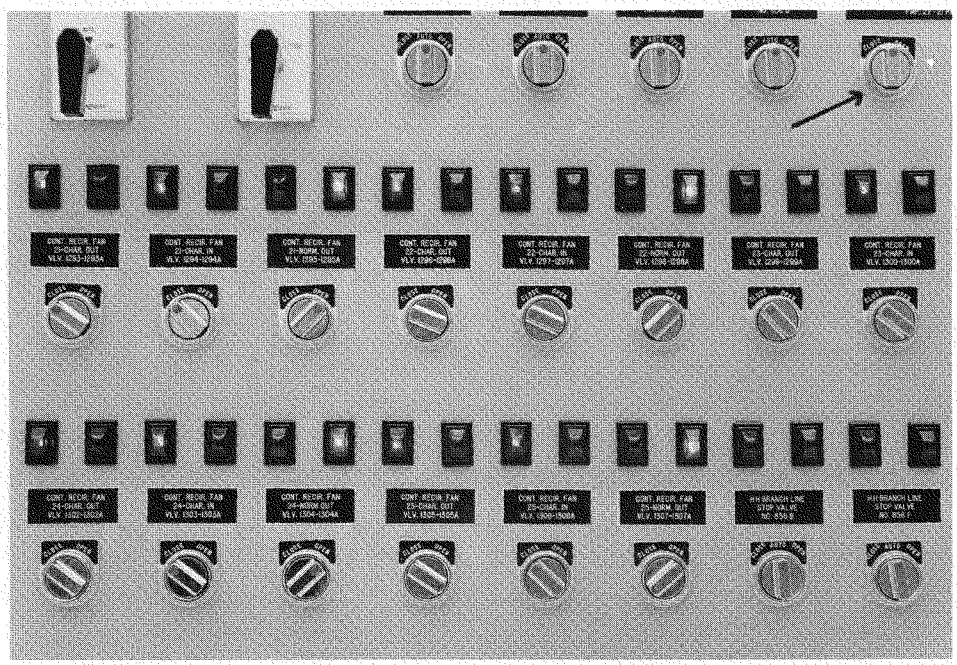


Fig. 7-19. Upper right-hand control points up between CLOSE/OPEN labels. Is this control in the AUTO position? Compare this labeling with the four controls to the left of the control singled out by an arrow.

first four switches different from the fifth switch proceeding from left to right? The upper row of three switches shows all three with the knob pointing at 12 o'clock. The switch on the left reads CLOSE/AUTO/OPEN. The switch is apparently in the AUTO position. The two switches to the right read simply CLOSE/OPEN and the knobs are not aimed at either of these options. Does this mean that these switches are also in AUTO mode? Does the absence of a center option label indicate that the switch is in an OFF position. Or, does this mean that the switch is in a center OFF position with spring-loaded momentary CLOSE/OPEN options?

Figure 7-19 shows similar problems. The selector switch in the upper right hand corner points up to an unlabeled option in contrast to the four similar controls to the left. Lower rows of controls are two-option CLOSE/OPEN switches with the control in either one or the other position. The two controls in the lower right are pointing to the AUTO option. The operation of the upper right control is not clear when compared to other controls on this panel. Surely, the operator, with experience, learns to operate each individual control on the board, but the board design does not expedite this learning process or minimize the chances of error.

The same situation exists at another plant with a different control configuration as depicted in Figure 7-20. Here the small rotary selector knob is placed in the center of an illuminated matrix of control options and function identifiers. Note that the selector pointer can assume a variety of positions. For six of the eight drain valve controls, the pointer permits an up, left, and right operation. The two upper right controls in this group show three options, CLOSE/AUTO/OPEN, and the control identification labels are added on a black plate immediately above the two controls. How does the operation of the six controls mentioned earlier differ from the two controls that include the AUTO option? What does the 12 o'clock position signify on the six controls? Additional labeling should clarify the operational characteristics of these controls.

DIRECTION OF CONTROL MOTIONS

There are natural relations between control motions and the function or display to which the control is related. For example, if the function of lever control placed on a vertical panel is to raise or lower rods, an upward motion of the lever should raise the rods and a downward motion should lower them. If this lever is oriented on a horizontal benchboard, a pushing or forward motion (away from the operator) should raise rods as is the case in Figure 7-21.

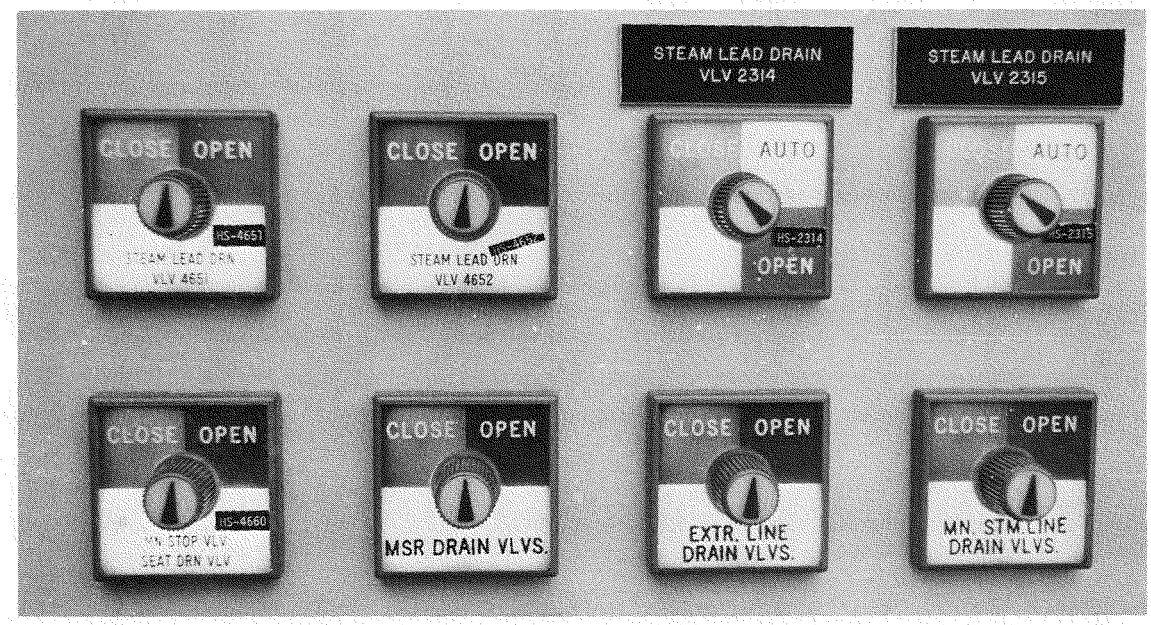


Fig. 7-20. Straight up orientation of the selector pointer is unclear as to its significance.



Fig. 7-21. RAISE/LOWER orientation is in the expected direction.

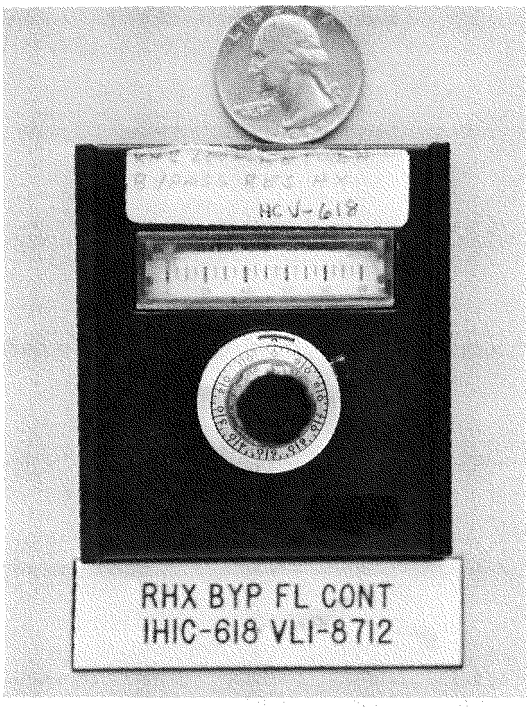


Fig. 7-22. Clockwise rotation of knob produces increasing values.

Similarly, a clockwise motion of a rotary control should reflect increasing scale values or quantities and a counterclockwise should decrease. The control shown in Figure 7-22 provides the natural control motion expectancies of the operator whereas the fixed pointer, moving scale control knob shown in Figure 7-23 is undesirable in that a clockwise motion of the control produces decreasing scale values. Figure 7-24 shows two side-by-side selector switches where in one case the operator turns the switch clockwise to the RAISE option and in the adjacent control the opposite system response is achieved when the control is turned clockwise.

When thumbwheels are used for discrete settings, movements of the thumbwheels in a forward or upward motion should produce an increase in the setting value. As can be noted from Figure 7-25, this rule is not always observed.

Problems of improper control motion direction were not at all widespread in the five plants reviewed. However, the few exceptions observed warrant mention to alert the reader to this potential problem area.

ARRANGEMENT OF REPETITIVE CONTROL GROUPINGS

Is the arrangement of functionally similar, or identical, primary controls consistent from panel to panel throughout the system? This design criterion, derived from MIL-STD-1472, is used in evaluating control room designs. The most frequently used controls in the plants observed are the SILENCE, ACKNOWLEDGE, RESET, and TEST pushbuttons that are distributed in four or five groups on the control boards in each plant. The operators were observed to operate these controls so frequently that they often reach for them "blind." Yet, this group of controls can vary in arrangement from one location to another within the same control board as illustrated in Figures 7-26 and 7-27. This situation invites accidental activation of the wrong control. Even the relatively short time that the study team observed control room and simulator operations, there were several cases of incorrect control activations. In one case a TEST instead of an ACKNOWLEDGE button was pressed and two entire annunciator panels began to flash during operations.

KEY-OPERATED CONTROLS

The control rooms visited varied widely in the number of key-operated controls available to the operators. The rationale behind key-operated controls is generally that these control functions are considered of such significance that they

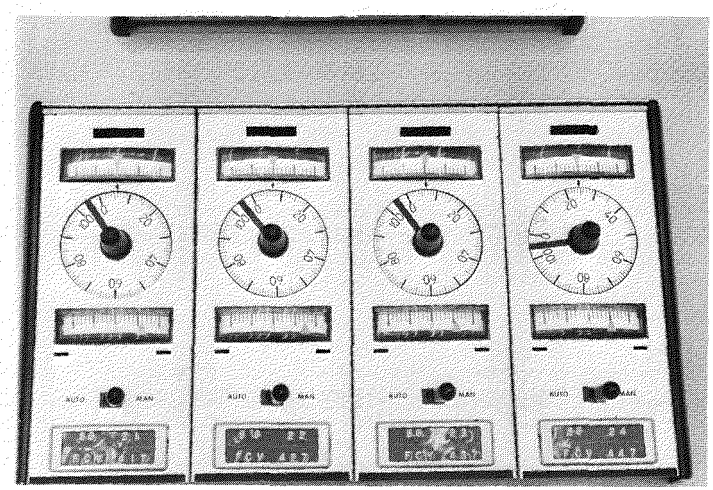


Fig. 7-23. Clockwise rotation of knob produces decreasing values contrary to natural expectations.

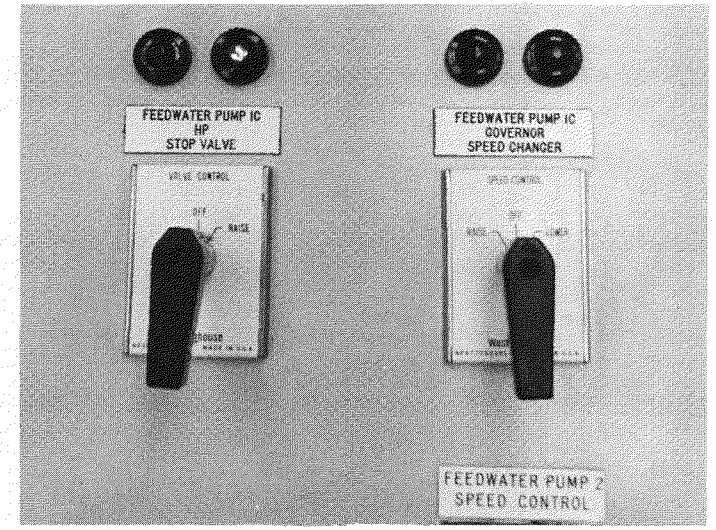


Fig. 7-24. Note the inconsistent positions to the RAISE options on the two adjacent controls.

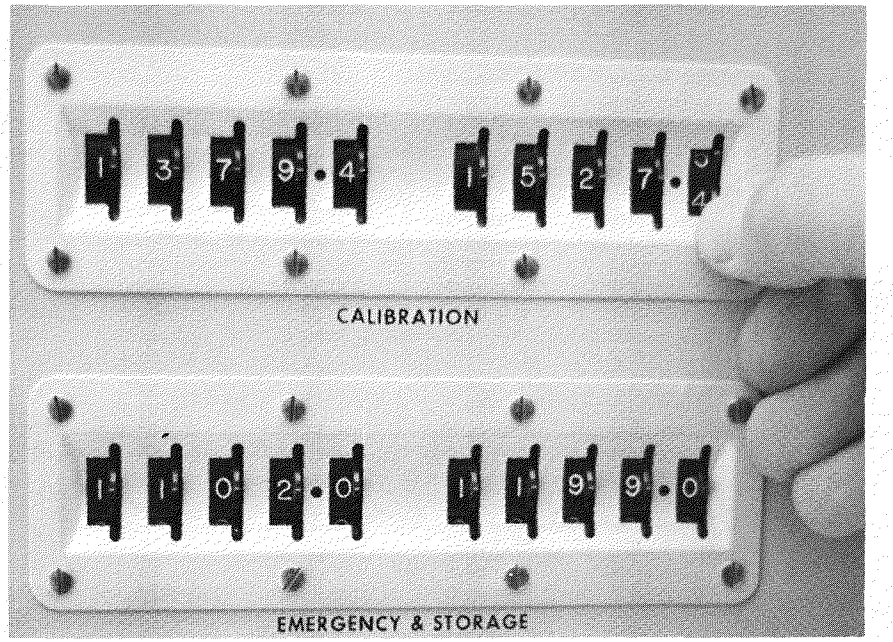


Fig. 7-25. Downward movement of the thumbwheels produces increasing values.

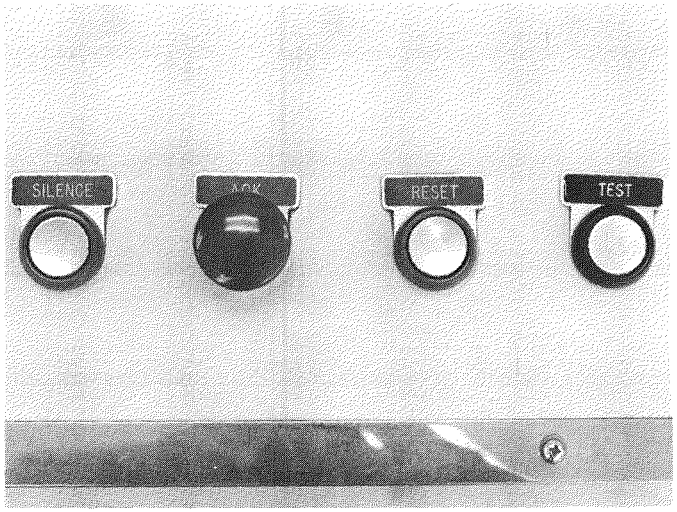


Fig. 7-26. The most common grouping of annunciator controls fround at one plant.

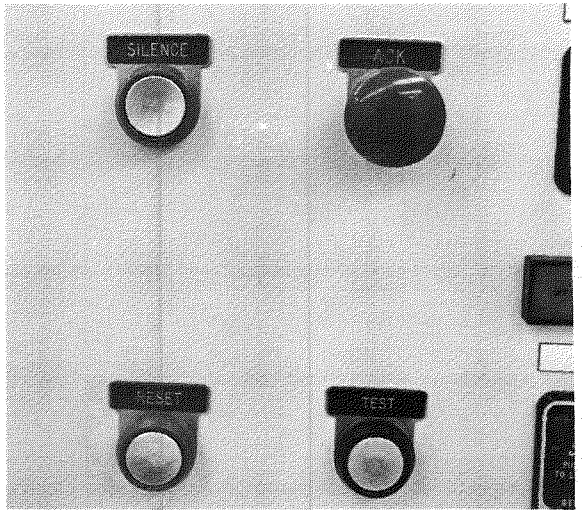


Fig. 7-27. A deviation from the common arrangements of annunciator controls shown in Fig. 7-26.

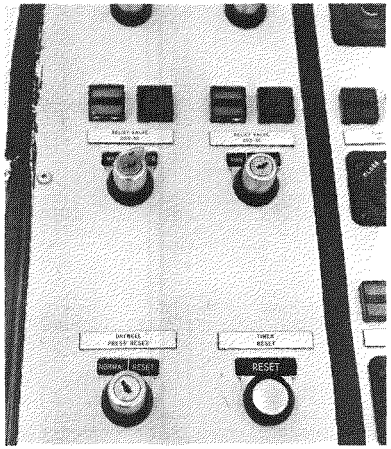


Fig. 7-28. Key-actuated controls with the key left in the control.

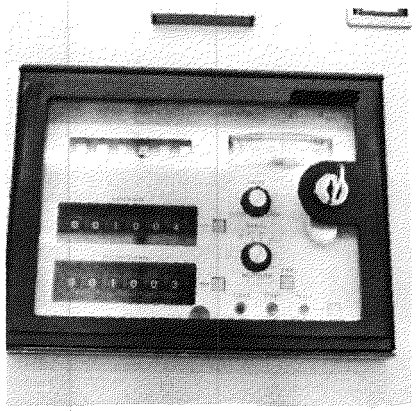


Fig. 7-29. Control panel protected by a lockable cover with the key left in the lock.

require extreme precautions to preclude accidental activation. This further implies that the special keys required to actuate controls should be kept under the surveillance of a supervisor or in a special place with limited access. Consequently, it was surprising to note that keys are commonly found inserted within their respective locked controls, as a matter of course (see Figures 7-28 and 7-29). This suggests that either the function does not require this special precaution or that closer surveillance over the keys is needed.

GENERAL

In addition to the problems brought out above, a number of other control parameters were checked which did not reveal any marked problems. Some of these findings are as follows:

- Space between controls or the separation of controls was generally adequate to prevent disturbance of one control while the operator was manipulating adjacent controls.
- Pushbuttons were generally adequately sized and protected. Pushbutton surfaces should be concave or indented to fit the finger. While this practice was not always followed, no operational problems were reported or observed.
- Toggle switches generally conformed to recommended dimensions. Some toggle switches located near the edge of benchboard panels appeared vulnerable and should be guarded. As observed earlier, space-saving toggle switches could be utilized to replace many of the more massive two and three position selector switches.
- Generally the color of controls was such that the controls contrasted well against the panel surface color.

AUTOMATIC VS MANUAL OPERATION

At all five plants the control system is designed to respond automatically for several minutes pursuant to the onset of major casualty modes. The operator's primary role during these periods is to track automatic system response and to intervene manually if the automatic system responses do not occur as programmed. The optimal balance between automatic and manual control of the system is a matter which is generally determined during the concept development phase of the hardware system development. Human factors specialists contribute by performing functions allocations trade studies in which the capabilities and limitations of men are pitted against those of machines. For example, when system response requirements are beyond the response time characteristics of the human operator, the situation clearly calls for automated system response. Humans, of course, are better at making complex judgments.

It was not possible for the study team to come to a definitive judgment regarding the balance between automatic and manual functions observed; this would have required extensive functions and task analyses, direct observations of operator behavior during casualty mode operations, and perhaps some experimental data comparing system effectiveness with different variations of automated/manual control systems. This was clearly beyond the scope of the present study. However, comments were solicited from operators and trainers by means of the following interview questions: "In your opinion, are too many or too few functions performed automatically by your system in controlling abnormal events, i.e., should the operator have greater or less control of the system in the initial response to abnormalities? Can you provide examples where direct control by the operator, in place of automatic system response, would be preferable? Are there examples where automatic system response would be preferable to manual control?"

The consensus of the interview sample was general approval of the automatic system response to abnormal events. The operators and trainers felt that automatic system response was essential in view of the complexity of the systems and the immediate control responses called for. The operators felt that a good balance between automatic and manual control had been achieved and where modifications were called for, more often than not, they were in the direction of more, rather than less, automated system response. The operators in no way felt threatened that the system would become automated to the point where the operator would be out of a job. Some representative comments from the operators and trainers illuminate these points:

- It is good to have the system take care of itself. It is too much for the operator to handle.
- With only two operators, you can only operate the plant automatically. The amount of auto control is not excessive in view of our staffing.
- Auto can do a better job than the operator when trouble first hits. If auto fails you do it manually, but usually things happen too fast to really override. There have been cases where manual operation has made the situation worse. There are too many interconnected functions.
- The more complex the systems get, the harder it is for the operator to find out what went wrong. The trend is towards greater complexity and it is more and more difficult for the operator to understand the system. Then it follows that there is a correspondingly greater emphasis on automation. With increased automation, there is a greater problem for the operator to know what happened when the automatic system fails. If they could automate the plant entirely, that would be great. But as it is now, the automatic systems fail and the operator has to step in.

The last comment highlights an important point. Some aerospace designers feel absolved of the responsibility of providing "human engineered" control boards when system operation is primarily automatic and the operator serves as manual backup to the automated system. However, it seems obvious that if the operator is to manually intervene successfully, the control boards must allow him to effectively track automatic system response, diagnose the nature of the malfunction, and restore the system to a normal condition through effective manual control options.

A small minority of the operators suggested modifications to the automated control system in the direction of greater manual override capability. One said: "In some cases the system may overrespond automatically. There is a tendency towards overprotection and it perturbs the whole plant unnecessarily. A downstream steam break accident could be handled automatically with steam isolation valves and a reactor trip. We don't need all the rest. We don't have a worst case in all cases." Others remarked as follows:

- There are cases where the operator should be able to override the automatic system. For example, take the boron injection tank. I should be able to defeat the system if I see no need for it. The automatic system can't tell the difference between a false signal and a real one. I can!
- I would like to be able to bypass the polishing bed (de-ionizing) and have manual control from the control room, as well as quantitative readings.

Several operators suggested modifications in the direction of increased system automation:

- I would prefer more automatic temperature controllers on process cooling systems, e.g., exciter cooling system.
- We need automatic control of the feedwater bypass valves for start-up and shut-down.
- They should automate the generator synchronizing and feedwater control for startup.
- Some functions that were designed for automatic operation are presently on manual because the automatic system is not trusted. It's too unreliable, e.g., generator hydrogen temperature is left on manual as opposed to auto. There is a problem in start-up and shut-down.
- We need automatic temperature control for the Residual Heat Removal System.
- Regeneration of the demineralizer in the plant is supposed to be automatic but it's not reliable so a man must be there to monitor and override as needed.
- The RCP seal system should be automated.

One shift engineer observed that "with the present caliber of operators we need more automation." He adds: "I would rather have more competent people and less automation." Some of the informal conversations with design personnel suggests a similar view. In effect, they are saying that since the operator is fallible, automation is viewed as a general solution to precluding operator error. This view, that today's operator or technician is not as capable as those of yesteryear, is common to other industrial situations. In view of the gross human factors engineering discrepancies uncovered by this study, we take the view that human engineered control boards might well obviate the need for increased automation. Automation is considerably more costly than the systematic application of human factors engineering principles to control board designs.

SUMMARY

A review of the design of controls incorporated on the control boards indicated that in four out of the five plants investigated unnecessarily large and cumbersome controls were utilized where smaller toggles or switch-lights would have served the same functions while consuming much less panel space. The use of these relatively massive controls for two or three option functions, in large part, accounts for the over-large and expansive control boards discussed in earlier sections.

Based on the human factors problems identified, it is recommended that future designs consider the following guidelines:

- Control activation force should offer sufficient resistance to reduce the potential for accidental activation but not require mechanical aids to accomplish control actions.
- Control pointer knobs should be shaped so that there is no possibility of mistaking the pointing end with the non-pointing end.
- Control pointer knobs should be selected which minimize or avoid parallax errors in relating the pointer with associated control option markings.
- Large controls that project from the panel surface obscure panel labeling and should be avoided or special pains should be taken to ensure that labeling is visible from the normal operating position.
- The mode in which a control should be operated should be self-evident from the nature of the control or by means of explanatory labeling. For example, if a pushbutton should be held down for several seconds, as opposed to requiring a momentary depression, a HOLD notation should be made on the button.
- The distinction between switch-lights and simple indicators which appear identical should be made obvious by special symbols on the legend face or by explanatory labeling.

- Required control motions should observe natural or expected movement directions, e.g., forward or up motion of a toggle to turn power on.
- Functionally similar or identical groups of controls that are repeated several time on the control boards, e.g., annunciator-warning system controls, should be arranged consistently from location to location.
- The necessity for incorporating large numbers of key-operated controls on the control boards should be reviewed in view of the fact that the keys are often observed left inserted in their respective controls.

Section 8

ACCIDENTAL ACTIVATION OF CONTROLS

"Have controls been selected and oriented to minimize accidental disturbance of control settings?" The response to this question, coupled with the observations of the study team, lead to the conclusion that present generation control rooms offer ample opportunities for accidental disturbance of controls. Seventy percent of the interview sample point to problems that remain uncorrected or that have been remedied in response to accidents or near-accidents. This section describes some of the sources of operator and trainer concern for accidental activation of controls and some of the measures taken to preclude accidents. As the operators pointed out, such accidents have been responsible for costly plant trips.

The problems reveal by this study can be categorized as follows:

- Inadvertent operation of controls of identical appearance and texture but having different functions.
- Location of controls in areas and in orientations that render them vulnerable to accidental contact and disturbance from operators and others who frequent the control room.
- Accident-prone activities that are required of the operator and which are unrelated to control board operation, e.g., annunciator lamp removal and replacement.
- Miscellaneous factors--factors difficult to anticipate by design, e.g., slipping or tripping on floor mats in the vicinity of the control board.

GROUPS OF IDENTICAL CONTROLS

The most common source of operator errors is inadvertent operation of one of several or many identical controls located in the same general panel area (see Figures 8-1, 8-2). The following statement by a senior reactor operator is representative: "The unit was at 50% load. One boiler feed pump was in service. The other boiler feed pump was being worked on by Maintenance. The operator was asked to shut down the feed pump being worked on. Due to the closeness of the controls for both pumps, and no distinction between the controls, the operator tripped the wrong pump. This tripped the plant. We were down eight hours or so

and lost a lot of dollars in megawatts." Figure 8-3 provides a view of the feed-pump controls in their original configurations as found in the simulator. Figure 8-4 shows the modifications made to the panels after the incident described. Star shaped controls were used to differentiate BFP 22 controls from the pistol-grip BFP 21 controls. Also note the taped line of demarcation provided by the operators to further differentiate BFPs 21 and 22.

In another context, the operators, after repeated errors, decided to paint adjacent pistol grips different colors. The most novel example of shape coding to prevent misidentification of controls is shown in the "before" and "after" sequence in Figures 8-5 and 8-6. At first the utility management objected to this seeming frivolity, but the operators apparently made a compelling case in behalf of shape coding.

Other factors that contribute to misidentification of controls, and which are discussed at length in other segments of this report, are inadequate labeling practices, lack of distinctive functional demarcations on panel designs, and inadequate use of control coding techniques other than shape coding.

CONTROLS LOCATED IN VULNERABLE AREAS OR ORIENTATIONS

The second major source of accidental control activation has to do with the type of control, its location and orientation, and its exposure to contact from plant personnel. Pistol grip controls located at or near the edge of benchboard segments of consoles are a persistent problem in some plants. Operators and other passersby can easily come into accidental contact with them (see Figure 8-7). In one plant, as noted in Section 7, the operators have remounted all of the pistol grip controls located at the edge of the benchboards so that the handles are less exposed to contact. As discussed in the preceding section, this makes operation of the controls awkward. In the view of the operators, however, this is less important than the possibility of accidental control activation. Similarly, the toggle switches shown in Figure 8-8 are vulnerable. Note the position assumed by the Shift Supervisor in Figure 8-9. He is instructing students in reactor panel operation in the vicinity of the panel shown in Figure 8-8. Aside from the physical body contact, these photos make the point that the type of clothing worn by the operator is of significance in regard to potential for snagging controls.

The control shown in Figure 8-10 was actuated accidentally by an operator reaching across the benchboard segment of the console to manipulate a control for the

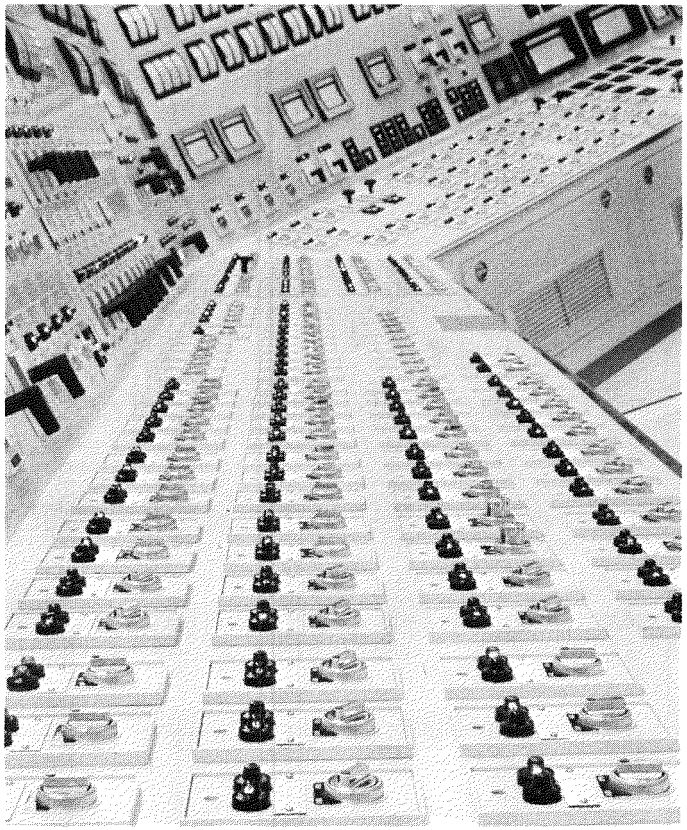


Fig. 8-1. Massive arrays of identical controls in the same control board area.

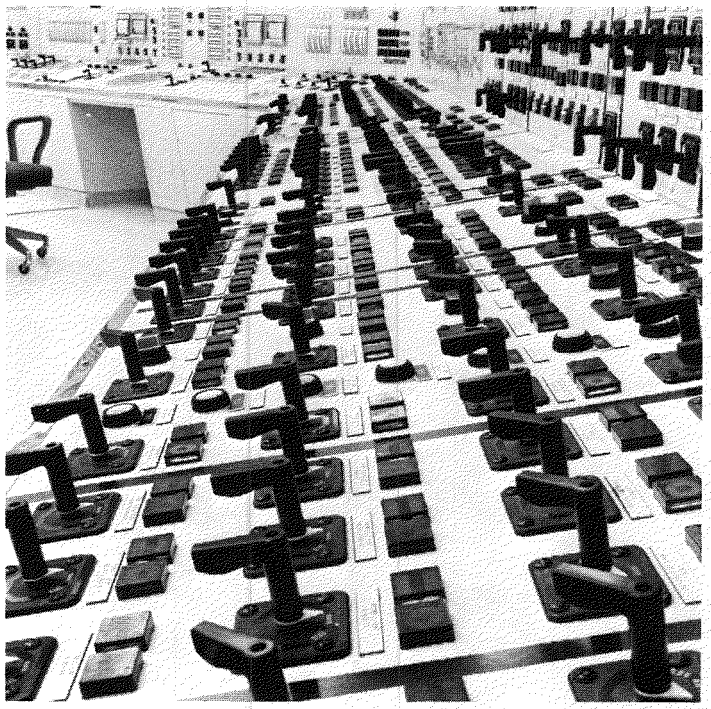


Fig. 8-2. A forest of identical pistol grip controls which are not coded.

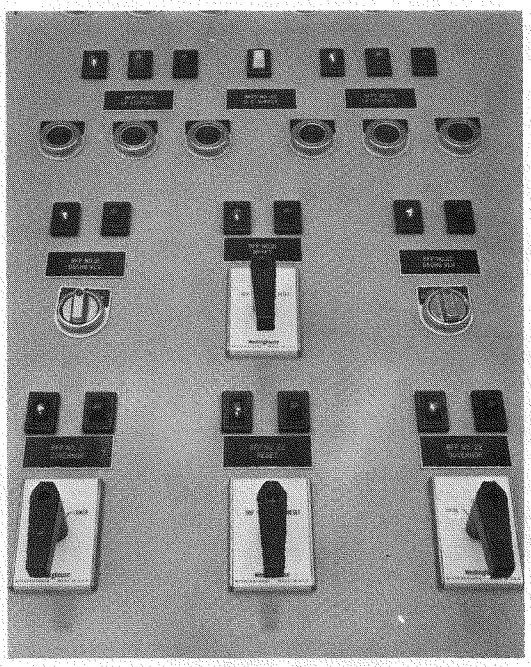


Fig. 8-3. Original configuration of group of controls which operator incorrectly manipulated causing a plant trip.

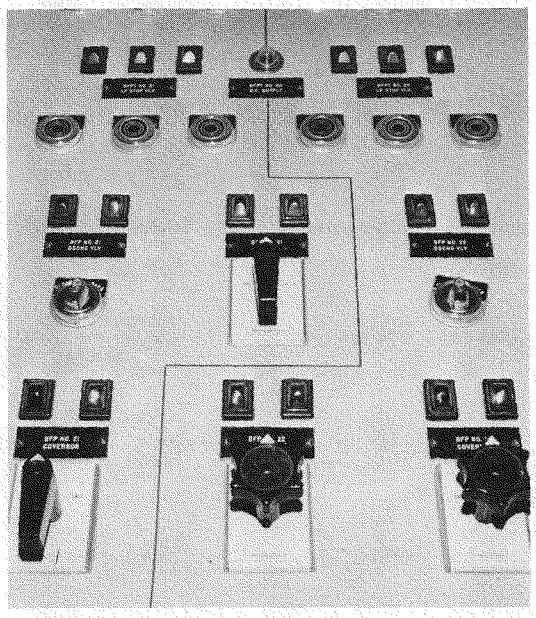


Fig. 8-4. Modifications in control shape and demarcation of functional areas to reduce likelihood of operator error.

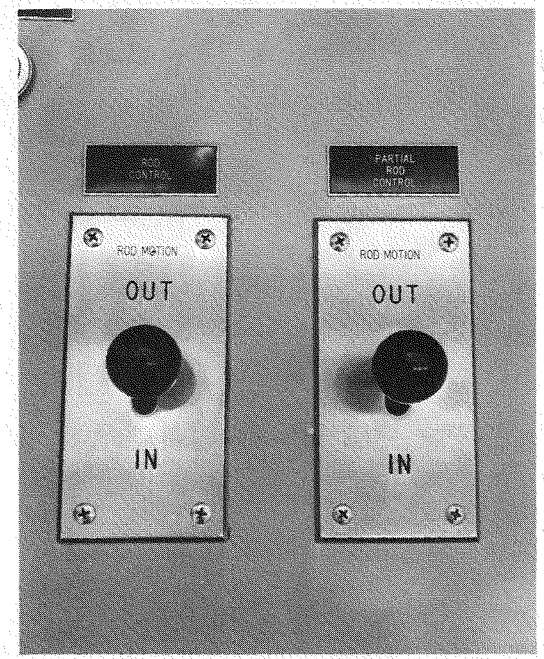


Fig. 8-5. The side by side ROD MOTION controls in their original configuration.

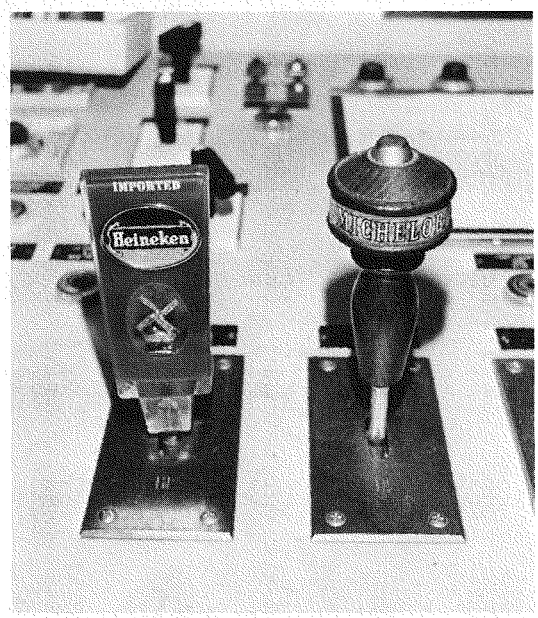


Fig. 8-6. Novel shape coding of the ROD MOTION controls depicted in Fig. 8-5.

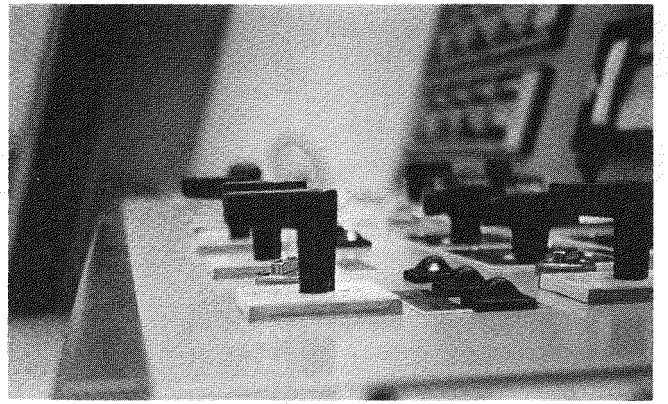


Fig. 8-7. Controls located near the edge of console benchboards are vulnerable to accidental disturbance.

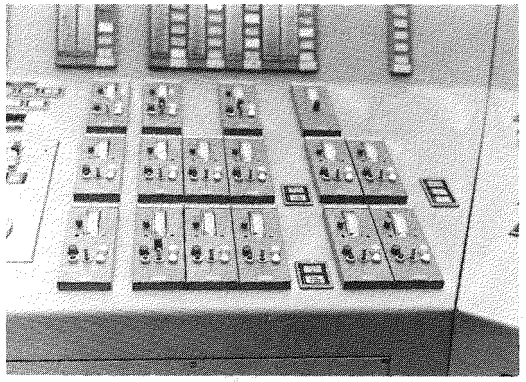


Fig. 8-8. Toggle switches at end of benchboard appear vulnerable.



Fig. 8-9. Note the potential for inadvertent actuation of controls on this console.

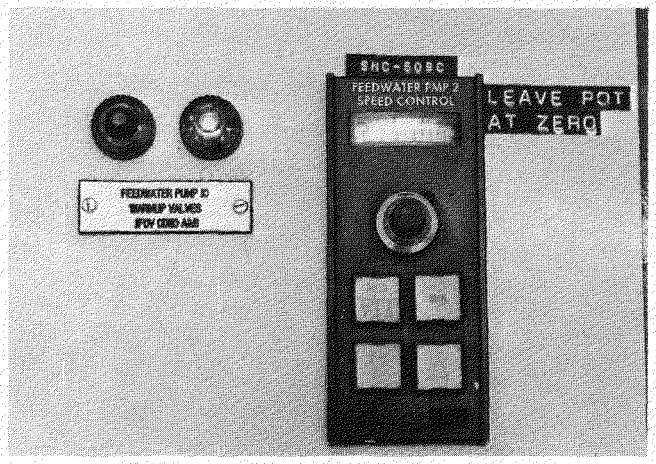


Fig. 8-10. Controller that was accidentally actuated by an operator.

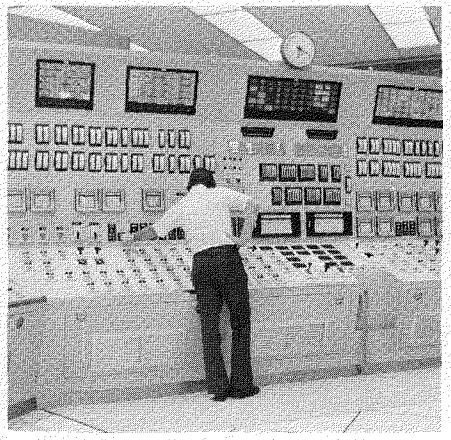


Fig. 8-11. Position assumed by an operator when the control shown in Fig. 8-10 was disturbed.

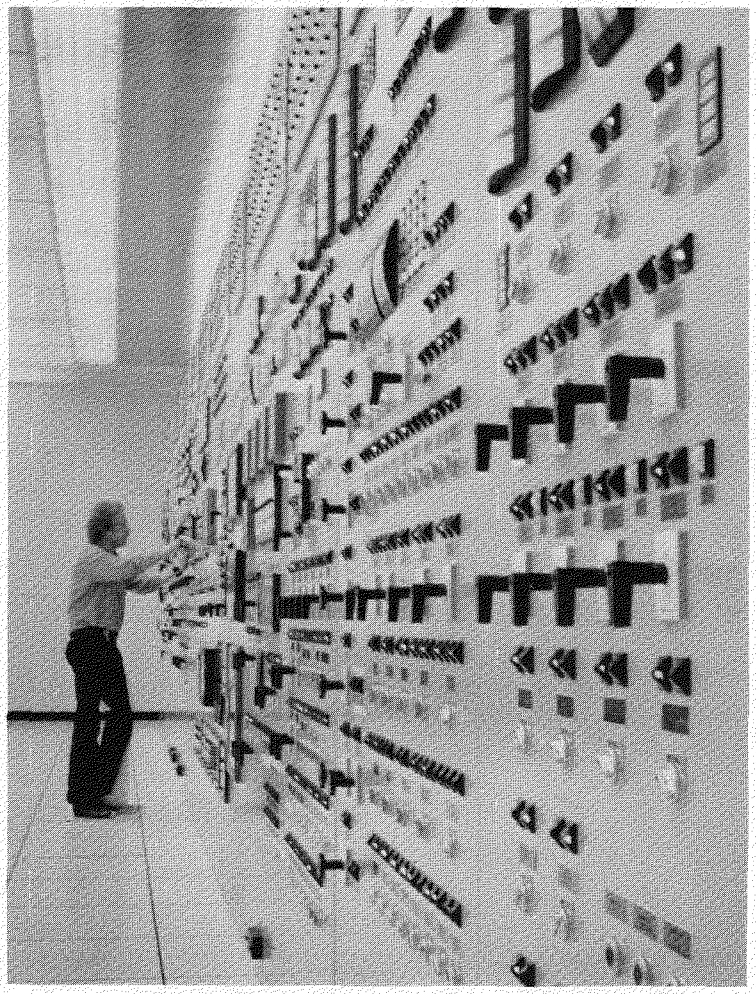


Fig. 8-12. Large vertical panel showing many projecting pistol grip controls.

feedwater pump master controller in the manner shown in Figure 8-11. The pushbuttons that were disturbed did not project from the surface of the control unit to any significant extent. However, in reconstructing the incident, the operator hypothesized that three factors combined to cause the accidental activation of the vulnerable control: loose fitting clothing, a heavy object in the pockets, and the operator reaching across the benchboard. These incidents point to the necessity of either locating controls away from the exposed benchboard edge or guarding the controls with raised barriers or built-in locking mechanisms.

Vertical panels also present problems when coupled with controls that project from the vertical surface and exposure to passersby. Figure 8-12 shows an example of a vertical panel with projecting pistol-grip controls. Figure 8-13 shows an electrical panel and an auxiliary service panel behind the center desk operator's station in a high density traffic area. Auxiliary operators stream through this passageway to coordinate activities with the center desk operator. The operators in this control room expressed concern, born of experience, over plant personnel brushing against control handles and causing improper operation.

At another plant the operators tired of technicians bumping into projecting control handles located on vertical panels behind the main consoles. The "homemade" guards shown in Figure 8-14 were devised to cope with the problem. In some cases (see Figures 8-15 and 8-16) controls are placed so far below the normal eye-level that an operator can be oblivious to their presence and accidentally disturb them when distracted by normal activities.

ACCIDENT-PRONE ACTIVITIES

Some operator activities contain elements that seem to invite accidents. For example, annunciator lights at all the plants visited are placed above normal operator reach. Some form of ladder is usually on hand to give access to the lights for replacement of lamps. As can be seen in Figure 8-17, one solution is a ladder which slides along a rail above the vertical expanse of panels. Unfortunately, this ladder becomes derailed on occasion and damage to the annunciator lights is evident.

Figure 8-18 shows a special stepladder for access to annunciator lights located on a different type of console configuration. It is possible for the operator to fall from this perch and disturb the controls or injure himself. There is an even greater possibility of accidents illustrated in Figure 8-19 where the operator

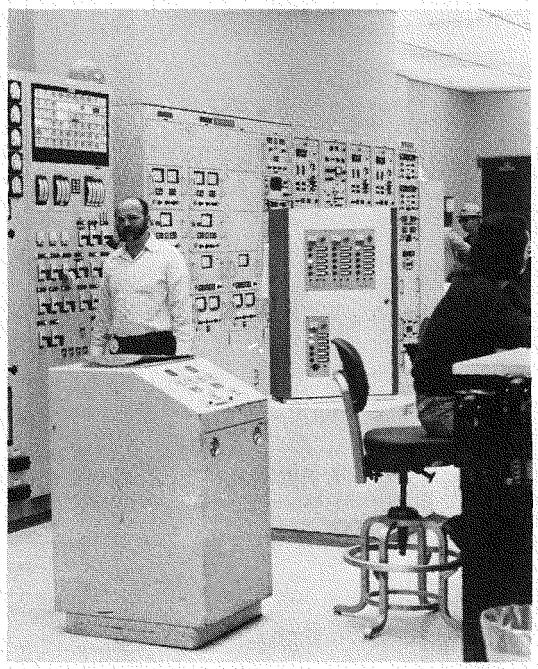


Fig. 8-13. High traffic area where the passerby can snag projecting controls.



Fig. 8-14. Protective covers for controls in the back rack areas that passing technicians can bump.

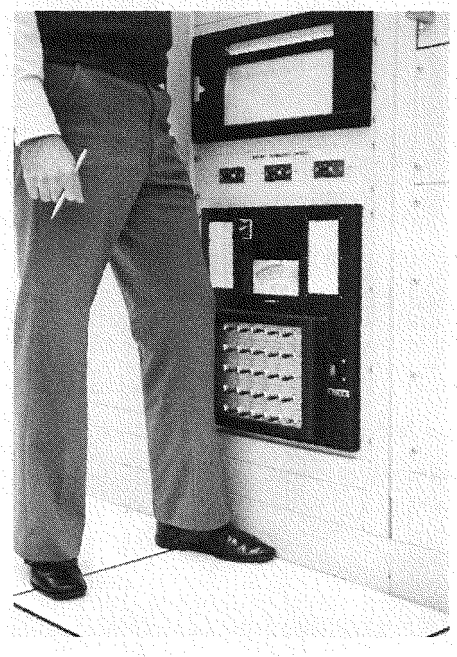


Fig. 8-15. Controls placed below normal eyelevel.



Fig. 8-16. Controls placed where operator can overlook their presence.

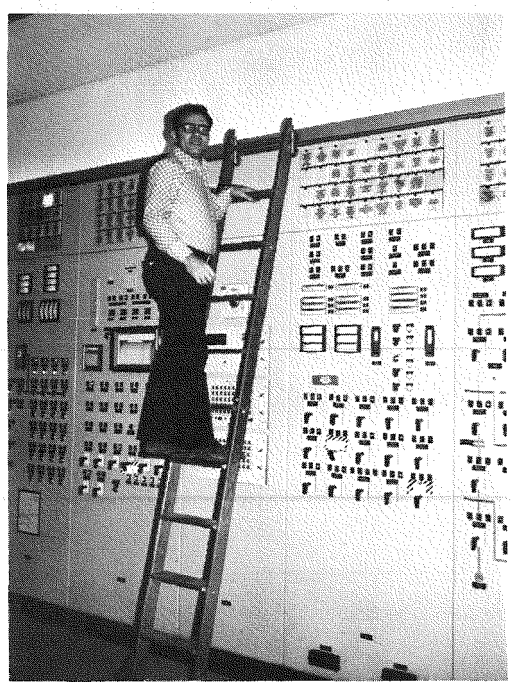


Fig. 8-17. Ladder provided for replacement of expended annunciator lamps has derailed on occasion.

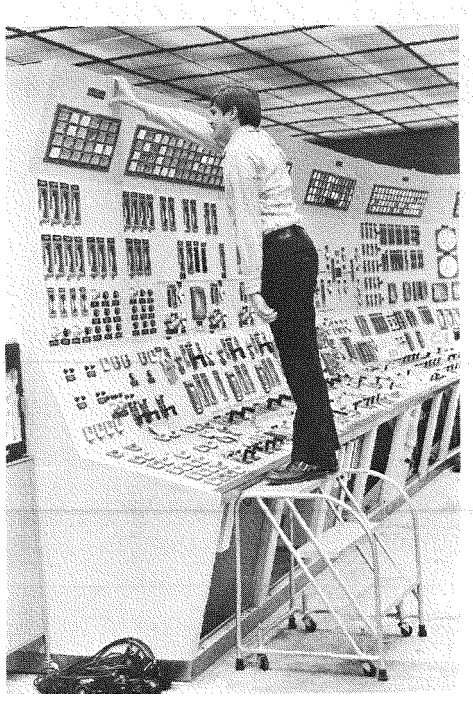


Fig. 8-18. Stepladder used to replace annunciator lamps provides a precarious perch.

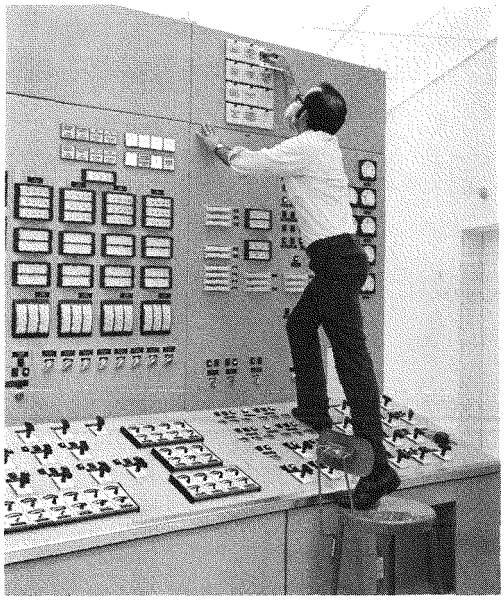


Fig. 8-19. The benchboard provides a "natural foothold" for the operator who does not trouble to get the ladder.

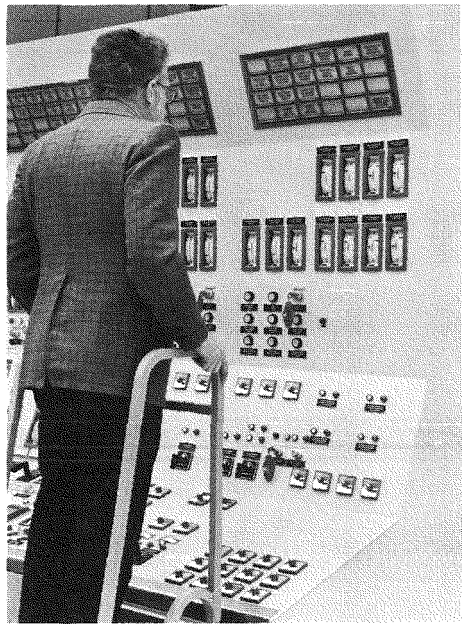


Fig. 8-20. Stepladder with handrails provides a more secure platform for the operator.

does not take the trouble to use a special step-ladder and steps directly onto the sloping console benchboard. Also, some step ladders are safer than others. Figure 8-20 shows a ladder with hand rails to help steady the operator. This ladder was found at the simulator that corresponds to the operational plant scene depicted in Figure 8-18.

MISCELLANEOUS FACTORS

It would tax the ingenuity of any designer to anticipate and prevent all of the factors that could lead to accidental activation of controls. For example, one of the study team members, while reviewing panel arrangements in an operational control room, almost tripped over the raised edge of the rubber mat located in front of the control boards (see Figure 8-21). Had he actually tripped, he would have fallen against the controls. When he asked the operator on duty about the problem, he was told that the problem was known to the operators and they have become accustomed to side-stepping that part of the rubber mat.

Another potential source of problems stems from the large numbers of plant personnel that either congregate in the control room or rush to it during an emergency or milestone event that occurs during the day shift. The following quote from one operator illustrates the potential for accidents: "The techs like to hang out in the control room. The biggest problem is during a casualty that occurs during the day shift. Then we have an overabundance of supervision. We have had as many as forty people in the control room, from the secretaries to the head of the plant, during the first criticality. We need a gallery."

Several plants visited had marked No-Trespass zones in proximity to the control boards, but with the large numbers of people in the control room in the situations described above, it is impossible for the control room operator to enforce these restrictions.

MEASURES TO PREVENT ACCIDENTAL ACTIVATION OF CONTROLS

Control board designers have incorporated a variety of measures to safeguard certain major controls from accidental, or even premature, actuation. These measures vary from plant to plant and there are also variations in the specific controls that are selected for special protection. Some of the measures taken to preclude incorrect control operation are illustrated in Figures 8-22 to 8-32.



Fig. 8-21. Raised lip of floor matting in one operational control room invites accidents.

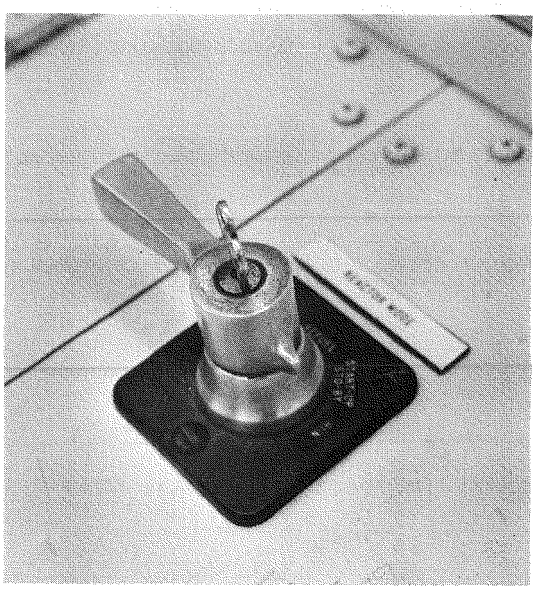


Fig. 8-22. Key locked REACTOR MODE control.

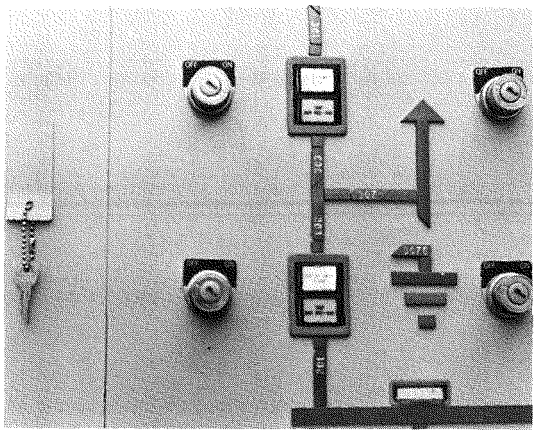


Fig. 8-23. Key operated controls integrated into a mimic panel arrangement.

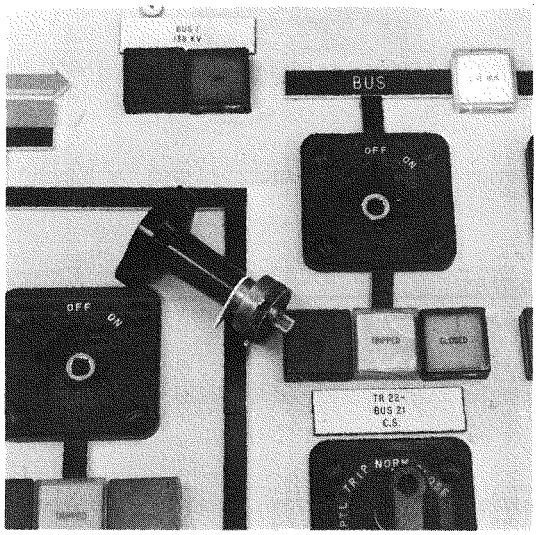


Fig. 8-24. Movable control handle to preclude simultaneous actuation of two busses.

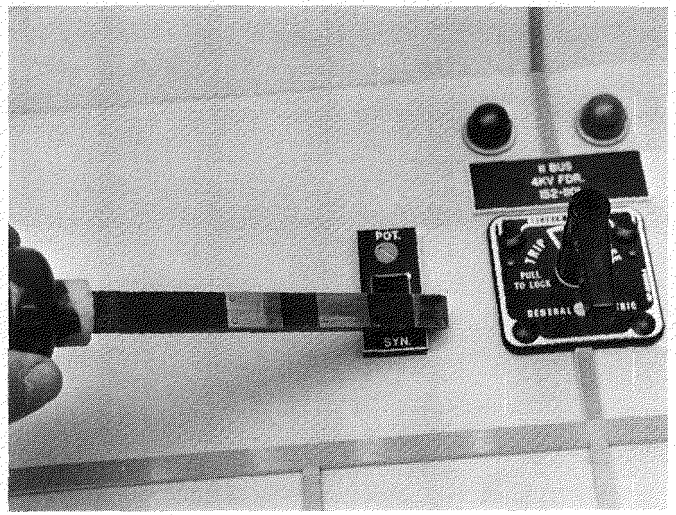


Fig. 8-25. Another movable control for the electrical panel.

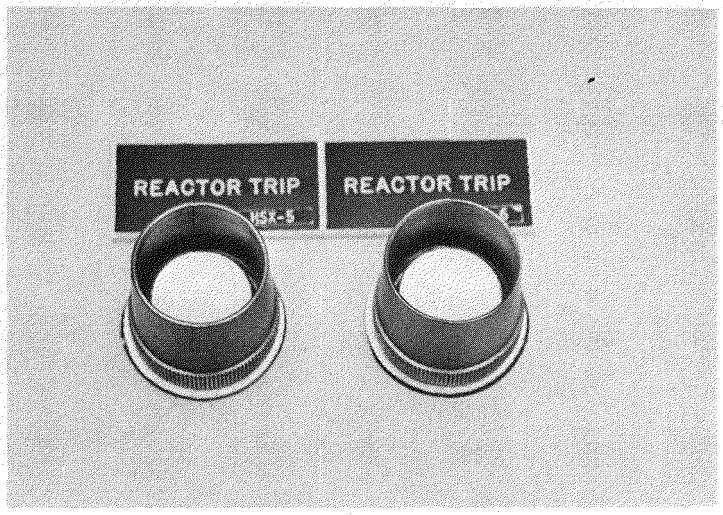


Fig. 8-26. Raised barriers used to protect important pushbutton controls.

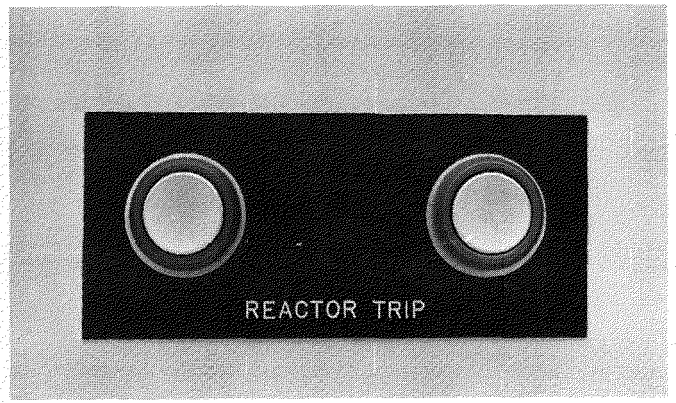


Fig. 8-27. Dual control arrangement to prevent inadvertent reactor trip.

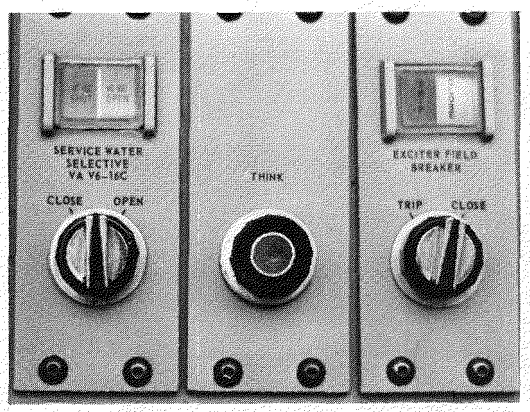


Fig. 8-28. THINK button designed to cause operator to reflect on his actions before effecting major control actuations.

A common technique for ensuring that critical controls are not manipulated inadvertently is the use of key-operated controls (see Figures 8-22 and 8-23). At one simulator several dozen control keys were stored in a special cabinet. Searching for a given key when required can offer some retrieval problems. The value of this protection approach hinges on the ready availability of keys when required. It was observed that in many instances the keys are left permanently in their respective controls, as noted in Section 7.

Electrical panels are typically designed to be operated with removable controls (see Figures 8-24, 8-25) that are transferred from one receptable to another as appropriate. This precludes incorrect simultaneous distribution of power to the various busses.

Another common technique is to place a raised barrier around an important button (see Figure 8-26). Often these barriers are added to panels at the urging of operational personnel. At one plant, for example, unit #2 control boards were under construction and were to duplicate the unit #1 design. The operators pointed out that the unit #2 design did not contain the raised barriers that had been added to unit #1. However, when the construction crew finished its work, the operators planned to add protective devices to the controls identified based on unit #1 experience.

Some plants employ dual control or two-step operation techniques to prevent inadvertent or premature activation of controls such as the REACTOR TRIP controls. Figure 8-27 shows a dual pushbutton arrangement in which the operator must depress both controls to effect a reactor trip. At another plant visited during the Systems Familiarization phase of the study, the control board houses a THINK button (see Figure 8-28). This THINK button is interlocked with ten control functions in such a manner that the functions can be activated only by first pressing the THINK button. However, in separate discussions with three operators, it was apparent that there was no agreement as to which ten functions were interlocked with the THINK button. In fact, the operators routinely pressed the THINK button before all control actuations, so that the extra operation had lost its original significance.

Another prominent protective device is provided by a cover for an individual control or subpanel. Sometimes these covers are further safeguarded by key-locks. Figures 8-29 to 8-31 show some of these protective measures currently being

employed. A problem observed with such covers is that the labels defining control options are often obscured. These covers are often placed at the edge of a benchboard panel and it is apparent that many were added as a result of a negative experience.

In some cases protective features are designed to prevent personnel in the control room from disturbing a calibration or other aspect of equipment operation that is not changed from day-to-day. Such barriers (see Figure 8-32) are designed to preclude tampering and require a tool to change the settings.

OPERATOR MODIFICATIONS TO CONTROL BOARDS

The operators do not lack imagination when it comes to devising cueing techniques to prevent accidental activation of controls. The need for such aids usually indicates an initial deficiency in the design of the control boards. Some operator-initiated modifications to protect the boards have already been discussed above. Others are depicted in Figures 8-33 to 8-36. Figure 8-33 shows an attempt to minimize incorrect operation of a group of three adjacent controls. A stiff cardboard wedge is placed over the pushbutton controls. Operators make errors when they are focussing their visual attention on an associated display in another segment of the panel and they reach for one of the three controls. The physical cardboard barriers have been placed over a wide series of control groups in both units #1 and #2 of this plant.

Figure 8-34 shows how operators have attempted to differentiate between four RANGE SWITCHES that were identical in appearance and feel. Strips of Dymo tape have been affixed to every other one. Again, the operator's attention while manipulating these controls is often directed to associated visual displays in another area of the panel. This problem is inherent to control panel designs which isolate controls to benchboards and associated displays to the vertical segment of the control above the benchboard.

Figure 8-35 shows another "homemade" hinged cover to prevent inadvertent operation of the rod control startup button. This button was not guarded in the corresponding simulator. Figure 8-36 summarizes the operator's concern for accidental activation of critical controls.

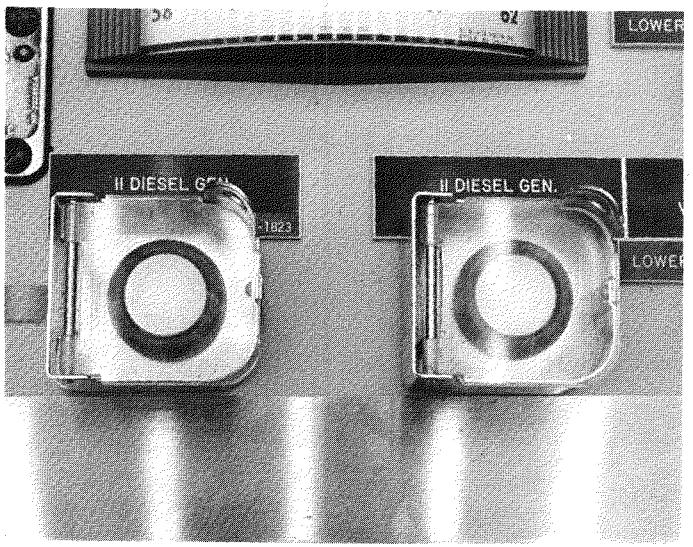


Fig. 8-29. Protective cover on pushbuttons placed near edge of benchboard.

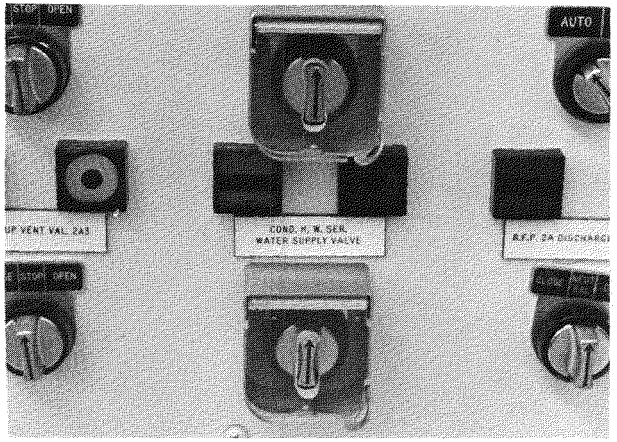


Fig. 8-31. Special lucite covers which maintain switch position in a fixed mode.

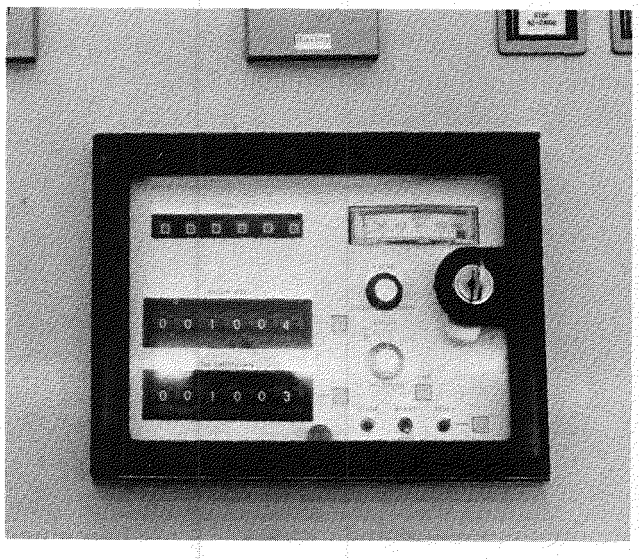


Fig. 8-30. Controls protected by key and hinged cover.

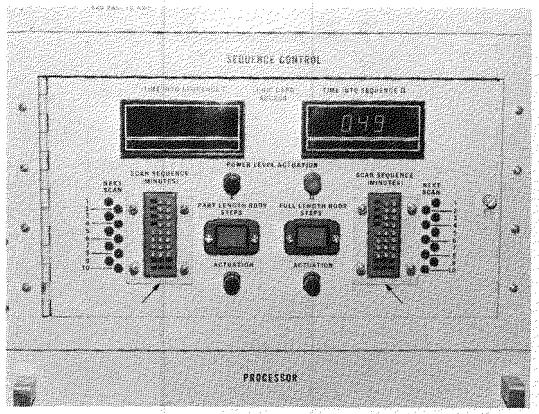


Fig. 8-32. Lucite barriers over scan sequence control requiring tool for removal of the guards.

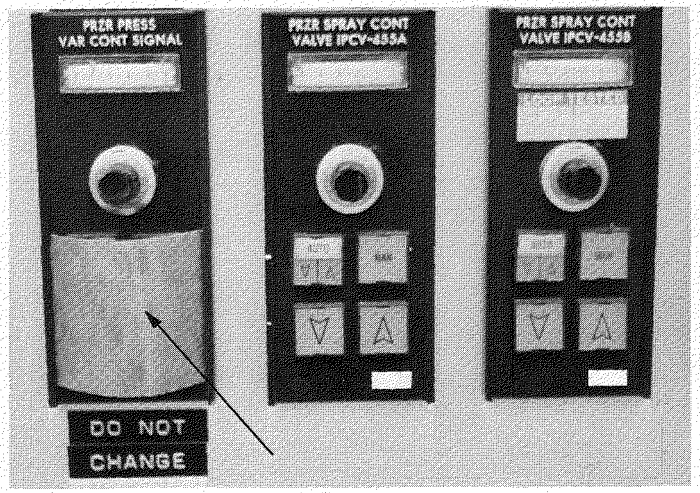


Fig. 8-33. Stiff cardboard barrier to prevent inadvertent operation of adjacent control.

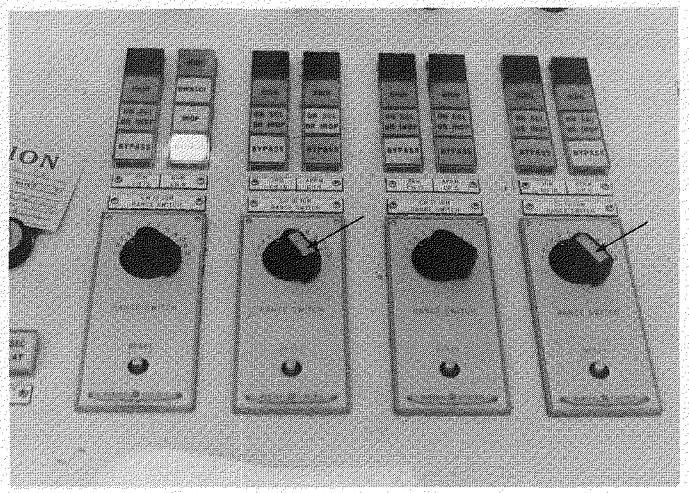


Fig. 8-34. Four identical range controls were differentiated by placing Dymo tape on every other one.

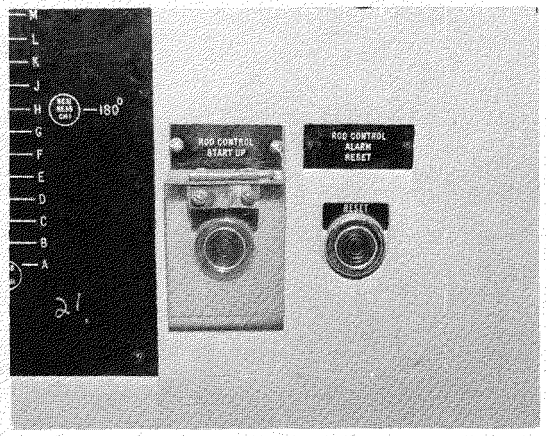


Fig. 8-35. Operator instituted hinged cover over the rod control startup pushbutton.



Fig. 8-36. Operator implemented cautionary cue.

SUMMARY REMARKS

There is a high degree of concern over the problem of accidental disturbance or inadvertent operation of controls among operational personnel. While many such problems have been anticipated by control room designers, it is evident from the accidents that have occurred and the magnitude of operator induced modifications to safeguard controls that much can be done to make the control room less vulnerable to accidents. It is also evident that there is a lack of consistency or standardization from plant to plant in regard to those controls deemed worthy of safeguarding or the techniques and operational practices employed in preventing accidental disturbances. Prevention of accidental activation of controls all too often appears to be accomplished in a trial-and-error manner. Based on the observations made during this study, there is a need to review thoroughly each nuclear plant control room design from the standpoint of accidental control disturbances and to effect a program of safeguarding controls that are most sensitive. Safeguards should be so instituted, however, as to not compromise rapid and effective operator response to abnormal situations.

Section 9

INDICATOR LIGHTS

Indicator light displays are used to provide information regarding the status of valves, pumps, subsystems, processes, and cautions or warnings. This section critiques indicator light display practices as observed in the five control rooms studied. We will consider such subtopics as indicator reliability, ease of lamp removal and replacement, proper and improper use of indicators, standardization, and positive vs. negative indications.

USE OF INDICATORS

Indicator lights are essentially attention-getting devices and should be used to display important aspects of equipment functioning. Generally, indicator lights should not be used to display the position of a selector or toggle switch, but rather the status of the subsystem being manipulated, i.e., the OPEN/CLOSE indications associated with a specific valve control should reflect the status of the valve and not simply that the operator has placed the selector switch in either the OPEN or CLOSE position. Indicator lights which merely reflect the position of a selector switch (see Figure 9-1) are superfluous. Superfluous indicators should be avoided to minimize the tendency towards confusing "Christmas Tree" control boards.

Generally, indicator lights provide qualitative information, e.g., HIGH, LOW, RAISE, LOWER, ON, OFF. Where quantitative values are required other devices such as meters are more appropriate. For example, the vertical series of indicators shown in Figure 9-2 are not necessarily the best format for informing the operator of fluid height level. A vertical meter would have served as well or better and uses less panel space. In association with the meter, HIGH and LOW limit indicators could have been used to alert the operator to a problem. This arrangement would receive more qualitative attention and the meter would provide more precise quantitative information. Some meters discussed in Section 10 incorporate indicator lights to inform the operator when a preset limit has been exceeded.

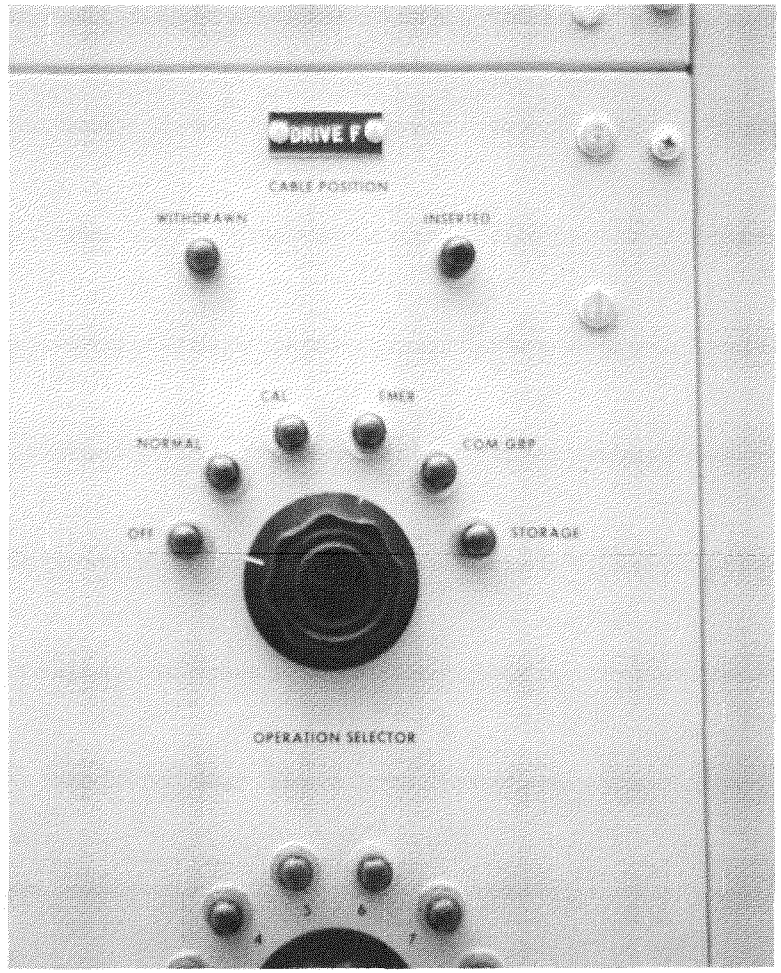


Fig. 9-1.

Indicator lights that merely reflect the position of selector switch are superflous and add clutter.

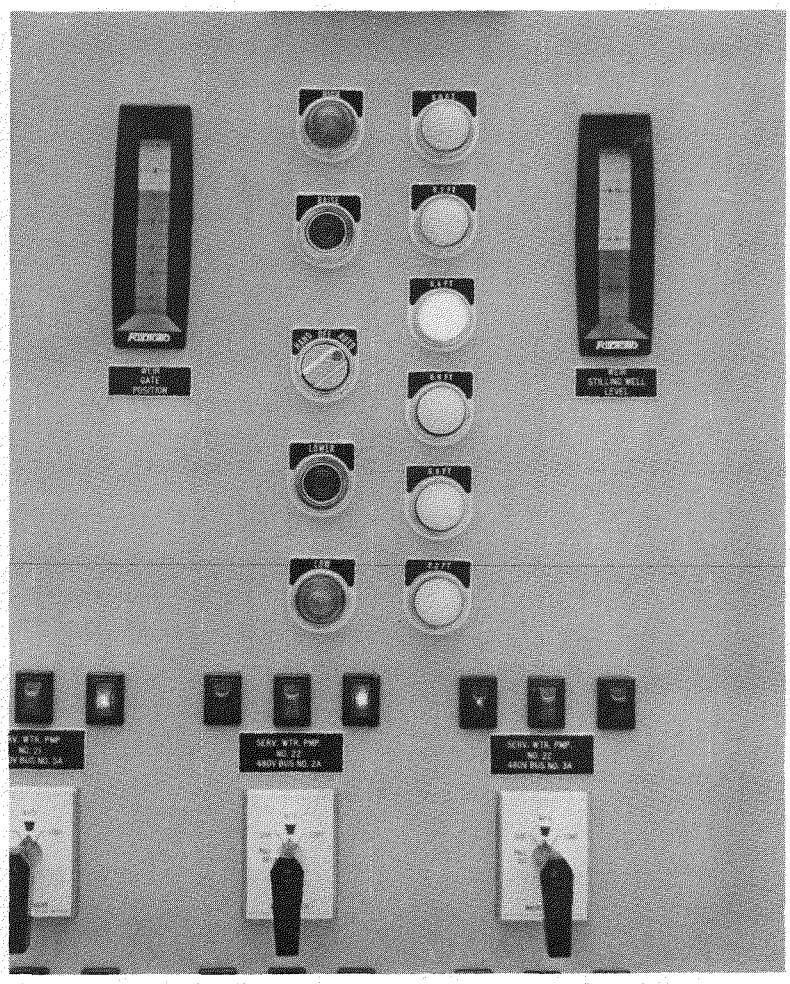


Fig. 9-2.

Series of white indicator lights used to display quantitative levels. A meter combined with HIGH/LOW limit light cautions would have been more appropriate.

INDICATOR RELIABILITY

There are several means to ensure that an indication is available when needed. One common means is to provide two-lamp redundancy since it is rare for both lamps to burn out simultaneously. A second approach is to provide lamp test circuitry to enable the operator to periodically check all lamps with the press of one or more lamp test buttons. Some indicators are designed with built-in "press-to-test" features.

In general, the five control boards incorporated adequate provisions for ensuring the reliability of annunciator panel indicators. Such panels usually have both multiple lamp redundancy and lamp test circuitry. However, indicator lights incorporated in the remainder of the control boards, more often than not, are single lamp indicators with no provision for lamp tests. While no quantitative measures were obtained, the study team was surprised at the number of indicators with expended lamps that were observed and the frequency with which the operator was required to routinely survey the control board for expended lamps.

EASE OF INDICATOR MAINTENANCE

One of the important selection criteria for choosing indicator lights is the ease with which the lamps can be replaced. Ideally, the task should be accomplished from the front of the panel, without special tools and without ladders or other access aids. To the extent that the chore is made inconvenient for the operator, there will be a natural tendency to put off this chore in the hope that the oncoming shift will take care of it.

Some indicator lights require a special tool for lamp removal and replacement. Figures 9-3 to 9-5 show the steps required to replace expended bulbs with one combined selector switch-indicator design. The obvious problem with special tools is that they are not around when you need them. Figure 9-6 shows some scratches and nicks in the immediate vicinity of these indicators. It is a safe bet that the special tool was lost and some simple expedient such as a pocket knife was used to pry loose the cover plate. With the exception of a few illuminated projection meters, all indicators observed were maintained from the front of the panel. However, some were difficult to manipulate. For example, the series of two lamp indicators shown in Figure 9-7 were obviously in need of lamp replacement. In some cases one of the two lamps had burned out and in other cases both lamps were gone. When the operator was asked why the lamps hadn't been replaced, the answer was that it was extremely difficult to get at the lamps without

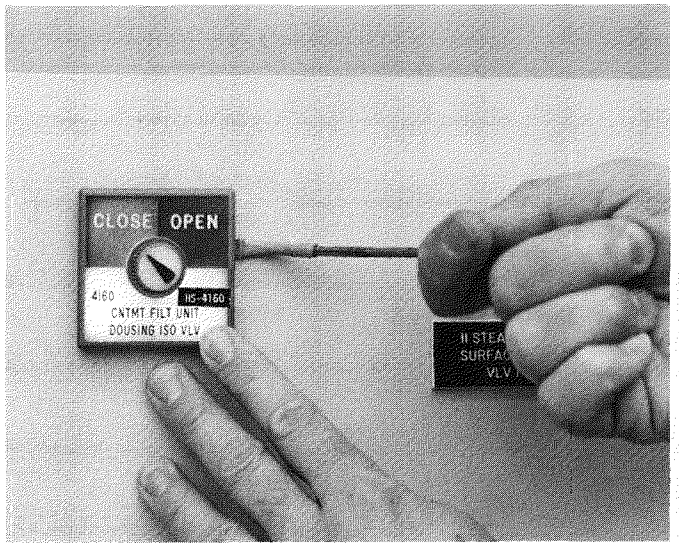


Fig. 9-3. A special tool is required to pry off the face on this indicator-switch for lamp replacement.

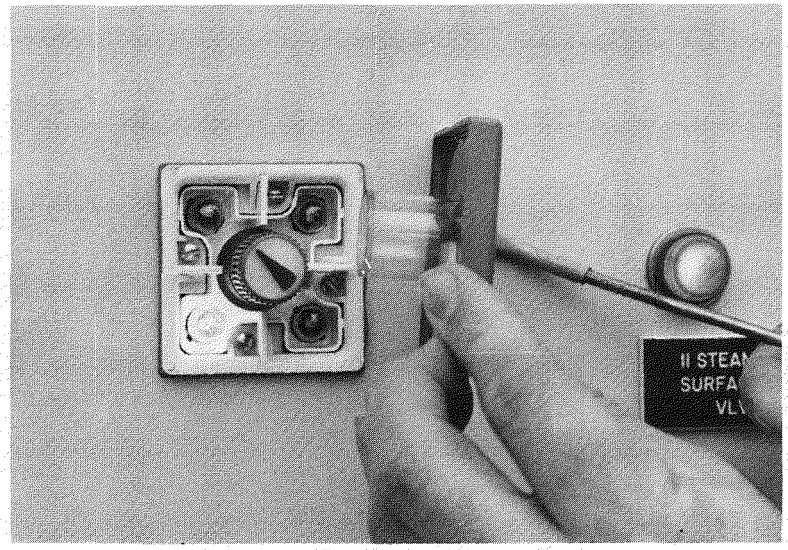


Fig. 9-4. With the face removed, an insert which houses the four lamps is exposed.

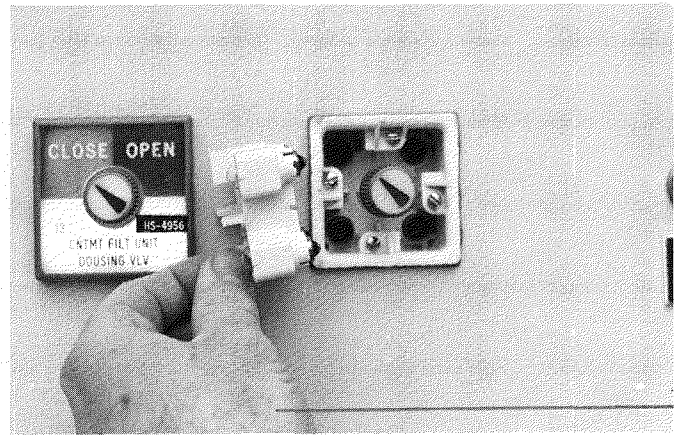


Fig. 9-5. The insert is removed and the lamps can be retracted and replaced from the rear of the insert.



Fig. 9-6. Scratches and nicks near the indicator face probably caused by a coin or other expedient when the special tool was lost.

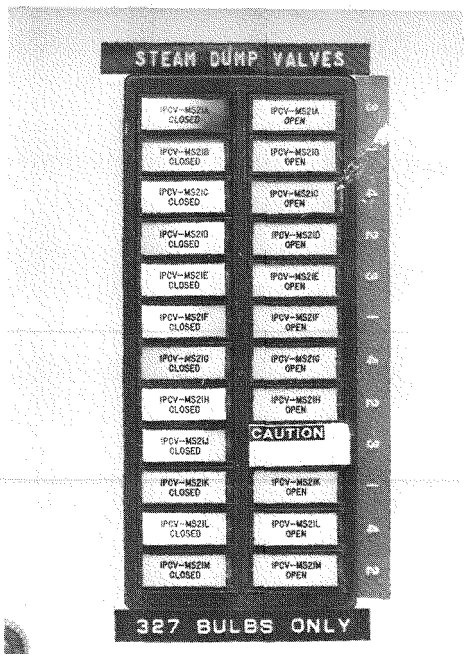


Fig. 9-7. The operator puts off replacement of expended lamps when the lamps are difficult to reach.

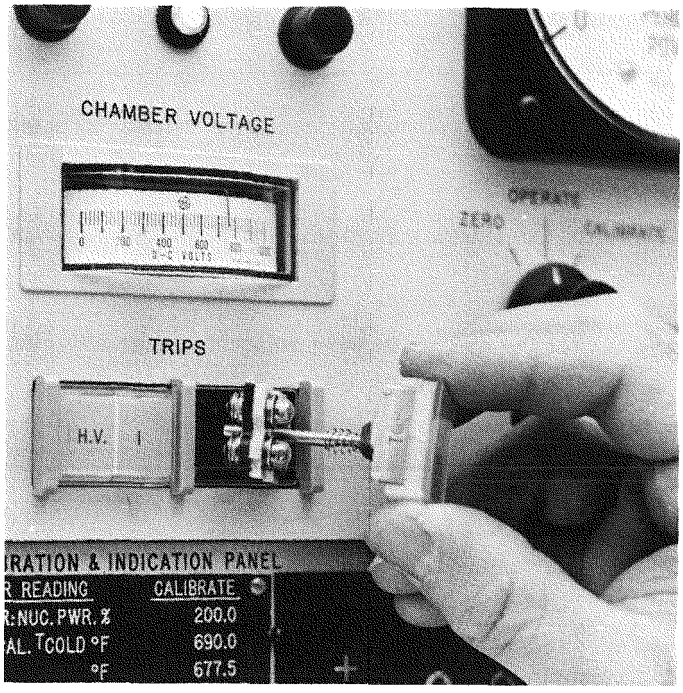


Fig. 9-8. This four-lamp indicator can be extracted for bulb replacement without special tools.

breaking fingernails. Other indicators such as those shown in Figure 9-8 require no special tools for lamp replacement. However, the operator must know the correct sequence of pull-twist-and-push motions required to remove and reassemble the indicator light.

The alarm annunciator panels at all the plants visited offered lamp replacement difficulties because a ladder or stepping on the benchboard was required (see Figures 9-9 to 9-11). Some operators complained that extraction of the annunciator bulbs was difficult because they were housed in very cramped quarters (see Figure 9-12).

POSITIVE VS NEGATIVE INDICATIONS

A human factors groundrule is that the absence of a signal should not be used to inform the operator of any aspect of system operation, i.e., avoid the use of negative indications. This point is clarified by Figure 9-13. Here four STEAM DUMP VALVE indicators are shown (within the taped perimeter). The unilluminated lamp is supposed to indicate the steam dump valve closed condition and the illuminated red lamp describes the valve open situation. The problem with these negative indications is that the operator cannot be sure that the lamp is not lit because the valve is indeed closed or because the lamp is burned out, i.e., a burned out lamp would fail to reveal a valve-open condition. This problem is aggravated when the indicator has only one lamp and lamp test circuitry is lacking. The problem of negative indication appeared in only a few isolated cases.

SIZE OF INDICATORS

As in the case of controls, indicators have not generally been selected to conserve panel space. The indicators in Figure 9-14 show the open/closed status of 12 steam dump valves. Two alternative designs (see Figures 9-15 and 9-16) are possible utilizing 12 four-lamp indicators. Note also how the labeling has been simplified to avoid the repetition of "IPCV-MS21" which is common to all 24 indicators in the original configuration. In the Figure 9-15 configuration the indicator is either red or green to represent the open/close status of the valve, while the Figure 9-16 configuration spells out these options rather than relying solely on the color code.

INTERCHANGEABLE LEGEND CAPS

A potential problem with indicator legend caps is that they can be inadvertently mismated with the wrong indicator when two or more are removed at the same time.

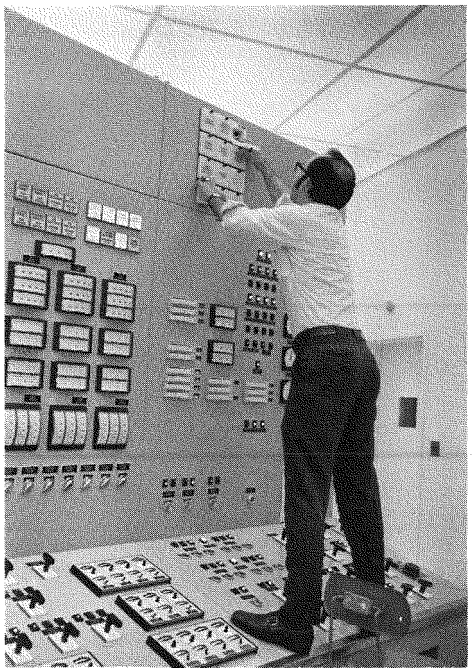


Fig. 9-9. The annunciator indicators are placed at a height which makes expended lamp replacement a problem.

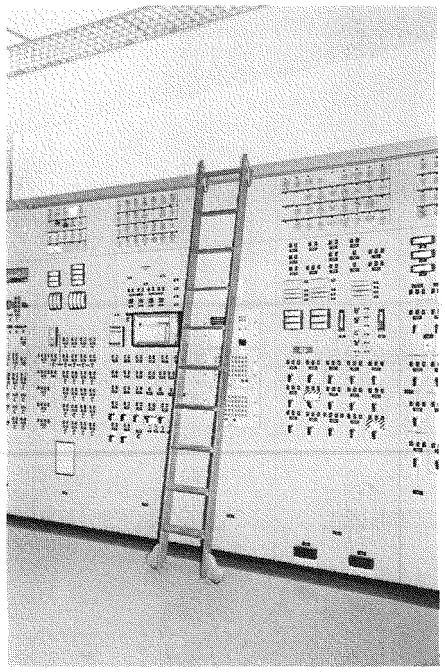


Fig. 9-10. Ladder integrated into the control board to provide access to annunciators for lamp replacement.



Fig. 9-11. Operator extracting an annunciator module for lamp replacement using a step ladder.



Fig. 9-12. Some operators complained of the difficulty of removing and reinserting tightly packed lamps.

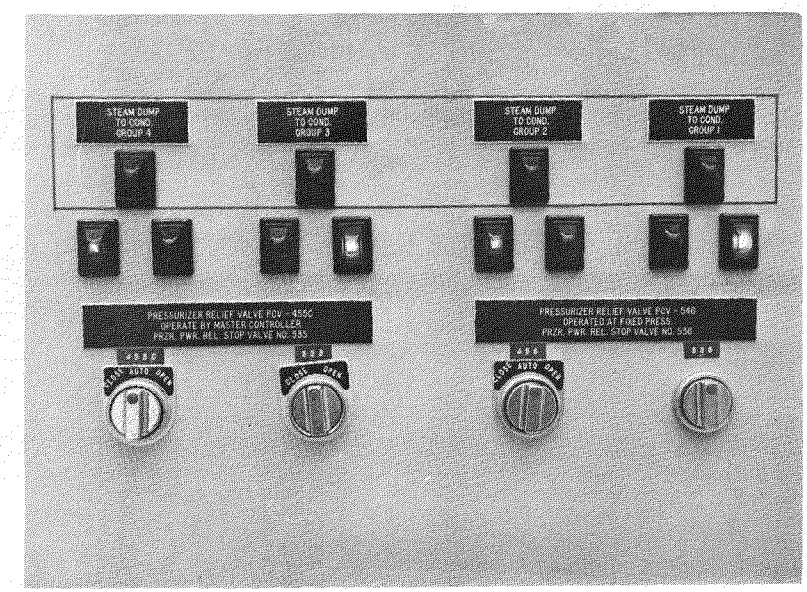


Fig. 9-13. The steam dump valve closed condition is indicated by the absence of an illuminated indicator light.

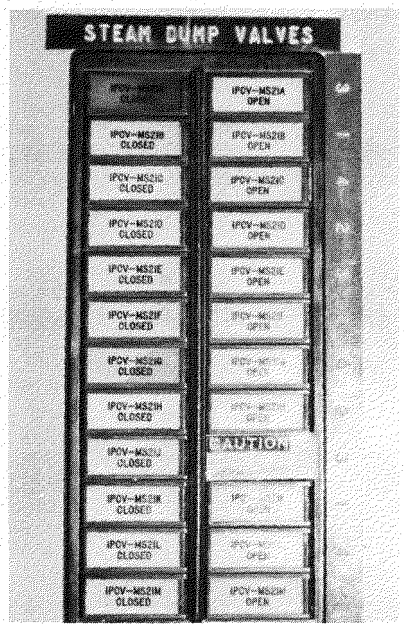


Fig. 9-14. The 24 steam dump valve indicators consume more space than necessary.

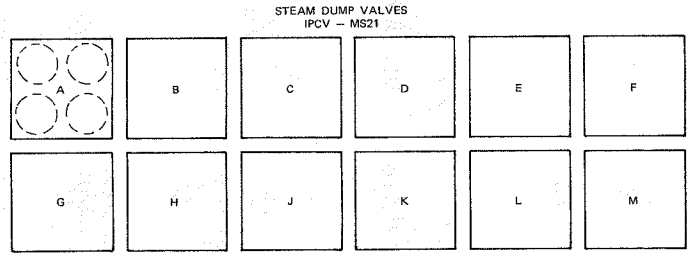


Fig. 9-15. The use of four lamp indicators; two red and two green to indicate OPEN/CLOSE status of valves.

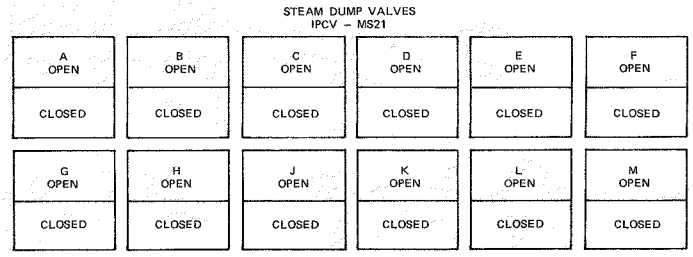


Fig. 9-16. The use of split-half indicators with four lamps to indicate valve OPEN/CLOSE status.

Figure 9-17 shows two groups of coded indicator lights with 24 indicators in each group. The group to the right describes valve and seal status for circulating water flow eastward and the group of indicators on the left does the same for circulating water flow westward. These indicators are coded with color and symbol logic which reverses itself depending on whether the water flow direction selected is east or west. Depending on this selection, the operator must exchange all the legend caps in the right hand group with those in the left hand group and vice versa. One of the operational problems reported with this arrangement is that operators make errors in this interchange and the color-symbol logic is compromised.

The above described task invites errors. Other, less obvious errors of legend cap mismates suggest that either keying of legend caps is required or the operational practice of not removing more than one legend cap at a time be adopted.

STANDARDIZATION

Within each control room there were generally at least seven or eight different types of indicator lights produced by different manufacturers. Aside from the impact of this diversity of lights from the aesthetic standpoint, a major disadvantage is the number, variety, and availability of spares required to replenish expended lamps, legend plates, etc. It was apparent from this lack of standardization

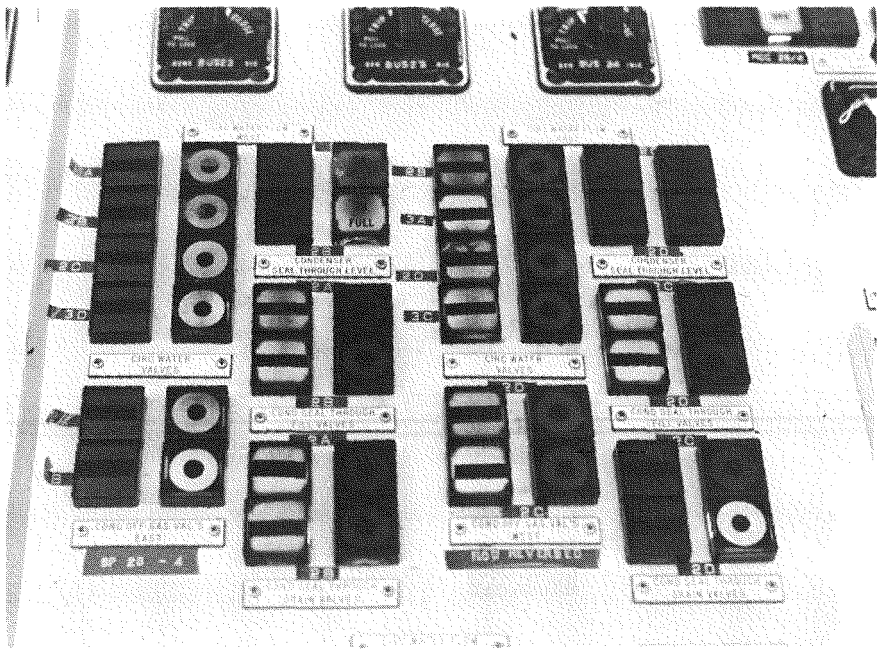


Fig. 9-17. When operators must switch groups of indicator legend caps the possibility for mismates is present.

that a variety of vendors and designers contributed to the design of the control rooms. Furthermore, those who modified the original design of the control room did not necessarily select the same components that were originally integrated into the control board design.

SUMMARY

Design practices associated with indicator lights were reviewed in terms of human factors engineering criteria. It was observed that in some instances qualitative indications are provided where quantitative readouts would have been more appropriate. Also, the need for more consistently ensuring indicator reliability is pointed out along with a discussion of alternate means for providing higher reliability. Based on some of the problems observed, designers are urged to consider ease of lamp replacement as an important selection criterion.

Other recommendations that emerged from these investigations are as follows:

- The practice of using negative indications where the absence of an indication informs the operator regarding some aspect of system functioning is discouraged.
- Economies in control board space utilization can be achieved by the proper selection of indicators combined with effective use of labeling and color coding practices.
- Measures should be taken to preclude the possibility of inadvertently mismating adjacent indicators with their respective legend caps.
- Greater emphasis should be placed on standardizing one basic indicator type instead of several different indicator designs on a given control board to reduce the number of required spares.

Section 10

METERS

The most common means to display quantitative information to the nuclear power plant operator is the meter. For this reason, special attention should be paid to the design of meters in terms of information transfer. Areas discussed in this section include the design of meter scales, parallax problems, arrangement of meters, problems of glare and reflections, and coding of meters to allow ready differentiation between normal and out-of-limit readings.

SCALE MARKINGS AND GRADUATIONS

The arrangement and number of minor or intermediate marks between numbered major scale marks influences the readability of meter scales. Human Factors standards specify that the number of minor or intermediate marks between scale numerals not exceed nine. Figure 10-1 shows a scale that conforms to this standard. Figures 10-2 to 10-4 show scales that slow the operator in his attempts to make precise readings. Note the mental gymnastics required to read the scales in these latter cases as opposed to the correctly marked scale in Figure 10-1.

Meter scale graduations should progress by one, two, or five units or decimal multiples thereof. Laboratory research has demonstrated that numerical progressions other than these lead to greater reading errors or slower operator response time. While a majority of the meters reviewed at the five study sites followed this dictum, exceptions were noted and documented at each site. Figures 10-5 to 10-8 provide examples of scales that offer problems or are less than optimal.

POINTERS AND PARALLAX

Pointers should be mounted close to the meter scale to minimize parallax. Also pointers should extend to, but not obscure, the shortest scale graduation marks. The width of the pointer, where it intercepts the graduation marks, should not exceed the width of the intermediate marks. Finally, the pointer color should offer good contrast to its background. The pointers in Figures 10-9 and 10-10 are examples of good pointer design. The scales are flush with the pointer plane

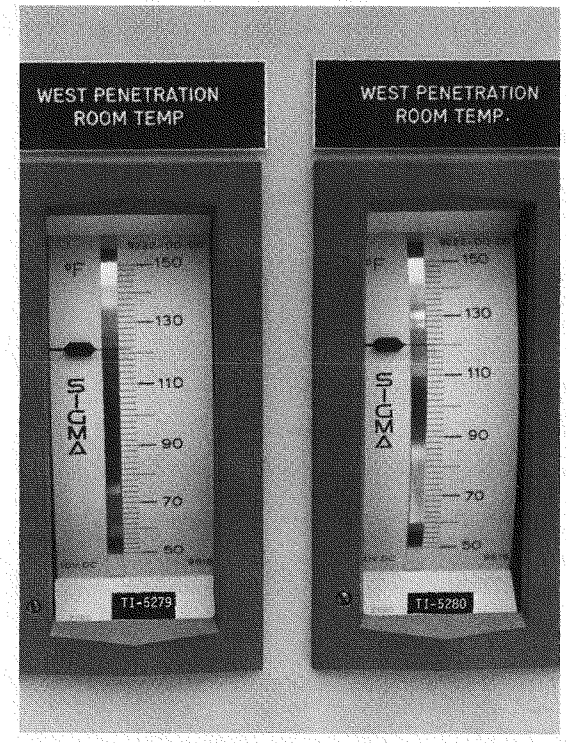


Fig. 10-1. Meter scale with the proper number of major, minor and intermediate markings between numbers.

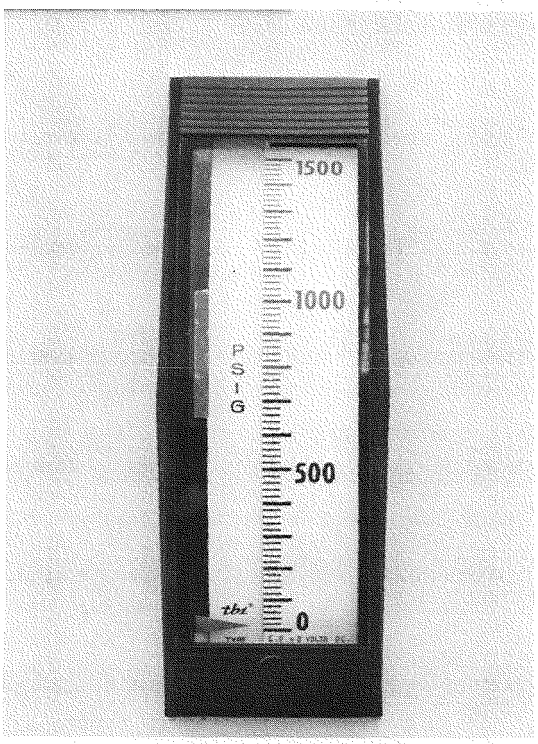


Fig 10-2. Meter scale with as many as 24 markings between numerals.

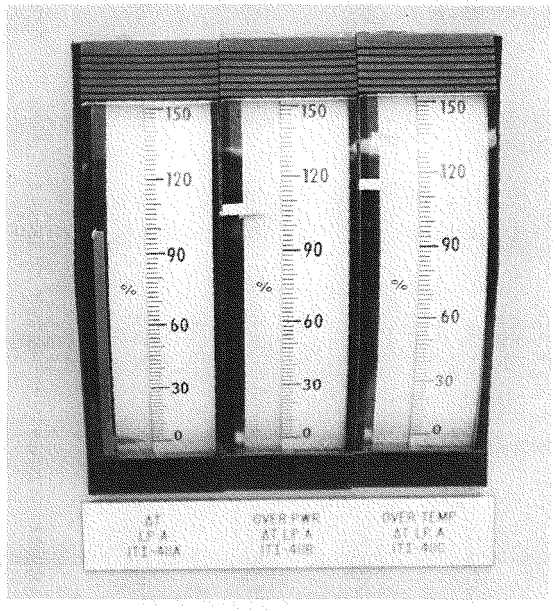


Fig. 10-3. Meter scales with 14 markings between numerals.

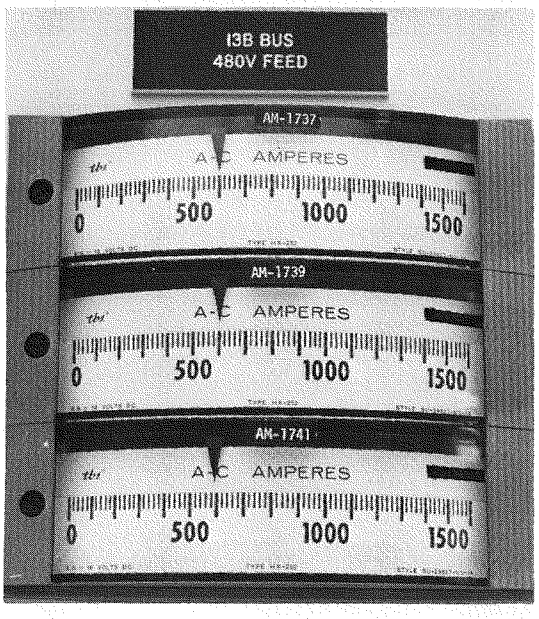


Fig. 10-4. These scales make no distinction between major and intermediate markings. Does the last marking to the right read 1500 or 1600?



Fig. 10-5. Difficult to read 3,6,9,12, progression.

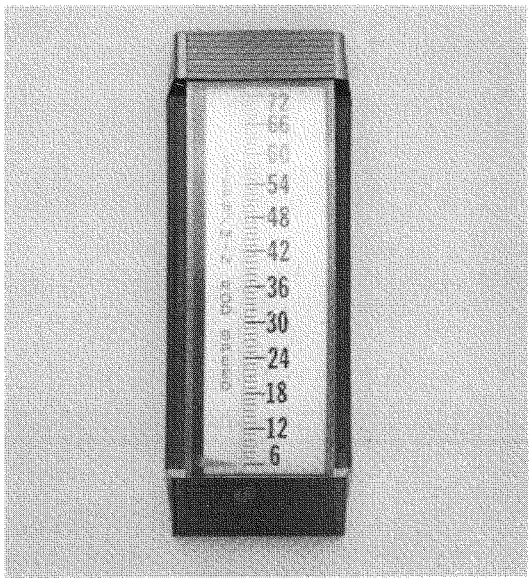


Fig. 10-6. Unusual and hard to read 6,12,18, ... scale progression.

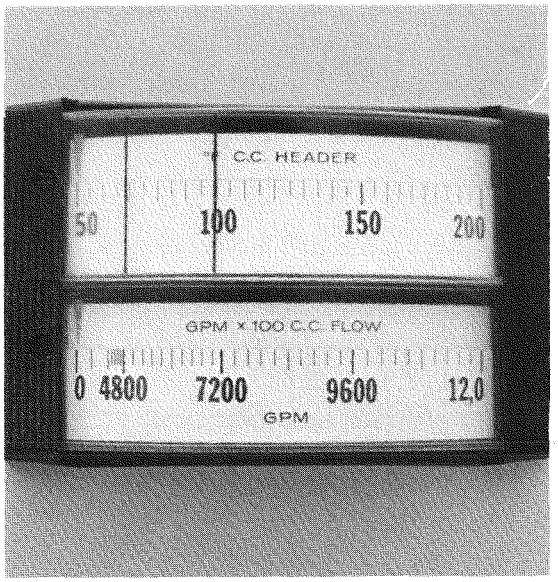


Fig. 10-7. Consider the effort required to interpret the lower scale.

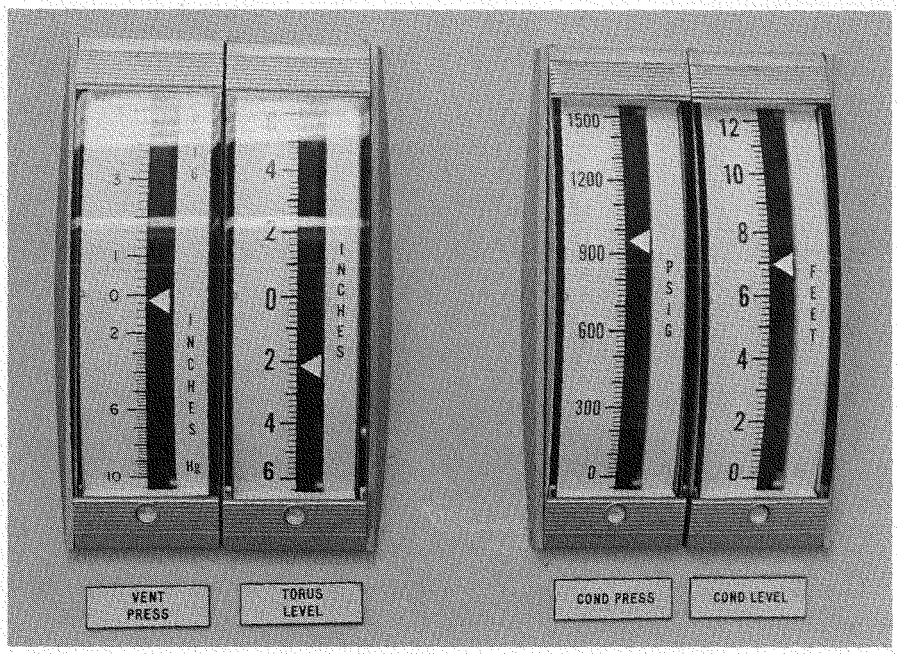


Fig. 10-8. The nonlinear scale to the left offers reading problems. Note also the absence of minus signs.

and parallax is avoided. Good contrast between pointer and background is available. The vertical scale has the added advantage of not obscuring any of the scale numerals.

Figures 10-11 to 10-16 show some of the problems observed with pointers. Figures 10-11 and 10-12 show two views of the same meters. When viewed head-on there is no problem aligning the pointers with respective scale markings. However, when the meters are mounted above or below eye level, as shown in Figure 10-12, the parallax problem becomes quite evident.

Figures 10-13 and 10-14 show an unusual meter design (observed extensively at only one of the five sites visited) where the scale markings, the pointer and the scale numerals are each on a different plane. Some of these meters were placed above the limits for adequate operator visual access. Another major problem is the use of multiple graduation interval markings on the same instrument so that two meters are essentially integrated into one display unit. These were unquestionably the most difficult to read meters observed during the study; the major and intermediate markings were barely distinguishable.

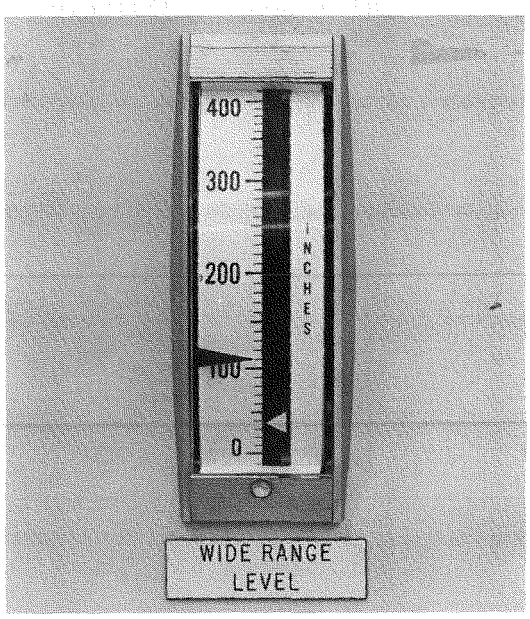


Fig. 10-9. The white pointer is well-designed. It contrasts well against a black background. The black arrow is a taped-on limit which at first glance looks like a pointer.

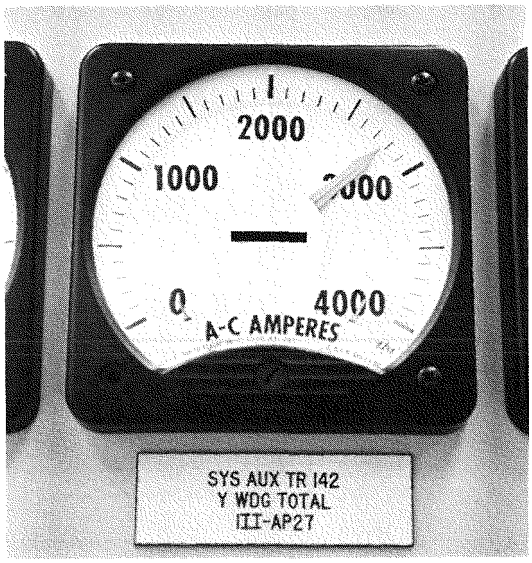


Fig. 10-10. Pointer which extends to the smallest scale marking and contrasts well against its background. The pointer is red.

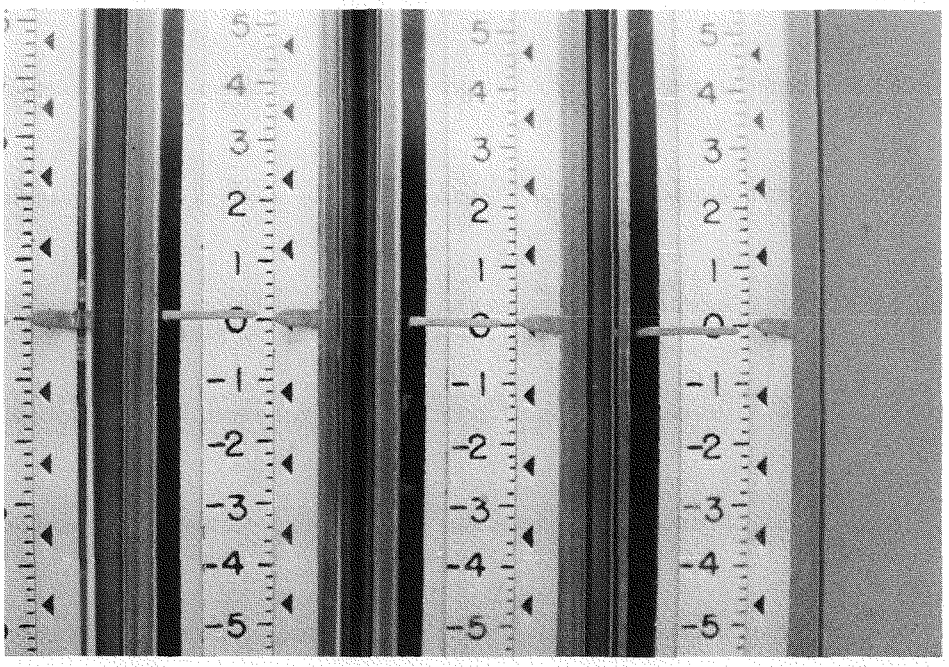


Fig. 10-11. Head-on view of meter pointers which provide parallax problems when viewed from other positions.

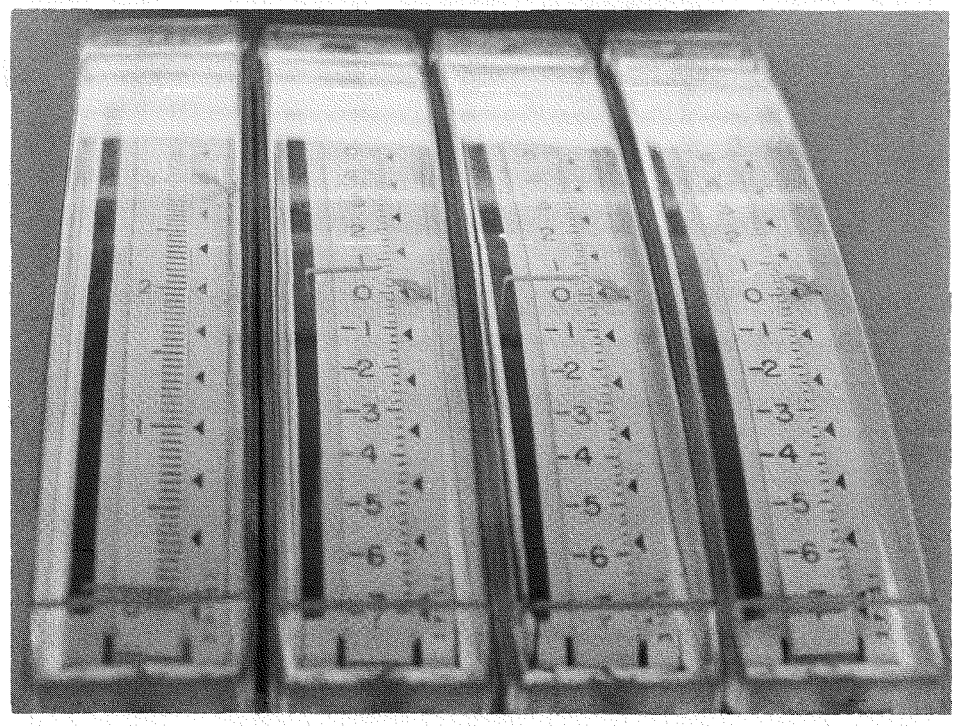


Fig 10-12. Parallax reading problem with the meters shown in Fig. 10-11.

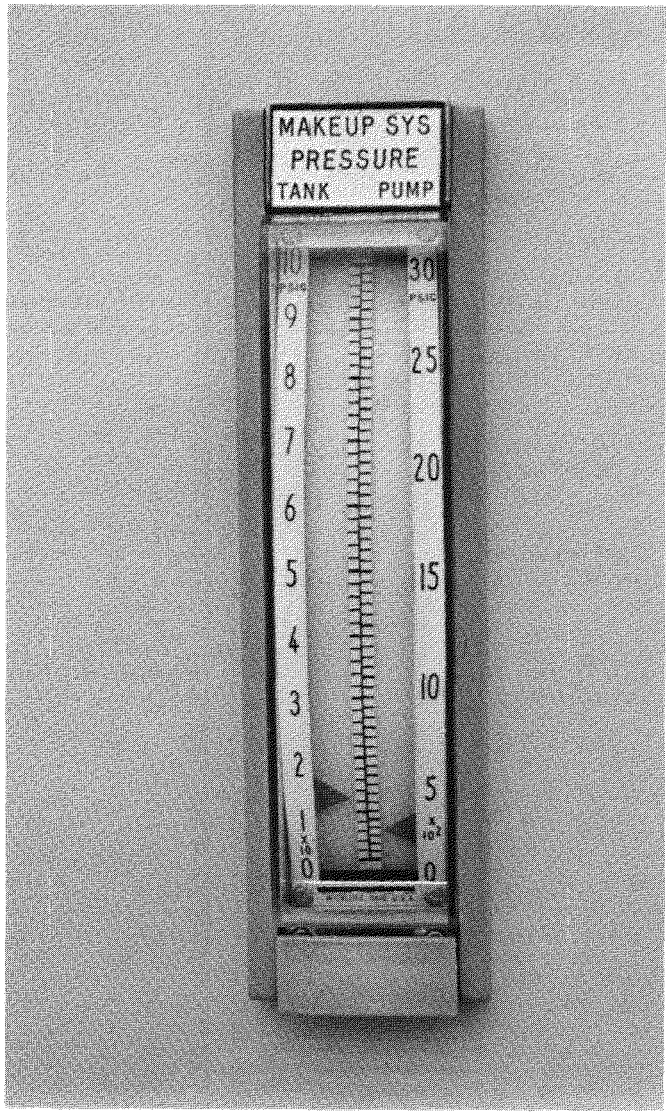


Fig. 10-13. The meter scale, markings and pointer are each on a different plane, producing parallax reading problems.

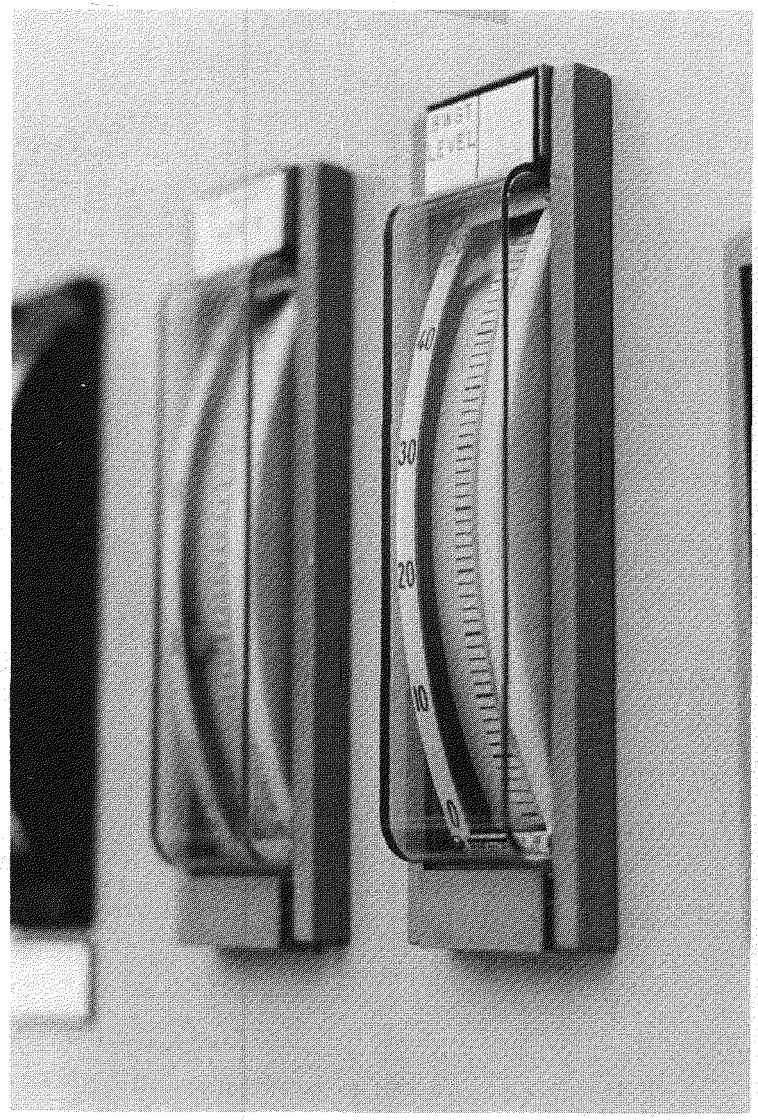


Fig. 10-14. Side view of meter type shown in Fig. 10-13. When such meters are placed above eye level, it is not possible to read the upper curved scale.



Fig. 10-15. The operator must kneel to avoid parallax on meters placed low on the panels.

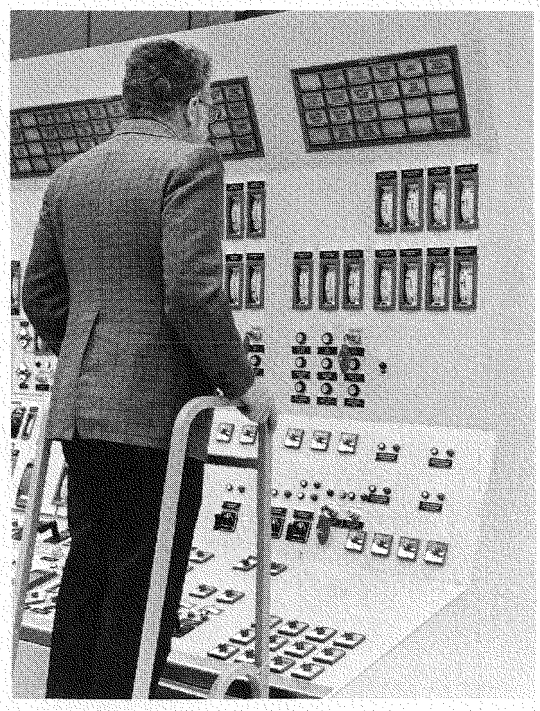


Fig. 10-16. The operator must use a step ladder to avoid parallax on meters placed high on the board.

Some meters incorporated a mirrored background along the path traversed by the pointer as shown in Figure 10-1. This measure allows the operator to obtain a precise reading, avoiding parallax errors, by aligning the pointer to coincide with its reflection so that the reflection is not visible. As discussed earlier in the section dealing with anthropometrics, the operator has been observed to assume the postures shown in Figures 10-15 to 10-16 to line up the pointer for exact readings.

The use of mirrored meters is recommended when precise meter readings are required. However, the one plant that made extensive use of these meters highlighted the importance of the parallax problem by showing the gyrations required of the operator to line up meter pointers and their reflections. In the other four plants, where non-mirrored meters were distributed on the boards in much the same fashion, the operator was not as cognizant of the parallax problem and less precise readings could, therefore, be expected.

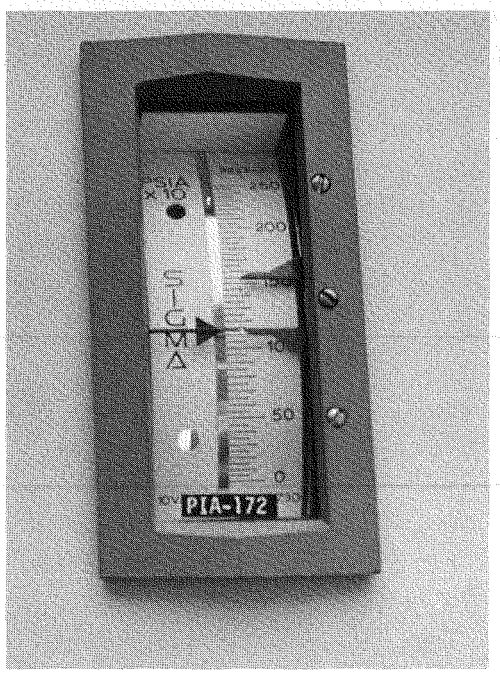


Fig. 10-17. Meter with built-in adjustable limits and associated indicator lights to reveal exceeded limits.

CODING METER SCALES

The most troublesome aspect of meter design is the lack of coding or the inconsistent coding practices for designating normal and out-of-tolerance bands of meter indication. Given the scores of meters in each control room it is unrealistic to expect the operator to remember the precise or even gross limits for each function displayed by the meters. Meters that are color banded or otherwise coded greatly help determine which system elements are operating normally and which are off-normal or trending in that direction. Designers often avoid placing fixed limits on meter scales since these limits have a tendency to become unfixed with operational history. One answer is to provide meters with limits that can be adjusted to suit the operational case, without having to disassemble the meters and order new meter faces. This assumes that adequate administrative control over these limit settings can be maintained.

Figure 10-17 provides an example of a meter with variable limits. The upper and lower limits are clearly bracketed to the right of each meter scale. When the meter pointer hits either limit, a small light to the left of the scale is illuminated to show that an upper or lower limit has been exceeded. The operator, who

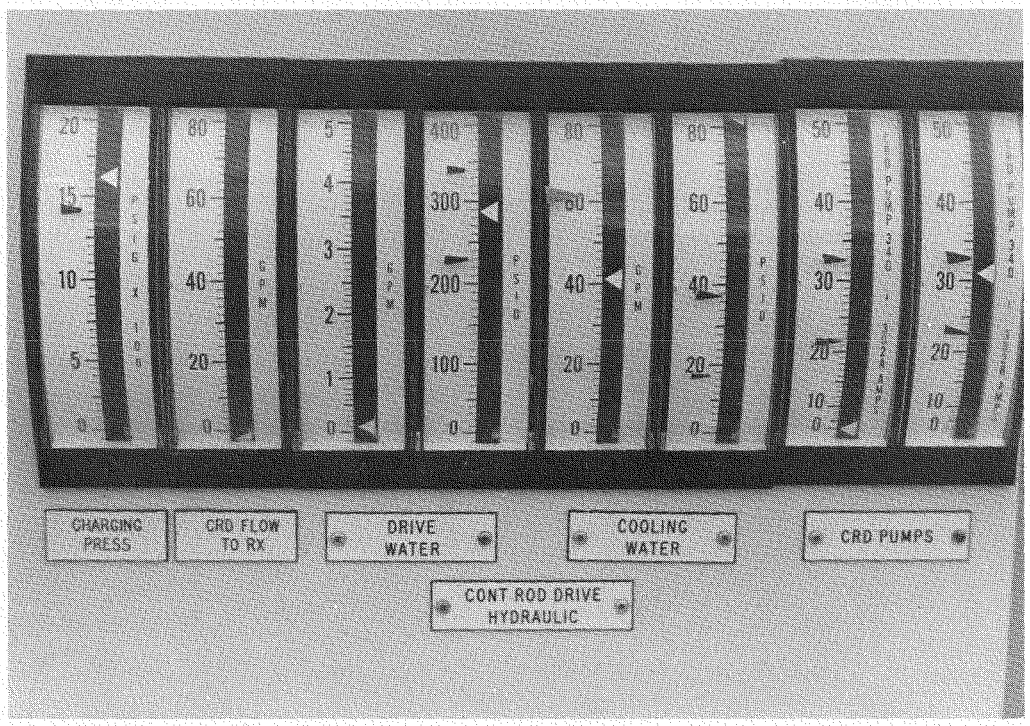


Fig. 10-18. Confusing array of improvised meter limits. In some cases upper and lower limit markings are provided. In other cases no limits are shown and in some meters only one limit is indicated.

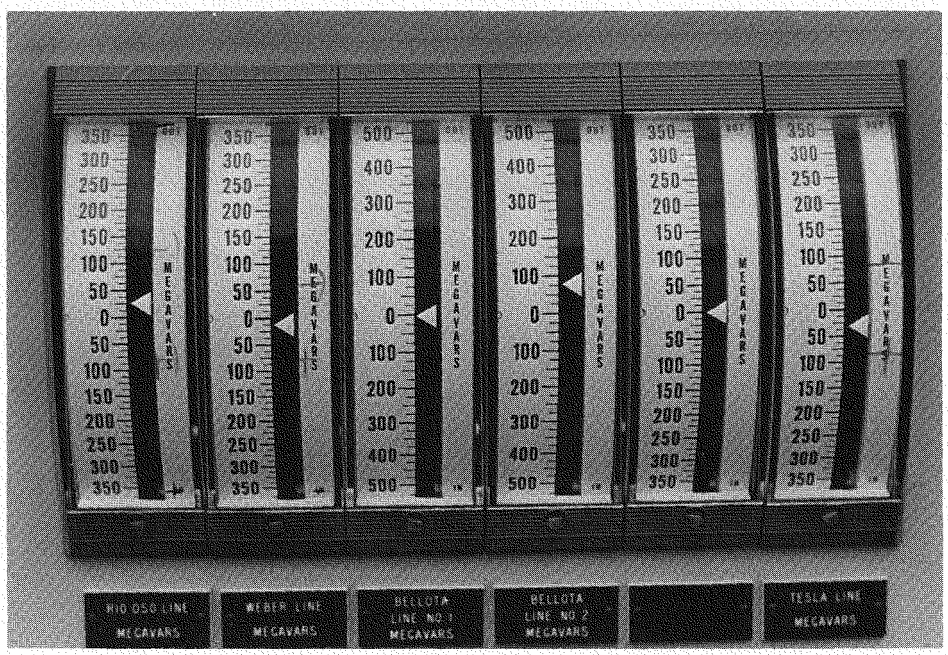


Fig. 10-19. Operators at this plant are discouraged from coding meters. They have, nevertheless, placed crude limits on the meters with crayon.

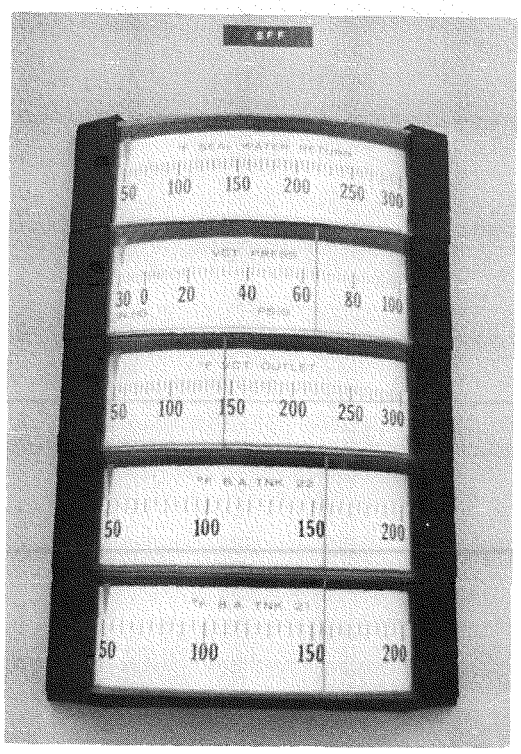


Fig. 10-20. Taped on meter markings. Do they indicate nominal values or limits?

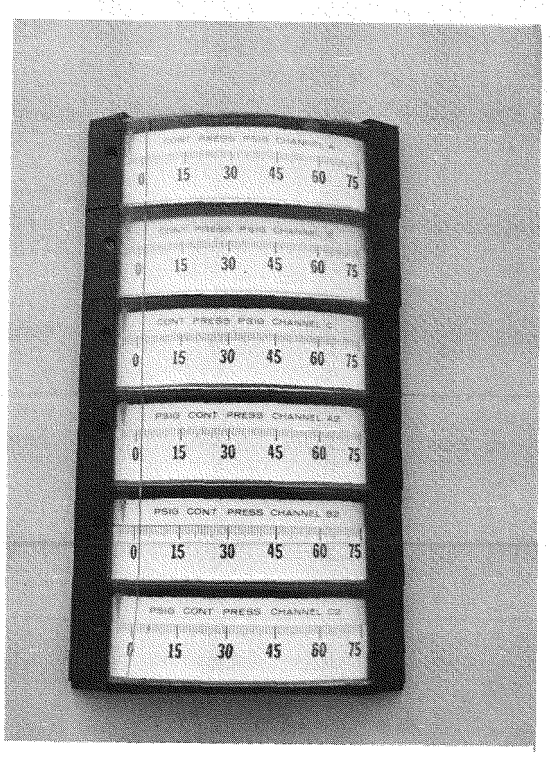


Fig. 10-21. Taped on meter limit peeling off at the lower end of this grouping.

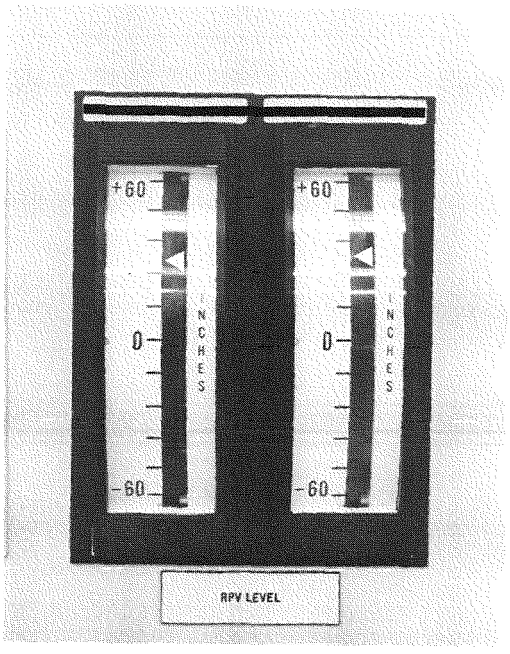


Fig. 10-22. Meter scales observed in the simulator. Compare with Figure 10-23.

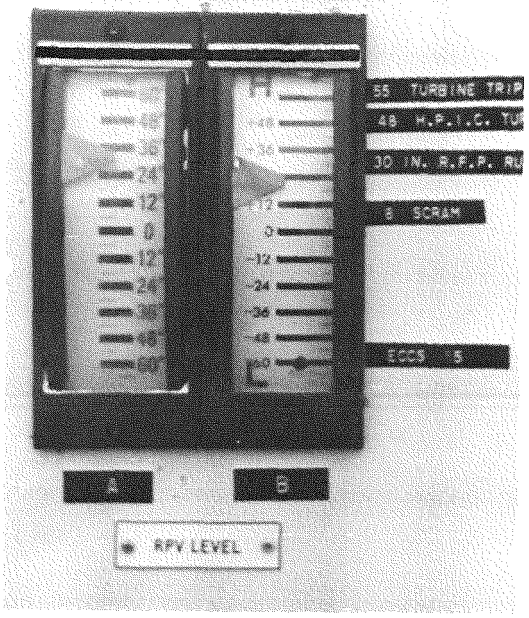


Fig. 10-23. Operator additions to meter scales to clarify scale meaning.

probably has been alerted by an auditory horn associated with an annunciator light indication, can immediately focus his attention on the appropriate meter indication.

Unfortunately, these excellent meters are the exception rather than the rule. More often, meters are not coded or crude and inconsistent attempts have been made by operators to define the tolerance limits. Figures 10-18 to 10-21 show attempts by operators to code meter scales. In some cases both upper and lower limits are marked in colored tape on the meter face. In other cases only one or the other limit is so marked. In still other cases, the nominal value is marked with no indication of the tolerance band. Also, there is no consistent use of color coding in taping the meter faces. Red, green, yellow, white, and black markings are used indiscriminately. These inconsistencies are the result of meter coding attempts by different operators at different times in the same control room. One wonders if the intended meaning of the meter code devised by one operator is similarly perceived by another operator working two shifts later. One might also question the accuracy of limits imposed by these makeshift approaches. We can also see clear possibilities for parallax problems in relating limit markings placed on the external face of the meter to the scale markings which are considerably displaced from the meter scale. Another problem observed with these impromptu markings is that they are sometimes so oriented and configured as to obscure the pointer over a portion of the scale band.

In at least one case, utility managers have avoided problems associated with improvised meter markings by preventing operators from coding the meters--a decision based on aesthetic considerations. The attitude of this plant, as described by the operational personnel, is that any operator worthy of being in the control room should know the limits of each meter. Judging from the conversations with operators across the country, this may be an unrealistic assumption. The before and after photos (see Figures 10-22 and 10-23) show the lengths to which operators have gone in clarifying the meter scales.

METERS THAT FAIL

An operator should be alerted to a meter that is inoperable for any reason. At one of the plants the operators pointed out that a number of their meters would fail with the pointer in the normal reading zone. As shown in Figures 10-24, the center meter in the group of three meters has been disconnected from its housing. In this condition it is inoperable, yet it is reading as it would be if its system were operating normally. This study did not determine whether this situation is unique to one plant or whether it is a common occurrence.

PROJECTION METERS

One of the plants visited made use of projection meters. These backlit meters use illuminated pointers. However, the lamps burn out and replacement is awkward. During the time the study team visited this plant, some of the meters were not operable (see Figure 10-25; note the absence of pointers) because no one bothered to replace the expended lamps. Had these meters provided ready front-of-the-panel access, this situation would have been corrected earlier.

GROUPING OF METERS

When groups of functionally related meters are arrayed in the same console area, (see Figures 10-26 to 10-27) check-reading of meters can be facilitated by placing in-tolerance zones on meter scales in the same relative location on each meter. This within-tolerance band should generally be at the 12 o'clock position for circular scales; although the 3 or 9 o'clock positions may serve for some applications. For straight vertical or horizontal scales, the in-tolerance zone should also be in the same relative segment of the scale--usually in the center. If care is taken to arrange consistently the normal bands, a pattern of pointer positions is established which readily permits the operator to observe a discrepant pointer orientation.

Achievement of this pattern effect to facilitate meter check-reading requires careful attention to meter scaling during the design phase and is difficult or costly to implement by means of a retrofit.

GLARE AND REFLECTIONS

As Figures 10-8 and 10-12 reveal, and as is well know in the industry, glare or reflections from illumination sources can interfere with effective meter reading. In some control rooms the operators are forced to maintain room illumination at abnormally low levels to reduce reflections from meter faces. The problems of glare and reflection are caused by characteristics of the room illumination system and the reflectance properties of instrument faces. Utility personnel should investigate such measures as non-reflecting coatings on instrument faces or overhead illumination diffusing techniques.

SUMMARY

Human factors problems observed with meter designs are fairly widespread rather than being confined to one or two of the plants investigated. The potential for

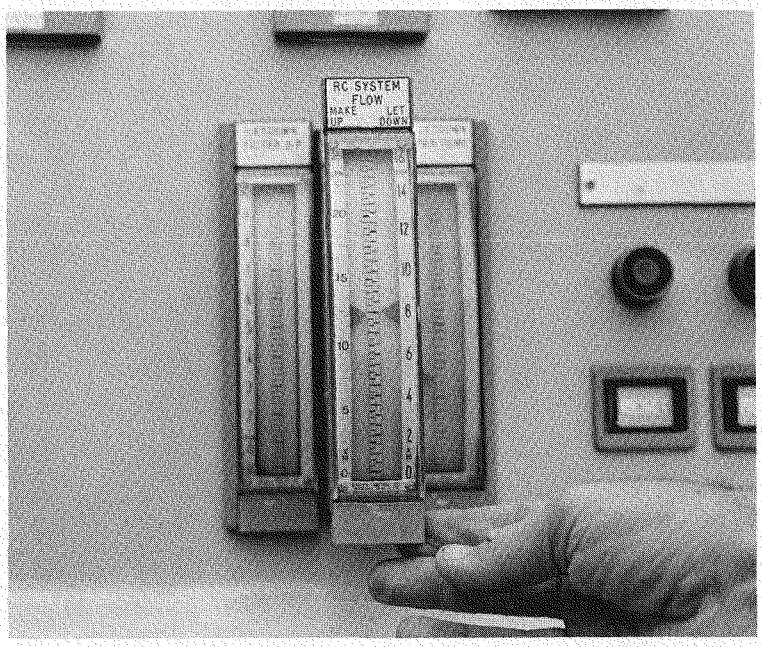


Fig. 10-24. An inoperable meter which reads in the normal in-tolerance zone.

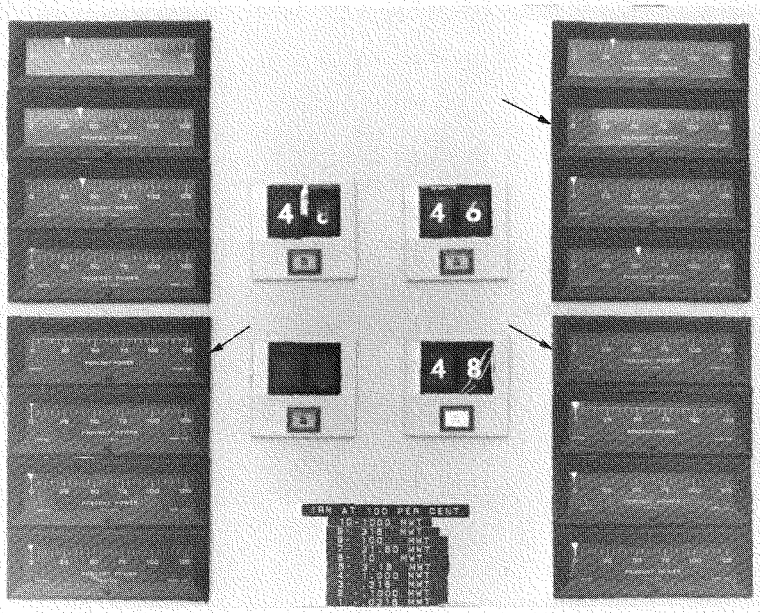


Fig. 10-25. Hard to replace lamps on projection meters produce nonfunctional meters.

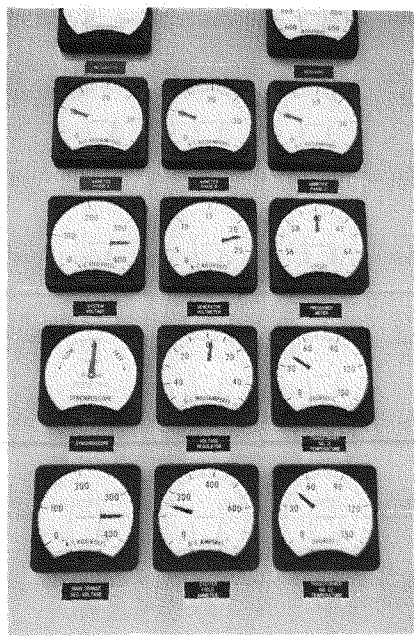


Fig. 10-26. Group of meters that could be checked more readily if all normal reading zones were in the same relative position.

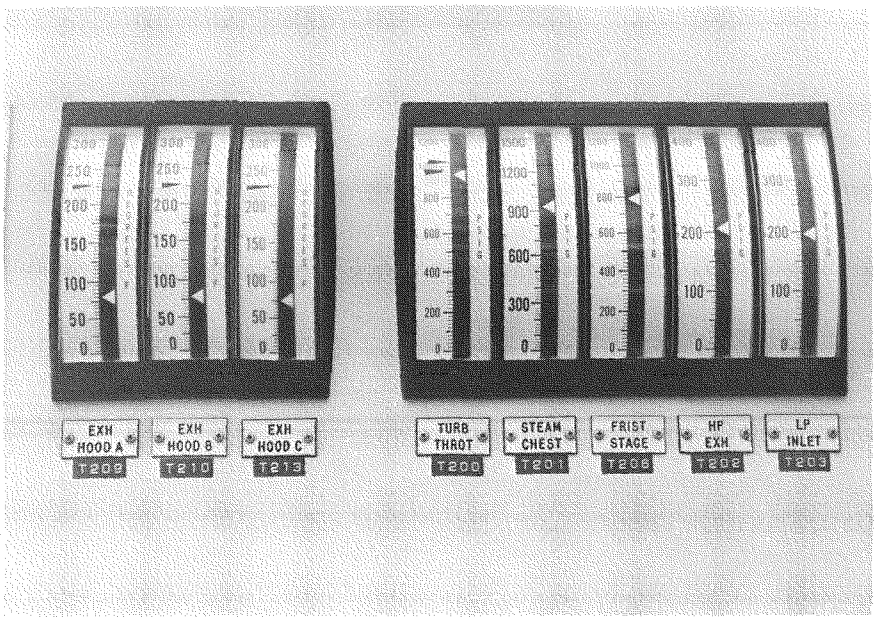


Fig. 10-27. Bank of meters that could be checked more readily if normal reading zones were all in the same horizontal band.

parallax-induced reading errors is significant and is caused by physical characteristics of meters combined with placement of these instruments beyond recommended anthropometric limits for visual access. Scale graduations are often difficult to interpret and intermediate and minor marks do not always conform to recommended practices. Some meters do not fail in a manner that is self-evident and the operator could easily be misled. Groups of meters are not designed to facilitate check-reading at a glance by means of pointer alignment cues. Reflections from meter faces are annoying and should be eliminated.

The most serious general problem observed, and the one most readily amenable to correction, is the lack of meter coding to allow the operator to differentiate between normal, marginal, and out-of-limit conditions. A thorough screening of each control board should be conducted and where appropriate the exact limits for each meter should be carefully documented. A meaningful color code could be adopted, for example: green, normal operating band; amber or yellow, marginal condition; and red, out-of-limit condition. Meter scales should be color coded directly on the scale face rather than on the glass face of the meter to avoid parallax and indiscriminate coding of meters.

In view of the extensive modifications to the control boards made by operational personnel in regard to meter banding, the addition of labels, and the attempts to functionally isolate panel groupings with tape, it might be appropriate for each plant or utility to develop a configuration control policy and associated procedures. A committee of operational and engineering personnel could see to the implementation of all changes to the control boards to ensure that these changes were appropriate and consistent.

Section 11

CHART RECORDERS

Nuclear power plant control rooms make extensive use of chart recorders and the operators place heavy reliance on them in the performance of system surveillance duties. Chart recorders are generally most appropriate for recording trend data. Two basic types of chart recorders were observed--those that provided numerical printouts, and multi-pen recorders that printed trend lines. The major problems observed with the chart recorders were (1) the reliance on chart recorders for real time data when meters or digital readout devices would have been more appropriate and (2) the location of chart recorders on back racks or other places out of the operator's primary work space envelope.

READABILITY OF CHART RECORDERS

A major problem was observed with chart recorders that produce a numerical printout. The chart recorder shown in Figure 11-1 provides a window in the upper right corner which displays a number corresponding to the parameter being measured at any given time. The black placard to the left of the recorder provides the list of parameters being recorded. The pointer at the top edge of the recorder provides a reading on the scale extending from 0 to 250 units. As shown in Figure 11-1, the pointer is at 72. At the corresponding position on the recorder paper, the number in the upper right corner is being printed. The limits for each parameter recorder are handwritten and placed on the inside portion of the recorder face (see Figure 11-2). This means the operator must use the recorder with the front door open. Figures 11-3 and 11-4 provide several close ups of the record of numbers printed on the moving recorder paper. The operator is unable to separate or distinguish the points on this record. What he then does is wait until the recorder cycles through to the parameter of his immediate interest, rather than try to decipher the record.

As one actual case history will reveal, poorly human engineered chart recorders can be quite costly to the utility. One such chart recorder was designed to accept 24 points. In the interests of economy, 42 points (see Figure 11-5) were incorporated into this chart recorder with six spare channels. The indentification window

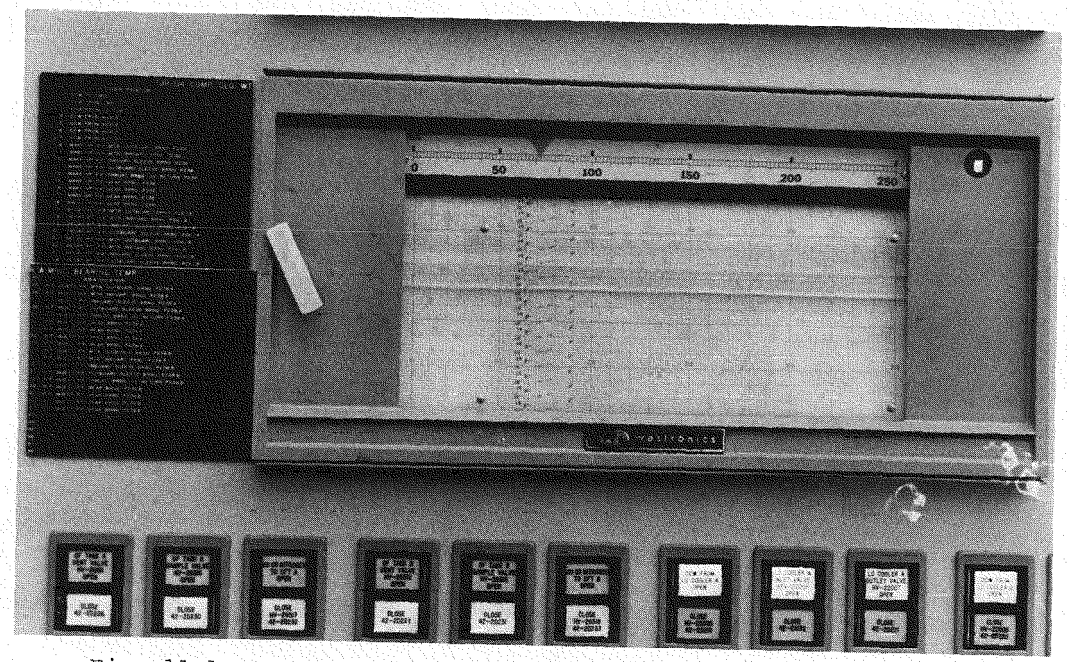


Fig. 11-1. A representative chart recorder used in control rooms.

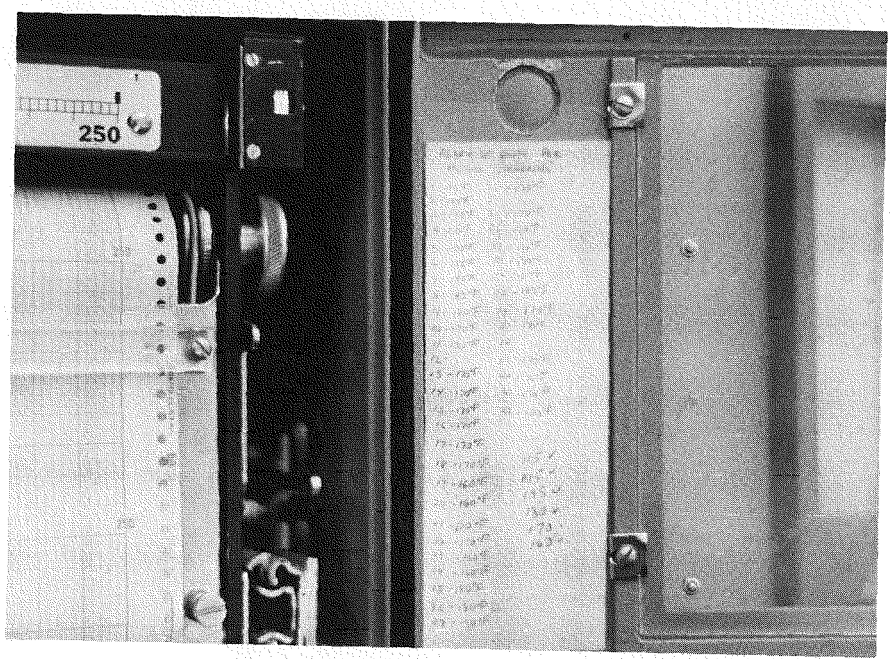


Fig. 11-2. The limits for each parameter are handwritten and placed on inside cover.

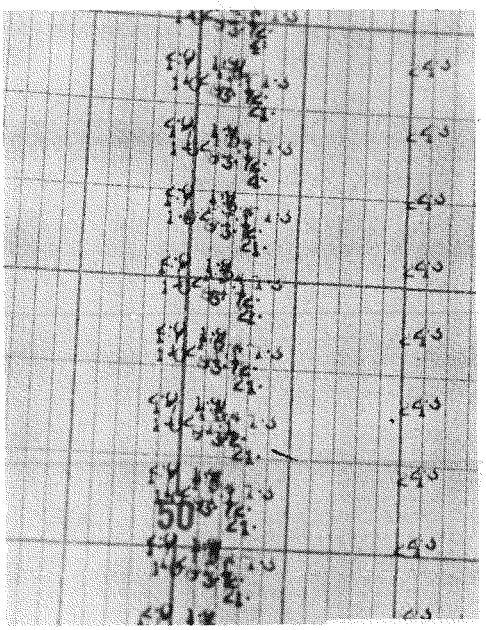


Fig. 11-3. Sample recorder print-out which is difficult to interpret.

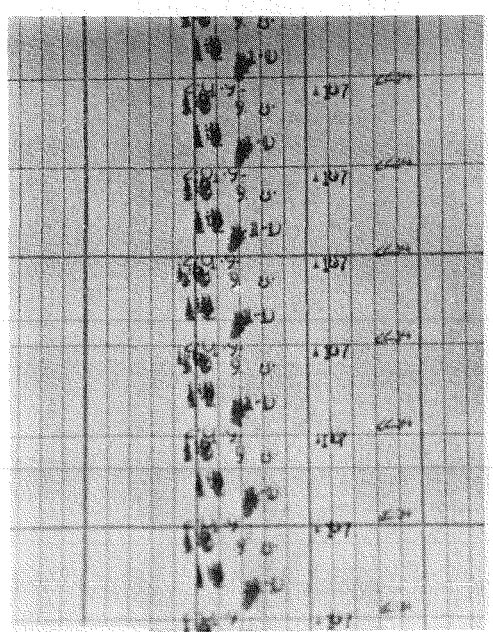


Fig. 11-4. Another difficult to interpret recorder readout.

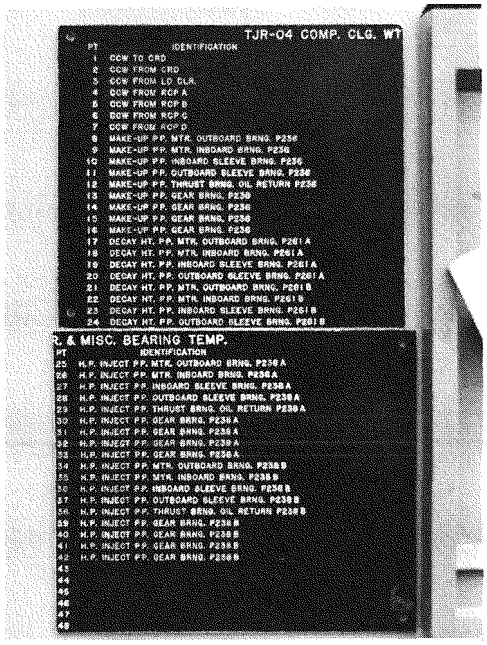


Fig. 11-5. Decal identifying 42 parameters assigned to recorder which was designed for 24 points.

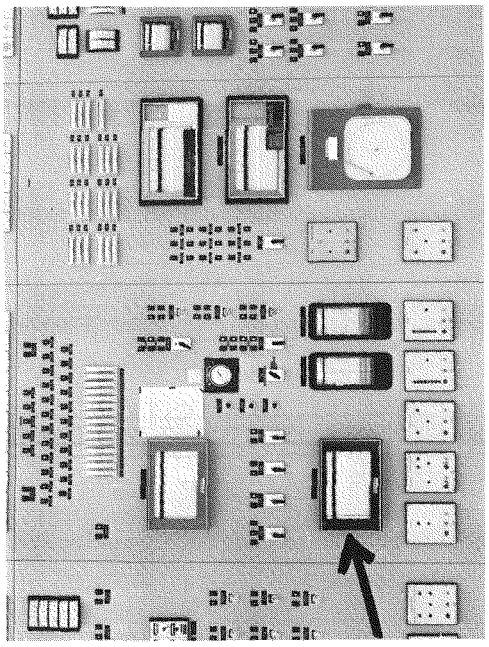


Fig. 11-6. Multi-point recorder in the lower left hand portion of the console shown.

in the upper right corner of the recorder provides numbers from one to 24. Therefore, when this display window reads "5" the operator must somehow determine whether the pointer is reading parameter "5" or "29." Because so many numerical point printouts are crowded onto the chart paper, it is extremely difficult to sort out individual numbers. On one occasion an annunciator alarm window announced the following problem: PRIM SYS MISC TEMP HI TJR-04. The suffix to this message referred the operator to the chart recorder with 42 points. The operator had to wait about four minutes before the relevant reading appeared and a high-pressure injection pump, which might have been saved, was destroyed.

This case of an overly taxed chart recorder is not an isolated one. Within the same control room there are other recorders that are overloaded and in another control room reviewed the operators had essentially the same complaint. The recorder shown in Figure 11-6 in the lower left portion of the photo displays turbine parameters. This chart recorder is about 12 paces from the main turbine panel. The operators complain of having to wait for the multi-point recorder to cycle through 24 points. As one operator put it: "You have to wait so long that a bearing vibration problem could get very serious. You could reach the trip point. You can't read the chart and distinguish the points. The instruments are too low on the panel and too far from the turbine controls on the main turbine panel."

Some recorders don't afford the operator the luxury of a parameter identification window as discussed above. The recorder in Figure 11-7 requires the operator to aim his eyes to the undersurface of printing head of the numerical printer. This recorder is located on the radiation monitoring console shown in Figure 11-8. The operator must be something of a contortionist to isolate readings (see Figure 11-9).

In some cases chart recorders have been improperly used in lieu of meters or other display devices that give a direct and immediately accessible readout. While the chart recorder plays an important role in allowing the operator to observe trends over time, it does not provide required data in time-critical situations.

Another problem with chart recorders in at least one plant was the compactness of the time scale. The narrow recorders shown in Figure 11-10 were found to be acceptable in monitoring some parameters, but the operators felt that the trend line was too compressed for applications such as reactor coolant temperature and make-up tank level. Since the trend line over a span of one inch or so covered one hour of history, the operator had problems in accurately determining rates of change. The operators felt that compactness had been favored while accuracy had

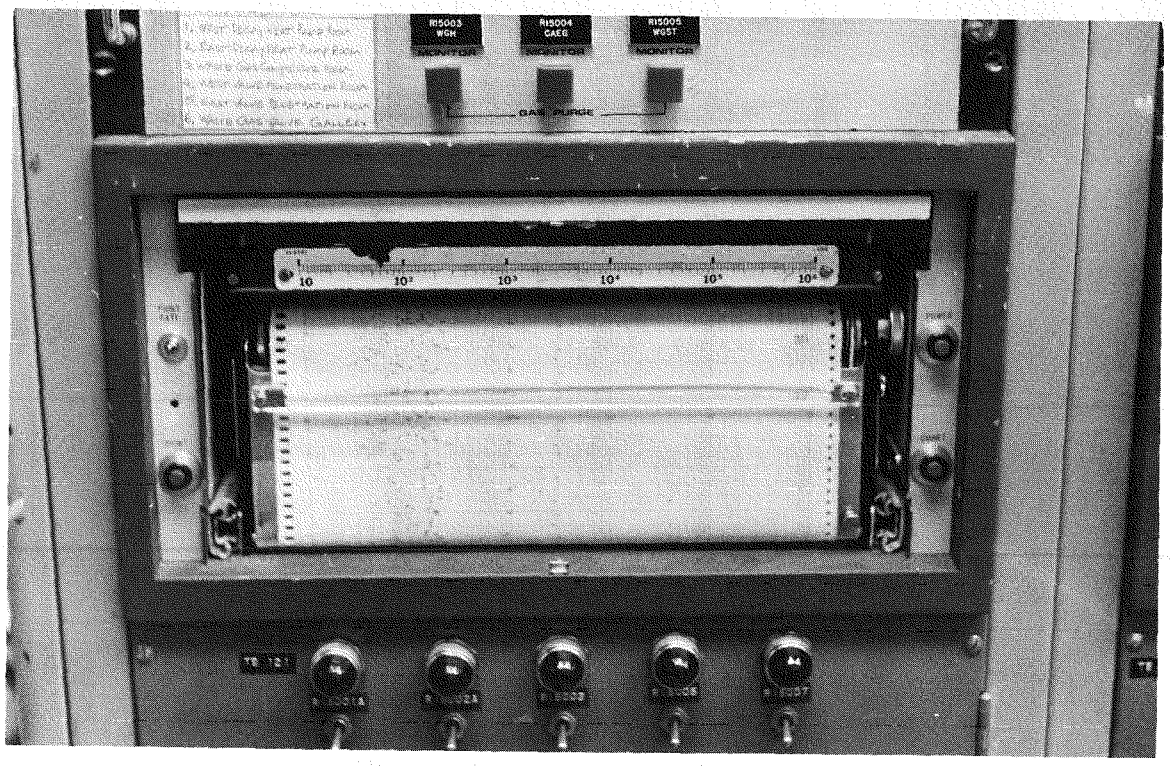


Fig. 11-7. Recorder without a parameter identification window.

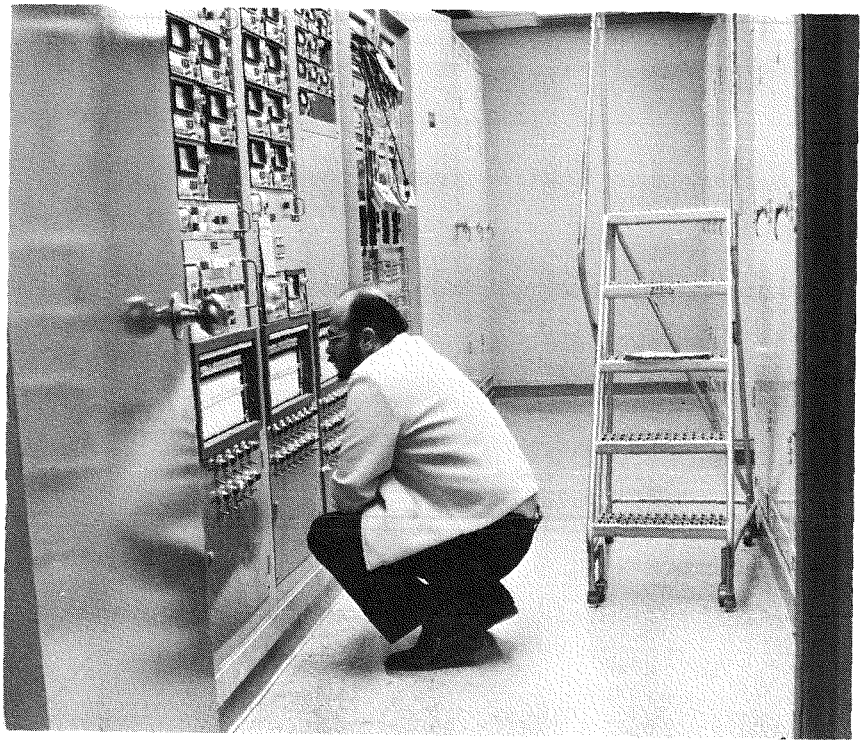


Fig. 11-8. Radiation monitoring console housing the recorder shown in Fig. 11-7.

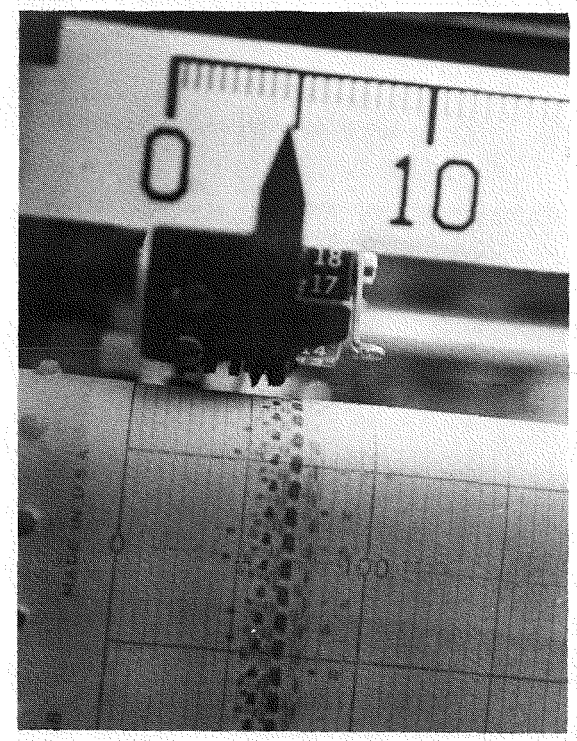


Fig. 11-9. The operator must look at the underside of the printer to determine the parameter being monitored.

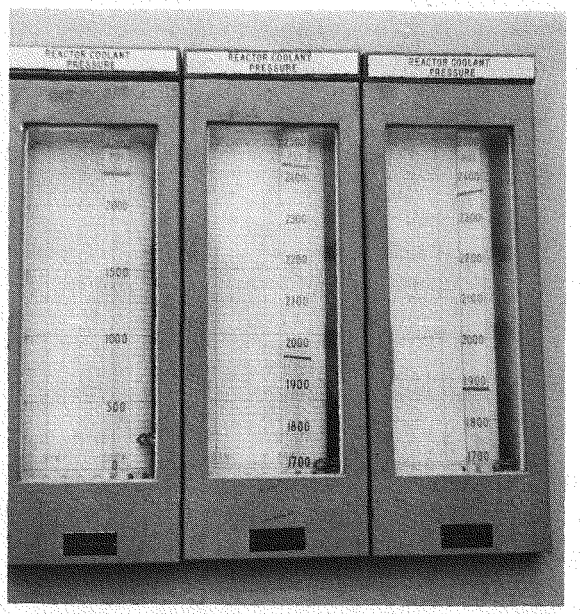


Fig. 11-10. Narrow recorders with compressed time scale.

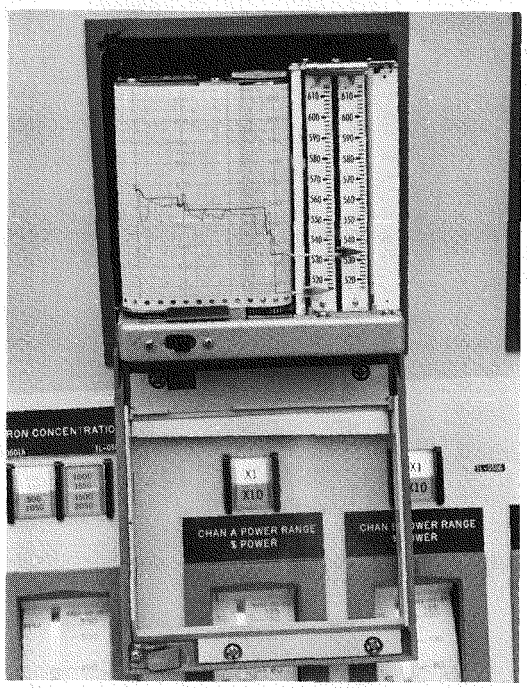


Fig. 11-11. Recorder operated with window open to expose additional data.

been sacrificed. Since these chart recorders did not provide the required level of accuracy, the computer was often relied on for more complete data. However, the operators pointed out that, in a transient situation, there was no chance to set up the computer to perform this function.

In a number of instances the operators use their chart recorders with the covers left in the open position as shown in Figure 11-11. This was done to expose additional data appended to the originally provided scale values, such as centigrade temperatures or the limits for the functions being monitored. The open covers obscured readings on other displays in the vicinity of the chart recorders or blocked access to controls. This finding may be of relevance to designers in the layout of control boards, or it may induce chart recorder manufacturers to allow room for adding more data. Also, dual-speed recorders have been designed to re-revert to high speed automatically subsequent to a trip so that more detailed trending is available to the operators.

Multi-pen chart recorders offered some problems where the tracks of the two, and sometimes three, pens coincided. Even though the pens were color coded, the operators had difficulty distinguishing them. In such cases, a pen that runs out of ink is not readily apparent to the operator. There were also some labeling problems. In one plant, the chart recorders were consistently labeled in a top/down scale order corresponding to A and B (see Figure 11-12). However, exceptions arose as is shown in Figure 11-13. The labeling beneath the chart recorder shows VESSEL FLANGE above SHELL TEMPERATURE. The scales at the top of the chart recorder are in the reverse order. Note the operator markings "S" and "F" handwritten at the left of each scale. These inconsistent labeling practices invite errors of scale-function misassociations.

SCALE FACTORS

The scale graduation and marking principles discussed in Section 10 apply here. Chart recorders are essentially read as meters when the printed record is obscure and subject to error. As one example of a troublesome scaling arrangement see Figure 11-14. The lower scale shows only three numerical points: 950, 1000, and 1050. There are 49 scale marks between each number, greatly in excess of the recommended 9 marks. The scale printed on the chart paper does not match the instrument scale markings. In this case the markings read: 950, 970, 1010, 1030, and 1050. The other scale from 0 to 10 is easily readable.

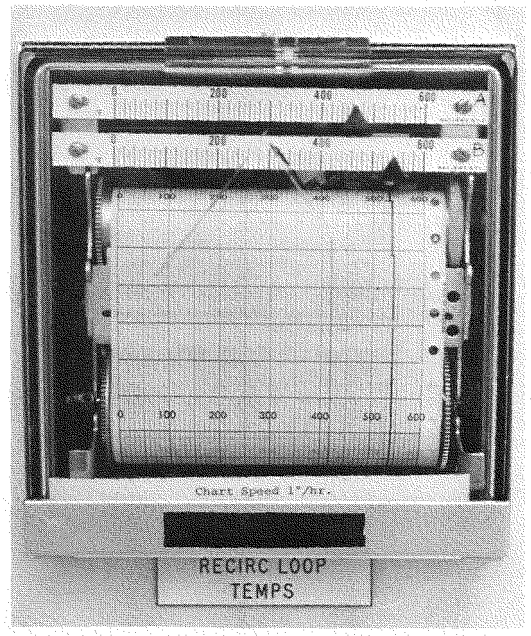


Fig. 11-12. A/B scales in Top/ Bottom order.

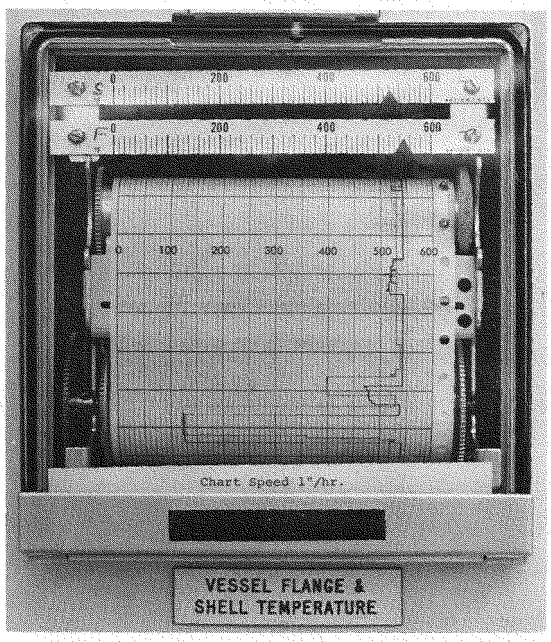


Fig. 11-13. S/F scales in reverse order as compared to label.

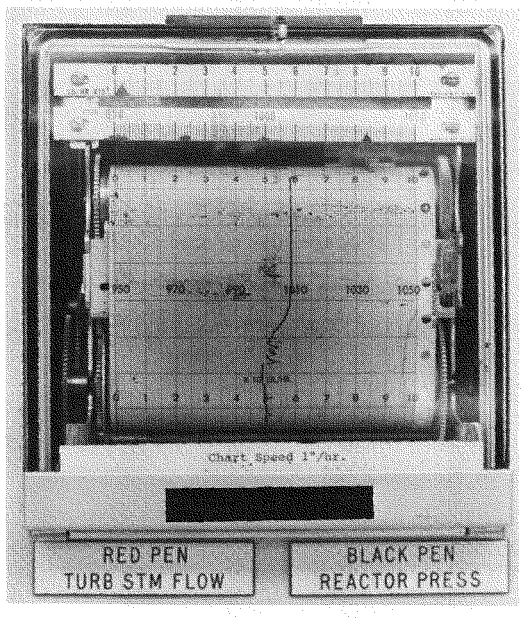


Fig. 11-14. Scales that are difficult to read.

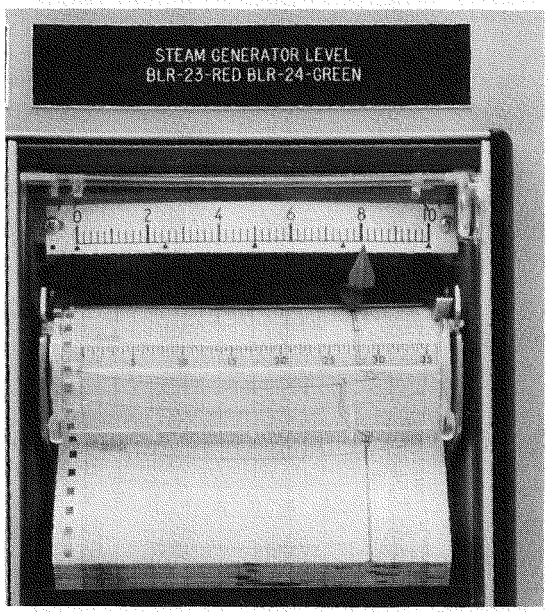


Fig. 11-15. Three scales, none which matches the others.

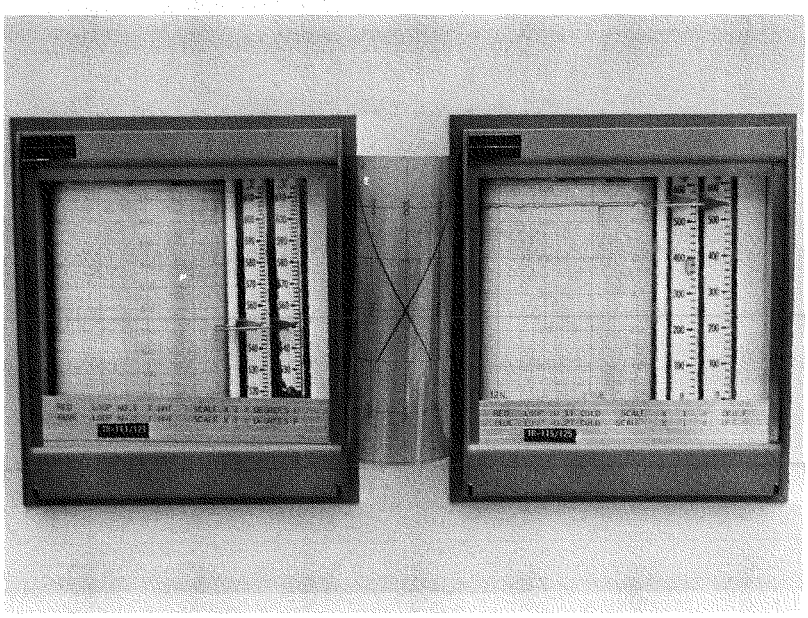


Fig. 11-16. Overlays used in conjunction with chart records wedged between two adjacent records.

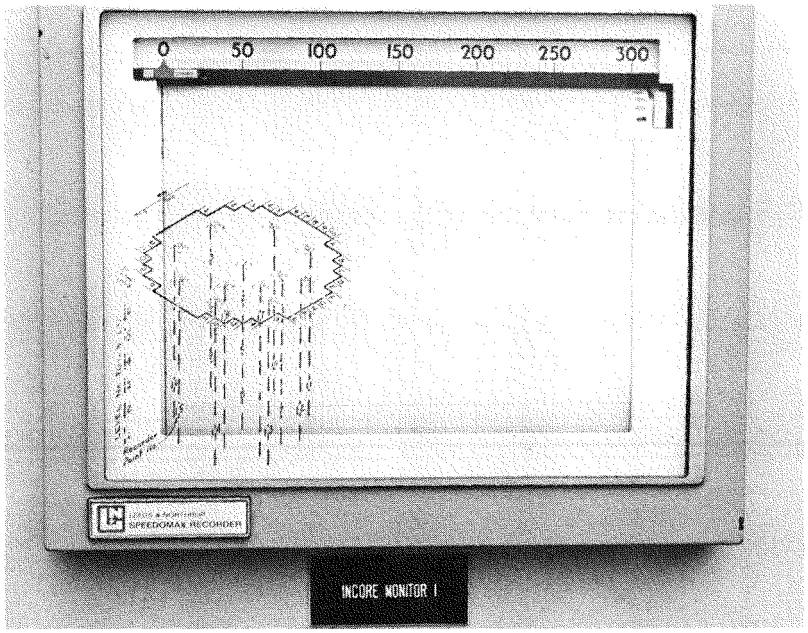


Fig. 11-17. Chart recorder overlay permanently fixed to recorder face.

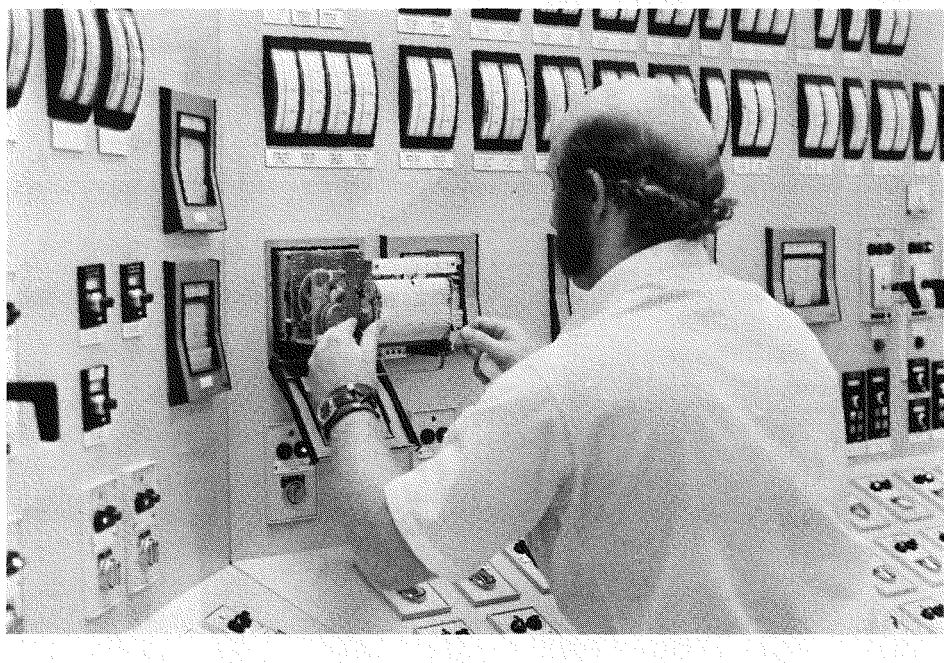


Fig. 11-18. Recorders vary in the ease with which paper can be replaced.

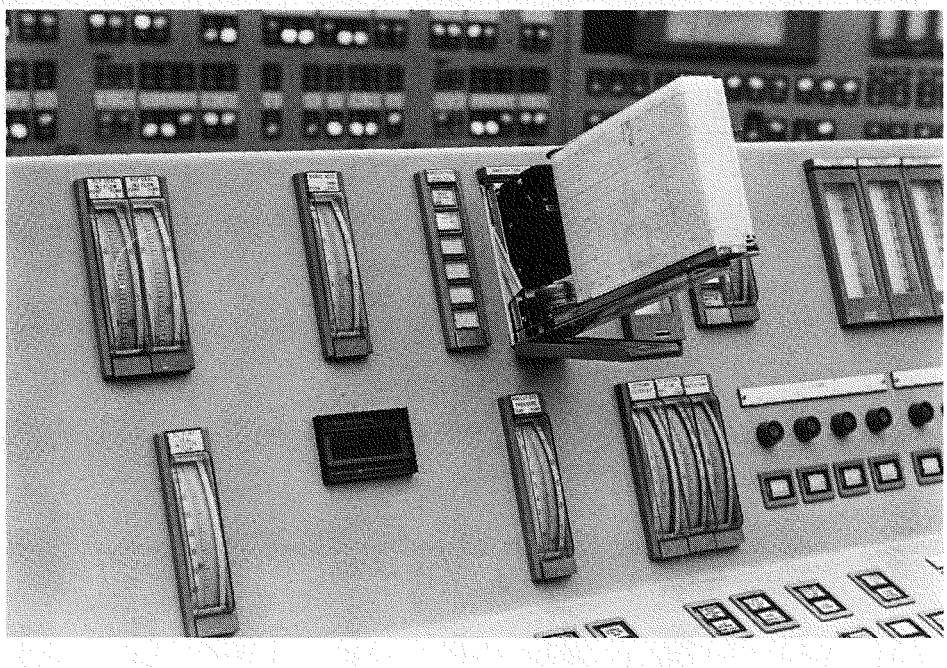


Fig. 11-19. Recorder pulled out for paper replacement.

Figure 11-15 shows a two-pen recorder with three scales, none of which matches each other. The upper scale reads from 0 to 10, the chart paper is scaled in increments extending from 0 to 100, and a plastic horizontal bar in the upper center of the recorder reads from 0 to 35. The rationale behind the diverse scales was not immediately apparent to those interviewed.

OVERLAYS AND PAPER

Overlays can be useful for interpreting charted data. Such overlays were seen at two of the plants visisted (see Figures 11-16 and 11-17). In one case the overlay was stored in the manner shown and used as needed. In the second case the overlay was incorporated directly on the face of the chart recorder. While this aspect of chart recorder usage was not explored in any depth, it may be appropriate for operational staffs to do so. A more suitable means for storing overlays may be required than that shown in Figure 11-16, and overlays should be clearly coded to prevent association with the wrong recorder.

Recorders vary in the ease and frequency with which chart paper must be replaced (see Figures 11-18 and 11-19). Only minor grumblings were overheard in this regard. However, it is a selection criterion that should be considered.

SUMMARY

Nuclear power plant operators place greater reliance on chart recorders than has been observed in comparable military settings. All too often, chart recorders are inappropriately used in place of meters. Chart recorders are best employed for recording historical trend data. The chart recorder readouts are often not legible due to the nature of the printout and the density of parameters tied to an individual recorder. This overburdening of an individual recorder has proven to be false economy. Control board designers should give more attention to the readability, labeling, and maintenance aspects of chart recorders.

Section 12

ANNUNCIATOR-WARNING SYSTEMS

Each of the control rooms visited has a horizontal band of annunciator lights across the span of the control boards, as shown in Figure 12-1. The number of annunciator lights can range from about 400 to more than 2,000. These indicators are associated with a variety of auditory warning devices. A considerable portion of the operator's time is spent responding to auditory cues, determining the cause of the auditory alarm which is coupled with one or more associated visual indications, correcting the situation that occasioned the alert so that the alarm can be cleared, and then resetting the annunciator system to its initial quiescent state.

Upon first visiting a simulated control room and being exposed to a simulated emergency, the novice cannot fail to be impressed with the vast number of flashing annunciator lights and blaring horns. The question that immediately comes to mind is: How can the control room operator possibly absorb and integrate all of the information that is being presented to him so that he can make an effective corrective response?

In this section we will examine the various types of indicators included within annunciator panels, the controls associated with these panels, coding of annunciators, the physical arrangement of annunciators, and some of the human factors problems that operators are presently having with annunciator-warning systems.

TYPES OF ANNUNCIATOR INDICATIONS

The annunciator panels have a variety of indicators that provide essentially qualitative information. The annunciator indicators can be categorized in different ways, one of which is as follows:

- Single Indication. An indicator that informs the operator a preset limit has been exceeded or is not being met by a given plant process, e.g., Low Charging Flow.
- Multiple Choice Indication. An annunciator indication that informs the operator of deviations from a set of predetermined limits, e.g., Pressurizer High/Low Level.

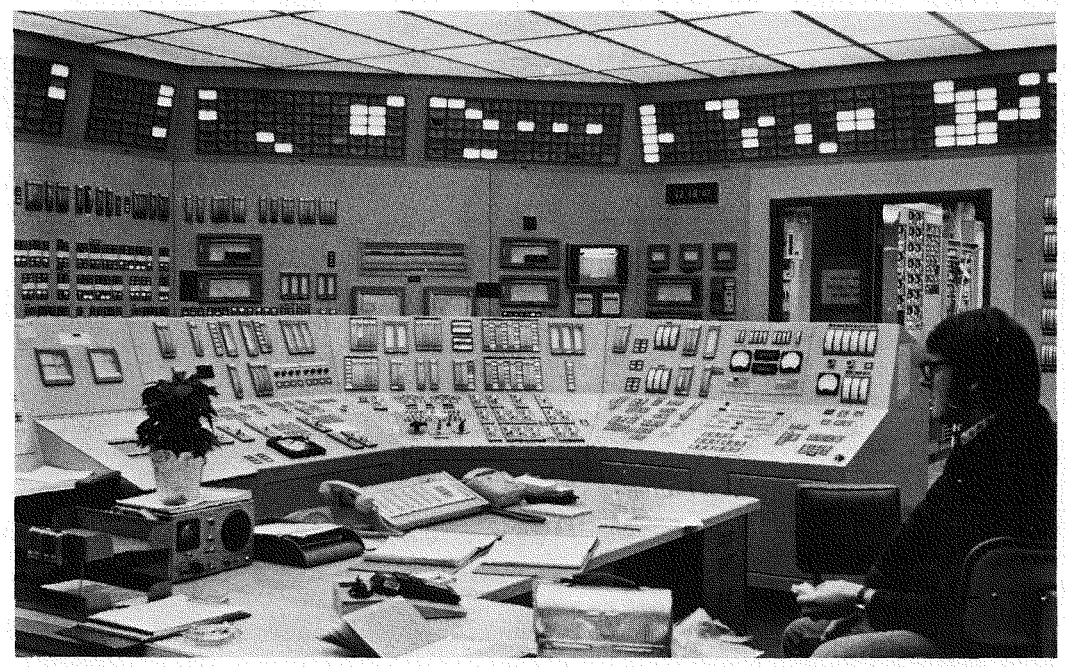


Fig. 12-1. A horizontal band of indicator lights above the control boards constitutes the warning-annunciator system at all five plants visited.

- Category or Common Alarms. A general indication that one or more of a category of alarms have exceeded a preset limit. Such alarms generally refer the operator to a subpanel of annunciator indications of another console located remotely from the primary control board, e.g., Rad Monitor Alarm.

As will be discussed below, the multiple-choice and the category or common alarms give operators the most trouble. The multiple-choice alarms confuse the operator as to which limit is exceeded. In some cases, if one limit as opposed to the other is exceeded, a very serious condition exists. The common alarms generally mean that the operator must either leave his primary area of control room responsibility or he must rely on an auxiliary operator to provide him with the full picture of the problem. In either case, the operator is not provided immediate information on which he can base corrective action.

Another categorization of alarms observed at the various plants visited establishes the following listing:

- Trip Alarms, e.g., Turbine Trip, advise that a unit or system has automatically shut down as a result of a malfunction. Immediate diagnosis and action is called for.

- Trouble or Malfunction Alarms, e.g., Flash Evaporator Trouble, inform the operator that one or more of many potential problems have occurred at a system location and, depending on the specific alarm, he may have to contact a local operator to determine the trouble. (This, in turn, is dependent on the correct diagnosis of alarms and displays at the local panel.) The control room operator may or may not be required to take further action.
- Fire Alarms, e.g., Fire, System (A), alert the operator to a fire at a designated location. This might be accompanied by another indication designating startup of the fire protection system.
- Security Alarms, e.g., Gate B, inform the operator that a gate or door at some plant location has been opened. This may relate to plant security, as with a perimeter gate, or to personnel safety, as with a reactor containment door.
- First Out Alarms carry system or malfunction designations and come on when the plant trips (automatic and sudden shutdown). These are usually specially coded or located to inform the operator what the first event was that led to the automatic shutdown. It is important data for diagnosis and appropriate corrective action.
- Confirmation or Advisory Alarms, e.g., an automatic startup or shutdown of a designated system, confirm proper or correct system actuation as a result of a plant trip or other event. Lack of these indications signify an abnormality.

One confusion encountered in the terminology is the use of the term "alarm" for all indicators appearing in the annunciator panels. The so-called "advisory alarms" report expected conditions. Yet, since these qualitative indications are grouped with true alarms, they are referred to as "alarms."

Typically, the first out alarms are differentiated by special color coding or position location. Plant trip, security, and some fire alarms were separately grouped for easy identification. All other alarms are generally undifferentiated except that they are often placed above the functionally related segment of the control board. The number of functioning alarm annunciators in the control rooms investigated ranged from 402 at one single-unit plant to 1,539 in a double-unit plant. There were many more unused, blank annunciators in the alarm panel matrices spread across the control room.

Among these annunciators at every plant there were many bearing tags that indicated that they were malfunctioning. There were also several mentioned by operators at different plants which remained untagged but also were malfunctioning. This was considered normal by all operational personnel, apparently for many different reasons. At one plant a complete review of alarm annunciators was underway and, as a result of this detailed scrutiny, many were being eliminated. Those being

eliminated were inserted upside down, taped over to obscure the legends, or the original legend faces were replaced with blank faces.

OPERATION OF THE ANNUNCIATOR ALARM SYSTEM

Each of the five annunciator-warning systems observed was slightly different. However, in the interests of brevity, only one system will be fully described.

Figure 12-2 presents the layout of the annunciator and acknowledge function groups. Table 12-1 summarizes the operation of the alarm system in the primary control area. There are basically two control board areas. One area contains plant-critical, first-out annunciators; the second area is divided into three sections controlled by three separate acknowledge switches, and contains all other alarms. The first section has a horn for the audible alert, the second broad section has a whistle. The whistle was an innovation of the operating personnel as a solution to continued malfunctioning of the originally provided buzzer.

Table 12-1 shows that any of three HORN SILENCE switches will silence the whistle for Board 2. Only the "Horn Silence" on Board 1 will silence that horn. Notice that the whistle is reset only after all Board 2 actuated annunciators have been acknowledged. The entries under the FLASHING WHITE blocks are used to describe the flash rates: once per second and equal on and off times (1:1). The alert for a cleared condition is the same as that for a new alarm condition, except that the brightness of the flashing annunciator is dimmed. Note again that the whistle is not reset until all flashing annunciators have been acknowledged.

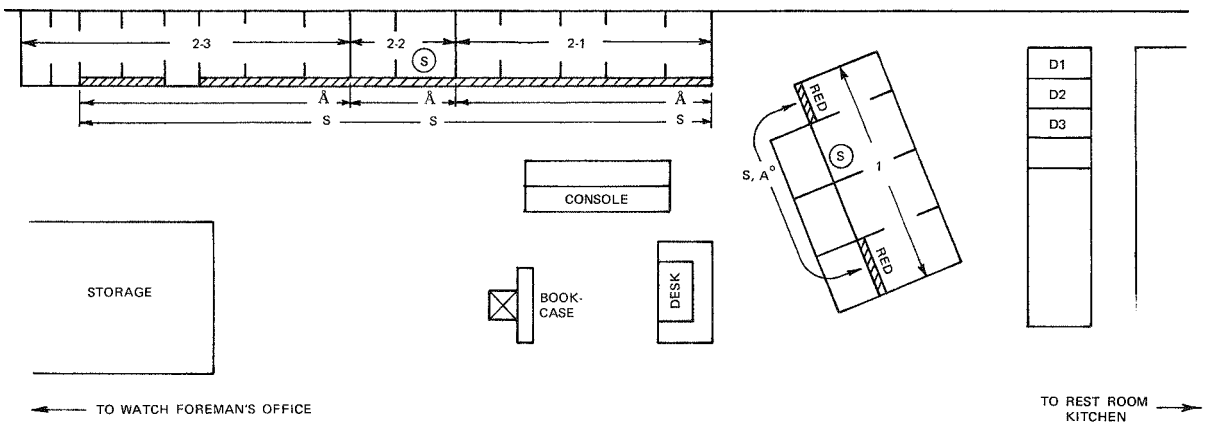
The original design for the control room provided red annunciators for first-outs and white for all others. Experience showed that some of the white annunciators were more critical than others, so 17 whites were changed to red. Five others were virtually always on at normal power and were therefore changed to green. These were observed ON during our visit. We were advised that an abnormal condition would be signaled if one of the green annunciators were to go OFF on signal CLEAR.

A loss of coolant accident simulation was observed at the simulator for this plant. A startling blast of a very loud horn signaled its onset and all control room overhead lights went out. Dimmed lighting came on in two or three seconds, signaling a shift to backup power. The whistle sounded simultaneously with the horn and recurred many times more as flashing red and white annunciators appeared across

Table 12-1

ANNUNCIATOR-WARNING SYSTEMS DESIGN AND OPERATION

	ONSET			RESET		
Board Location	ALERT	OPERATOR ACTION	SYSTEM RESPONSE	ALERT	OPERATOR ACTION	SYSTEM RESPONSE
	HORN		SILENT	NONE		HORN RESET
1	FLASHING RED (First Out) STEADY RED (Others)	HORN SILENCE ANN ACKN.	STEADY (STEADY)	NONE	REACTOR TRIP BREAKER	ANN'S OFF
2	WHISTLE		SILENT – Disabled RESET	WHISTLE		SILENT – Disabled RESET
2-1	FLASHING WHITE OR RED (Bright) (1/sec; 1:1)	ANN ACKN. And HORN SILENCE or	STEADY	FLASHING WHITE (Dim) or RED (1/sec; 1:1)	ANN ACKN. And HORN SILENCE or	OFF
2-2	FLASHING WHITE RED OR GREEN (Bright)	ANN ACKN And HORN SILENCE or	STEADY	FLASHING WHITE (Dim) or RED	ANN ACKN. And HORN SILENCE or	OFF
2-3	FLASHING WHITE RED OR GREEN (Bright)	ANN ACKN. HORN SILENCE	STEADY	FLASHING WHITE (Dim) or RED	ANN ACKN. HORN SILENCE	OFF



1, 2-1, etc.	Segment of the control board
//////////	Location of annunciator arrays
(S)	Shows approximate location of audible alarm source
A	Location of ACKNOWLEDGE control (arrows show range of control)
S	Location of SILENCE control (arrows show range of control)

Fig. 12-2. Layout of the annunciator-warning system elements. See Table 12-1 for operational characteristics.

the board annunciator panels (see Figures 12-3 and 12-4). Many plant transient states occurred and so annunciator alarm clear signals, both audible and visible, were given concurrently with the onset of new alarms. Many meters and banks of lights across the boards began changing states, which both operators began to monitor while tracking, silencing, and acknowledging alarms. The basic task of the operators was to ensure that all required safety systems were actuated and that the reactor core remained in a safe condition while they diagnosed the cause of the plant trip.

It is understood that the best immediate operator response to this emergency is not to take manual action, but to monitor actuation of built-in automatic safety systems. This barrage of stimuli therefore seems contradictory, and the operator rushed to silence the loud horn. One operator continually moved back and forth across the broad board, never missing the ACKNOWLEDGE and SILENCE switches as he walked by them, regardless of whether they were functionally called for. When later questioned, he said he found it easier to keep pushing them while tracking displays and events, rather than to try to determine which switch applied to which annunciator.

Operators are instructed to "Acknowledge" immediately in order to clear annunciators and to ensure the resetting of the audible alarm. During one simulation, an operator "Acknowledged" at the First-Out panel and the pertinent annunciator went steady, blending in with all others, thus losing that important piece of data. The rule to acknowledge, it turns out, should not be followed during the most psychologically critical mode for the First-Out panel, but still holds for the other annunciator panels. This inconsistency was mentioned as a problem by several operators.

ANNUNCIATOR SYSTEM CHARACTERISTICS

A number of annunciator system characteristics were examined for compliance with military standards. The results of this analysis are provided below.

Flash Rates

Annunciator flash rates recommended by MIL-STD-1472 for warning lights is 3 to 5 flashes per second with approximately equal on and off times. This rate is selected because of its proven high alerting ability. The flash rates at the plants utilizing this code is summarized:

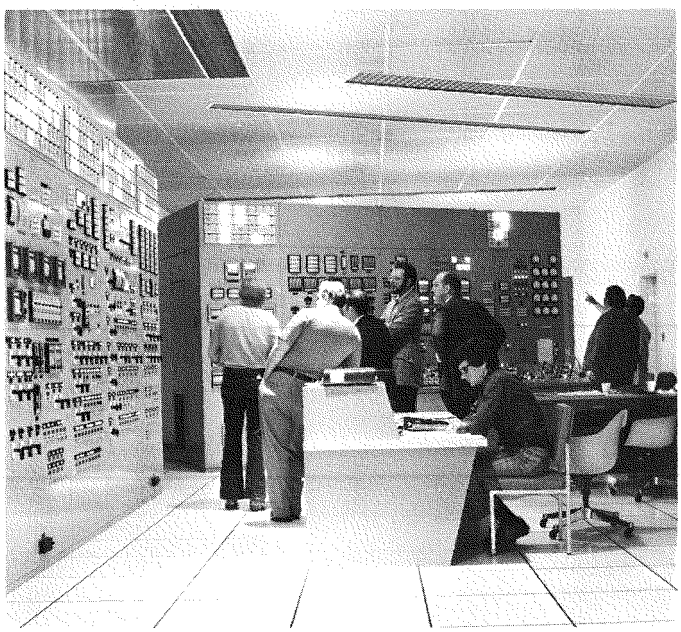


Fig. 12-3. Annunciator lights that have been activated during a simulated emergency.

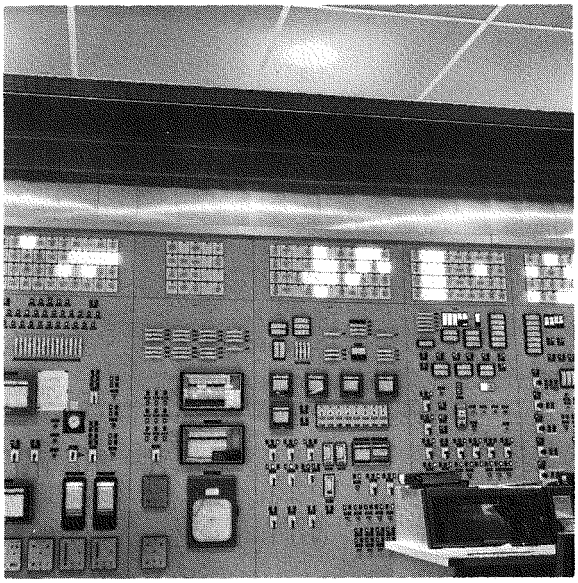


Fig. 12-4. Another segment of the control room shown in Fig. 12-3. The room is on back-up lighting.

	ALERT	CLEAR
Plant A	1/sec; 1:1 (bright)	1/sec; 1:1 (with audio) (dim)
Plant B	2/sec; 1:1	2/sec: 1:2 (with audio)
Plant C	2.5/sec; 1:1	1/sec; 1:1 (no audio)
Plant D	1.6/sec; 1:1	N/A (no audio)
Plant E	Not Measured	Color of Annunciator Changes

The difference in flash rates from the recommended values was not observed to induce operator difficulties; however, an optimum flash rate is not provided. A more serious matter is that the difference between the Alert and the Clear flash rates and on:off ratios is not always immediately apparent to operators. A Clear alert is seen as desirable, particularly where an annunciator is not able to re-alarm until it is cleared and reset. The use of color coding employed at one plant to distinguish between Alert and Clear conditions is seen as a superior technique which provides an immediately distinctive, unequivocal signal to the operator. Coupling of the Clear signal with a unique audible alert is also a desirable feature.

Auditory Signals

As will be discussed in Section 13, better use could be made of the auditory channel for transmission of information to the operator. While auditory cues were available at each plant to alert the operator to the onset of an annunciator indication, clear coding of auditory cues was lacking. One means for distinguishing annunciator signals would be to have two classes of audible alerts: the first signifying urgent warnings demanding immediate attention; the second class signal describing a caution condition, alerting the operator to a marginal condition and not demanding instantaneous response. Furthermore, the urgent warnings could be additionally coded with distinctive sounds to provide an indication of the major subsystem involved and hence the segment of the control board to which the operator should address his attention. Another technique that would provide a directional cue would be to position horns or separate speakers so that the sound emanated from the location in which the affected bank of annunciators was located. This practice was employed at only one of the five plants studied.

The audibility of alarms was a problem at some plants. A computer generated alarm at one plant could only be recognized when the operator was standing near the computer console. In the same control room one alarm is set at a frequency beyond the

hearing range of at least one operator. He indicated that he became aware of this alarm when he started to get a headache after the alarm was on for a while.

The loudness or intensity of auditory alarms varied. Our observations in both simulators and operational control rooms indicated no differences in the responsiveness of operators based on the loudness of the alarms, except that with very loud and annoying alarms, there was typically a rush to get to the silence switch. In some plants the intensity of auditory alarms seemed more calculated to startle the operator rather than alert him to a problem.

Alarm Silencing

At all plants investigated, the operator must manually silence the auditory alarms either by pressing a horn silence control or by pressing the annunciator acknowledge button. A case can be made for automatic silencing of auditory alarms. The requirement to manually silence alarms often interferes with the diagnosis and corrective actions required subsequent to the onset of a malfunction alarm. Also, operators were observed to press alarm silence buttons as a matter of course, almost without thought. Furthermore, the alarm silence buttons should be located so that the operator isn't taken away from the segment of the board where corrective or diagnostic action is being made. If, as some operators suspect, manual silencing of the horn is predicated on getting the operator on his feet, there seems no need for such concern. The operators at all plants visited were extremely attentive to the onset of annunciators and did not allow themselves to be distracted from attending to them.

Physical Arrangement of Annunciators

The degree to which annunciators were grouped by function or subsystem and were placed above correlated controls and displays varied among plants and within plants. In one case annunciators were reasonably well grouped and located, but because of the lack of functional grouping of the control board displays and controls, there was really no annunciator location close to all relevant panel elements. As a result, the operator had to acknowledge and read the annunciator at one location but then take control action at another location.

The grouping of the annunciator panels with respect to silence and acknowledge control switches was sometimes a problem. At some plants the audible alarm could be silenced from any control switch location, while at others, dedicated switch operation at specific panel locations is required to ensure that the operator will go

to the appropriate panel without forgetting it. But when he is forced to go to a panel location to silence, acknowledge, and read the annunciation, and then go to another location to take action, the intended design advantage becomes a disadvantage. In this context, one operator remarked, "In critical points of operation, I have to pull myself away from a critical task at the (reactor) panel to take care of a (non-reactor) panel alarm which is far away. I tend to lose track of 'generations,' for example."

Readability of Annunciator Indicators

With the exception of one plant, the operator must stand close to the annunciator in order to read it. Because of the relatively small letters using up to six lines of print on one annunciator face (see Figure 12-5), reading from a distance is usually impossible. It is interesting that some operators claimed to be able to recognize annunciators from great distances (about 20 feet) based on the position of an annunciator window within the panel matrix. This belief was most prevalent where the same individual annunciators occurred repeatedly. Military Standards recommend a letter height of 1.13 inches for viewing distances of between 12 and 20 feet. The labeling on annunciator windows did not approach this recommended size.

Although not put to a test, operators may be deluding themselves into thinking that they can accurately read present annunciator windows correctly at a distance of 20 feet. They may in fact be reacting to position or pattern cues. The problem is compounded in situations where multi-unit control rooms have mirror-imaged annunciator panel arrays. At one plant, the silence and acknowledge controls are 17 feet from the furthest affected annunciator light. This means that the operator must shuffle between the locations of annunciators and these controls to manage both the reading and horn silence tasks.

Annunciator Control Switches

As mentioned in Section 7, repetitive groups of annunciator-related controls should use the same arrangement and relative location on the control boards on all panels. Due to lack of uniformity in some control rooms, (see Figures 12-6 and 12-7), operators have been observed to reach "blind" for an ACKNOWLEDGE button and press a TEST button by mistake. It would also help to shape code the individual controls that are associated with the annunciator system.

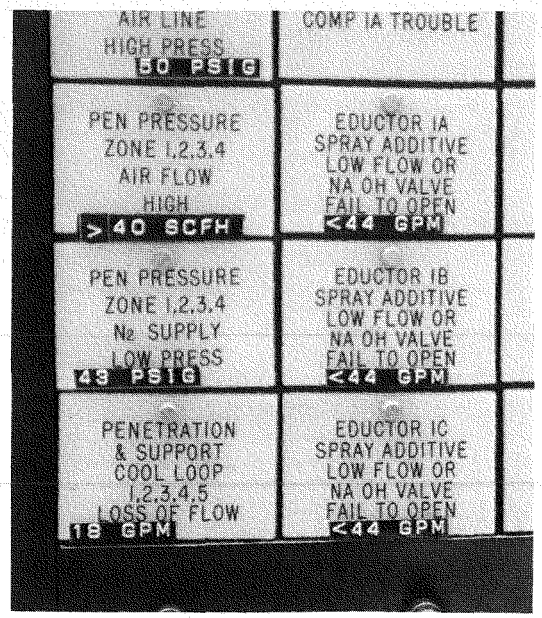


Fig. 12-5. Legends on annunciator windows are too dense with up to six lines of labeling and the size of lettering is too small to be read from the operator's station.

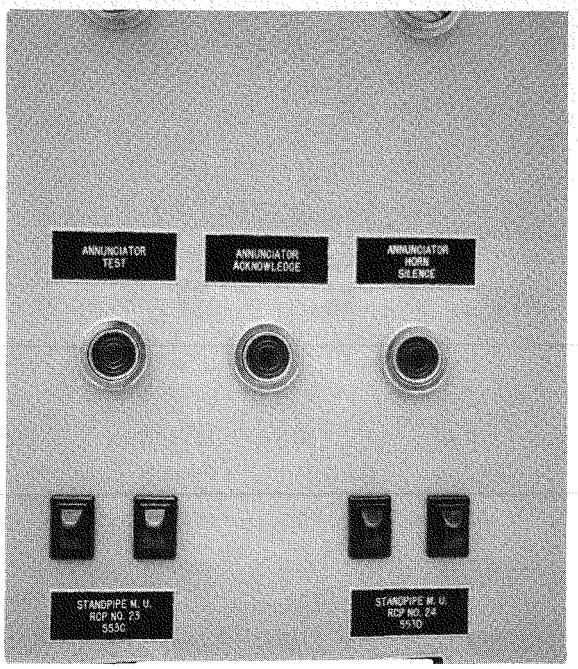


Fig. 12-6. Note the pattern of annunciator control pushbuttons and compare with Fig. 12-7.

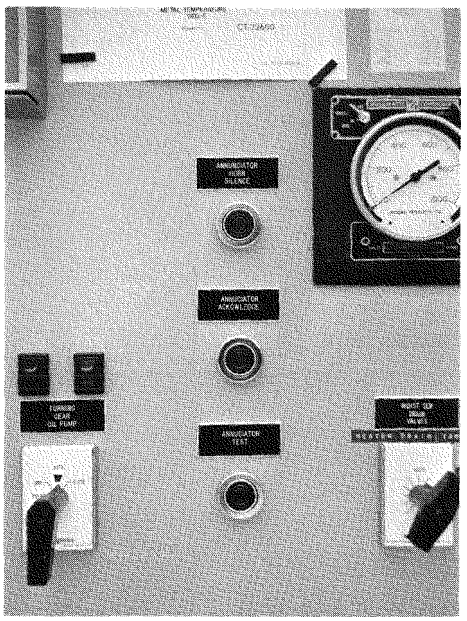


Fig. 12-7. Note the arrangement of annunciator controls. Compare with Fig. 12-6. Two different arrangements of these frequently used controls are provided.

OPERATIONAL EXPERIENCE WITH ANNUNCIATOR SYSTEMS

The operators and trainers were asked about the effectiveness of the annunciator-warning system. This questioning uncovered several significant problems and some avenues towards improving present control room designs.

Nuisance of False Alarms

Operators at all plants complained about the high number of nuisance alarms. The reasons for their occurrence varied. At one plant there was a blank, supposedly nonfunctional, annunciator window that would occasionally alarm. The maintenance and operational people had been unable to determine its cause, but an acknowledgement, silence, and reset were required on each occasion. In many cases alarm setpoints were known by operators to be too sensitive to normal transients. As a consequence slight deviations or transients, thought of as normal, would set the alarm off even though no further operational action was required. Maintenance or calibration operations often caused recurring alarms that were a nuisance. The net result of the many false alarms is a "cry-wolf" syndrome which leads to lack of faith in the system and a casual attitude towards the constant presence of certain alarms. On many occasions operators were observed to casually silence and acknowledge alarms without further concern or surveillance of plant status; the alarms had become "old friends."

At all five plants the annunciator system displayed alarms over which the operator showed no apparent concern since they did not require operator action, and many were nuisance alarms that were always present. Figure 12-8 shows one such case where ten annunciator lights are clearly illuminated.

When nuisance or false alarms occur persistently and the associated blaring horns become especially wearisome, the operators are driven to extremes to preserve their sanity. Figure 12-9 shows a coin inserted in an alarm ACKNOWLEDGE push-button housing to maintain the button depressed, thereby defeating the audible alarm associated with a bank of annunciators. The "culprit" responsible for this measure was one annunciator circuit on the edge of a limit. However, the audible alarm was defeated for a whole bank of annunciators and not just the offending one. In another plant troublesome alarms were disabled and the annunciators were coded with a dot as shown in Figure 12-10. One wonders whether or not the original function served by the disabled alarms is no longer required. The problem of nuisance alarms is a serious one. As discussed further in Section 19, the lack of timely information or the imbedding of valid warnings in the midst of numerous

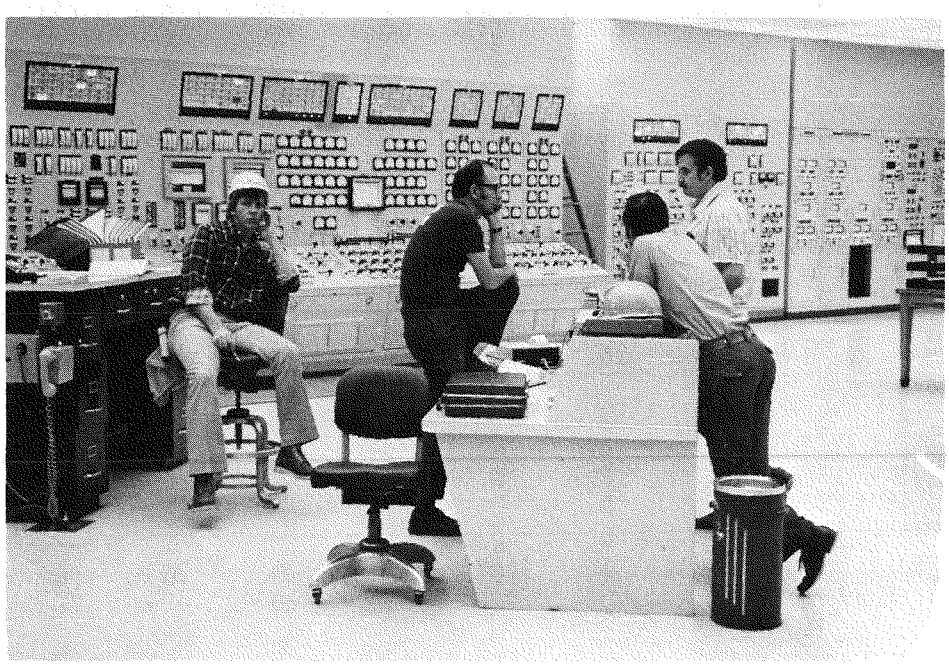


Fig. 12-8. Although ten annunciator lights are illuminated (of those in view) there is no apparent concern since these do not represent conditions requiring immediate operator response and some may be nuisance alarms.

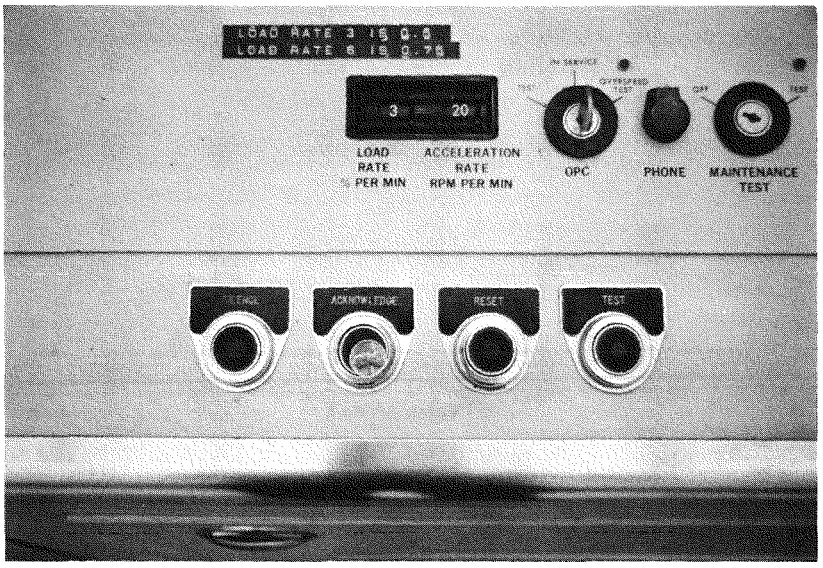


Fig. 12-9. When nuisance alarms persist, the auditory alarm is defeated by use of a coin to hold down the ACKNOWLEDGE button.

false warnings can and has led to the destruction of hundreds of thousands of dollars worth of equipment.

Some comments made by the operators:

- We average 50 to 100 false alarms per watch. These are due to faulty equipment or the limits are set wrong or the range selection is off.
- The control room is so big that you have to run down the room to RESET. Take the PRIMARY WATER AND BORIC ACID FLOW DEVIATION alarm. By the time you ACKNOWLEDGE and walk back to the desk you have to return to the panel to re-silence it.
- We get many false alarms. The logic should disable alarms when they don't apply. For example we get LOW OIL PRESSURE alarms on idle pumps and LOW LEVEL alarms on empty tanks, etc. The warning tones are extremely annoying. Some means should be provided to block out an alarm at the operator's discretion when something is repeatedly alarming.
- We get a bunch of false alarms and there is no way to eliminate them. The Shift Engineer should have a ready means to disable alarms when necessary.
- We have lots of problems with our alarm system. Sometimes the alarm sounds but the light doesn't come on. Some security gates cause alarms to sound one hundred times in an hour and after a while the alarms cry wolf too often.
- The radiation monitoring alarms are particularly unreliable and are often ignored. Rad monitoring alarms come on every time it rains.
- The clean-up system that purifies reactor water has quite a few false alarms. We learn to live with these. A few alarms indicate a problem when the situation is normal. The limits are set wrong. This could hide a real alarm on that function.
- In a trip or scram there are lots of nuisance alarms that come in. At that point they are normal and the operator doesn't care about them. Yet, he must keep acknowledging or silencing them. He should have only significant alarms that have meaning come on. Sometimes, someone else will come over and acknowledge them for you. That helps.
- We don't RESET nuisance alarms and that leaves them disabled. We SILENCE and ACKNOWLEDGE them. Other alarms on the panel will come in. Otherwise, they (the nuisance alarms) would come in frequently and this is a problem ... alarms become meaningless.
- With nuisance alarms the card is pulled in the cable spreading room and the alarm window is marked (with a blue dot) to indicate that it is inoperable (see Figure 12-10). The operator should have the ability to disable the alarm in the control room.

Specificity of Alarms

As indicated early in this section, a common complaint of the operators had to do with the lack of specificity of alarms. One annunciator window can announce the

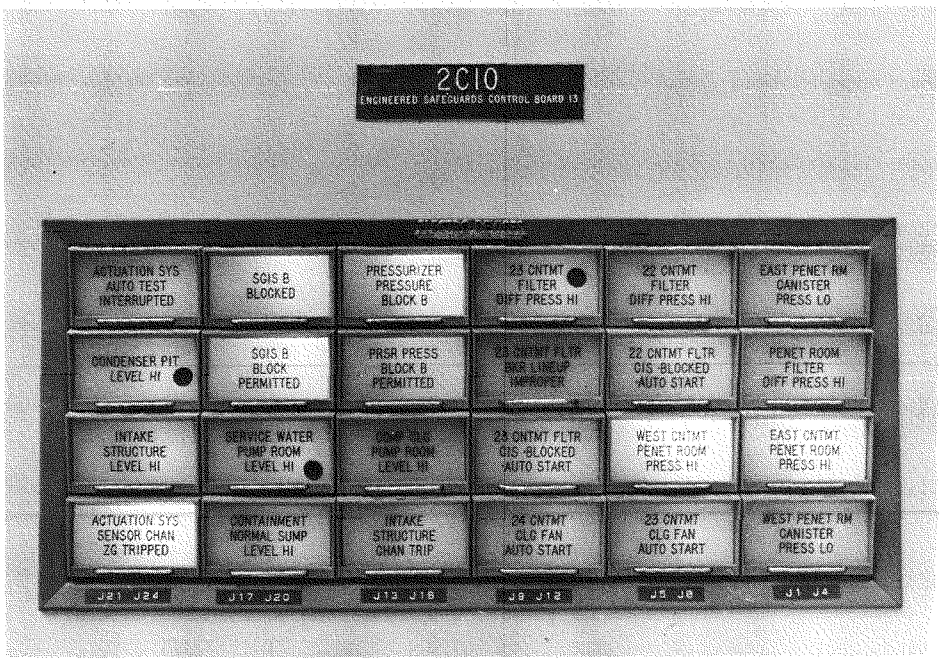


Fig. 12-10. The blue dots on the three annunciators shown indicate that the alarm circuit has been deactivated.

following: HIGH/LOW - LEVEL OR PRESSURE. The operators feel, with justification, that four discrete indications are required to provide timely information, especially when the associated quantitative readouts are far removed from the annunciators or when the auxiliary operator must be called to clarify the situation. The annunciator windows should be separated into the following four indications: LOW LEVEL, HIGH LEVEL, HIGH PRESSURE, and LOW PRESSURE. Also, operators often add labeling to the annunciator windows so that they do not have to look up the limits for each function (see Figure 12-5).

Operators were also concerned about the inadequate information content of so-called "common" or "category" alarms. One comment summarizes this concern especially well: "The STATOR COOLING PANEL TROUBLE alarm could mean about a dozen different alarm conditions, e.g., high conductivity. We have to get a man out there to see and it is sometimes hard to get him. We should have the specifics. If it is high conductivity, we should trip the unit in three minutes by Technical Specification requirements. It can take five minutes to get the man out there."

Timeliness of Alarm Annunciations

Some operators questioned the timeliness of alarm indications. Their attitude implied that the limits for the onset of alarms were set too narrowly, thereby allowing insufficient response time for the operator to correct the situation. Some comments along these lines are:

- Most alarms are after the fact with very little anticipation built into the system.
- Sometimes an alarm comes up after it is too late to do anything about it, e.g., the LOW VACUUM alarm comes up at the same time as the LOW VACUUM TRIP. The system should give you some advanced warning of an impending condition.

SUMMARY

Much could be done to optimize the man-machine interface of annunciator-warning systems. In our view, the annunciator panels have served as a catch-all for a host of qualitative displays. Some of these displays are true alarms and many are simply advisory or status indications that do not alert the operator to abnormal conditions. When a major accident occurs, the annunciators come on in such bewildering numbers that it is not humanly possible to read, much less absorb, the meaning of all the annunciators. The operator must interpret what is happening in spite of all this confusion, rather than with the help of the annunciator panel. One training director says: "You can determine the nature of abnormal events but it is not so simple. Alarms go on simultaneously and it's confusing. The information is there and you can come to the right conclusion. For the novice, this is confusing and could easily cause the guy to panic." In another context, this individual says: "The job is boring, so the board creates a challenge. If the board is too straight-forward, or human engineered, then the operator will lose his edge." In our view, the annunciator-warning systems observed over-challenge the operators. The operators that we have interviewed generally concur in our assessment of problem areas.

As noted in Section 5, the annunciator panels observed have separated most of the qualitative displays from their associated quantitative displays and controls. This leads to a control board design that is not functionally integrated into meaningful panels, subpanels, and consoles. The fragmented arrangement observed serves to impede malfunction diagnosis. Warning-annunciator panels should contain a minimum of displays; the displays should merely direct the operator's attention to the appropriate segment of the control board. This requires a major redesign of control boards to integrate qualitative indications into selected panel areas.

This recommendation may be appropriate to future control room designs but may be totally unrealistic in upgrading operational control boards. Existing annunciator systems can be improved by the following measures:

- Annunciators should be located directly above their related control board panels.
- The limits for troublesome annunciators should be reviewed and adjusted to eliminate nuisance alarms.
- Auditory warning signals should be reviewed for adequacy in terms of intensity and discriminability. Coded auditory signals should be used to differentiate minor cautions or advisories from major problems. Coding may also be appropriate as a location cue.
- The use of multi-input annunciations which alert the operator to a host of unspecified possible problems should be avoided. These serve to confuse and frustrate the operator.
- Alarm silencing provisions should be reviewed and consideration given to automatic silencing of alarms.
- More attention should be given to consistent color coding of alarms to allow differentiation of alarms according to severity or according to the onset or clearing state of the annunciator.
- The limits or alarm set-points should be reviewed to allow operators to make timely responses to impending malfunction conditions.
- Common alarms that require the operator to call an auxiliary operator for interpretation should be avoided if insufficient time is given for the operator to take action.

Section 13

CODING OF DISPLAYS AND CONTROLS

A primary technique for allowing the operator to sort out the immediately relevant from the irrelevant stimuli is the coding of displays and controls. Effective coding permits timely acquisition of meaningful information, facilitates correct identification of relevant control options, and allows the operator to maintain effective cognizance over system status. Coding techniques are designed to allow discriminations via the operator's sensory and perceptive mechanisms. The operator's visual sense is used most often, auditory coding the second most common, and the tactile sense third. This section will explore the use of coding techniques in nuclear power plant control rooms and will attempt to show how coding practices could and should be used to greater advantage.

COLOR CODING

The most common form of coding in operational controls rooms is color. In three out of five five control rooms studied, the most prevalent color code for panel indicators was as follows:

Color	Meaning
Red	Valve open or circuit closed. Red is interpreted to signify fluid or electrical flow.
Green	Valve closed or circuit open. Green is interpreted to signify a no-flow condition for electrical or fluid channels.
Amber	Automatic relay trip, or valve in midway or transition position, or an in-process condition.
White	General status indications, e.g., power available.

In a fourth control room no predominant color code emerged with the exception of the Safeguards Panel. On that panel the following code was observed:

Blue	Automatic system operation.
White	Manual system operation.

Table 13-1

INCONSISTENT USE OF COLORS FOR INDICATORS, LABELS, AND CONTROLS AT ONE OF THE FIVE PLANTS

FUNCTION	COLOR
PREDOMINANT COLOR CODE:	
VALVE OPEN OR CIRCUIT CLOSED INDICATOR	RED
VALVE CLOSED OR CIRCUIT OPEN INDICATOR	GREEN
IN-PROCESS CONDITION INDICATOR	AMBER
GENERAL STATUS INDICATION	WHITE
EXCEPTIONS TO THE PREDOMINANT CODE:	
BISTABLE STATUS LIGHTS - FOUR CHANNELS	RED, WHITE, BLUE, AMBER TO SEPARATE CHANNELS
TURBINE ECCENTRICITY ALARM INDICATOR	RED
TURBINE DIFFERENTIAL EXPANSION ALARMS (INDICATORS)	RED
TEMPERATURE MONITORING PANEL - PARAMETER SCAN LIGHTS	RED
COMPUTER KEYBOARD PUSHBUTTONS - COMPUTER FAILED, TREND FAILED, INVALID REQUEST, START/ADD, STOP/OMIT	RED
LOW WEIR GATE POSITION INDICATOR	RED
HIGH WEIR GATE POSITION INDICATOR	RED
EMERGENCY BORATION VALVE (LABEL)	RED
ROD BOTTOM LIGHTS	RED
CONTAINMENT SPRAY PHASE "B" ISO. PUSHBUTTON	RED
PUMP ON INDICATOR	GREEN
PUMP OFF INDICATOR	WHITE
LOW FLOW INDICATOR	RED
HIGH PRESSURE INDICATOR	RED
FILTER FAILURE INDICATOR	RED
INSTRUMENT POWER ON INDICATOR	AMBER
LOSS OF DETECTOR VOLTAGE INDICATOR	AMBER
HIGH LEVEL TRIP INDICATOR	AMBER
HIGH LEVEL ROD STOP INDICATOR	AMBER

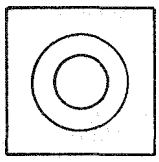
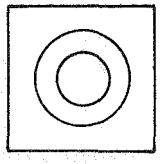
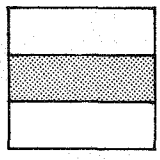
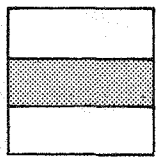
Green	Stop
White	Start

The major problems with these color codes were: (1) the color code scheme was not applied consistently throughout the control room and (2) the color scheme provided no indication as to whether a specific color was associated with a normal or abnormal event. For example, if a RED, valve open indication appears on the board, the operator is not told whether the valve open condition is proper or improper for the circumstances at hand.

Let us examine these two problems in greater depth. First, let us consider the consistency issue. For any code to elicit an expected operator response, the elements of the code must have consistent meanings throughout the control room. If we change code meanings as we move from panel to panel, the code becomes useless and a valuable cueing mechanism is lost or compromised. For example, Table 13-1 presents a sample of the color coding used with displays and controls at one plant. Red signifies valve open or circuit closed conditions. However, note the exceptions to this prevailing code in which red is used to denote either an alarm condition or a very important control function. In many situations, these inconsistencies are a result of many different vendors supplying equipment for the control room. It is a simple matter, however, to specify legend caps of the colors appropriate to the color code devised for the control room to eliminate inconsistencies.

The second problem, the absence of normal/abnormal color connotations, is more complex. Telling an operator that a valve is open or closed, without any mention of which position the valve should be in, is not telling the operator very much. It requires that the operator has firmly committed to his memory the correct position of a host of valves, activated or deactivated motors, etc. Furthermore, the correct pattern of open/close valves and ON/OFF motors changes with plant status, e.g., startup versus full power.

Only one plant visited attempted to overcome this problem. In this plant, symbols are superimposed on indicator lights to indicate "open" or "closed" valve condition or ON/OFF motors. The colors indicate normal or abnormal situations. As shown in Figure 13-1 the "donut" symbol represents the open or flow position. The "bar" symbol represents the closed or deenergized position. This permits the following unambiguous interpretations:

RED		Valve open but should be normally closed; hence an abnormal situation.
GREEN		Valve open as it should be in a normal condition.
RED		Valve closed when it should be open.
GREEN		Valve closed as it should be.

This plant has made a serious attempt to implement what the military calls the "green board philosophy." These panels are designed to tell the operator that all is fine as long as all indicators are green. However, the operator jumps to attention when a red light appears. The use of red is reserved for only one meaning--an abnormal state requiring operator attention or action. Usually, the green and red colors are augmented by white status lights, e.g., power ON/OFF, and amber lights, which signify a marginal condition which, if left unattended, will cause a red light.

Unfortunately, this plant has not fully implemented this philosophy. While the red and green color associations are correct for the plant when it is at full power, the red/green abnormal/normal associations do not hold when the plant is down or during startup. The operator needs a master mode switch which permits a change in indicator color logic as is appropriate to plant status. While this is an expensive design feature, it promotes more effective, reliable operator responses to emergencies or impending danger and simplifies operator training.

One of the major ways in which present operational plants can be upgraded from the human factors standpoint is to substitute a meaningful and consistent color code

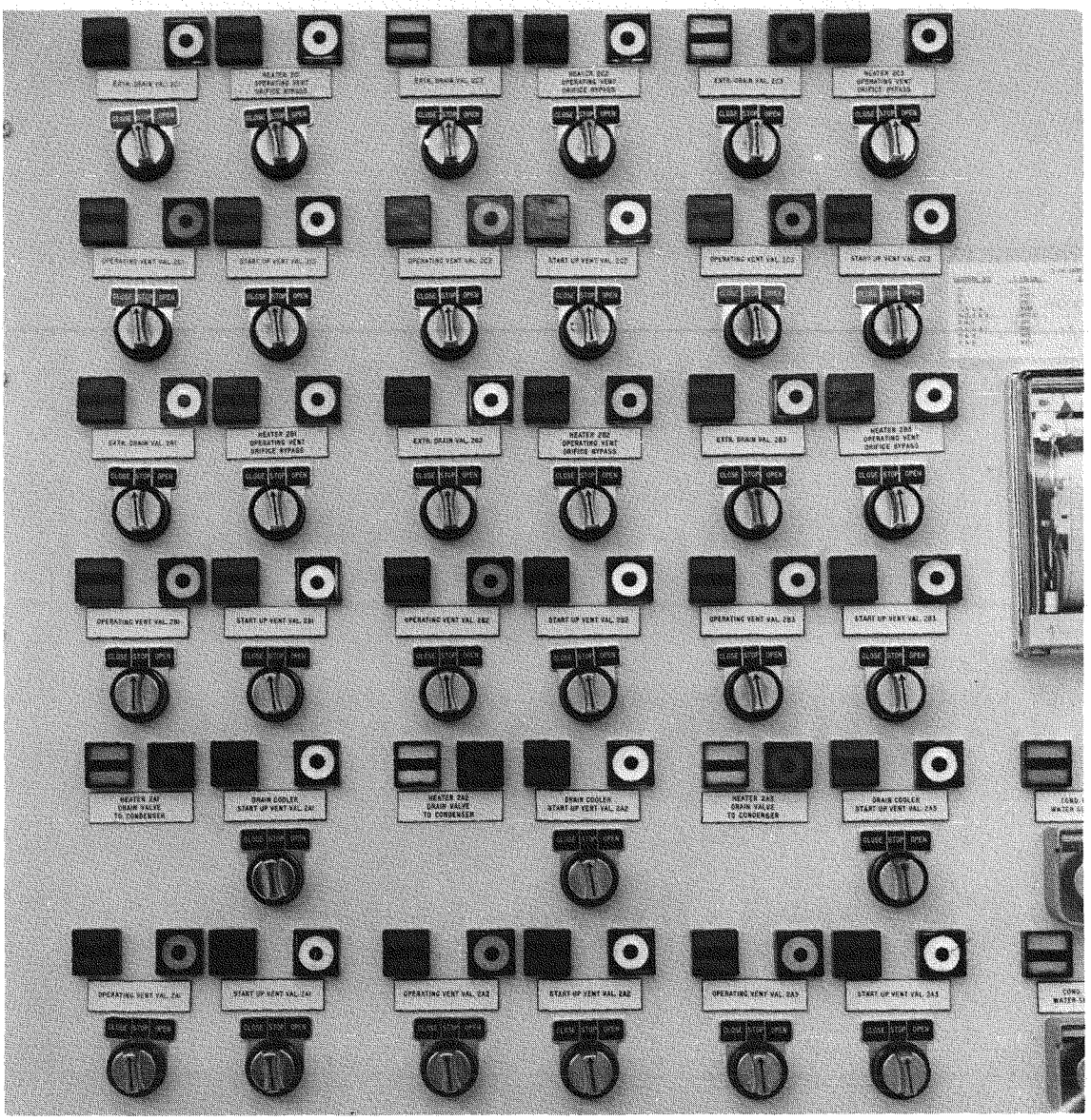


Fig. 13-1. Donut/Bar symbols on indicators represent OPEN/CLOSE status. Green/Red colors indicate Normal/Abnormal status.

for controls and indicators. The large arrays of annunciator lights in each control room discussed in Section 12 would benefit most from color coding attention.

WHITE IS RIGHT CODING

In two of the plants visited, a "white is right" coding scheme was used. In one application of this principle, the matrix of lights was normally dim white. When the Safeguards features were brought into play during casualty modes, the dim lights were actuated to form bright white lights and the operator looks for a solid array of bright white lights to tell him that all the safeguard actions have been properly effected. The absence of one or more bright white lights informs the operator that manual action is required to effect a safeguard feature that was not achieved by automatic system response.

This type of coding and display is an attempt to provide a discrete summary of all the necessary system responses to a casualty and can be of tremendous assistance to the operator. Without this aid, the operator must again rely on his memory to be certain that all the proper system responses have been made. One problem noted with this approach is that the distinction between dim white and bright white is not always clear. The presence of one expended lamp in a two-lamp indicator

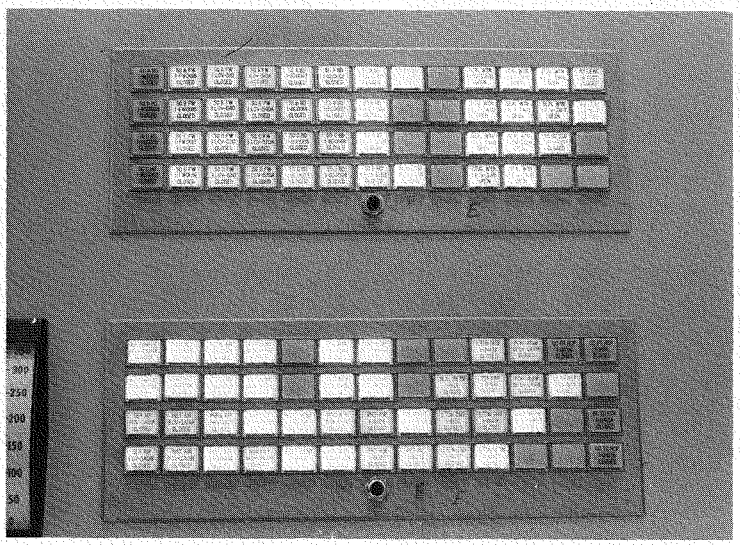


Fig. 13-2. Application of the "white is right" display principle. The operator looks for exceptions to an all dark or all illuminated matrix of displays.

created confusion. Also, as the translucent indicator legend masks age, their light transmission qualities change and the matrix appears mottled.

The second plant had a series of engineered safeguard panels from A through G (see Figure 13-2). Rather than changing from dim white to bright white, as in the case described above, these panels were supposed to be either all dark or all illuminated. The problem with these panels is that there are exceptions and the operators are required to memorize them. This places an unnecessary burden on the operator, especially during the stress of an emergency. In practice, the operators scan a particular panel and determine what the majority of lights are (dark or light) and then look at the exceptions and decide whether these exceptions are expected or unexpected.

DIFFERENTIATION BETWEEN CONTROLS AND DISPLAYS

In one plant, the operators had problems differentiating between single indicators and indicators that incorporated switching functions, commonly referred to as switch-lights. The simple indicators appear identical to the switch-lights (see Figure 13-3). The operators had to read the labels to make this distinction and at times even the labels did not clearly distinguish between the indicators and the switch-lights. One solution that was developed for missile checkout equipment is illustrated in Figure 13-4. The legend caps on switch-lights are simply inscribed with a circle to denote correspondence with a pushbutton. Note that this approach does not severely limit the space available for labeling.

ORIENTATION CUES

At one plant, orientation cues were effectively used to distinguish between meters that tracked different parameters (see Figure 13-5). In this case all level-indication meters were vertical; horizontal meters were used to provide pressures and steam or water flows. This coding technique was unique to one plant of the five investigated but may have wider application.

AUDITORY CUES

While each of the control rooms investigated makes use of auditory alerting signals in conjunction with the onset of annunciator alarms, such alarms are not coded or differentiated in any way that would cue the operator to the nature of the off-normal condition. Auditory coding could be applied in a variety of ways to provide an immediate indication of the system or component that is in an abnormal condition.



Fig. 13-3. Operator facing a panel composed of simple indicator lights and switch-lights. There is no differentiation between indicators and controls.



Fig. 13-4. Simple indicators can be differentiated from switch-light controls by inscribing a circle or the suggestion of a circle on the legend plate of the switch-light.

For example, distinctive sounds could be provided for reactor, turbine, generator, radiation monitoring, and other subsystem elements. Such coded auditory signals would orient the operator immediately to the correct segment of the control boards.

In addition to nonverbal coded auditory warning signals, there may also be an application for verbal warning systems in the nuclear power plant control room. These have been applied in conjunction with aircraft malfunction warning systems (14).

CONTROL CODING

The lack of control coding is almost as serious as the lack of effective color coding of indicator lights. In fact, many operators would argue that control coding deficiencies are more significant than the lack of consistent indicator color coding. In response to the question, "Have groups of controls which are identical been coded in any way to permit the operator to readily distinguish between them?" 89% of the operators and trainers indicated problems. The following are sample responses:

- We have tried to zone off the controls. We need coding near the boiler feed pump area. I frequently grab the wrong pump handle. It's confusing.

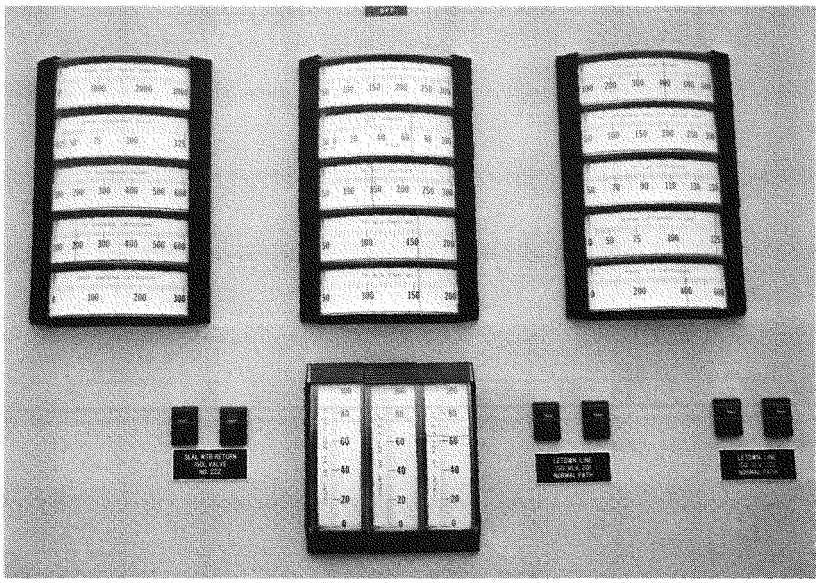


Fig. 13-5. Vertical or horizontal placement of meters used as a cue to parameter.

- Controls weren't coded initially but the operators have added white marks to help. I feel that different handle shapes for different systems would be an improvement.
- Lack of coding is a major problem. I sometimes get confused. I recommend solid background colors for different groups of controls.
- There isn't much differentiation between controls. I haven't had serious problems myself but it has been because of blind luck. I found myself grabbing the wrong control but I caught it by reading the label before operating it.
- Heater drain pumps, condensate pumps, and circulating water pumps are identical switches in one row and you can easily operate the wrong one. Power relief valve controllers and feedwater regulating valve controllers are identical and side-by-side. These have been mis-operated many times.
- No, there is no coding! I always read before I touch anything--but, I'm frequently thinking about five different things.
- Everything is labeled and, with training and motivation, the operator shouldn't make serious mistakes--only when he is in a hurry or in a casualty type mode.

Much could be done to help the operator differentiate between masses of identical controls placed side-by-side on control boards. As discussed in Section 8, operators have attempted to correct this problem. They have hand-painted control knobs different colors, added lines to break up different subgroups of controls, have provided protective covers over especially troublesome controls, and have substituted different control handles to achieve some shape coding. These "fixes" are not applied consistently throughout the control board and are generally made after an accident or near-accident.

Greater attention must be given to this problem during the design phase. The aerospace community has developed distinctive shape coded knobs (see Figure 13-6). While these may not be appropriate for the utility industry, it suggests that a unique and proven set of shapes should be developed specifically for the nuclear power plant control room.

Other means that are available to prevent control misidentification are size coding, texture coding, and location cues. Location cues are given by placing controls with the same function and that are repeated from panel to panel in the same relative location and in the same configuration from panel to panel. The annunciator acknowledge, silence, and reset buttons are good candidates for location coding. As discussed in Section 12, these sets of controls are not always placed in the same relative location or configuration.

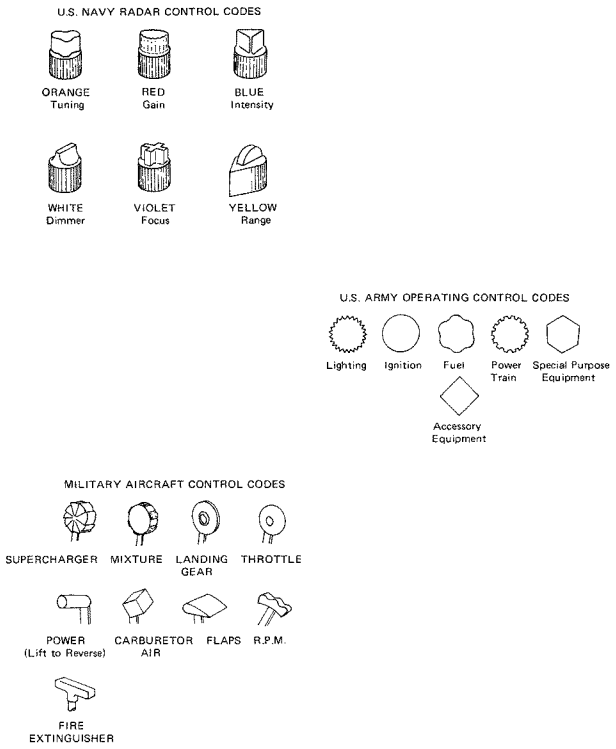


Fig. 13-6. Distinctive shape codes developed for military applications.

Controls can also be differentiated on the basis of the color of the entire handle or a portion of the handle, depending on the specific configuration of the control. Color can also be used to tie a given control to its related display. When the operator is about to minipulate a given control he usually fixes his attention on the related display. If the labels, the display, and the control handle are color coordinated, we increase the probability of the operator reaching for the correct control.

SUMMARY

Control room designs reflect a serious lack of attention to available and proven display and control coding techniques. This needlessly complicates the task of the operator, places an unnecessary burden on his memory, and leaves him a less than optimal reserve for coping with emergencies. Some of the operational errors or near mishaps discussed in Section 19 can be traced directly to a lack of adequate coding to properly cue the operator. Since operators move from plant to plant within a given utility and sometimes between utilities, standardized coding techniques should be adopted by the industry. As will be seen in our discussion regarding advanced control room designs (Section 20), no move in the direction of industry-wide coding standards is in evidence.

While consistent coding of controls and displays should ideally be effected during the design phase, this is one area that lends itself to relatively inexpensive retrofits, (with the exception of introducing normal-abnormal logic into the color coding of indicators). Indicator legend cap colors can be changed to fit a given code and knob shapes can often be modified by substituting alternate and distinctive shapes.

Section 14

LABELING

Labels are used so ubiquitously that there is an understandable tendency to take them for granted. However, effective labeling practices can do much to promote reliable operator performance. While human factors design principles for labeling are simple to state, uniform adoption of these rules is a rarity. As in other areas of human factors investigation, obvious operator modifications to the original control board designs provided cues regarding labeling deficiencies.

VISIBILITY OF LABELS

In order for a label to aid the operator in locating or identifying a panel element, it must be visible to him. A number of factors observed in the control rooms obscure the visibility of labels.

The placement of labels with respect to the operator's eye can create problems, especially when controls project from a panel surface. Figures 14-1 and 14-2 illustrate the problem. Figure 14-1 was photographed with the camera at normal eye-level. Originally this photo was taken to represent a case where the design had not included labeling to differentiate among the four buttons shown. Upon closer inspection, and with the camera pointed directly at the panel, the scene depicted on Figure 14-2 emerged. If the designer had consistently labeled all panel elements above the controls as was the case with the switches on the right side of the panel, the button labels would have been visible.

Figure 14-3 shows two eye-level views of a control on a vertical panel. The control obscures the operator's view of the option markings at the base of the control shaft. When the control is viewed from the left, the pointer is not visible to the operation. In manipulating this control, the operator is required to weave and bob and his hand further obstructs visual access to the control options.

Projecting controls placed on benchboard panels also present problems. Figures 14-4 and 14-5 show eye-level illustrations of problems that the operator has in reading

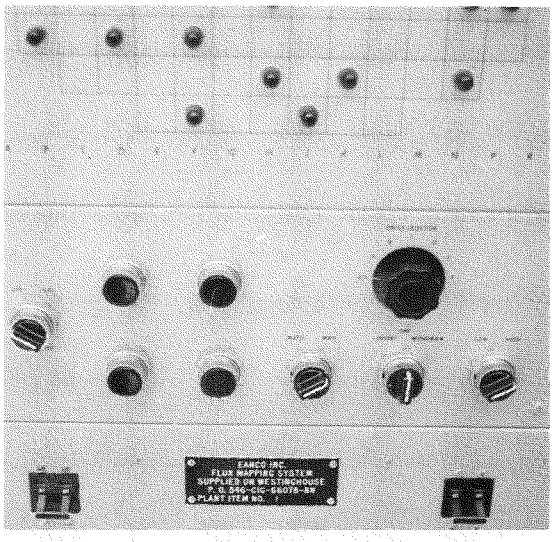


Fig. 14-1. Operator's view of "unlabeled" buttons.

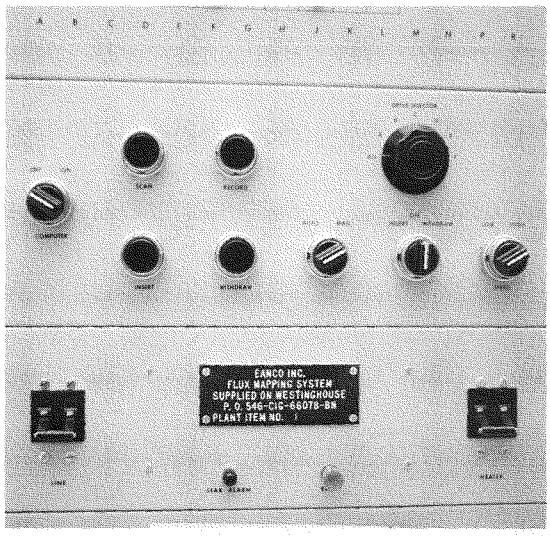


Fig. 14-2. Viewed head-on in a crouched position the button labels are visible.

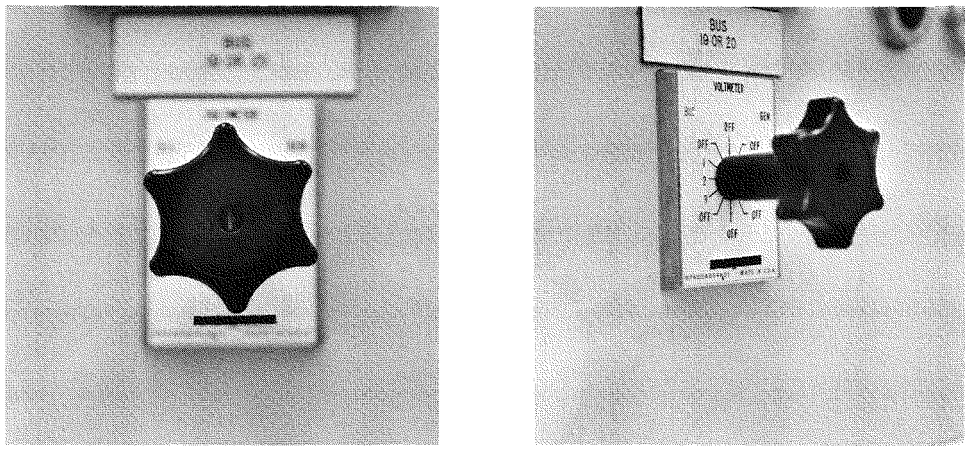


Fig. 14-3. When viewed head-on, control option markings are obscured by large knob and operator's hand. Side view of control is shown on the right.



Fig. 14-4. Projecting controls on benchboard panels obscure identifying labels.

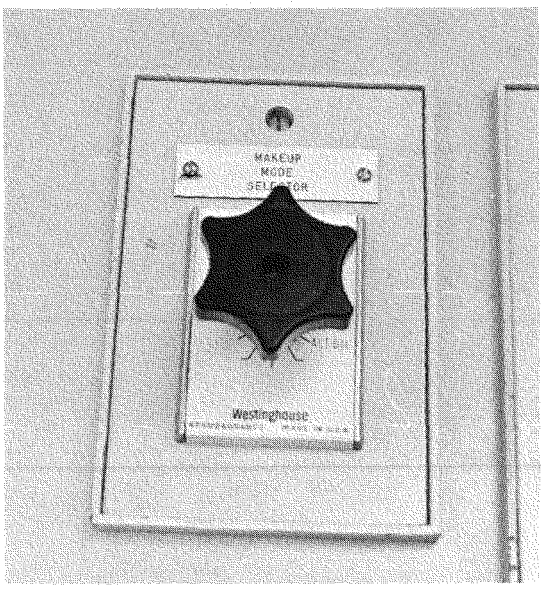


Fig. 14-5. Projecting knob on benchboard panel obscuring option labels.

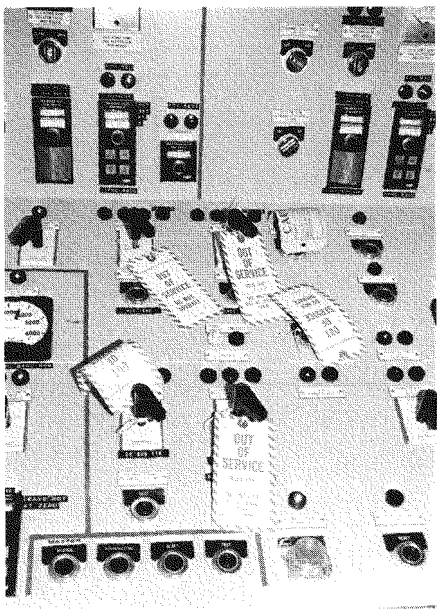


Fig. 14-6. Tags hide labels.

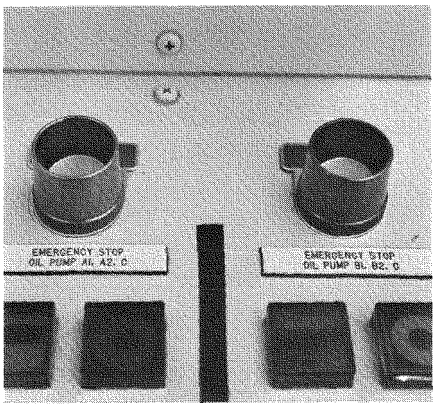


Fig. 14-7. Raised barrier guards tend to obscure labels.

both the identifying labels and the control option markings, especially with the benchboard controls farthest away from the operator's standing position.

Another factor that obscures panel labels is the liberal sprinkling of tags (see Figure 14-6) appended to controls of systems that are receiving maintenance attention. These tags are large and often cover the labels of adjacent controls.

Finally, as discussed in Section 8, some of the measures used to prevent accidental activation of controls obscure labels and control option designations. As seen in Figure 14-7, the barrier added to protect two buttons obscures the original labels. Section 8 provides other examples where, had the need for safeguarding a given control been anticipated, the protective measure would not have compromised visual access to the labeling.

CONSISTENCY OF LABEL PLACEMENT

One important labeling rule is that labels should be located consistently above or consistently below the elements being identified. Consistency reduces the possibility that labels and corresponding panel elements will be mismatched. Deviations can be readily spotted in the control rooms, (see Figures 14-8 and 14-9). In Figure 14-8 meters are labeled below and switch labels are placed above the element being identified. Meters located on the benchboard portion of this console have labels placed above the meter being identified. Similarly, Figure 14-9 shows an inconsistent pattern of labels with some above and some below the panel elements.

ORGANIZATION OF LABELS

A major problem observed with current labeling practices is the lack of differentiation required to focus the operator's attention from a general panel area to a specific panel element. Examine the morass of identical control elements in Figures 14-10 and 14-11. The operator must isolate the object of this immediate concern from nearly 200 similar elements. All that differentiates this multitude of identical control-display units are the labels located roughly in the center of each unit.

This places a search or memorization burden on the operator. Even experienced operators do not overcome this problem entirely. The problem is most acute on those panels that are not operated on a daily basis and even the experienced operator is reduced to a "hunt and peck" operation. The problems with these arrangements are seen most readily when observing a highly motivated student trying to locate

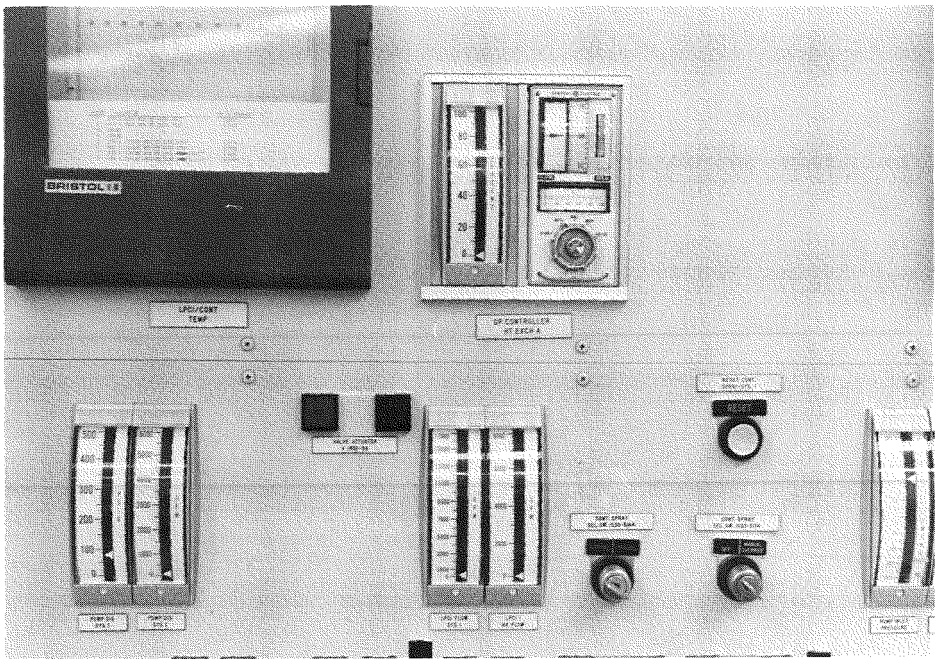


Fig. 14-8. Inconsistent placement of labels--some below and others above panel elements.

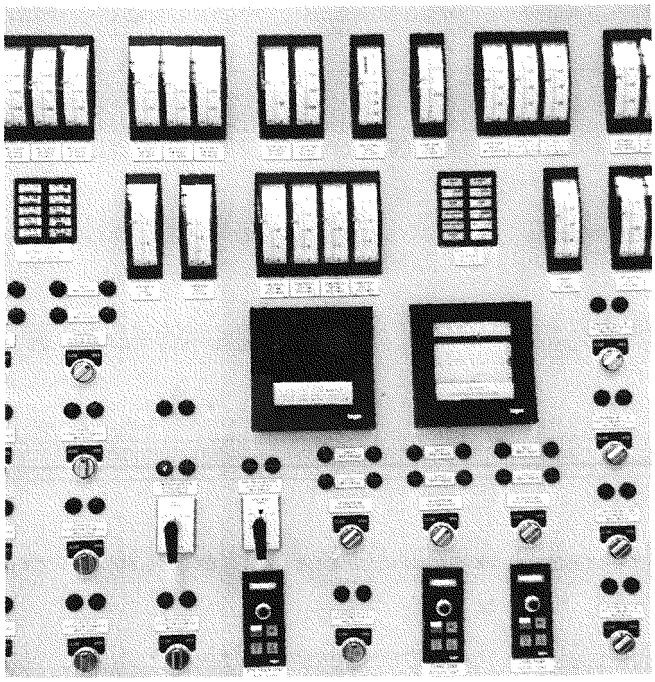


Fig. 14-9. Another example of inconsistent labeling above and below the panel elements.

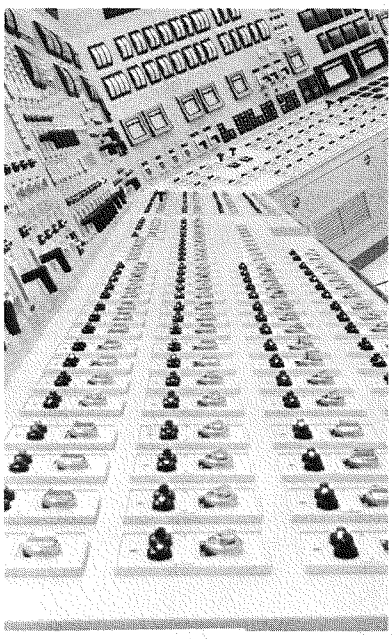


Fig. 14-10. Masses of identical control-display elements which could be better differentiated through effective labeling practices.

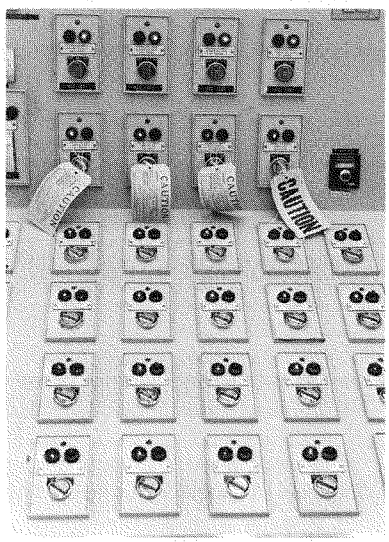


Fig. 14-11. Lack of major identifying labels for subgroups of elements increases search time and slows operator responses.

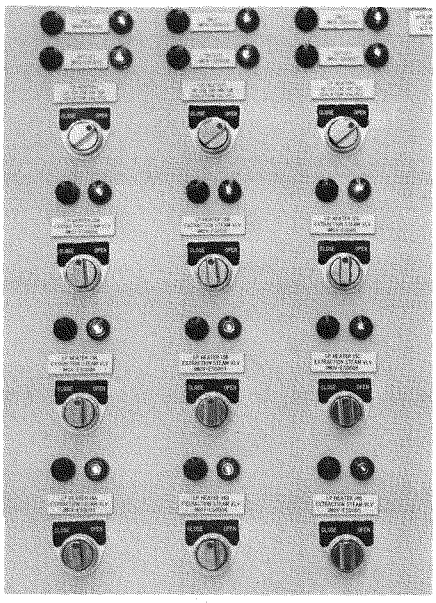


Fig. 14-12. Repetition of "LP HEATER" and "EXTRACTION STEAM VALVE" for each panel element.

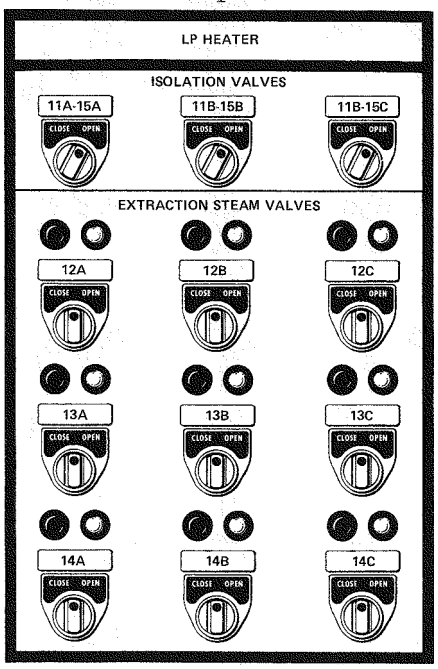


Fig. 14-13. Use of major and minor labels to facilitate identification of panel elements.

specific controls in response to a simulated emergency. There is little doubt that the lack of differentiation between related groups of controls and displays increases required training time and slows the operator's responses to system events.

One solution to this problem is to provide major, intermediate, and minor panel labels to functionally group related panel elements. Figure 14-12 shows the repetition of LP HEATER and EXTRACTION STEAM VLV on every switch label. Figures 14-13 shows a sketch of an alternate labeling approach. The repetitive element of each unit label has been extracted and an intermediate size label has been provided to differentiate a related group of panel elements. Techniques for further differentiating subpanels are discussed in Section 5.

The largest labels should be reserved for identifying major segments of the control board, e.g., REACTOR CONTROL, TURBINE CONTROL, SAFEGUARDS, etc. Of all the control rooms visited, only one identified major panel areas in descriptive words. Most operational personnel feel that it would be superfluous to do so since all operators would know the function of each panel. In lieu of verbal designations, panels are labeled with such terms as 903, 904, etc. This needlessly complicates communications between the plant's operational staff and technicians or plant guests.

ABBREVIATIONS

Abbreviations are a necessity in many instances in order to conserve panel space. However, abbreviations must be such that their meaning is obvious. For example, how clear is it that SJAE stands for steam jet air ejector? Furthermore, abbreviations should be standardized to avoid confusion as one moves from one part of the plant to another or from one plant to another. This study did not test operators or students on the intelligibility of abbreviations used. However, it was apparent that standardization had not been universally achieved. For example, on one control board, within a span of several square feet of panel area, four different abbreviations were observed for "pump:" PP, PU, PMP, and PUMP.

While lists of standard abbrevations are available to designers, the operators do not always have access to them. In view of the large extent to which operators add labels to their control board, the operators, as well as designers, need to be provided with the standard abbreviations.

INSUFFICIENT LABELING

It is apparent from the multitude of hand-crafted labels and graffiti-like pencil or crayon scribblings on the control boards that the operators desire additional information on their boards. Figures 14-14 and 14-15 show several crude attempts to add needed information. Such measures are not prevalent. More often hand-made labels have been added to the panels. Figure 14-16 shows a control switch with four pairs of associated but undifferentiated indicator lights above it. This photo was taken in the training simulator.

Figure 14-17 shows the same control-display unit in the corresponding operational control room. Note the labels added to distinguish indicators associated with valves A-D. Also note the alphanumerical designations placed below the TURBINE SPEED VALVE POSITION label and directly beneath the control handle. These notations allow the operator to correlate specific valves and controls with schematics and procedural documents. This example could be repeated many times in different control room contexts. Figures 14-18 and 14-19 show useful data that operators have appended to control boards.

ASSOCIATION OF LABELS WITH PANEL ELEMENTS

Labels should be placed on or in close proximity to the component being identified and should be distinctly separate from other components. While in the majority of cases, this rule is observed, several instances were detected that might lead to operator confusion. Figure 14-20 shows a cluster of 22 horizontal meters. The labels are equally spaced between meter columns, instead of being closer to the meters being identified. The same logic applies to the array of buttons shown in Figure 14-21.

CODING LABELS

Labels can be coded to highlight critical controls or to differentiate one subgroup of elements from others. Some coding of labels is in evidence but not utilized to its full potential. The general lack of coding standardization in the control room obscures the potential benefits of label coding. For example, some labels for especially important controls, e.g., REACTOR TRIP OR TURBINE TRIP are engraved lettering on a red background, while the majority of labels are either white on black or black on white. Since the color red is not exclusively reserved for danger or extreme importance, the attention-getting value of a red label is somewhat diluted.

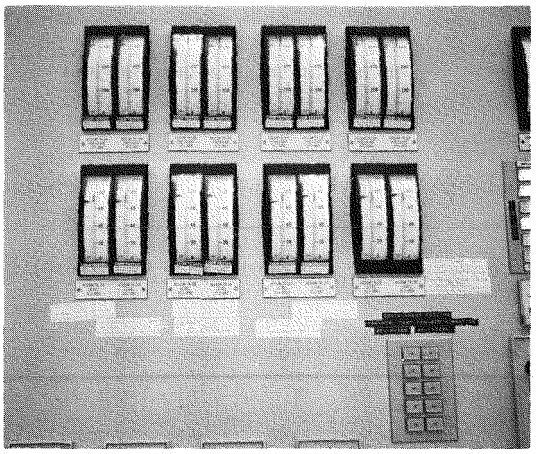


Fig. 14-14. Hand written labels added to the control boards.

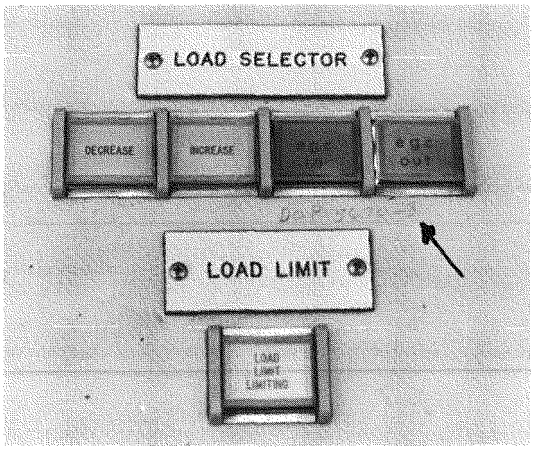


Fig. 14-15. Related procedure designation scribbled on the control board.

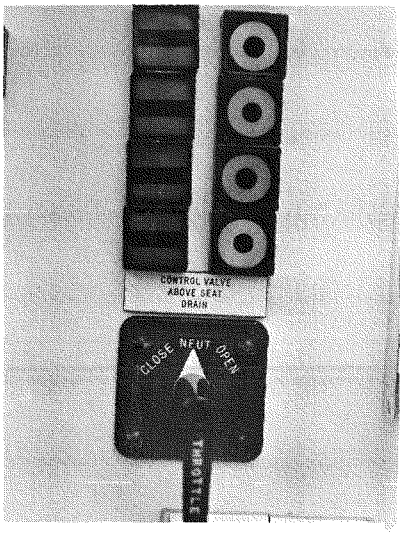


Fig. 14-16. Four pairs of unidentified indicator lights in the simulator.

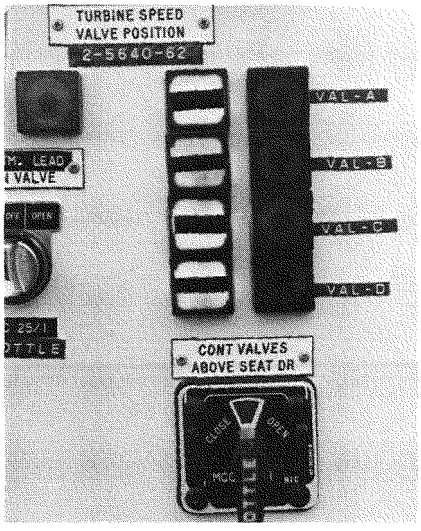


Fig. 14-17. Operators added labels to correct omissions.

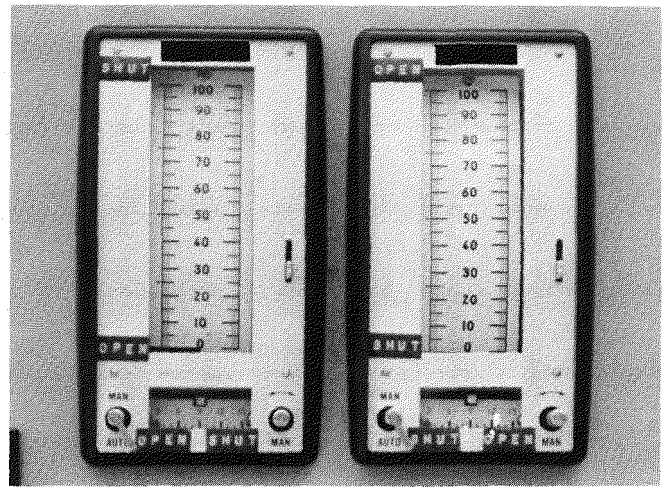


Fig. 14-18. Labels added to clarify operation of the controllers.

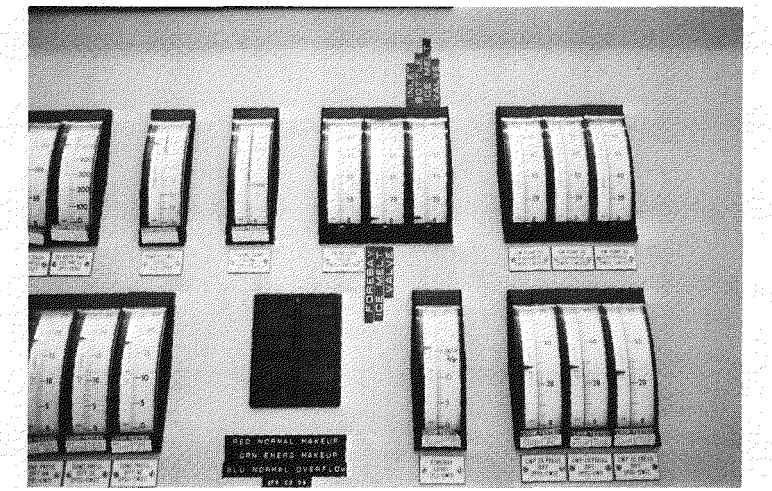


Fig. 14-19. Labels added to explain meter functions and the color code for displays. Note unusual orientation of meter add-on labels.

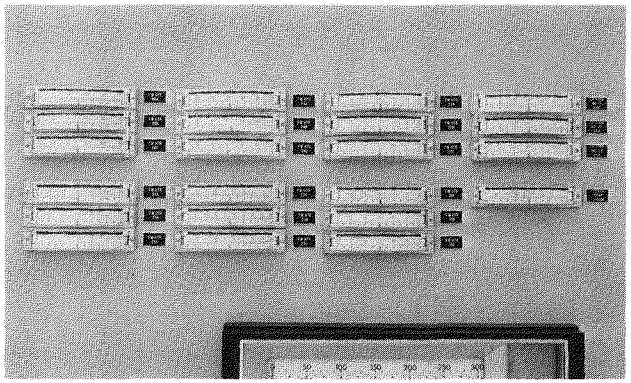


Fig. 14-20. Cluster of meters with labels spaced equidistant to adjacent meters.

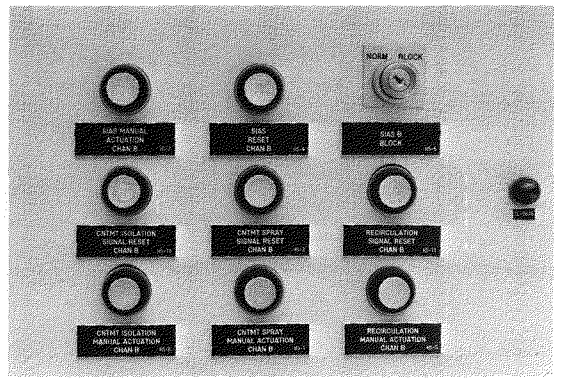


Fig. 14-21. Operators can make incorrect associations between pushbuttons and labels.

Labels can also be size, shape, and color coded to functionally isolate related groups of panel elements. These techniques are not in evidence in the control rooms visited. Rather, we observed a mixture of labeling practices that were applied to the boards as originally installed coupled with a variety of inconsistent labeling techniques applied in supplementing the original labels.

ORIENTATION OF LABELS

One of the checklist items reads as follows: "Have labels and information thereon been oriented horizontally so that they may be read quickly and easily from left to right?" This rule was generally followed on labels originally placed on the panels. Not so with many of the labels added to the control boards by operational personnel. Several examples are presented in Figures 14-19 and 14-22.

CLARITY OF LABEL MEANING

Labels should clarify the identity of system elements and, where appropriate, the labeling should inform the operator of the physical location of the system element that a given control regulates. One case of misleading labeling practices, in particular, illustrates the confusion that can be generated by improper labels. The architect-engineer developed an A,B,C,D, designation for the primary coolant loops. The NSSS supplier used a 1,2,3,4, designation for the same coolant loops. However, the ordering of the alphabet code and the numerical code do not coincide, so we have loops A1, C2, D3, and B4. Valves are identified by such designations as 8002A, 8002B, 8002C and 8002D. The 8002A valve is associated with coolant loop D and 8002D is related to coolant loop B. The annunciator alarms are labeled to reflect the numerical 1,2,3,4 designations for coolant loops. If we have confused the reader, he is not alone. The operators are also confused.

Fig. 14-23 reveals another type of labeling problem. The RWST level meters have scales with the zero position at the bottom and 40 foot level at the top in a natural relationship with water level. To the right of these meters, the Containment Sump indicator lights have values which progress from bottom to top in the reverse order as was observed for the meters. The order used for the indicators appears unnatural and contrary to normal expectations. Moreover, the values stamped on the indicator legend faces are wrong and contradict the correct decal values added to the display unit.

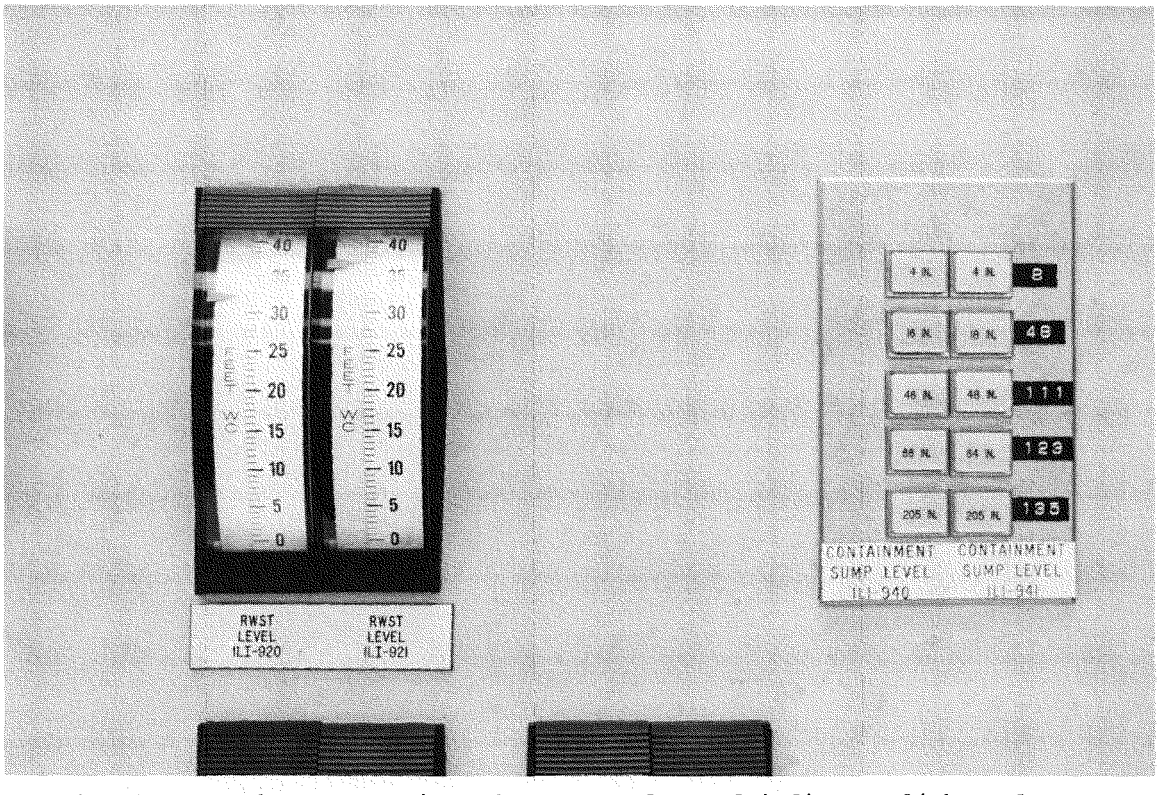


Fig. 14-23. The progression of meter scales and indicator light values contradict each other. The order of indicator light values is "unnatural."

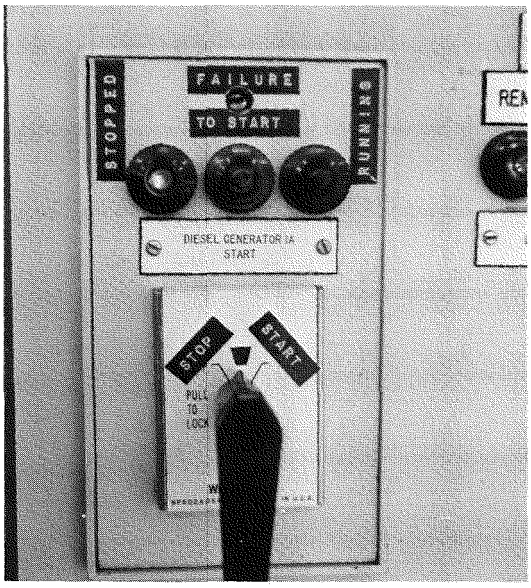


Fig. 14-22. Labels placed in an abnormal reading orientation.



Fig. 14-24. Hand made labels which do not meet human factors standards.

LABEL CHARACTERS

Much human factors research has been conducted to establish optimum physical dimensions and characteristics for label characters. Some of the rules that have emerged include the following:

- Labels should be sharp, with high contrast, and mounted to minimize wear or obscurement by grease, grime, or dirt.
- Where the ambient illumination is above one foot-candle, black characters on a light background should be used.
- Label characters should be in capital letters; the simpler the letter style, the better.
- The width of letters and numbers should be 3/5 of the height, except for the letter "I" and number "1", which should be one stroke width and the "M" and "W", which should be 4/5 of the height. The number "4" should be one stroke width wider than other numerals.
- The minimum space between words should be the width of one character.
- The required heights of letters and numerals is determined by the reading distance, ambient illumination, and the criticality of markings. Recommended character dimensions are provided in MIL-STD-1472.

There was some variance in the extent to which these rules were followed in the control rooms investigated. While all control rooms had ambient illumination levels above one foot-candle, three of the control rooms had the recommended black characters on a white background and the remaining two had the less desirable white-on-black labels. Of greater concern, however, is the poor quality of the large number of makeshift labels that have been added to the panels. These hand-made labels offer poor contrast between characters and background and offer other legibility problems, as can be seen in Figure 14-24, and they could easily become detached.

The size and style of alphanumerical characters on control board labels generally did not offer legibility problems for the operator reading distances required. The exception to this was the label character sizes for annunciator lights when read from the operator's station. This was discussed in Section 12.

The spacing of characters and words on labels did not offer serious problems in terms of legibility.

SUMMARY

Much can be done to improve the labeling of control boards. A large body of the information that operators feel is necessary to include in the form of labels was

lacking in the original design of the boards. Operators at some plants have made extensive modifications in the form of added labels. However, in some cases, management has discouraged the addition of supplementary labeling on aesthetic or configuration control grounds. As one operator put it: "Originally the labeling was poor. We added the labels ourselves. We have a machine available to produce the labels." Unfortunately, the quality of labels that have been added to the boards is often shoddy and basic human factors principles to maximize legibility have been ignored. The informational content of labels is sometimes confusing to operators and there are many instances where a label is simply not visible due to its placement or some obstruction.

Section 15

COMMUNICATIONS

Speaking at the EPRI workshop on power plant operator selection methods (7), C. J. Hodges, Jr. of the Tennessee Valley Authority said: "The control room operator is the key communications man on the unit. No maintenance, tests, or operations should be performed until he is informed. He is the disseminator of information from the shift supervisor to operators under his direction. The communications required are both written and verbal, and it is vital that he keep a complete and accurate log. An operator who is unwilling or unable to communicate is an accident looking for a place to happen."

With these words in mind, one of the questions put to operators and trainers as part of the structured interview reads as follows: "The operator has need to communicate effectively with others in the plant. What improvements, if any, are required with regard to your communication system?" The responses to this question reveal the need for major improvements in the design of communication systems. Eighty-one percent of those interviewed pointed to inadequacies in their ability to communicate with plant personnel outside the control room. These problems stem mainly from the inability of paging systems to overcome the extremely high ambient noise levels within many sections of the plant. Another class of problems results from the design of communications gear and its integration and distribution in both the control room and the plant. A third, and less frequently encountered, category of communications problems is related to plant discipline and the possible unwillingness of auxiliary operators to consistently heed the paging system.

EFFECTIVENESS OF COMMUNICATION SYSTEMS

The plants varied in the nature, number, and configuration of communications devices and channels available to the control room operators and the auxiliary operators in the plant. The situations uncovered at the five plants is described below.

Plant A

The control room operator has telephones and access to a public address paging system. The paging system is neither reliable nor always audible in high noise

environments. The person the operator is trying to reach may be wearing ear muffs for noise protection. Moreover, the operator cannot override other messages on the paging system and his messages, when superimposed on others, will be garbled. The telephone is not effective as a backup system since the men in the field move about and the operator does not always know the specific phone location at which they can be reached. Furthermore, the operators claim that with the loss of power they lose public address communications.

The reverse problem, that of incoming communications deficiencies, is also reported. One operator states: "When we sound the EVACUATE CONTAINMENT ALARM there is no feedback that the page or the audible alarm has been heard by the men in that area. We can expose people to radiation because there is no way for the operator to know that the people in the containment can hear the alarm."

The operators at this plant see the need for "tweeters," devices that sound in the protective ear muffs, and "beepers," radio page devices worn by men in the field. They also feel that a redundant power supply for the public address page system is needed.

Plant B

The operators in the Plant B control room have four primary means for reaching outside operators: a page phone, ordinary telephone lines, portable two-way radios, and bell signals coupled with red lights in high noise areas, referred to as the Auto Call system for key people.

The operators at this plant also found the phone page system unreliable for reaching people in high noise areas. They feel that an increased distribution of speakers is needed. There were also complaints that portable radio systems were too bulky and were ineffective. Others feel that the number of phones in the plant is insufficient. The Auto Call system is also unreliable for reaching outside personnel. Some of the operators recommended that pocket page systems be added to the present list of communications devices.

Plant C

This control room included a phone page system, the usual telephone, and a "hands-off" telephone-speaker arrangement. These operators also remarked that the page system was unreliable in high noise areas. Some complained that they got cross-talk and low-volume problems on phone lines. The operator had to yell to be

understood on the "hands-off" phone system. This plant had the largest number of auxiliary operators under the control room operator's supervision and, therefore, the communication needs were greater than at other plants. Normally there were two operators in the control room even though only one operator is required by tech specs. When two men are in the control room one goes out into the plant when communications with outside personnel break down. However, when only one man is in the control room, this option is no longer available and the lone operator feels especially vulnerable.

The operators suggested a better distribution of phones in the plant. More important, they felt the need for a combined audio-visual system with which by dialing a special code on an emergency call basis, both a visual alert and a coded horn message would be transmitted throughout the plant's high noise areas.

Plant D

Operators at this plant have a paging system, telephone, walkie-talkies, and an Auto Call signal bell system that is available by dialing the phone. There are also visual signals in high noise areas. Despite these Multiple channels for reaching auxiliary operators, all of the operators and trainers interviewed agreed that the communication system is inadequate for high noise areas.

Specifically, the complaints were as follows: plant personnel away from their stations do not hear the phone ring; the PA system is frequently garbled due to echoes and can't be heard in high noise areas; the Auto Call bells can't be heard; and the visual signals are so placed that they go unnoticed.

Only one auxiliary operator is assigned per generating unit and as one operator said, "If you can't get him to respond, sometimes you just stand and watch the plant go down." Another says plaintively, "We have a problem reaching people in high noise areas. It's a bad feeling when you can't reach your man--a lonely feeling."

Plant E

The operators at this plant had the fewest complaints regarding their communications system. They indicated the availability of page phones and five telephone lines. The operators stated that the communications system was recently adjusted. Speakers that had been disabled or turned down during construction were "turned up real loud." Since these improvements were made the operators generally felt there were no problems in reaching auxiliary operators.

ARRANGEMENT OF COMMUNICATIONS EQUIPMENT IN THE CONTROL ROOM

Because the operator spends a considerable portion of his time communicating with others, the manner in which his communications equipment is integrated into the control room has an important impact on his effectiveness. This is readily observable in Figures 15-1 and 15-2. In this control room the phones and the page systems are arranged at the operator's desk so that the operator sits with his back to the control boards most of the time. This arrangement is extremely undesirable from the human factors standpoint. Fortunately this problem was found at only one of the plants visited.

Another problem is that the operator must have access to the control boards while communicating with others, e.g., during maintenance activities (see Figures 15-3 and 15-4). The distribution of phone and the length of phone coards proved a problem in some plants. For example, at one plant an operator pointed out the lack of a paging phone on the radiation monitoring panel and the service water panel. Both of these panels are far removed from the primary control board area and the operator's desk phones.

During a plant trip, or whenever the plant is experiencing trouble, the number of phone calls to the control room increases considerably. This adds a communication burden to an operator who feels his primary task should be to attend to the emergency at hand rather than explaining the situation to others. In cases where the control room houses multiple-unit control boards, the operator controlling the quiescent unit pitches in with the communications task, thereby relieving the operator who is coping with the emergency (see Figure 15-5). Often, it is the center desk operator in a multi-unit control room (see Figure 15-6) who assumes primary responsibility for communications during emergencies and with the outside during back shifts. Coping with outside calls when the center desk operator is relieving one of the unit operators or when a test or evolution is in progress is a nuisance and distraction for the center desk operator. Perhaps a switchboard operator is required to handle incoming calls around the clock.

MISCELLANEOUS COMMUNICATIONS PROBLEMS

A few operators stated quite openly that a problem sometimes encountered in reaching auxiliary operators was due to a refusal to answer the control room operator's page, perhaps as the close of shift neared. The auxiliary operator presumably did not want to become involved in an activity that might cause him to delay his leaving the plant on time. It was, of course, not possible to verify the accuracy

of this complaint. In any case, this was not a widespread concern. However, if it is an accurate observation, remedial action is required because operators have reported instances where the plant has gone down for lack of timely support from an auxiliary operator. Delays are also reported in locating or reaching a shift supervisor who is away from the control room.

SUMMARY

With over 80 percent of the interview sample reporting communication problems it is evident that further attention should be directed at designing more effective communications systems. If the control room operator cannot count on timely support from personnel outside the control room, the design of his control boards need to reflect a greater degree of central control rather than remote control of events through the intervention of hard-to-reach auxiliary operators.

In times of emergency, there is no more frustrating experience for the control room operator than to be unable to reach his manpower resources in the field. The importance of effective communications and the serious problems encountered in four of the five plants visited suggests a more detailed study of this topic.

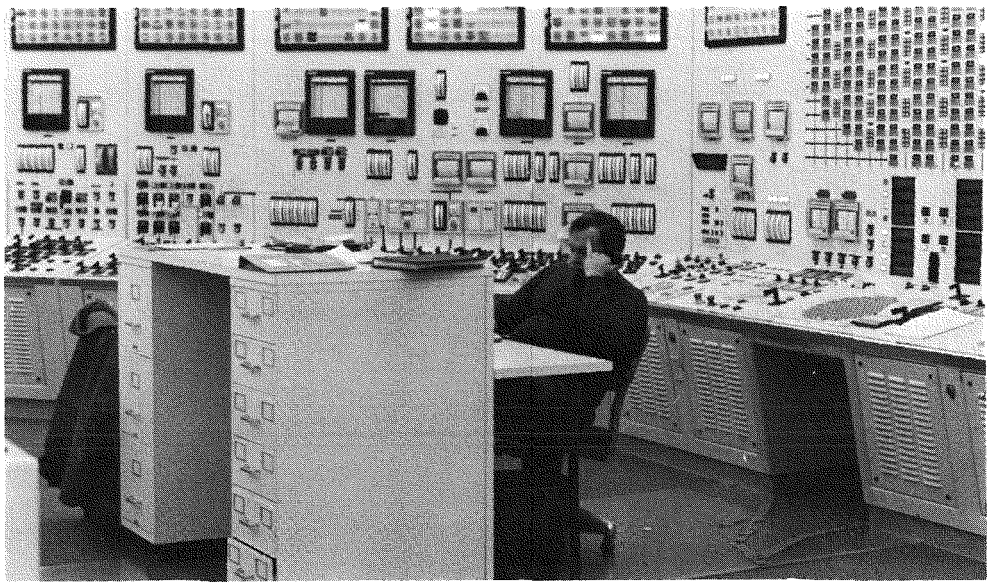


Fig. 15-1. Use of communications equipment required operator to sit with his back to the controls.

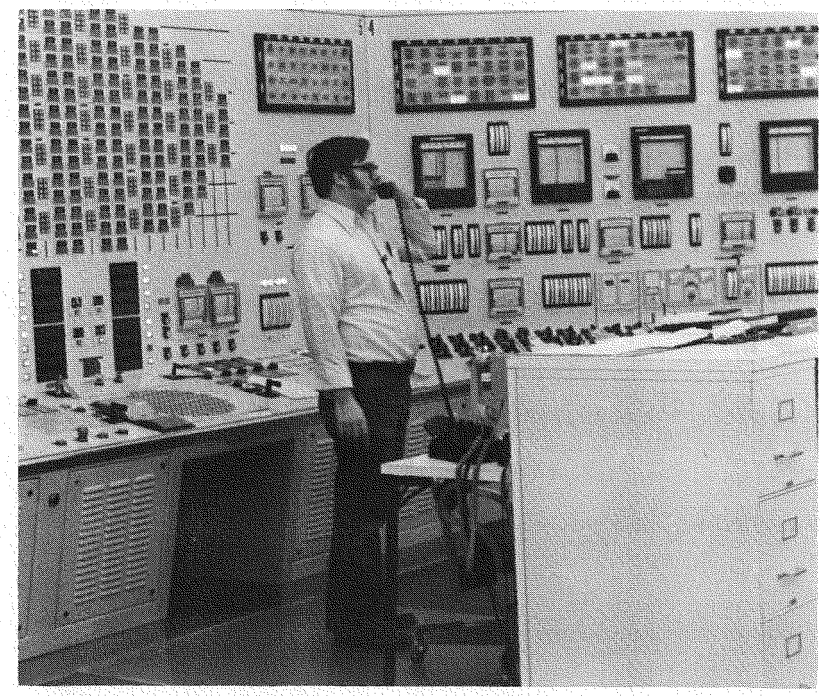


Fig. 15-2. Another operator shown with his back to the control boards when using the telephones.

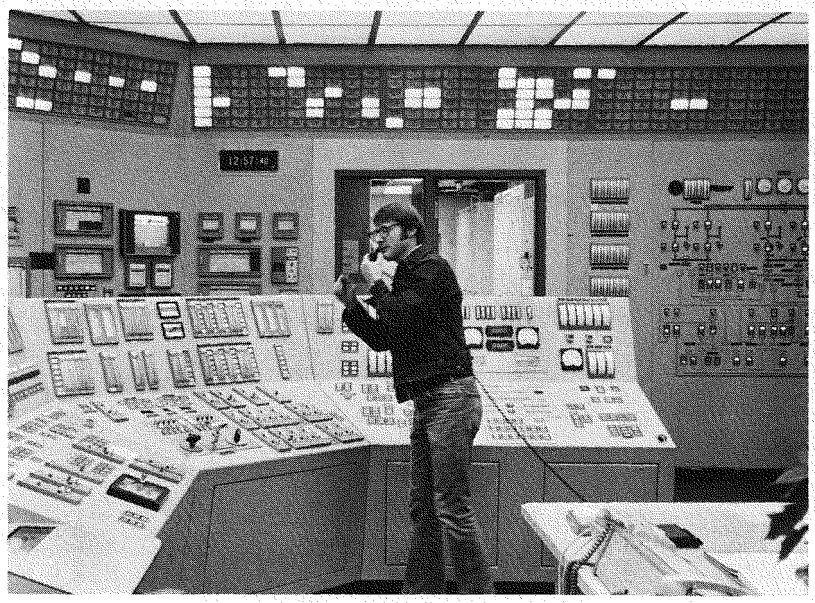


Fig. 15-3. The operator needs long extension cords to communicate while using the controls.

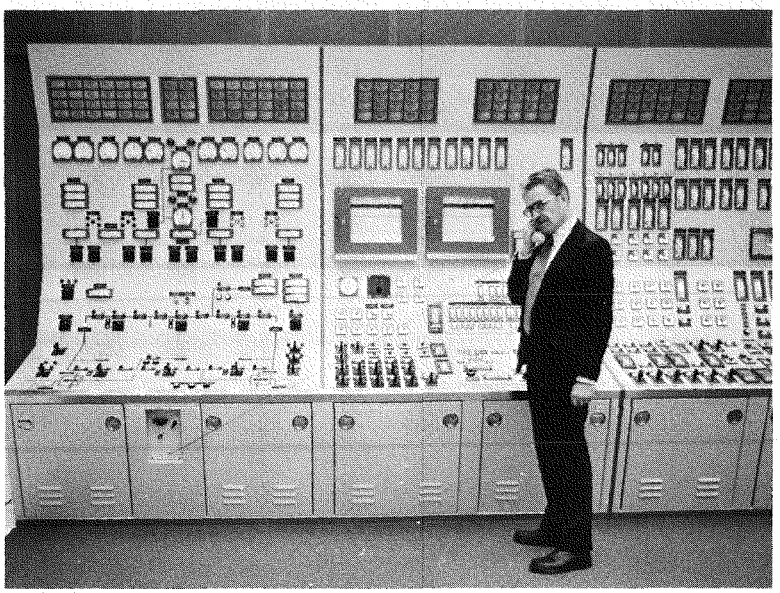


Fig. 15-4. The distribution of phones and cords is a problem in some control rooms.

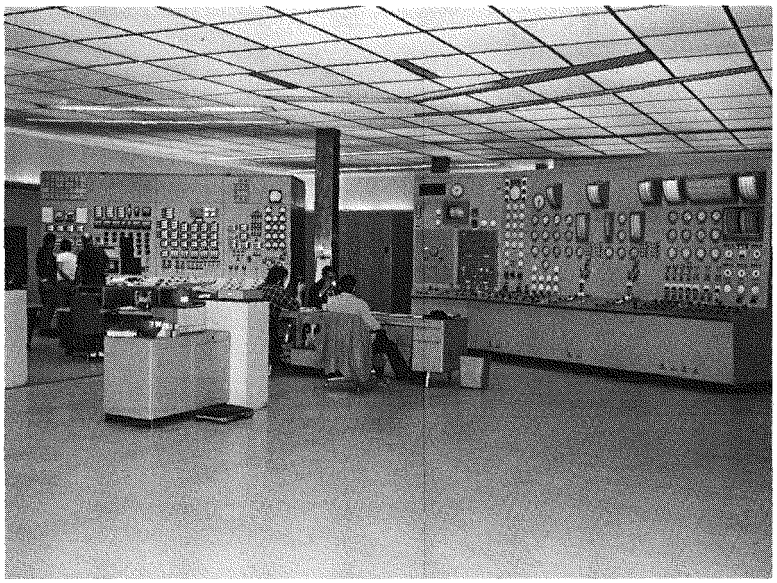


Fig. 15-5. In multi-unit control rooms the operator from one unit helps the other unit with communications chores when an emergency occurs.

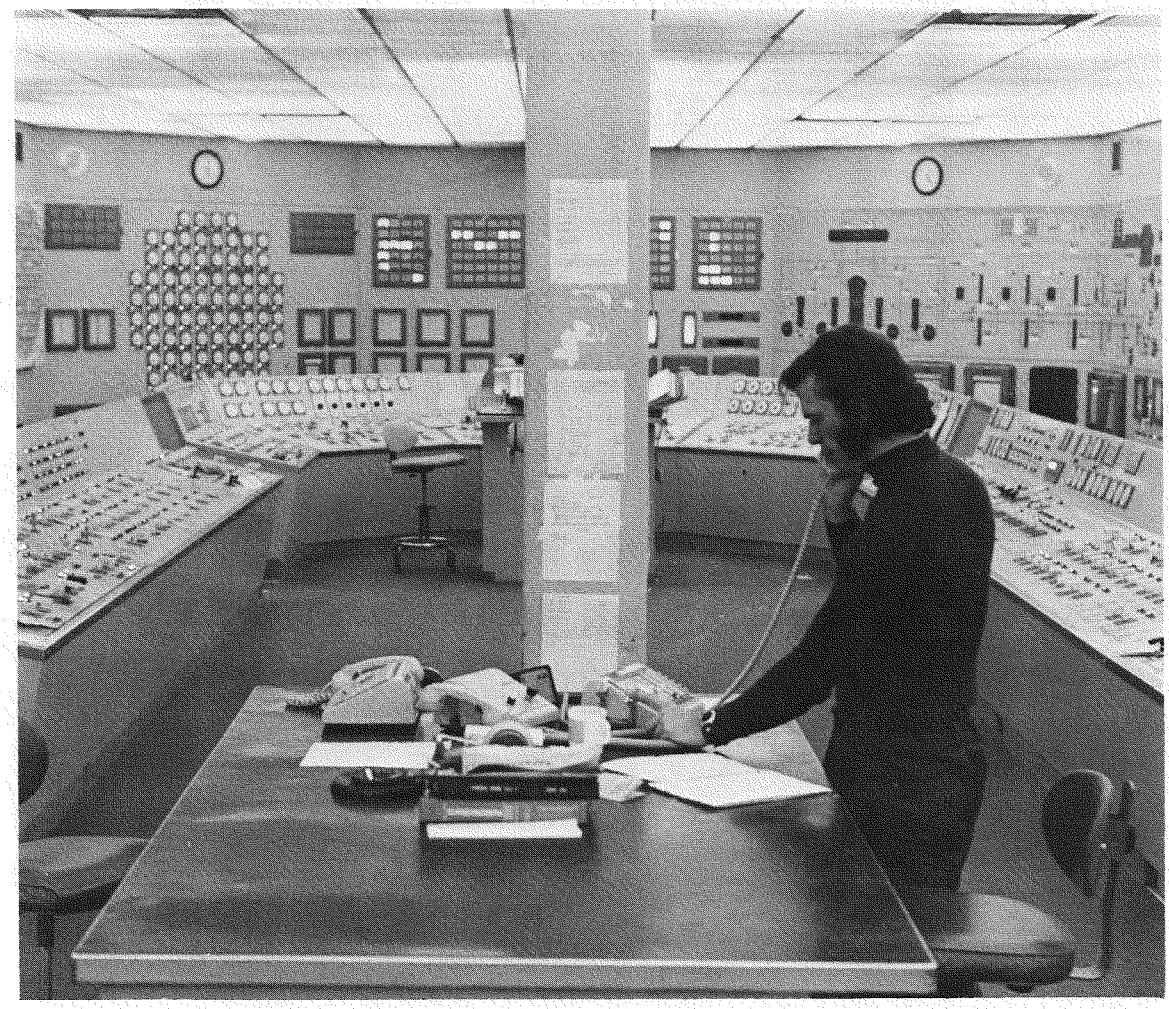


Fig. 15-6. The Center Desk Operator handles all calls to the plant during back shifts.

Section 16

TASK ANALYSIS

Earlier sections of this report have presented evaluations of various facets of control room design. These evaluations are based primarily on the extent of compliance with aerospace human factors standards and analyses of operator experience and attitudes drawn from the structured interviews. This section describes a third major approach used by the study team, task analysis. Task analysis is a systematic and detailed examination of the sequence of operations performed by an operator in performing normal and energency events. It is a time-consuming analytic process that involves intensive examination of the man-machine interface for each procedural step.

A thorough task analysis is typically the basis for establishing human factors requirements during the design development phase. In this study, the task analysis approach was used, atypically, as an evaluation tool. The data derived from our task analysis provided a closer glimpse at man-machine factors than could be obtained from other study tools. A complete analysis of all control room operations could easily require two man-years of effort. This was obviously beyond the scope of the present study, so a representative task or emergency situation was examined at each plant.

TASK ANALYSIS METHODOLOGY

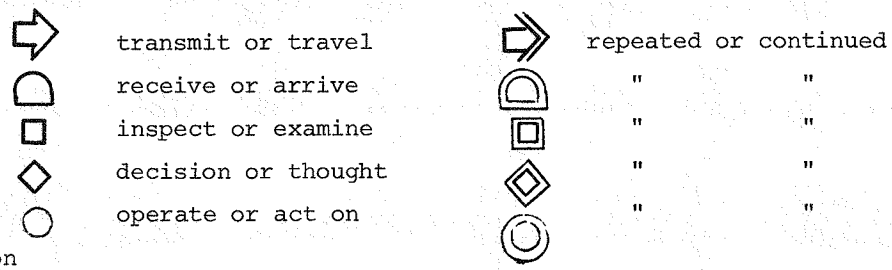
The situation selected for analysis at the four PWR plants visited was a steam generator tube leak or rupture. The emergency hypothesized was a leak that eventually required shutdown but was preceded by diagnostic activity and control action to avoid an immediate emergency trip. At the BWR plant investigated, the subject for task analysis was a reactor vessel feedwater valve controller failure in which the controller failed open.

Depending on the availability of the simulator at each site, the procedural events were first exercised and reviewed on the simulator with the assistance of the simulator instructors. Subsequently, these events were analyzed with the assistance

of the NUS member of our study team. In each case, the NUS representative had extensive operational experience and, with his assistance, each displayed event and operator action was carefully documented on a worksheet referred to as an Operational Sequence Diagram (OSD). Operational sequences were further confirmed and refined based on verification with control room operators.

Symbols and letters used in the OSD (see Figure 16-1) have the following meanings:

Actions



Modes of Action
(letters contained within action symbols)

V visual
S sound
W walk
T tactile
E electronic or electrical

Explanatory names, descriptions, and voice communications are noted adjacent to each action as needed. The connecting lines aid in tracking an operator and events of transmission. Transmissions are shown as horizontal lines and represent movements of the operation (W) from one place to another; sound or voice transmissions (S); and sight or visual transmission (V).

The Time column on the left permits a (vertical) tracking of time during the sequence of actions. Chronology and concurrency of actions have been depicted so that time relationships can be approximated. For example, on the first sheet Operator 2 (OP-2) announced (S) that the "Containment area monitor has tripped." This is heard (S) by Operator 1 (OP-1) and the Watch Foreman (W.F.). Operator 1 then says, "Take the charging pumps" (S) to Operator 2, who then walks (W) to panel FBF. He then hears Operator 1 tell him the flow rate at panel SFF, as he is monitoring (continually inspecting) the flow rate. Concurrent with this action the Watch Foreman walks (W) from the console to the desk and picks up the telephone

OPERATIONAL SEQUENCE DIAGRAM

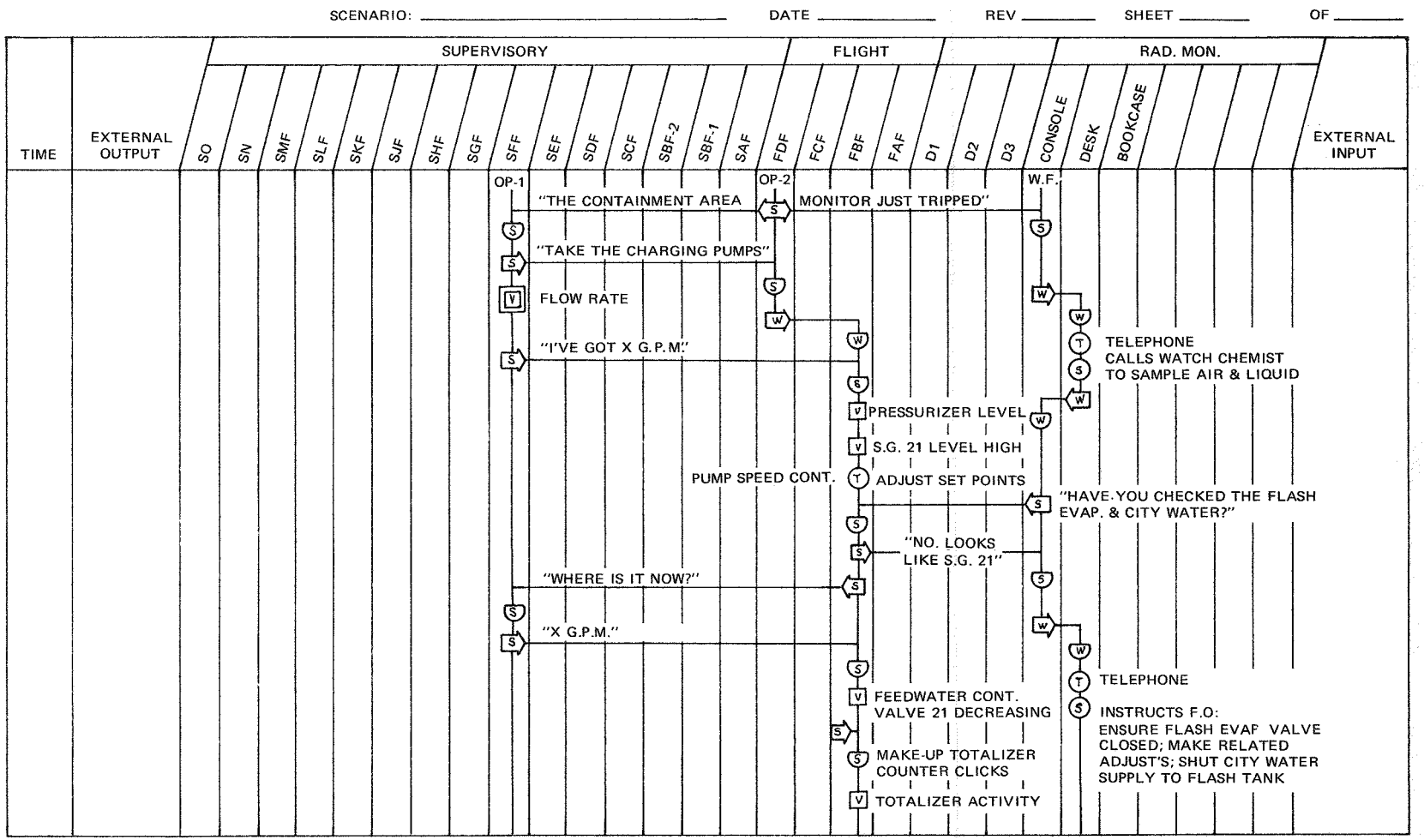


Fig. 16-1. Operational Sequence Diagram

(T) and places a call (S). The advantage of the OSD is that this lengthy description takes about two inches of space on the worksheet and provides a readily discernible pattern of related activities.

Once the OSD is in final form, it serves as the basis for more detailed analyses such as the pattern of operator movements within the control room and the implications of such movements regarding the adequacy of the control room layout.

TASK ANALYSES USED IN CONTROL BOARD EVALUATIONS

The OSD lends itself to the Sequential Use Evaluation depicted in Figure 16-2. This shows the links between segments of the control board as represented by consecutive operator interactions (visual, voice or movement) between these points of contact with the boards. Dark lines in Figure 16-2 represent high frequencies of sequential use. Light solid lines represent moderate frequency of sequential use. The dashed lines show the lowest frequency of sequential use. The circled numbers of each specific control board location represent the actual number of times activity occurred at the designated location with no reference to sequential use. This analysis is based on the premise that the more often two panels or other elements are used in sequence, the closer to each other they should be located to facilitate the operator's task.

Figure 16-3 illustrates another technique for analyzing OSD data. In this case the physical movements or traffic patterns of operators are tracked as they perform their tasks. This analysis ignores voice and visual contacts where no physical movements are involved. The emphasis is on frequency of use, rather than on sequential use.

From the analyses shown in Figures 16-2 and 16-3, two conclusions can be drawn. First, because of the frequent use of the "D" panels located in the back panel area, (out-of-view from the primary control room envelope), the "D" panels should be located closer to, or integrated with, the main control room area. Second, the primary control board arrangement is relatively inefficient for the task analyzed. The ideal picture (Figure 16-2) would show short distances for the heavy lines, moderate distances for the light lines, and dashed lines would represent the longest distances. Since this was not the case, we can conclude that the arrangement is not optimized for ease of operations, at least for the specific tasks analyzed. These analyses support similar conclusions drawn from direct observations and operator interviews discussed in Sections 4 and 5.

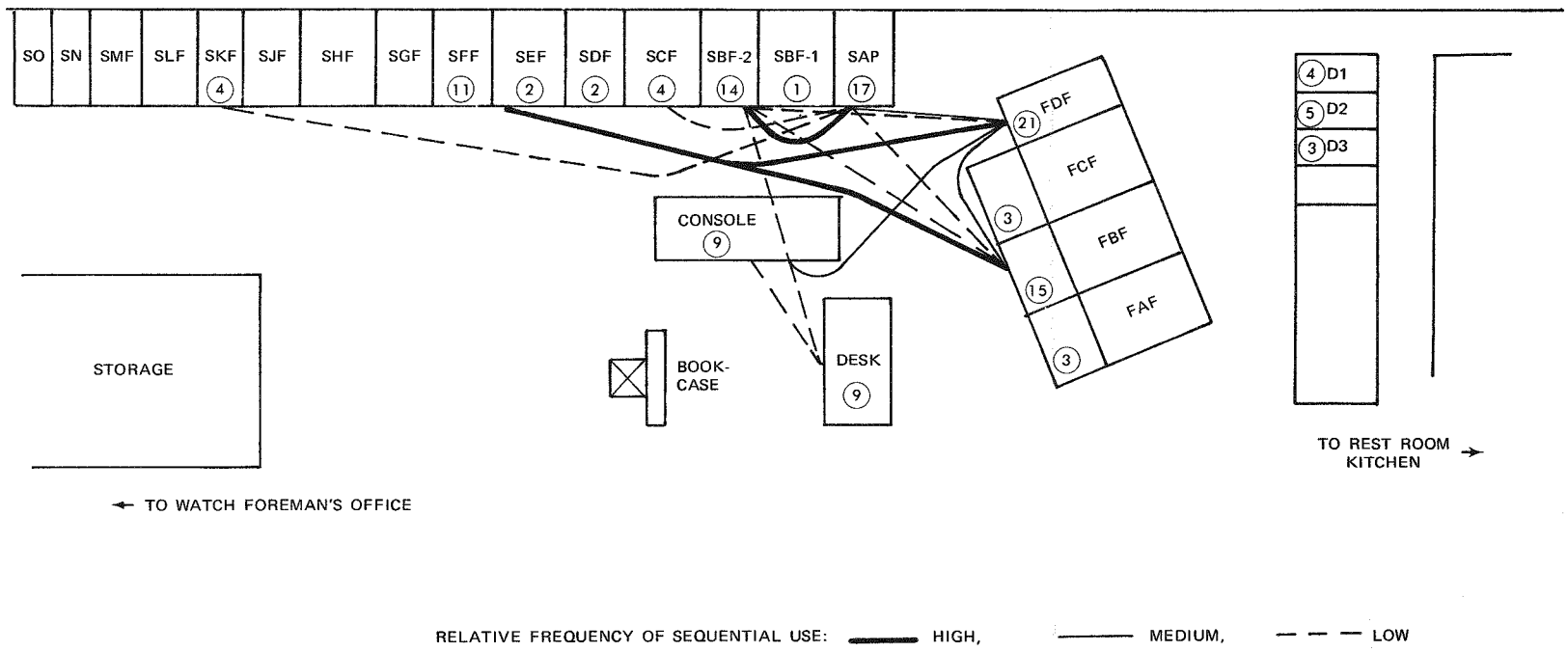


Fig. 16-2. Sequential use evaluation based on operator response to a steam generator tube rupture.

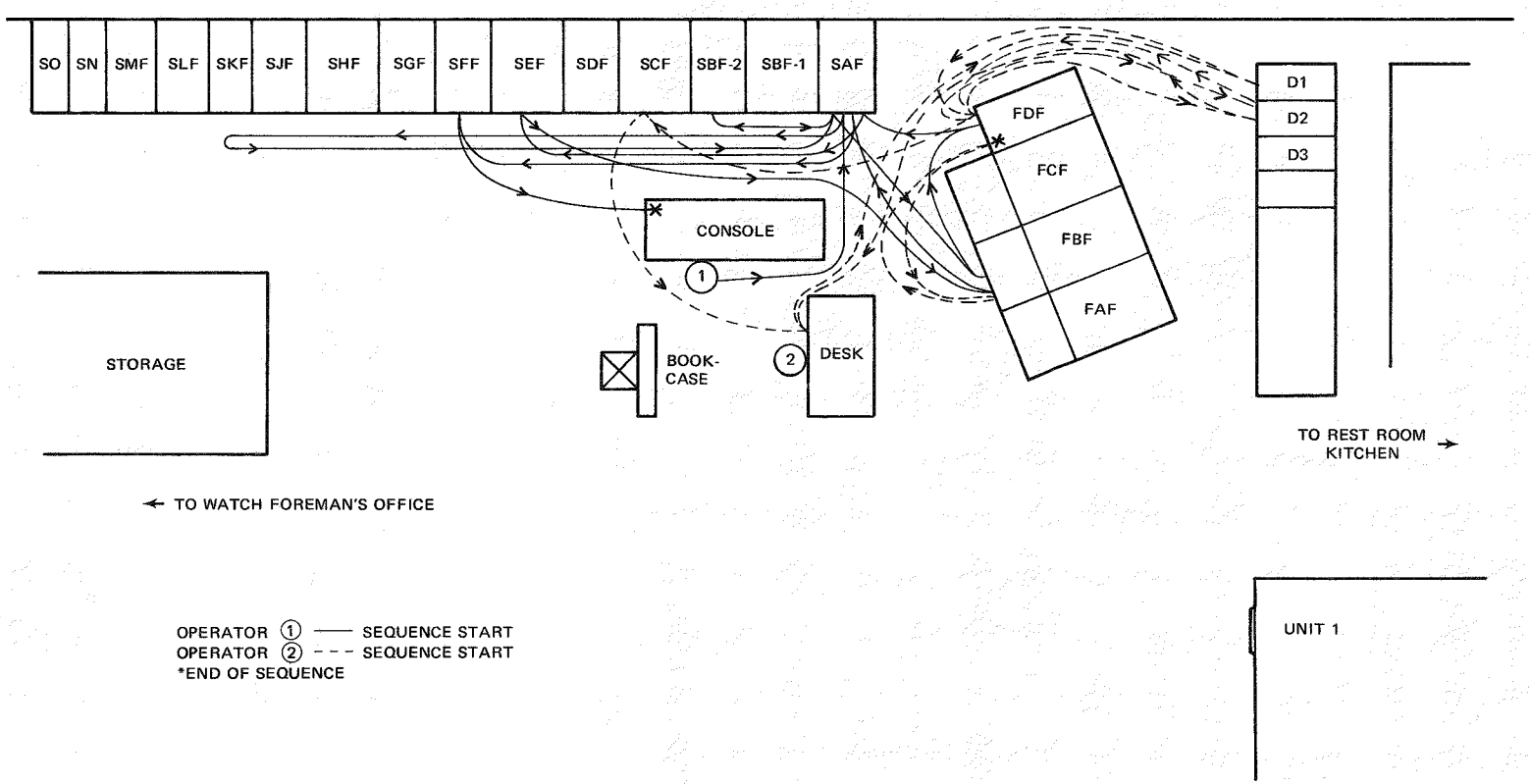


Fig. 16-3. Analysis of operator movements within the control room in response to a steam generator tube rupture.

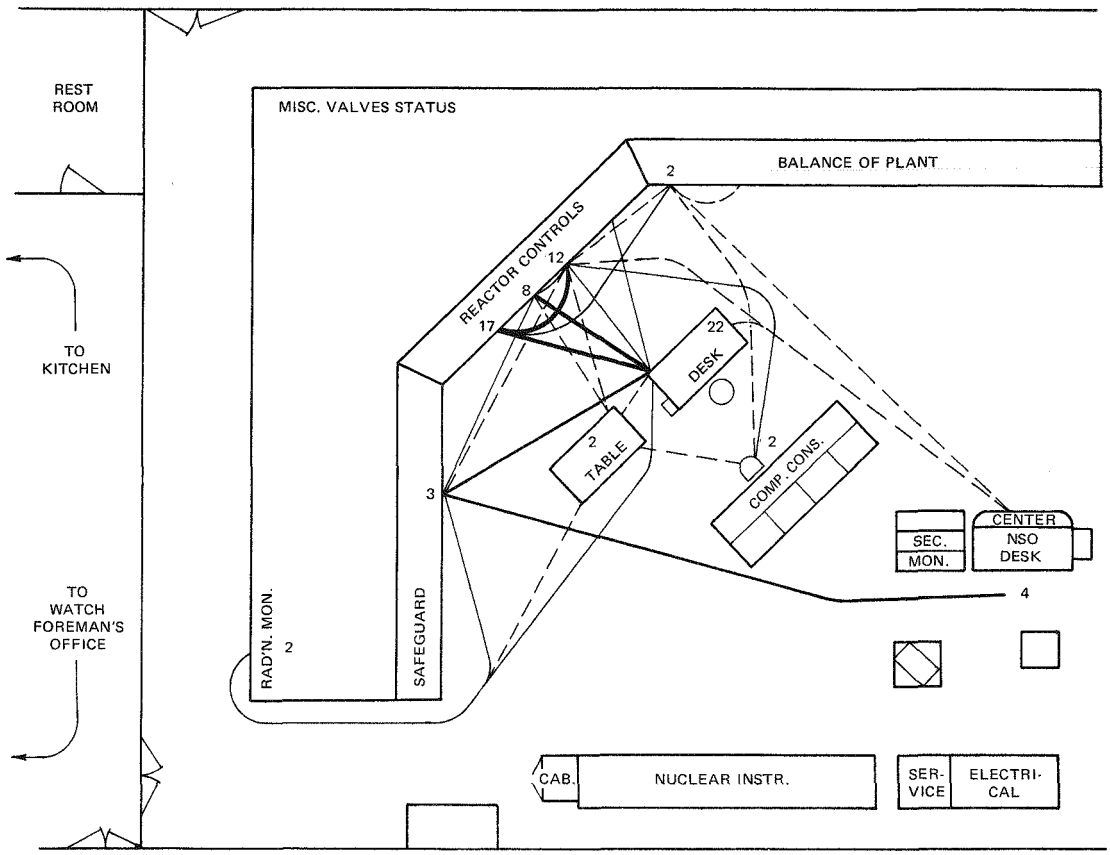


Fig. 16-4. Adjacency evaluation for a steam generator tube rupture.

Figure 16-4 shows a comparable analysis of the operations associated with a steam generator tube rupture at a second plant. Again, the analysis confirms the experience reported by operators and the study team observations:

- The moderate link to the radiation monitoring panels indicates that these panels should be more conveniently located. This was a frequent complaint of the operators.
- The high-use links to the NSO desk are the result of phone use and frequent voice communication between the operator at the boards and the operator using the procedures manual. (The two-man requirement for use of the procedures manual is discussed in Section 17.) Noting that the watch foreman's office is remotely located and that the center desk man may be in charge while the assigned operator is in the rest room or kitchen, the two-man use requirement poses a problem in what may be a worst-case condition. Use of the phone is similarly a two-man requirement as shown by the analyzed task sequence.
- Some delay was experienced in the use of the procedures manual due to cross references and the omission of some data. Additionally, at the instruction of the watch foreman, the center desk man left the procedures manual for another task, thus losing his place in the manuals, which the foreman was required to relocate. (This finding was derived from the task analysis and is more thoroughly discussed in Section 17.)
- The heavy link between the two locations at the reactor control panel calls for additional analysis to determine whether it is possible to design a more efficient arrangement without introducing other problems.
- The several links to the safeguards panel location are the result of trips to silence and acknowledge alarms and of conversation from that position. The reason for "acknowledging" at this position is because the "common" radiation monitoring panel annunciator is located there, yet the related controls and displays are at the back of the primary boards. In this case, not only must the operator travel to the rear of the primary panels to use the radiation panels but he is further delayed by the need to acknowledge or silence at the Safeguards panel. A more efficient means of acknowledging these "back panels" should be devised, such as actual acknowledgement at the panel and silencing from any location. This type of deficiency was discovered by the intense scrutiny afforded by task analysis techniques and probably would not have been noted otherwise.

TASK ANALYSES USED IN PANEL ARRANGEMENTS

The above example discusses Sequential Use Analysis in the context of establishing priorities for adjacent components in control room configuration. The same technique is applicable for evaluation of the arrangment of displays and controls within a panel.

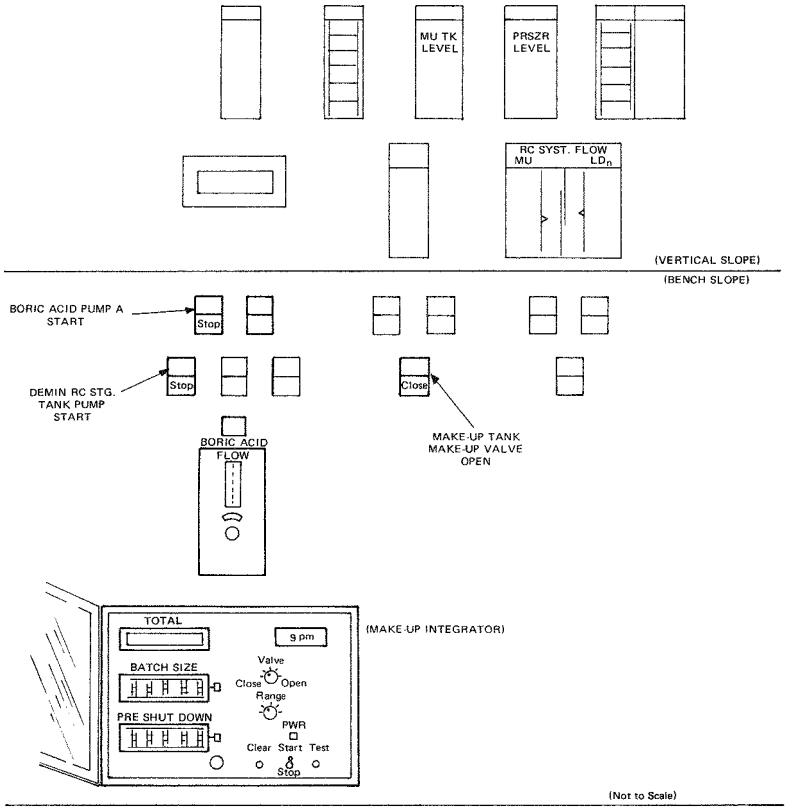


Fig. 16-5. Layout of the Coolant Console utilized to control a steam generator tube rupture. These control and display elements related primarily to manual increase of make-up tank level.

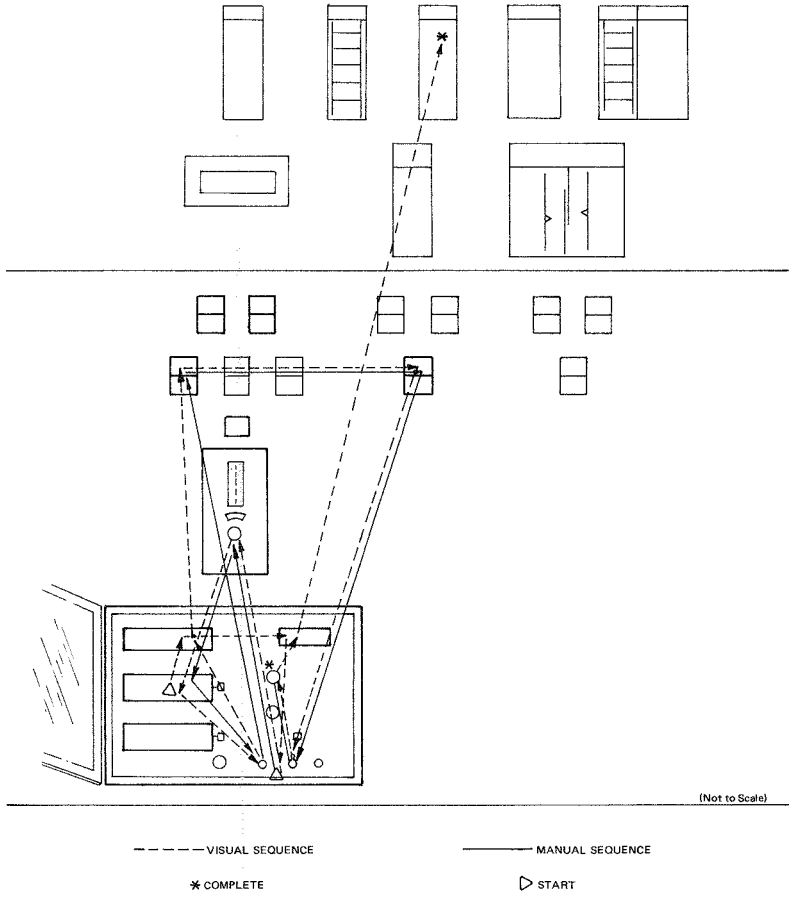


Fig. 16-6. Visual and manual sequence of activities performed in responding to a steam generator tube rupture.

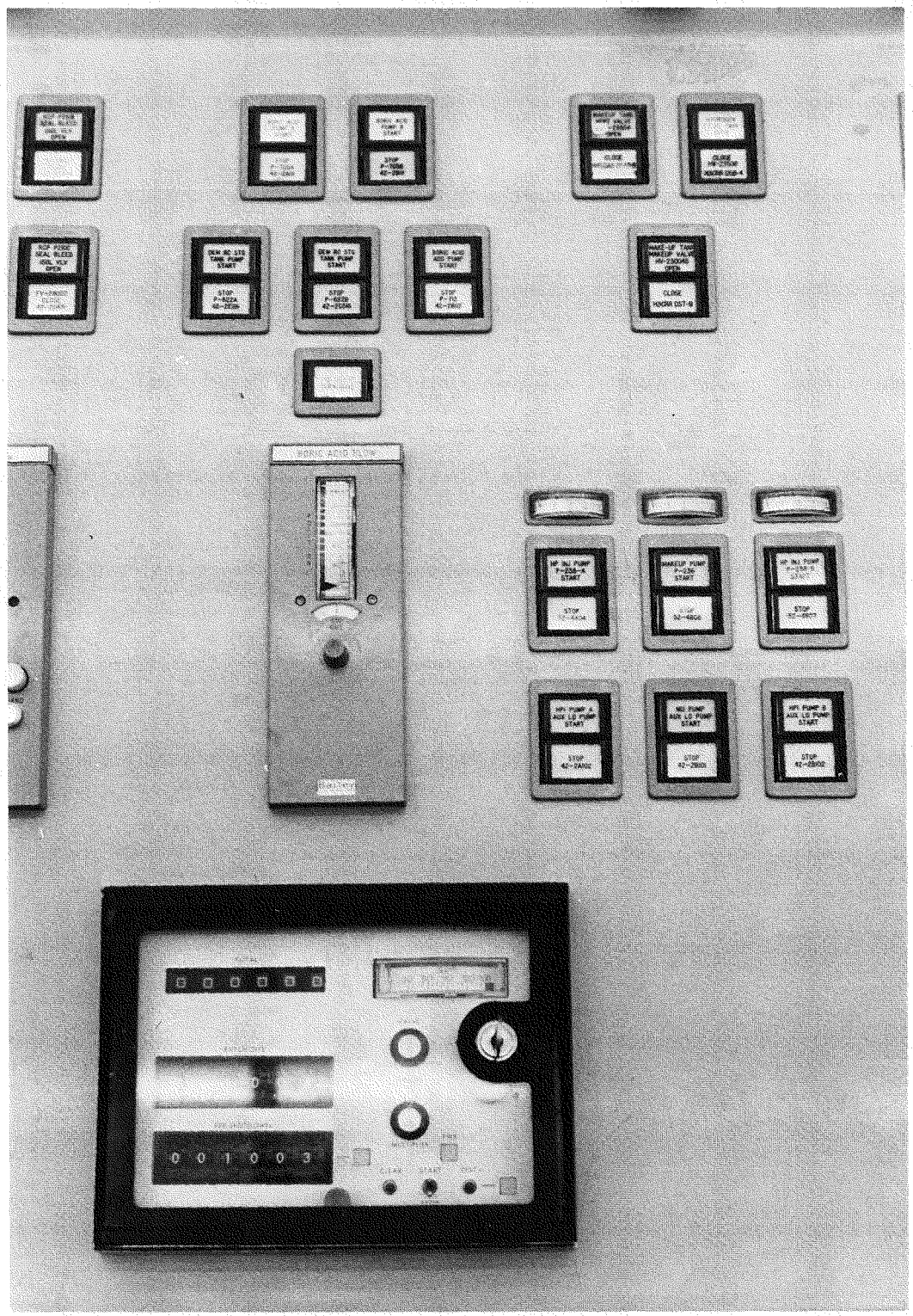


Fig. 16-7. The make-up integrator panel under lock and cover.

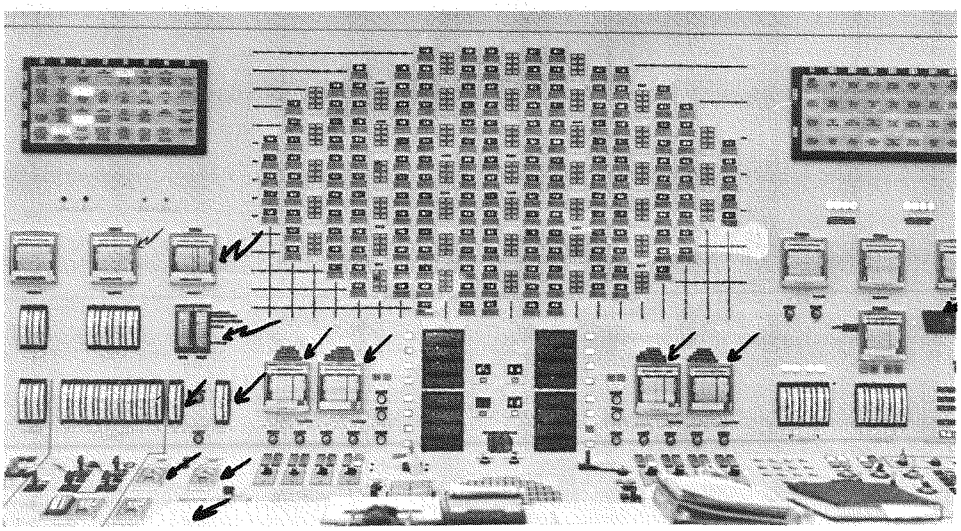


Fig. 16-8. Control board elements that are analyzed for sequence of use.

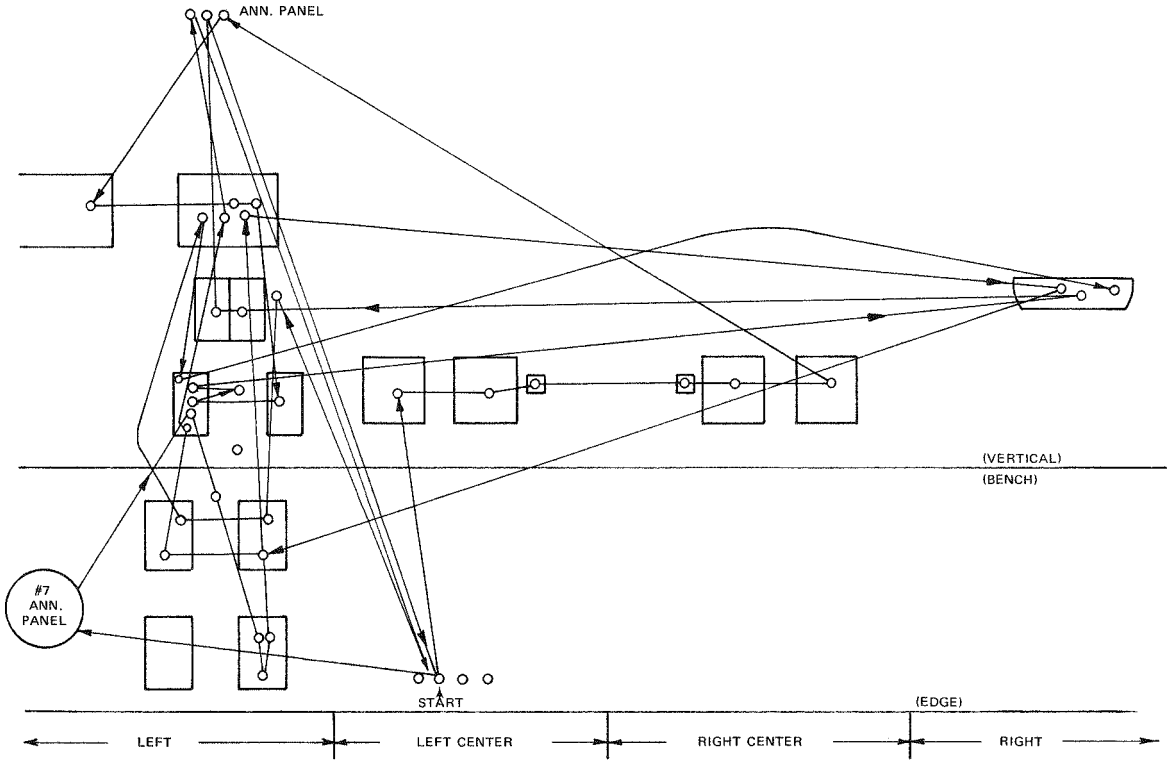


Fig. 16-9. Sequence of use analysis for procedural steps associated with the task of diagnosing and correcting reactor vessel level increase.

Figure 16-5 is a sketch of a control panel segment at one plant. The sequence of use at this panel examined by the task analysis is shown in Figure 16-6. Because almost all equipment is in a relatively small area, the criterion of functional grouping has been satisfied. The criterion of arrangement according to the sequence of use has not. The task requires adjustment of the charging make-up system: turn off boric acid; turn on demineralized water. It is not a difficult task, but the proper sequence of valve and pump adjustments is important, especially during the emergency conditions examined by the analysis.

Figure 16-5 identifies the relevant displays and controls for reference in reviewing the sequence of actions. Figure 16-6 shows the visual and manual sequences of the task. An optimized arrangement would locate individual panel items from left-to-right or top-to-bottom, in accordance with the sequence of use. An additional point is that the MAKE-UP INTEGRATOR panels, (which incidentally is not labeled such, see Figure 16-7), is under a glass cover secured by a key-locked latch. This key is left permanently in the lock. It can be extracted when the cover is in a locked position. The unlatching operation is an extra step that is probably unwarranted since a key that is left permanently in place serves no purpose. Also, it would be troublesome if the key were lost, leaving the cover in a locked position.

A second example of the sequence of use technique to evaluate control panel arrangements is shown in Figures 16-8 and 16-9. Figure 16-8 shows the reactor control segment of the control board. Figure 16-9 provides the complex sequence of use associated with the operations of diagnosing and dealing with an abnormal reactor vessel level increase. An analysis of the task sequence reveals the following:

- The computer call-up display, a five-digit, projection-indicator display, is about ten feet to the right of the high-use group at the left of the panel. This requires the operator to move in that direction in order to read it. It is the most sensitive of the displays that provide reactor vessel level data, and so is relied on most heavily. No means is provided on the control board to identify or confirm what computer-generated information is being displayed at any given time on the multi-purpose projection indicator display. This lack was mentioned during operator interviews, although the confirming display was not considered necessary by questioned personnel because the reactor vessel levels are the normally displayed data. It was confirmed, however, that there are other parameters that might give similarly appearing values. If it was recognized that vessel levels were not being displayed, a trip to the computer is required to call up this data. The computer is 12 to 15 feet away, beyond the operator's desk, facing away from the panels. The delay and interruption to monitoring could be

significant and confirms the complaints of some operators about the location and arrangement of the computer. A means for identifying what data are appearing on the call-up display is a recommended improvement for this panel.

- The redundancy of six separate vessel level displays seems excessive. Because of the importance of closely tracking the reactor level during this task, the operator looks at all of them to confirm reliability of the data. A single meter with input channel select options would reduce the number of displays, the scan area, and valuable panel space. A trade-off study is required to determine whether six separate indications offer an operational advantage that offsets the associated penalties.

- A trend recorder (see Figure 16-10) displays the reactor vessel level and total FW flow. This is the only locally available indication of feedwater flow and the lack of redundancy is surprising, especially in view of the redundant reactor vessel level displays and the importance of this data. A chart travel speed selection (fast and slow) is available, but access requires opening the face of the recorder, an unnecessarily time-consuming operation. The scribed indication is a broad band, representing approximately a three to four inch fluctuation. Notice in Figure 16-10 that the uppermost pointer for FW flow covers the index marks, unlike the LEVEL pointer below it, making interpolation necessary. Another point to be made from the photograph is that the lower label (on the panel) shows "Vessel Level" above "Total FW Flow"; the scales are in the reverse position, that is, "Flow" above "Level," making this a point of potential confusion or error.

- A controlled rate of level decrease is required after the reactor vessel level is brought under control. The required rate is about one inch decrease per five minutes, thus making trend data valuable. While there would be time to increase the trend recorder speed--and thus gain sensitivity--the widths of scale increments on the strip chart do not permit adequate tracing of this parameter. The resultant operation was therefore awkwardly performed, using the computer call-up display and the clock, with confirmation monitoring of the trend recorder. The task sequence, which had to be repeated many times as the process continued, is shown in Figure 16-9.

A third example of detailed human factors problems uncovered by the task analysis is the use of a trend recorder associated with the radiation monitoring console shown in Figure 16-11. The task sequence for the steam generator tube leak problem indicates that trend or history data are of diagnostic value for the operator in evaluating the leak rate and seriousness. There are several process monitoring subpanels on the console, each of which is labeled according to an assigned number. The trend recorder is installed below these. Its data points appear as coded numbers on the appropriate locations of the calibrated chart, each number representing a different monitor. However, the numbers on the chart, (which are difficult to read as noted in Section 11), do not match the assigned numbers on the monitors. This translation is permitted by a list that is taped to the glass door that covers the recorder. Because of the difficulty of reading

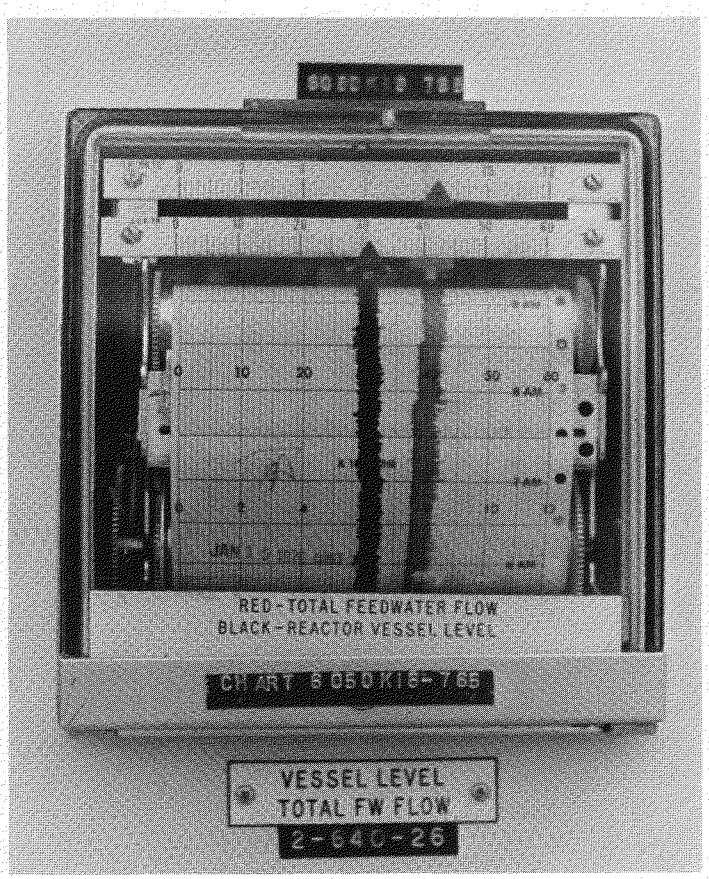


Fig. 16-10. Trend recorder for Reactor Vessel Level and Total Feedwater Flow.

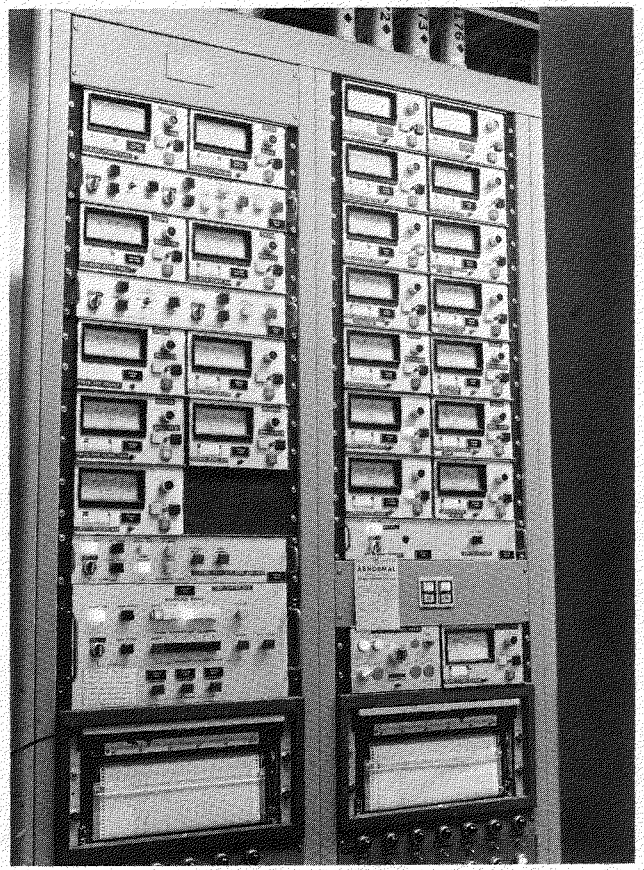


Fig. 16-11. Radiation Monitoring console. The cover on the chart recorder is retracted.

the recorder through the glass (and poor lighting) and because of the partial obstruction of the list, the door is normally open--moved upward--and retracted into a slot. In pulling the door out to read the list, it was noted that neither the sequence nor the nomenclature of monitors exactly matched the sequence or names of the panels. This lack of correspondence invites errors and unnecessary delays in bringing the system under control.

DECISION ANALYSES

Finally, the task analysis process can take another form called decision analysis. A task sequence is carefully documented to identify points at which the operator makes decisions. The control board design and procedures are then reviewed to examine how well they allow the operator to make decisions in a timely fashion.

At one plant, the emergency procedure read: "Manually trip the reactor and turbine as soon as the tube leak is verified by blowdown radioactivity and pressurizer level drop."

This instruction clearly spells out a decision point. During the sequence of required tasks, an operator responds to a radiation alarm and goes to the (backracks) radiation monitoring panel to find an air ejector monitor is alarming HIGH. He then returns to the primary area, only to later receive another radiation alarm. Upon returning, he sees that the blowdown monitor is alarming, at which point his diagnosis is confirmed. An analysis of the task sequence indicates that this decision point, (diagnosis), could have been made sooner if he had been given positive indication of an increasing rate of blowdown radioactivity. The display, however, is a simple meter without a rate-of-change alarm or positive indication of trend. If a rate-of-change alarm based on real-time increasing values had been provided, the operator might well have been fully alerted at the first trip to the radiation monitoring panels and could thus have diagnosed his problem more readily. Provision of an adequately scaled trend recorder, at a minimum, might also provide sufficient rate-of-change data to the operator.

Further discussion of the decision analysis technique is not warranted in the present context, but one final note is that such analysis can be used during the design development phase to determine when automated system response, in lieu of manual operation action, would be most effective.

SUMMARY

Presentation of the detailed OSDs and findings from the task analysis effort would substantially increase the length of this report out of proportion to any general interest that these data would have for most readers. However, it is hoped that sufficient detail has been provided to illustrate how the task analysis approach was used to confirm and amplify observations made through other approaches described in this report.

The task analysis approach should be used more widely in the development of new control room designs to ensure maximum effectiveness of the man-machine interface. Moreover, the task analysis approach needs to be extended to a wide variety of normal and emergency tasks, beyond the sample tasks examined during this study. Otherwise, it may be possible to optimize control board arrangements for one set of tasks and provide an arrangement that is less than optimal for other important tasks.

Section 17

PROCEDURES

Procedures define the man-machine interactions for normal and emergency control room operations. This study examined the content, format, and clarity of a sample of procedures obtained from each of the five plants visited. We were also concerned with the provisions in the control room for storing procedures manuals, ease of locating or retrieving them, and the means provided to operators for using them in conjunction with control board operations.

CONTENT EVALUATION

A detailed checklist was developed to evaluate procedures. In addition, our interview sample of operators and trainers was asked a series of questions to discover their attitudes towards procedures and any problems associated with their development and use.

A 55-item checklist developed to evaluate procedures is provided as Appendix C. A sample of several written procedures was obtained from each of the plants visited. The procedures evaluated also served as the basis for the task analysis effort described in Section 16. There appears to be a large emphasis in four of the five plants examined in the upgrading of procedures. In some cases our review encompassed procedures that were in transition from old to new versions.

The results of our checklist evaluation of the sample of procedures indicates 74% compliance with the criteria provided in Appendix C. The major deficiencies encountered were as follows (the number that precedes each item refers to the evaluation criterion in the checklist):

- (#11) Pages are not consistently numbered "x of x (total)" in order to insure that the operator knows he has all pages of a procedure or checklist. In one case a reactor tripped because an item on a checklist had been omitted. The item was the last of a long list of steps, but it appeared on a second page and the responsible persons were unaware that the page was missing.
- (#13) All applicable or referenced documents are not listed for convenience prior to getting into a position of need during a task event.

- (#15) Warnings and precautions are not consistently placed ahead of applicable steps. In some cases these warnings are shown as "note," several steps after the first appropriate location.

- (#29) Language is sometimes verbose and confusing; at other times, it is so brief that important clarifying statements are lacking. A mixture of styles makes it evident that different writers have contributed without their efforts being coordinated.

- (#31) When emergency shutdowns are required by procedural criteria, instructions should generally be comprehensive enough to follow through the action without the need to seek and obtain a separate emergency manual-trip procedure at a time-critical period.

- (#38) The required level of detail is a difficult judgment area and must allow flexibility for variations in conditions and operator judgment. In performing the task analyses, however, the omission of important steps and information from corresponding written procedures was confirmed with training and operational personnel.

- (#40) In emergency procedures, probable magnitudes are often omitted. While these sometimes cannot be stated, some conditions seem to allow quantifiable criteria. When an operator is unsure and goes to an emergency procedure for guidance, those instructions should be as definitive as possible.

- (#43) "Immediate operator actions" sometimes omit an instruction to confirm and ensure the function of automatic systems actuation.

- (#44) Procedures omit instructions to ensure that automatic modes were not switched to manual unless it was apparent that the automatic capability had failed.

- (#49) The instruction to confirm the existence of an adequate source of power in an emergency is often lacking.

- (#54) Decision criteria and instructions are sometimes stated in dimensions that are not provided in the displays, thus requiring conversions or calculations during an emergency procedure.

In addition to these discrepancies, more serious problems with procedures were discovered by the task analyses. Each step of a procedure was checked against the knowledge and experience of operational personnel and, depending on the availability of the simulator, was simulated and checked with training specialists. In no case did the sequence of events or steps in the procedure match the experience or knowledge of operators and trainers. A considerable amount of time at each site visit was spent attempting to reconcile differences between written procedures and actual operational practices as understood and conveyed by operators and trainers.

Specific examples of the lack of clarity of procedure contents are useful. A quote from one "Immediate Automatic Action" is as follows:

"Steam generator blowdown and blowdown single isolation valves are closed and city water supply valve to the blowdown flash tank is shut if steam generator blowdown activity monitor alarms."

A restructuring of this instruction would clarify it:

"If the steam generator blowdown activity monitor alarms:

(A) Steam generator blowdown valves close.

(B) Steam generator sample isolation valves close.

(C) City water supply valve to the blowdown flash tank closes."

A second example points up the need for procedural terminology to match control and display practices of the control board. One "Immediate Operator Action" requires the operator to confirm that the "steam jet air ejector discharge is diverted to containment." An examination of the related panel elements on the boards reveals a red and a green light located above a label that reads: STEAM JET AIR EJECTOR DISCHARGE VALVE. The unlabeled red and green lights represent OPEN and CLOSED status according to the prevailing code, rather than "diverted" and nondiverted" as stated in the procedures.

To avoid any possible confusion between OPEN/CLOSED and DIVERTED/NONDIVERTED meanings, there should be consistency betwen terminology used in procedures and the control board coding and labeling practices.

A third example shows inconsistent use of units specified in procedures. One emergency shutdown procedure instructs the operator to set a controller to maintain a specified psig. The controller display provides a scale extending from zero to 100%. The procedures should call out values in the same units that are used on corresponding displays on the control boards.

OPERATOR EXPERIENCE

The interview sample was asked the following question: "Are your procedures sufficiently detailed and clear to permit effective operation of your control room? If not, please describe how procedures could be improved." The responses to this question varied from plant to plant. It is interesting to note that satisfaction with procedures varied as a function of the responsibility for originating them. In some plants the operators prepare the procedures and in other plants the operations engineering staff writes the procedures. In plants where the operators had the primary responsibility for procedures there was less dissatisfaction. The problems experienced by operators are reflected by the following statements:

- Procedures are generally O.K., but for special evolutions we need more detail, for example, startup is too vague, especially for a new operator.
- The procedure does not spell out what valves or controls to use. We must go to the blueprints.
- Some procedures are too brief and proceed in the wrong sequence.
- Procedures cannot be relied on. Operator judgment is required. In some cases procedures are too specific and in others there isn't enough detail. The operators don't write procedures. They just review them. The operator is most qualified to write procedures.
- One procedure will refer to a second one which may refer to a third, etc. All the information should be in one document.
- The majority of our procedures are good but there are a lot of bad ones. They are constantly being changed and constant changing of procedures is a problem. Operators don't write procedures and some don't make sense.

Fifty-one percent of those interviewed had problems with their procedures. Forty percent felt that their procedures were adequate and the remaining nine percent were undecided. However, concern for procedures varied markedly from plant to plant. At two plants there was almost unanimous satisfaction with procedures and at two other plants there was almost unanimous dissatisfaction with the adequacy of procedures. One source of satisfaction or dissatisfaction highlighted by several operators was the ease or difficulty of modifying a procedure once it was determined to be incomplete or in error.

Attitudes Towards Procedures

Although procedures were often not sufficiently detailed to permit effective operation of the control room, this did not uniformly cause great concern. There is a strong division of opinion among operators and trainers regarding the value and purpose of procedures. This was brought out by the following interview question: "In general, is too much or too little emphasis being placed on procedures and doing things by the book?" Those who felt that there had been too little emphasis on procedures outnumbered those who felt that too much stress had been placed on procedures by roughly two to one. Advocates of better procedures and greater reliance on them made comments such as the following:

- We've damaged enough equipment here that folks are taking procedures more seriously.
- We have put too little emphasis on following procedures. I believe in procedures. These plants are too complex to fly by the seat of the pants any longer.

- Procedures are good to have. I know of a few mistakes that could have been avoided if the operator had followed procedures.

The minority who felt that use of procedures was overstressed had the following to say:

- It (procedures) takes away from an operator's freedom, his feeling of worth as a thinking, capable man. There is a trend to thinking that you can't get into trouble (with the NRC) if you follow the book.
- A man has to be free to do what he thinks is best. He can't take time out to read the procedures when he is busy.
- There can be too much emphasis on following procedures and we could lose the battle. Procedures should be written in general terms; however, you must be sure your people are qualified.

The division of opinion regarding the value of procedures extended to the trainers. Some were frankly skeptical:

- You need a knowledgeable operator to interpret the procedures. Ours are not cookbook procedures. They are general as opposed to being specific. There are two schools of thought on the matter. The first feels that the operator should be able to operate with general guidelines since there are many ways to do evolutions. The second feels that there should be rigid procedures. I'm not sure which is best. The NRC feels we need definitive procedures. Emergency procedures should be as detailed as possible. They could serve as a checkoff lists. Procedures should be written down somewhere in detail but it is not necessary to follow them in detail.
- The book (procedures) should be a detailed guide and not the law. A checkoff list is O.K. and we do some now. The sequence should be up to the operator since every situation is a little bit different. We spend $200K per operator for training. Why have some flunky in the office develop a Bible? If you are going to spend time and money to train an operator, let him do the job.
- Procedures can become an exercise in reading. Good operators shouldn't need procedures. Unfortunately, there aren't that many good operators. There are cases of operators following good procedures and not thinking. He misses a step and trips the plants.

There was some indication that past experience has much to do with the operator's attitudes towards procedures. Those operators with a Navy background accepted procedures more readily than those with fossil fuel experience.

Memorization of Procedures

At each of the plants visited the operators were required to know the immediate actions required pursuant to a series of possible emergencies. The number of

procedures that the operators had to commit to memory varied from plant to plant. Our interview sample was asked, "Is the operator required to commit an unreasonable number of procedures of an emergency nature to memory? If so, what measures could be taken to help the operator?"

A majority of our sample (58%) felt that the number of emergency procedures committed to memory was not excessive. The minority held the view that it was impossible to commit all the emergency procedures to memory and that it was necessary to rely on the well-trained operator's analytic abilities and judgment. One operator pointed out that some procedures are used so infrequently that they "don't stay with you."

The response to this question varied with the plant. For example, all operators at one plant agreed that the memorization burden was acceptable since only 15 emergency operating procedures had to be memorized. However, at another plant we received the following response: "Yes, it's too much to memorize 17 emergency procedures and 10 out of 40 casualty procedures. We must have instant knowledge of a 140 page emergency plan. There are also 10 administrative procedures." Other operators frankly admitted that they did not memorize emergency procedures but instead relied on their judgment and experience.

A remedy suggested for alleviating the burden on memorization was usually the use of a CRT for ready display of procedures. At one plant, the equipment has been purchased to allow presentation of emergency procedures by means of a random access slide projector, TV camera, and CRT readout. The system had not yet been installed at the time the plant was visited.

ACCESSIBILITY OF PROCEDURES

Control rooms contain an impressive quantity of documentation, including log books, operating procedures, drawings, and administrative instructions. A good system for organizaing, filing, and accessing this documentation is an important requirement for smooth control room operations.

Figure 17-1 shows the location (behind the operator's desk) of the bookcase containing procedural documentation at one plant. Thirty-nine separate binders are maintained, covering 25 titles such as:

Plant Operating Procedures
Checkoff Lists
Detailed Procedures

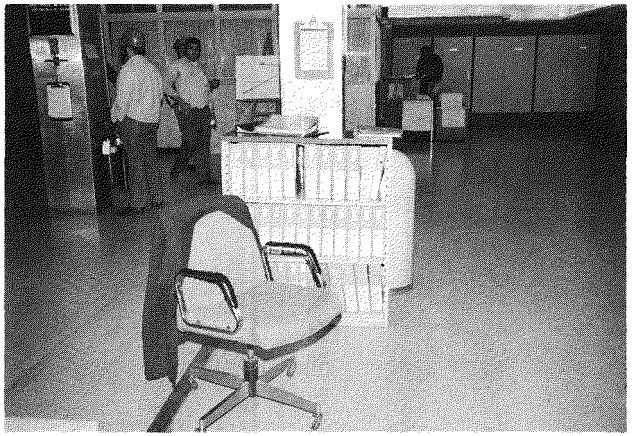


Fig. 17-1. Location of procedures bookcase behind the operator's desk.

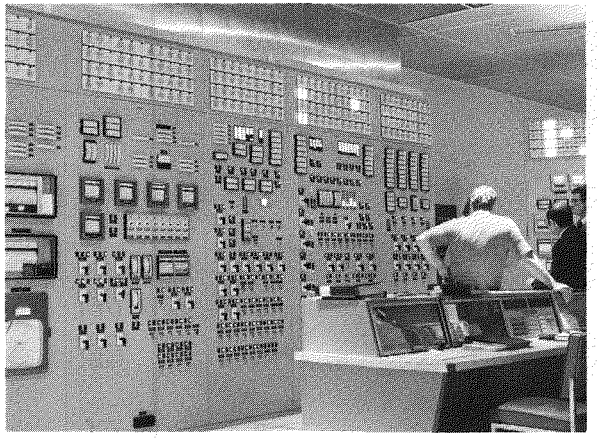


Fig.17-2. The control boards have no provisions for laying down procedures to be used in conjunction with the boards. Operators place procedures in any convenient location, in this case, impeding illumination to the computer typewriter readout.

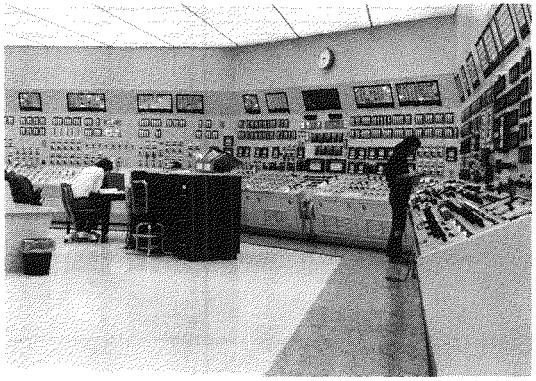


Fig. 17-3. Procedures are placed in a special slanted rack on the operator's desk. The adjacent table holds other procedures.



Fig. 17-4. The rack of procedures is placed too high for the 5th percentile operator and is hard to move.

Emergency Plan
Special Instructions
Station Administration Orders
General Administrative Directives
Emergency Procedures, etc.

Many different volumes with similar titles subdivide the documentation to such an extent that a "search and locate" problem occurs. One technique for easing the access is to provide a primary location solely for operational documentation and a secondary location for other documentation.

During operations at this plant, procedures manuals are typically pulled from the bookcase and laid on top of the computer printer glass cover for reference while the operator is at the control boards. This, in turn, causes a difficulty in reading the printout, which is shadowed from the overhead source of light as shown in Figure 17-2. (A placard warning against this practice appears on the simulator computer.) An important point to be made here is that the control consoles are not designed to accommodate procedures. There are no empty spaces on benchboards on which to lay the procedures. There are also no pull-out shelves at any of the plants on which to rest procedures. Consequently the operator must either hold procedures or find an out-of-way place for them.

At Plant B, four sets of procedures are in a slanted rack, facing the control boards at approximately chest height. These sets are: Emergency Operating, General Operating, System Operating, and Annunciator Response Procedures. Additional volumes on a table next to the desk (shown in Figure 17-3) include such things as Piping Diagrams, Technical Manuals, and Plant Emergency Plan. At a third, more remote location, a bookcase contains Administrative Procedures, Fuel Handling Instructions, and Maintenance Instructions.

When compared to Plant A, the operating procedures at this plant are more directly accessible for control board operation, although they are in a fixed position and cannot easily be moved from one operational area to another (see Figure 17-4). The rack is placed on a high desk, 43 inches above the floor. Because of the rack angle (about 29°) the highest part of a page is roughly 53 inches above the floor, approximately the 5th percentile shoulder height of the military man, making it uncomfortably high to use. The books fit tightly into the rack and are constrained to a maximum open angle of about 110°. Operators were observed having to use

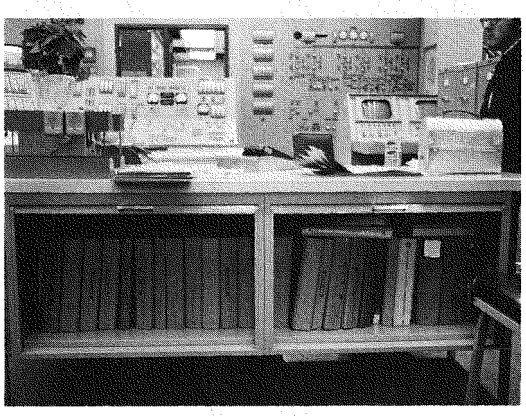


Fig. 17-5. Procedures stored in a roll top cabinet next to the operator's desk.

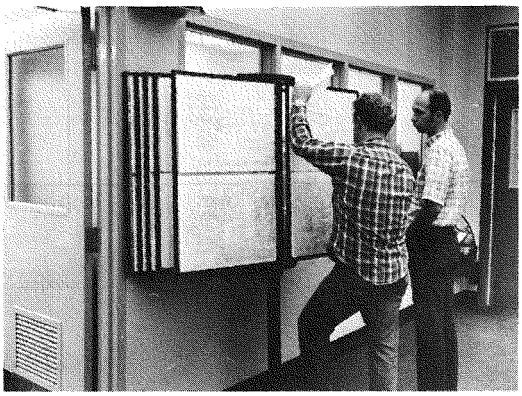


Fig. 17-6. Special rack for displaying plant schematics.



Fig. 17-7. Procedures rack which is shared between two units, and which is equally remote from both operators.

hand pressure to maintain an open place in the book, since the books would otherwise close or "leaf" over.

At Plant C (see Figure 17-5) procedural documentation is kept in binders that are stowed in a low cabinet with roll-top doors, next to the operator's desk. The Plant Emergency Plan and Emergency Operating Procedures are in red books; all others are blue or gray. The arrangement leads to random placement of binders within the cabinet and a search by operators was generally needed to locate a specific book. This was made more troublesome by the cramped spacing, low positioning, and the fact that the glossy gold lettering on most of the books was difficult to read in the shadowed storage area.

Drawings and schematics are stowed open, upright between sheets of plastic on a rack, pictured in Figure 17-6. Changes, special notes, and a system status can be immediately updated with a grease pencil. This arrangement proved very convenient and operators reported success with this design. It is especially convenient at startup or major evolutions which require close surveillance of plant systems.

Plant D has one set of procedures shared between two of the three units controlled in this control room. The procedures are located on a table between the two units. The table and slanted rack are shown in Figure 17-7. Procedures are filed by system number. Behind each system number tab are filed the System Procedures, Surveillance Procedures, and Abnormal and Emergency Procedures. The tabs are color coded green, amber, and red. It was observed that many tabs were missing, some color tab inserts were gone, and binders were misfiled. Annunciator Response Procedures were maintained in three separate binders near the operator's station. When questioned, operators thought that there was a set for each unit but only one was found.

This arrangement is judged to be inadequate from several viewpoints. Compounding the difficulties of locating a specific procedure was the fact that procedures were undergoing revisions which included the indexing redesignation of many. In order to locate a procedure, an operator must first determine its appropriate system number. If not committed to memory, this can be determined by referring to a list of systems that is filed in the rack. Some delay was observed when operational personnel were trying to find the list. Apparently, because of the overlapping system designations, procedures may not be filed where the operator first searches for them. A search for procedures relating to the task analysis sequence

for this study was eventually abandoned and the procedures were found in another office. The search for the alarm response procedures exemplifies the problem of not having a fixed, designated location for these documents.

In summary, the problems seen in this system are:

- Using one set of procedures for two units does not allow for a situation in which both units simultaneously require the same procedure--an emergency can occur at both units at the same time.
- The central location is selected because of the shared use, but the result is a remote, inconvenient location for both operators.
- The index tabs and inserts are flimsy so many are torn or lost.
- Filing by system designation is inadequate because of the problem of determining to which system an item of equipment or subsystem belongs.
- The placing of the system designation list within the bound volumes is inefficient. A permanent master system list placard fixed above the volumes offers one feasible option to avoid prolonged searching.
- A master volume number or other coding scheme is needed to avoid misfiling binders within the rack.
- The great bulk of paper, as shown in Figure 17-7, poses a challenge in handling and leads to inevitable tearing and wear on the documentation and tabs. Pages at the extreme left end of the rack cannot be laid open because of the adjacent bookcase, thus requiring either an awkward reading position or the removal of binders with greater potential for misfiling.

At Plant E procedures are kept on a special bookcase on wheels. This cart can be moved freely by the operator (see Figures 17-8 and 17-9). Operating and Emergency procedures are kept within this case, while other volumes are filed at a more central location in the control room. This is an excellent means for allowing the operator immediate access to procedures and a place to rest them while operating the boards. Trainers report that visitors from other plants often copy this idea.

No one system of indexing and accessing procedures is best for all plants because control room geometry is a major factor in developing a good filing and access design. This review represents an attempt to point out some of the pitfalls to be avoided. To the extent that procedures are difficult to retrieve, operators will avoid their use and rely on experience. Also, in four of the plants use of procedures was generally a two-man job--one operator reading procedural steps and the other manipulating the control boards. Lack of convenient arrangements for laying procedures down in the vicinity of the work station is responsible for this being a two-man task. In some cases procedures are placed directly over controls and displays inviting disturbance of controls or loss of a meaningful indication (see Figure 17-10).



Fig. 17-8. Special rolling bookcase which proved very effective for storing and using procedures.

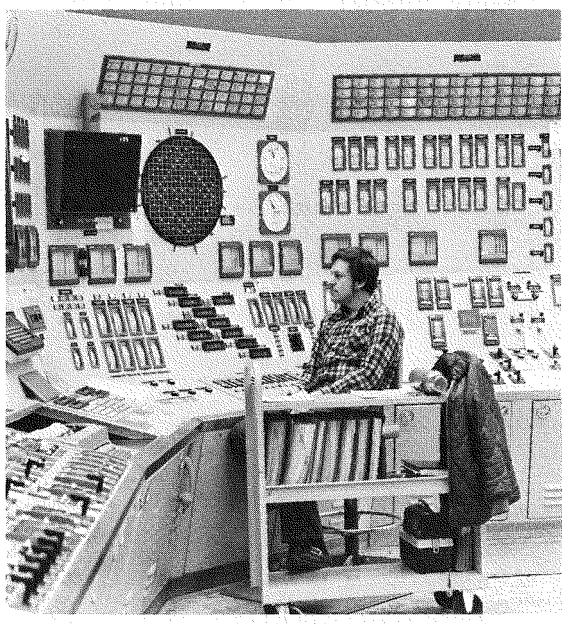


Fig. 17-9. The rolling bookcase serves to hold personal effects of the operator responsible for the reactor panel.

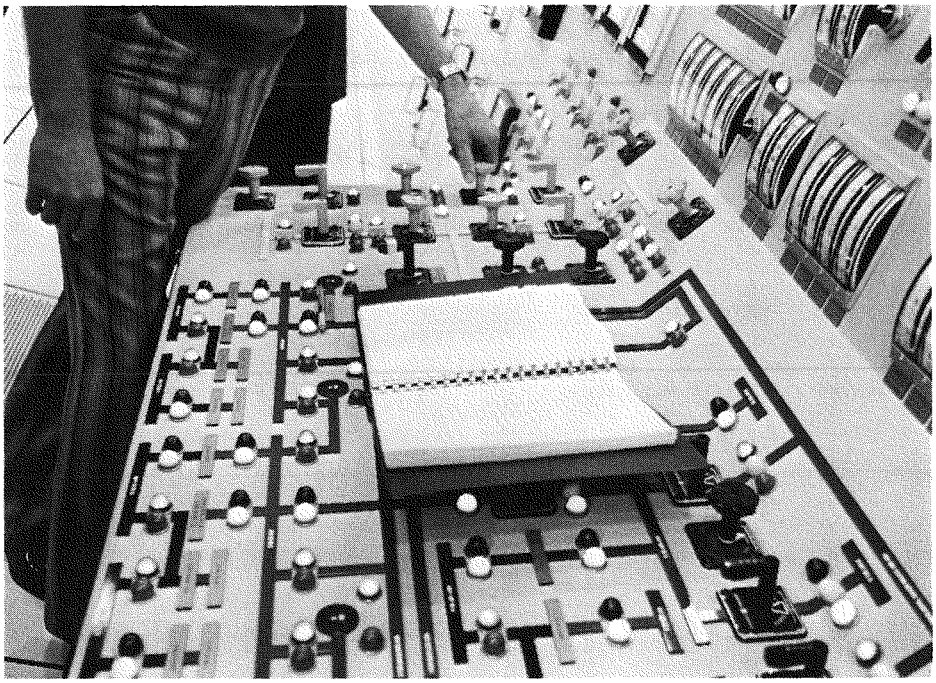


Fig. 17-10. Laying procedures manual directly on the benchboards obscures displays and invites accidental disturbance of controls.

DIVISION OF RESPONSIBILITY

"Are your emergency procedures designed so that there is clear definition and division of responsibilities among control room operators in dealing with off-normal events or is there a duplication of coverage or other problems?" This question was put to the interview sample and drew a uniform response indicating that procedures did not spell out responsibilities according to specific operators. The operators and trainers did not view this omission as a problem. In general, a two-man crew will divide coverage of the boards at their own discretion. Similarly, the center desk operator and the unit operator will work out an arrangement in unison in observing procedures. The procedures do not, likewise, spell out the responsibilities of the operator and the supervisor or shift engineer. While the operators do not see this as a problem it is our view that procedures should be more specific in delegating tasks or procedural responsibilities to the various operational personnel. If concurrence is required of the Shift Engineer before a given control event, the procedures should state this clearly. This becomes especially important, for example, in an emergency shutdown from an emergency shutdown panel which would be used in the event that the control room had to be evacuated.

SUMMARY

Considerable effort is currently underway to upgrade the quality of procedures governing control room operations. A majority of operators see this as a healthy trend, although some resent being bound by fixed procedures and see this trend as an affront to their individuality and their capabilities.

The operators should be given a larger or primary role in formulating procedures and validating their adequacy. A review of the contents of sample procedures indicates that they are sometimes confusing, incomplete, and inaccurate. Also there exist serious problems in the storage and retrieval of relevant procedures when they are urgently needed. The control boards have not been designed to facilitate the use of procedures while simultaneously allowing the operator to manipulate controls and take readings. It is our expectation that as the quality of procedures improves and as better means are provided for retrieving and using procedures, the operators will place greater reliance on them. There is a growing realization that nuclear power plants are too complex and the risks are too great to conduct control room operations without a comprehensive and tested set of procedures.

Section 18

OPERATIONAL PRACTICES AND TRAINING

An examination of control room man-machine interfaces would be incomplete if we failed to consider current operational practices and the operational climate in which the operator functions. Such factors condition the operator's vigilance, morale, attitudes towards his work, and his physical response limits. For example, an optimized or "human engineered" control board would not by itself guarantee error-free operator performance if the operator were unduly fatigued after working six successive 16-hour days because his normal relief was ill. Similarly, the operator who has been off duty for three days and who is about to switch to his first graveyard shift might understandably not be at his best. Such factors are more difficult to evaluate than panel design principles because there is so much variability among individuals. However, such factors can and do compromise the quality of the man-machine interface. Under the heading "Operational Practices" this section will examine such topics as: watch turnover, shift crew composition, extent of overtime work, effects of shift transitions, stress, and boredom.

The latter portion of this section will address operator training prior to licensing and subsequent requalification training. Training and human factors engineering are closely intertwined in that the greater the attention paid to human factors in control room design, the easier it should be to train operators to master operation of the control room.

OPERATIONAL PRACTICES

Watch Turnover

The operator coming on duty after an absence from the control room of 16 hours or more needs to apprise himself of system status before he can effectively take control. This watch turnover function, where a transition is made from an outgoing to an oncoming crew, is the source of much operator dissatisfaction. Furthermore,, inadequate watch turnover practices cause serious operational errors when the operator who assumes control is not entirely cognizant of plant status.

Some power plants have detailed watch turnover procedures designed to ensure a successful transition from one crew to another. Others are much less formal. The following activities have been spelled out at one plant for operators coming on duty:

- Review the control room operational log for the unit back to your last watch or for the last two days.
- Review the tag out log (out of service equipment).
- Review the lifted wire and temporary jumper log.
- Review the printout of the alarm typewriter.
- Review all special work permits in effect for the unit.
- Review the nuclear plant engineering operations notes and instructions.
- Review the control board in detail and ongoing maintenance operations, instrument status, controller mode, and testing.

It is difficult to estimate how long it would take to accomplish the above list of activities. This study did not gather empirical evidence on this because at no time were oncoming operators observed to accomplish all these activities before relieving the outgoing crew. Usually, there was only a several- to ten-minute verbal exchange between outgoing and incoming crews. Only after the outgoing crew had left were some or all the checks prescribed above effected. Our study team was often enjoined not to interview incoming crews for a half-hour to one hour subsequent to the start of shift so that the operator could catch up with system status. The problem observed was simply one of insufficient overlap between one crew and the next.

The operators feel that it takes from 15 to 30 minutes at each end of the shift to effect a satisfactory watch turnover. However, they resent not being paid for the extra 30 to 60 minutes per day that turnover communications requires. Some belong to car pools that will be held up or missed if the watch turnover becomes lengthy. With the long commute distances for most operators, car pools are important. It was clear that most operators appreciated the importance of a good watch turnover, though some performed it grudgingly.

Shift Crew Composition

Control rooms are generally manned by two to four operators depending on the number of generating units being monitored and the number of operators assigned to each unit. The problem of assigning men around the clock to operate the control rooms

is of great concern to both the operators and utility management.

From the operator's standpoint, the choice of compatible teammates can make the difference between an enjoyable or tedious eight hours of work. The operator is also looking for a teammate that complements his skills and who can be counted on in an emergency. Operator teams that have worked together for a long time have become quite adept at sharing responsibilities during times of emergency and double checking each other without tripping over one another.

Utility management is primarily interested in providing the proper mix of talent and experience so that effective operator performance can be counted on at all times. These goals of management and operators are not always entirely compatible, and this leads to problems where operators have the predominant say in how they will structure shift manning. This generally occurs in cases where the operators select shift-mates based on seniority. This leads to situations where the most senior operators select their friends, who naturally are also senior and experienced. After these selections are made, based on seniority, some shifts are manned with the most experienced hands and some shifts are manned entirely with novices, each with only several months experience.

This situation is a cause of concern to management and an attempt is made to compensate by having the Shift Engineer stay closer to the control room when only junior people are on duty. However, this is not a complete answer since the Shift Engineer's duties take him out of the control room despite his efforts to stay close to the operational center of activity.

The writers question the wisdom of operator shift scheduling based exclusively on seniority, as opposed to providing the best possible mix of talent and experience in the control room around the clock.

Overtime and Shift Work

Control room operators work many overtime hours because of several factors: insufficient licensed manpower; peak load demands imposed by operational conditions, e.g., during startup; and special factors such as requalification training requirements. The key problem appears to be one of an insufficient number of licensed operators.

Our concern is that excessive overtime inevitably decreases operator effectiveness. The research findings that bear on this point, while developed in other work

contexts, are quite clear and applicable to the nuclear power plant control room. Seidenstein (11) has summarized the literature bearing on the effects of time stress on human performance. Based on this review, there is little question that work performance suffers if we spend too much time working, if we work at the wrong time, and if we frequently change our working times. These effects are due to the development of fatigue and the manner in which we adjust to biologically based rhythms.

The operators recognize their limitations when subjected to excessive periods of overtime. The operator interviews contained the following questions: "What percentage of your work is overtime over a period of one year? Have you noticed any problems with operators working extensive periods of overtime?" Based on interview data, the overtime worked by operators varies from a low of 5% overtime (100 extra hours) to 50% overtime (1000 extra hours), based on a 2000-hour base work year.

While 1000 overtime hours is clearly excessive, even 100 to 200 hours per year overtime can reveal serious potential for problems depending on the distribution of overtime. One operator commented: "I would hate to get a LOCA during the 15th hour of duty. Anything over 12 hours is trouble. If a guy doesn't show up for his watch you work 16 hours. This can happen 20 to 30 times a year." This is not an isolated case. For example, an operator from another plant stated, "The operator can work up to 16 hours per day, sometimes 6, 7, or 8 days in a row."

At three of the plants the operators perceived problems of reduced effectiveness due to stresses imposed by overtime. At the remaining two plants no serious operator performance decrements resulting from overtime were expressed. Some of the performance problems noted by operators are shown by the following:

- One 16-hour shift isn't so bad, but two or more takes it out of you.
- Your level of concentration goes down. If you have enough people to cover the normal routine, overtime does not become a problem. There are always people who will take the overtime. If you are understaffed then you can expect problems.
- People get tired and irritable and don't really care any longer. We need more people!

Shift work, which is demanded for around-the-clock surveillance in the control room, has an important impact on human performance, especially when coupled with excessive overtime. A representative shift rotation schedule is as follows:

Midnight shift--7 days, off duty--2 days; swing shift--7 days, off duty--2 days; day shift--6 days, off duty--3 days; spare days on day shift--5 days.

The operators were evenly divided in their attitudes towards their present shift rotation schedules. Half felt that their present schedules were as fair as possible or they liked their schedules. The other half were dissatisfied and wanted a change. In attempting to match satisfaction-dissatisfaction ratios with particular shift schedules, it was not possible to draw clear conclusions. With one or two exceptions, shift work was regarded as a necessary evil associated with their chosen line of work. Those who preferred shift work did so for such reasons as being able to have access to uncrowded facilities and shops at times when most "normal" people were at work.

A majority of operators (55%) feel that shift work takes its toll in reduced operator effectiveness, while 45% of the operators feel that operator performance is not seriously impaired from shift transitions. From the responses obtained, adaptation to shift transitions appears to be a matter of individual differences. Some sample responses from operators revealing adaptation problem are as follows:

- There definitely are adjustment problems. Morale is down and there are negative attitudes. I would prefer to work a regular shift. I hate the four to twelve shift. I don't see the kids. I'm not at my peak at midnight. I don't know if you ever get used to it.
- You just can't prepare for the first night of the midnight shift. I can't sleep eight hours just before coming to work. You find yourself wanting to go to sleep after a few hours and not caring. first coming on to the midnight shift take turns staying alert (in this case there were two men assigned to one unit).
- While it's not a personal problem, it flat kills some people. I would like longer shift periods--maybe two weeks. This may help people adapt.

While there is probably no one answer to the shift problem that would satisfy all operators, some alternative solutions should be explored empirically to establish the most effective compromise. The "permanent" shift notion that a number of operators bring up seems worth pursuing, but is viewed with alarm by junior operators since they are concerned that the senior operators would have their pick of the best schedules. Perhaps special incentives for the less desirable shifts might eliminate this problem.

Aside from the fatigue and sleep deprivation, shift work makes an important impact on the operator's personal life which can affect his emotional state and consequently his attentiveness to his job. Nearly two-thirds of the interview sample

felt that shift work and excessive overtime were the source of personal problems for operators.

Boredom and Stress

The operator's job has been characterized as "hour after hour of debilitating boredom interspersed with periods of abject terror" (7). A surprising majority of the operators and trainers (69.1%) agreed that there was much truth to the boredom half of the statement and no one disagreed that the job had elements of intense stress.

There was some variation among plants regarding the degree of boredom experienced. At one plant the consensus (nine to one) was that the operator's job was not at all boring, while in another plant the interviewees agreed ten to zero that the job was essentially boring. One interviewee described the job as so boring that he would talk to a broom handle if it went by him while he was on a backshift.

The remaining three plants were divided two-to-one in characterizing the job as having a large boredom component. The data on this point are insufficient, but it appears that the more hardware troubles the plant is experiencing, the less boring the job of the operator. Conversely, when the plant is humming along month after month, the operator's job is largely boring.

Boredom is of concern to us, not solely out of an altruistic regard for the operator's well-being, but also in terms of the effect of boredom on operator vigilance. Many contemporary jobs involve little actual physical labor, yet they produce fatigue. Fatigue can result from monotony and boredom due to relative inaction, combined with psychological stress associated with critical tasks. This is the well documented vigilance phenomenon. Vigilance decrements typically are associated with monitoring situations where the detection of discrete signals is critical but the operator does not know when to expect the signal. Typical well-studied tasks involve monitoring radar and status displays where the operator has only a minor role.

The operators were not lacking in suggestions for dispelling boredom. These suggestions fell into the following categories:

- Restructuring of job activities--providing relief for operators to make the rounds of the plant in order to observe plant conditions first-hand. The operators who had risen from the ranks of auxiliary operators once knew the plant "like the palms of their hands," but

after being confined to the control room they lost touch with actual plant functioning. Others suggested scheduling of requalification training to break up the normal routine instead of training on overtime. A third suggestion was to spread job-related activities across all three shifts instead of conducting the majority of activities during the day shift.

- Use of spare time for non-job related activities--advanced educational studies, requalification studies.
- Distractions or amusements.

It was clear operators feel they can effectively carry on their duties in the control room while at the same time conducting a variety of other activities designed to kill the tedium of the job. In fact the operators feel such activities tend to keep them awake and enhance their alertness to plant conditions.

In summary, boredom seems to be a serious problem associated with the operator's job, primarily during back shifts and when all is going well for the plant. Boredom induces fatigue and job dissatisfaction which in turn can degrade the operator's state of vigilance and consequently his effectiveness as an operator.

In attempting to find some resolution to this problem, the alternatives recommended above by operators, their supervisors, and trainers should be explored through human factors research designed to shed light on the following questions:

- What activities can the operator conduct in the control room to supplement his primary watch-keeping duties? Do such activities enhance or degrade the operator's level of vigilance, or do they have no effect one way or the other?
- Can the operator's schedule of activities be restructured to provide a balance of watch keeping, training, in-plant activities outside the control room, procedures writing, etc., in order to reduce the long stretches of continuous and often boring and debilitating hours in the control room?

Such research is needed to enhance the utilities' return on the wages paid the operator while at the same time creating an operator role which is more stimulating and effective in terms of vigilance behavior.

While the operators and trainers were quite vocal and imaginative in prescribing antidotes for boredom, they were generally at a loss to find easy answers for coping with the intensely stressful moments that all agreed were part of the job. Some of the operators felt that stressful moments were part of the job and the primary reason for their being in the control room.

There was a general feeling that stress declined with experience. While stress was viewed as natural, abject terror was associated with the inexperienced or insecure operator. Some felt that basically insecure operators should have been weeded out in the selection process. One operator said: "Select the right man to start with--one who is cool." As one trainer put it: "If a guy feels moments of sheer terror, he shouldn't be there in the first place."

Specific suggestions made by operators for alleviating stress are as follows:

- The operator should have the ability to lock the control room and keep out non-operational people during emergencies. As one stated: "Thirty people came in during our last casualty." It was clear from the responses of operators that the stress of the situation is heightened by the presence of superfluous people in the control room; some whom the operator cannot easily disregard since they are management personnel. One operator said: "Keep people out of the control room including the bosses in a casualty situation. I don't have time for explanations before I have things settled."
- Operators and trainers placed great value on training with simulators to alleviate stress. The simulators allow operators to experience casualty situations which would only be expected to occur on a highly infrequent basis, if ever. When the operator is exposed to such simulations, the "shock" of the real thing would presumably be less traumatic, since the operator would be trained to diagnose the situation and respond properly.
- A third category of responses dealt with communications with auxiliary operators. One said, "The guys outside should let you know where they are and that they are ready to help. You want to know where all your resources are to help you. It is a comfort to you." The operators viewed the unavailability of outside personnel as extremely frustrating in critical moments and they sometimes felt utterly helpless. Some implied that this unavailability was sometimes deliberate, especially as the end of a shift approached (see Section 15).
- Some operators felt that the answer to alleviating stress was the availability of a reliable backup operator. These operators were from control rooms where only one man per generating unit was available with a centerdesk operator to help as needed. The second man could pull out procedures, give guidance, handle communications, etc.
- Others saw the need for better control board designs to allow better analyses of the casualties. In the same vein, some operators felt that improved procedures would help. One suggested that a higher level of automated system response coupled with better indication of system status was the answer to reducing operator stress.

Control room operator performance under intense stress would be a useful study area. The major problem in conducting such research would be the creation of realistic subjective stress under artificial laboratory or simulator conditions. In any event, an investigation of stress on operator effectiveness is recommended

along with an evaluation of possible antidotes for stress, e.g., improved control board designs, improved procedures, and increased "hands on" simulator training.

OPERATOR TRAINING

The interview sample was asked a series of questions dealing with training. Operators and trainers were invited to comment on current training programs for reactor operators and senior reactor operators and to indicate what major changes, if any, they felt were needed.

The most frequently voiced and most emphatic recommendation was the need to place greater emphasis on operational training and experience and less on formal training on theoretical subject matter. One operator echoed the sentiments of many of his colleagues when he stated, "Only ten to fifteen percent of the theoretical training we get is relevant. The rest is worthless. You have to have hands-on experience and learn the controls to become a good operator." Another said, "The training is too theoretical for a reactor operator. It's not operational enough. You only need all that theory if you're going to design a reactor. Some guys (trainees) got so hung up over the math that they weren't ready for the simulator."

Some trainers agreed with these sentiments but were not as unified in this view as the operators. One trainer states, "We should reduce the time spent on reactor physics, e.g., the six factor formula. It is not used in power plant operation. The operator only needs a general understanding and not so much depth." Many trainers chose rather to stress the need for highly motivated students. These trainers felt that the selection process for operator candidates was less than perfect. As one put it, "Select license candidates based on the personal initiative exhibited, i.e., the willingness to do extra work when they are selected."

Training Simulators

Operators regard simulators as the best vehicle for obtaining operational training. Many would substitute many of the formal classroom hours for time in the simulated control room. A representative statement is, "We need more use of simulators to get the feeling of the equipment without tearing it up. It helps you to see casualty modes. We should also send trainees to any operational plant prior to startup of their own plant."

While there was a unanimity of response in favor of the usefulness of simulators for training, the operators had some suggestions for improving the value of simulator training. Some felt that simulator drills focused exclusively on the "one-in-a-million" casualties that operators rarely, if ever, encountered. These operators felt that in addition to the "far-out" accidents, simulator training should give the trainee more experience in day-to-day operations. Some operators observed that the usefulness of simulators for training was proportional to the degree of similarity between the simulator and the operational plant. In some cases there were complaints that the simulator responses were not typical of actual plant system responses, e.g., "Computer response time for specific cases have excess lag time." In one case, the operator complained that operational procedures followed at the simulator were markedly different from those developed at the operational plant. He had been sent to the simulator for requalification training.

Control Room Design and Training

One of the major justifications for applying human factors engineering principles to control room design is that greater attention to the man-machine interface reduces the training demands on the operator. In other words, to the extent that control-display arrangements are logical and interrelationships are self-evident, the operators will have an easier time in mastering the operation of the control boards. Accordingly, the operators and trainers interviewed were asked, "In your opinion, in what ways could the control room be redesigned to reduce the time it takes to learn to operate the control board?"

The most frequently voiced suggestion was more intensive use of mimic panel arrangements. This recommendation was made at each of the five plants. Some representative statements by operators were:

- Mimic boards would help. The operator could see how each individual system related to the other. The hardest thing for the operator to do is correlate all the systems and get the big picture of what is going on.
- Mimicking would be greatest help. In most cases the operator comes with outside plant experience (was recruited from the ranks of auxiliary operators). Therefore, it would help him in operating the plant if you could relate the control boards to the physical layout of the plant.
- The use of mimic panels would make it (the control boards) a whole lot easier to grasp. You wouldn't have to memorize the whole thing or reach for a print.

Other suggestions for reducing the time to learn control room operation offered by the operators and trainers are as follows:

- Functionally grouped panels
- Better differentiation of components within panels
- Coding of displays and controls
- Improved labeling
- Reduce the number of redundant controls and displays
- Miniaturization of controls and displays
- Standardization; e.g., avoid purchasing turbines from two different manufacturers
- More concise alarm picture
- Use of tape to functionally isolate related groups of control-display elements.
- More logical arrangement of panels to reflect operational use.

At both of the plants that used mirror-imaged control boards for two adjacent control units, operators suggested the elimination of this design practice to facilitate operational training.

Finally, some of the devices used to prepare for NRC exams provide an indication of the problems with the control boards as presently designed. On one midnight shift, the operator trainees tied strings from the controls to the associated displays, 10 or more feet away. In another instance, the trainees made light pencil arrows by each control so that they would have a clue as to the general direction of the associated indicator during the exam. Needless to say, a "human engineered" control board would not require the operator trainee to resort to these memory aids.

THE NRC LICENSING EXAM AND EFFECTIVE JOB PERFORMANCE

A central issue in operator training is the relationship between current training programs, the requirements to pass the NRS licensing examination, and the preparation of the trainee to become an effective operator. Stated another way, Does passing the NRS examination predict eventual success or effectiveness of the operator?

Eighty percent of the sample felt that passing the NRS licensing examination was largely or totally unrelated to subsequent effective job performance. The operational personnel interviewed were more emphatic in this view (87%) than the trainers (62%).

A number of operators said passing the exam was the price of admission into the control room, but that becoming an effective operator was largely a function of on-the-job training and experience. As one stated this sentiment, "The test (NRC examination) doesn't make an operator! It would take six months in the control room to make an operator." He went on to note that his utility had developed their own operations test which was administered after licensing and six weeks of on-the-job training.

A few stated that the NRC examination was not a good predictor of operational performance because of the NRC's emphasis on public safety rather than the utility's combined interests in public safety and production of power. One points out that "You could be a safe operator but not necessarily a good operator. The NRC is always looking for a safe operator."

It was beyond the scope of the present study to perform a content analysis of the NRC licensing examination and match this against the repertoire of skills and knowledge required of an effective operator (assuming that we could arrive at a commonly accepted definition of what constitutes an effective operator). Therefore we cannot substantiate or refute the opinion that the NRC examination is largely unrelated to future operator effectiveness. However, since the utilities spend between one- and two-hundred thousand dollars to train each operator, some research effort should address this basic question. The study team sensed that most operator training activities are directed at preparing the trainee to pass the NRC examination. It may be necessary to modify training programs to not only ensure public safety, but to better equip the operator to maximize plant output.

REQUALIFICATION TRAINING

During the systems familiarization portion of this study, one operator told the study team that had he known of the necessity to undergo requalification training, he would not have made the transition from fossil fuel to nuclear plants. He viewed requalification training as one more "hassle" on top of many imposed on the nuclear power plant operator. He felt that he was a competent operator and requalification training implied that he wasn't up to his job.

These remarks lead to the inclusion of the following question in the structured interview, "What is your opinion of requalification training for ROs and SROs? Does this required training pose any problems?" The survey results on this question were surprising. Not a single one of the operators, supervisors, or

trainers felt that requalification training was unnecessary for operators nor was such training regarded in any way as an affront to the operator's capabilities. Some stated that at first they didn't like the notion of requalification training but later saw the wisdom in it. Others ascribed such training to the "necessary evil" category. Aside from the beneficial training aspects of such programs, it was apparent that in some cases the operator welcomed the opportunity to get out the control room to break the tedium of the long shifts. The "R & R" (rest and recreation) aspects of requalification training were pointed out by some.

Despite the unanimity of opinion in favor of requalification training, some serious problems were consistently pointed out to the study team. First, requalification programs bite into the operator's time. As was pointed out earlier, nuclear power plants are generally under-staffed; the time required for this special training must be superimposed on other overtime demands, on vacation schedules, and on weekends that the operator expected to have free. Furthermore, the time paid for requalification training varies from plant to plant and some operators resent having to "bone up" for exams on their own time.

The content and structure of requalification training programs formed another category of complaints. While such programs appear to the operators to be steadily improving with time and experience, it is apparent that the utilities were initially at a loss to establish good programs to meet this NRC requirement. One operator made this point, "Our program hasn't been too good but it is getting better. They used to sit you in a room and you were given the books and told to read them. Now we have lectures and it is better. Our operators are paid for training but not enough time is set aside for it."

Considering that much of the requalification training is performed on overtime, after eight hours on shift, a special burden is placed on trainers to come up with stimulating training programs to avoid incurring the hostility or apathy of the operators. A burden is also placed on the utilities to spend the funds required to put together a top-notch training program with qualified instructors and the latest teaching aids.

Operators place great value on use of the simulator for requalification training programs. However, some operators felt that some latitude should be provided by simulator training specialists in allowing practice on those aspects of the operator's tasks in which the operator himself perceived some deficiencies. Plants

with a training simulator corresponding to the design of the operational control room had a marked advantage over those plants that did not have such simulators at their command.

As in the case of the training in preparation for the NRC licensing examination, some operators felt that requalification training placed too much emphasis on theoretical subject matter rather than operational skills. One operator expressed this view as follows, "All requalification should be based on operation--nothing else. We don't care about the lifetime of a neutron or how to build a plant."

SUMMARY

We have examined a number of operational practices and training issues that can profoundly affect operator performance. While this section admittedly raises more questions than it answers, the questions may be significant topics deserving more intensive investigation. Watch turnover practices should be reexamined to ensure that there is an adequate transfer of information regarding plant status. Shift crew composition selection methods should be devised to ensure a balance of talent and experience across all shifts. The utilities should have sufficient operational manpower available to preclude excessive overtime hours. Shift work and shift transitions create problems of adjustment for the operator, some of which may be a natural condition of the job. However, special incentives for undesirable shifts and permanent shift assignments may be worth exploring. Boredom may be alleviated by efforts to restructure job activities. Restructuring may yield a better return on the dollars spent for operator salaries, while at the same time, improve operator vigilance in the control room. Antidotes for the intense stress that operators experience from time to time need to be investigated to ensure that the operator is maximally effective during emergencies.

The most emphatic recommendation for training programs is a shift towards operational training and a corresponding deemphasis in formal training on the theoretical matter. It is still an open question whether the operator with the best foundation in the underlying theory and design of plant systems makes the better operator. Similarly, while the majority of operators felt that the NRC licensing examination should be more operationally oriented, no evidence to substantiate or refute this view was developed within the scope of this study. However, in view of the large expenditures required for operator training this issue deserves further investigation.

Based on the observations of the study team and the remarks made by operators and trainers, human engineering improvements in control board design would facilitate the learning process in training the operator to master control board operation.

Finally, training on a simulator that differs from the control room the operator will eventually operate is open to serious question. It would not make much sense to train a pilot on a Lockheed L-1011 simulator if he were being trained to operate a Boeing 747.

Section 19

OPERATOR ERRORS

Earlier sections of this report have attempted to define man-machine interface problem areas or factors that could compromise operator performance. The findings reported above were based on an evaluation of control rooms in terms of conformance with established military-aerospace human factors standards. In addition, task analyses were conducted to take a more detailed view of the demands imposed on the operator for a selected casualty mode. Also, the opinions of operators and trainers were solicited on a variety of control room design issues through structured interview. There are many human factors discrepancies that render existing nuclear power plant control rooms less than optimal. It seems reasonable to assume that the human factors discrepancies noted should have caused a series of operator errors or near-errors. Accordingly, another approach taken during this study was to focus specifically on operator errors or near-mishaps. This was done primarily by means of the critical-incident technique.*

The critical-incident technique calls on the operator to cite a specific case of an operator error, accident, or near accident and to examine the causes of the mishap. Second, the technique requires the operator to provide examples of both "poor" and "good" human engineering aspects or features of the control room. The following questions were asked of each operator and trainer interviewed.

- Based on your operational experience, cite one example of an operator error, accident, or near accident with serious or potentially serious consequences. Describe the specifics of the case and indicate how the situation could have been averted through either improved control room design, improved procedures, or special training provisions.
- Based on your operating experience with your control room, cite one example of a particular control, display, panel, warning device, etc., which is not "human engineered" or is poorly designed from the operator's standpoint, and has or could lead to a malfunction or operator error.

*The terms "critical" and "incident" used here in the layman's sense rather than having the special meanings attributed to these terms in the nuclear industry.

- Now think of an example of a particular display, control, label, panel layout, warning device, or other control room feature which is well "human engineered" and which might have prevented a serious or potentially serious accident or operator error. Please describe this equipment with particular emphasis on the features which make it desirable from an operational standpoint.

In addition to the responses to these questions, reports of operational problems appearing in Nuclear Power Experience (22) were investigated at the five plants studied. These reported problems were often the same ones brought up by the operators in response to the first question above.

ACCIDENTS OR NEAR-ACCIDENTS

Operators in four out of five cases described actual errors or accidents rather than near-accidents. Whereas the operators spoke quite freely in all other parts of the interview, questions regarding accidents or near-accidents drew some resistance at two of the plants visited. About half of the operators at each of these plants declined the invitation to describe specific cases with such comments as, "I'd rather not say." Since the interview was entirely voluntary, these operators were not pressed for a response.

The accident and near-accident reports were analyzed in conjunction with published reports of operating errors that had occurred at each of the plants visited. The apparent causes of the accidents were sorted into categories provided below. Assigning causes to accident data is somewhat subjective; it is difficult to obtain precisely the same story from any two people describing the same incident. Furthermore, most accidents do not have a single causal factor. Often there is a mixture of such elements as incomplete procedures, faulty control board design, needless distractions, and lack of specific training in a given operation. The operators sometimes feel that accidents are improperly and unfairly attributed to "operator errors" since it is more expedient for management to recommend changes in procedures or additional training instead of modifying the control board. This criticism may be unjustified. However, the study team did note a number of control board deficiencies that had persisted for years despite numerous operator complaints. The categories of errors are listed in the order of frequency in which they occurred. For each category a sample case is provided to illustrate the nature of the class of problems. Each case was sorted into a given category by singling out the most prominent causal factor, although in some cases this was not entirely clear.

The largest category of operator errors was caused primarily by the absence of a timely, clear, attention-getting indication, either qualitative or quantitative, to inform the operator that the system was not operating properly or was trending in that direction. The second most common category of operator errors involved incorrect lineup of valves.

- Lack of information display or warning annunciator (18 cases). Five out of nine operators at one plant described a costly accident that burned the control rod drive motor stators. The causal factors given for this accident were: (1) the computer auditory alarm was not connected; (2) the computer printout alarm was not noted by the operator; (3) the operator in the field did not communicate adequately with the control room operator, and (4) the control room operator energized the control rod drive stators without cooling water, relying on alarms to advise of the lack of cooling water. This accident cost about $750,000.

- Improper valve lineups due to control panel procedural deficiencies (8 cases). "The feedwater regulator valves failed open, causing an increasing high level in the reactor vessel. The best operator action would have been to trip the feed pumps. He, instead, attempted to close the isolation valves, but they bound up. He eventually tripped the feed pumps but did not disable the backup pumps. The feed system tripped on high level, but when the level dropped, the backup pumps came on. The result was that water got into the main steam lines and the lifted safety valve wet down the dry well."

- Lack of control coding (3 cases). "The unit was at 50% load. One boiler feed pump was in service. The other boiler feed pump was being worked on by Maintenance. The operator was asked to shut down the feed pump being worked on and due to the close proximity of controls and no distinction between them, the operator tripped the wrong pump. This tripped the plant. We were down eight hours or so and lost a lot of dollars in megawatts."

- Watch turnover inadequate (2 cases). "The unit was in the mode of going through a power increase and control rods were being slowly withdrawn. During the shift change, the wrong positions in withdrawal sequence were either passed on or incorrectly understood. Consequently, the wrong rod was withdrawn. This caused a local overpowering of fuel rods. Proper action of inserting control rods was taken but the wrong rods were inserted. The result was a flux tilt and initiation of other local overpowering. Flux got into a bad situation and eventually there was a gaseous release to the environment. The release was within limits, but might have been serious."

- Operator failed to respond to an alarm, distracted by other events, or acknowledged alarm inadvertently (2 cases). The drywells were being inerted and the Unit #2 operator was very busy at his control board, being assisted by the center desk man. An alarm came in on the service and auxiliary panel (this panel is located in a remote area of the control room) showing that the nitrogen heating boilers had failed. The center desk man acknowledged the alarm but then got called away to Unit #1 and forgot about it. The result was cracked pipes caused by the influx of supercold nitrogen. The plant had to be shut down for repairs."

- Errors due to inadequate written procedure (2 cases). The primary cooling system was overpressurized at low temperature. The plant was shut down at the time. Three events were happening at the same time: (1) filling large storage tank, (2) periodic test of control systems, (3) raising reactor coolant system pressure test. Written procedures did not include a precaution to prevent overpressurization. Also, confusion resulting from many activities and too many people in the control room interfered with diagnosis of the problem.

- Lack of training (1 case). "A #21 steam generator feedwater override pushbutton was tapped accidentally by an operator. The operator asked himself, 'I wonder what that does?' The plant was tripped. We added a barrier around the button. It was obvious that he needed training on that function."

- Technician procedural error (1 case). "The I & C group was doing tests on the reactor protection system with a quality assurance man assisting. The technician skipped a step in the procedure that the QA man was reading. It tripped the plant. We lost $500,000 in megawatts. It was a matter of being hasty at the end of the workday."

- Mismatch between procedure and display units (1 case). A reactor was taken critical with the borated storage tank low. It was below the minimum 390,000 gallons required. The shift supervisor thought that the technical specification minimum volume was 350,000 gallons. The readout in the control room displays volume in units of feet while the procedure read in gallons and a conversion chart had to be referenced.

- Displays remote from primary control boards (1 case). During a xenon transient combined with a very low fuel exposure at the core bottom, rapid changes in local power low in the core resulted in fuel rod perforation. "An OFF-GAS alarm was set off. If the OFF-GAS chart recorder was not on the back panels, but rather in the operator's view, the operator might have caught it in time and could have minimized the fuel damage possibility."

- Lack of appropriate interlocks (1 case). "The containment spray system is backed up with the RHR spray system. Sometimes the RHR system is in service during normal operations. If the wrong valves are inadvertently opened it would be possible to spray numerous systems with radioactive borated water. They should interlock the valves so that they would be inoperable when the RHR is in normal function."

- Faulty communications (1 case). "We had a plant trip. The turbine was down and the reactor was up. We were opening a valve to change the steam line. It had to be done slowly; 'slowly' means different things and there was a communications problem between the supervisor and the operator. We had a lack of training or inadequate instructions."

ERROR-INDUCING HUMAN ENGINEERING PROBLEMS

The operators and trainers were asked to review their control boards and provide examples of poorly "human engineered" features which had or could lead to malfunctions or operator errors. The interview sample was quick to highlight deficiencies. The following categorization of these deficiencies shows the frequency with which each type of problem proved troublesome. The data are summarized in Table 19-1.

Table 19-1

EXAMPLES OF HUMAN FACTORS DEFICIENCIES

	HUMAN FACTORS ENGINEERING DEFICIENCY	FREQUENCY OF MENTION
(1)	Control Board or Panel Layout Arrangement Unclear, Illogical, Too Complex, or Mirror-imaged	18
(2)	Lack of Control Coding or Separation Leading to the Operation of the Wrong Control	7
(3)	Inadequate Information Display Formats, e.g., Specific Annunciator Alarms, Illegible Chart Recorders, Use of Chart Recorders Instead of Meters	7
(4)	Labeling Inadequate or Confusing	5
(5)	Placement of Displays or Panels Outside of Primary Viewing Areas, e.g., Back Racks or Too Low on Control Boards	4
(6)	Unreliable Equipment, e.g., Computer, Radiation Monitoring	3
(7)	Controls Susceptible to Accidental Activation	3
(8)	Confusing or Incompatible Scales on Instruments and Controls	3
(9)	Lack of Manual Override Option for Automated System Response	1
(10)	Need for Automated System in Place of a Manual System	1
(11)	Lack of Interlocks to Prevent Operator Error	1

EXAMPLES OF GOOD HUMAN ENGINEERING CONTROL ROOM FEATURES

When asked to single out a well-designed feature of their control rooms from the human engineering standpoint, the operators and trainers most often pointed to a particular panel which was relatively easy to operate and comprehend. The second most frequently mentioned category was a particularly useful display, e.g., "The Metrascope tells you what you need to know. The Core Monitor display is useless." The third most frequent category referred to the logical color coding of indicator lights. These responses came from the operators at one plant where a "green board" color logic was attempted (see Section 13). Table 19-2 presents a summary of the examples of good human-engineered features in the control rooms.

Tabel 19-2

EXAMPLES OF GOOD HUMAN FACTORS ENGINEERING FEATURES

	GOOD FEATURE	FREQUENCY OF MENTION
(1)	Good Panel Layout--Functionally Grouped Panel Elements, Sequentially Ordered Displays and Controls, Mimic Arrangements	31
(2)	Well Designed and Informative Displays	9
(3)	Logical Color Coding of Displays	4
(4)	Controls Located Within Easy Reach	3
(5)	Proper Scaling of Related Meters	3
(6)	Shape and Color Coding of Controls	1
(7)	Good Use of the Computer and Associated Alarm Systems	1

SUMMARY REMARKS

Considering the magnitude of human factors engineering problems uncovered by this report, the study team was surprised by how few operator errors were uncovered. Operators apparently overcome deficiencies in control room design through extensive training and a high degree of motivation. Most operators appear to be intelligent, resourceful, conscientious, and highly aware of the importance of their role. However, even the low error rate uncovered is not to be tolerated if alternatives exist. An unnecessary plant trip is a serious matter when the loss in revenues is measured in hundred of thousands of dollars. Plant systems are expensive and operator errors have collectively destroyed many millions of dollars worth of equipment. More important, operator errors can lead to radioactive releases that can endanger the community.

In a 1972 AEC evaluation of eight incidents of primary coolant release from operating boiling water reactors (4) it was concluded that: "The actions of operating personnel during the incidents tended to aggravate and prolong several of the incidents. The cause for the operating errors and deviations from operating procedures experienced during the incidents could not be determined. Although the consequences of these errors and deviations were not significant for the incidents studied, collectively they may reflect shortcoming in one or more areas such as the control room design, operation, and personnel training."

This study concludes that the extensive training of operators and their natural zeal need to be complemented with "human engineered" control rooms that reduce the probability of human error. The analyses of past errors plus good and poor features identified by operators and trainers support the need for better designed control boards which speak clearly to the operators, for controls that are coded to prevent misidentifications, for logical and color-coded displays, for better labeling practices, and many other improvements highlighted in this report.

Section 20

ADVANCED CONTROL ROOMS

This study has focused attention on the human factors aspects of present generation nuclear power plant control room designs. An effort was also made to examine advanced control room concepts in order to determine whether the control room of the future will avoid some of the human factors problems observed throughout the present study. It is also thought that systematic attention to human factors considerations is relatively more effective in shaping future control rooms than in retrofitting existing control rooms.

Meetings were scheduled with representatives of advanced design organizations associated with the General Electric Company, San Jose, CA; Combustion Engineering Inc., Windsor, CN; Babcock & Wilcox, Lynchburg, VA; Bechtel Power Corporation, San Francisco and Norwalk, CA; and Westinghouse Electric Corporation, Pittsburgh, PA.

Of the companies reviewed, G. E. is farthest ahead in marketing the Nuclenet system. G. E. has secured more than 30 orders for the Nuclenet System from utilities. The first U. S. control room based on the Nuclenet concepts is being installed by G. E. and Bechtel for the Pennsylvania Power and Light Susquehanna plant. This system will not use the sit-down console arrangement envisioned for later Nuclenet systems. The Susquehanna plant is expected to be operational in the early 1980s. G. E. plans to build a Nuclenet simulator that is to be available within three to five years.

Figures 20-1 to 20-4 show mockups of the Nuclenet system; Figures 20-5 to 20-8 show prototypes of Nuclenet CRTs and display formats. The G. E. advanced control room will use four computers that provide four paths between the system and the control room. The system will function as long as two out of the four computers are operating. The Nuclenet command console will house ten CRTs on the upright sloping surface of the U-shaped console. The benchboard segment of the console will house miniaturized controls. A horizontal band of annunciator lights is

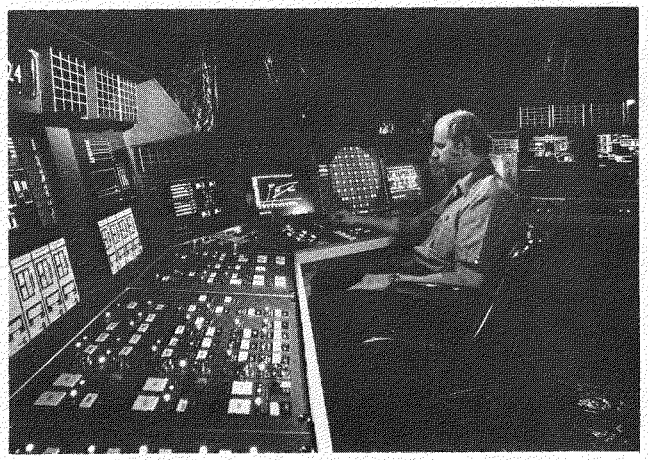


Fig. 20-1. Mockup of the G. E. Nuclenet advanced control room.



Fig. 20-2. Operator position at the Nuclenet console.

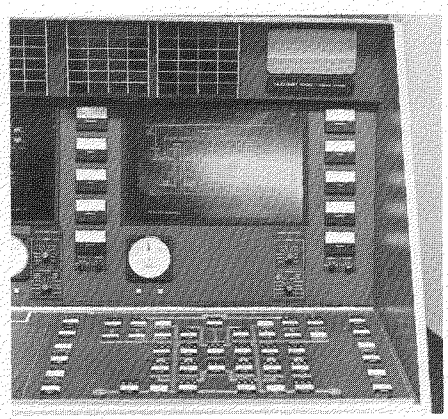


Fig. 20-3. Arrangement of annunciators, CRT, and benchboard controls on a segment of the Nuclenet console.

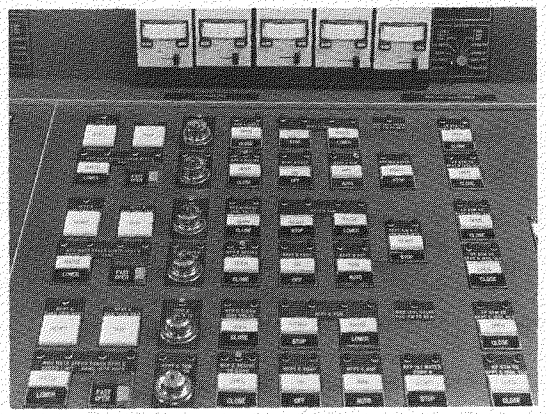


Fig. 20-4. View of the controls on the Nuclenet console.

placed uppermost on the console, above the CRTs. In addition to the U-shaped command console, a backup panel with dedicated displays and instruments is located on a wall 12 feet from the main console. G. E. does not anticipate extensive use of the backup panel because they expect high reliability for Nuclenet. The Supervisor's Console and an auxiliary functions console are at either end of the U-shaped console.

The Nuclenet CRTs are related to the power generation systems and not the safety-related systems. G. E. analyses indicate that one man can normally operate the Nuclenet system. During such periods as startup, two men will be required.

Considerable effort is being expended on developing CRT display formats, including color and symbology. Nuclenet will accommodate 200 CRT format pages. G. E. will define and format 60 of these. The architect-engineering firm will develop 40 display pages, and the utility will have responsibility for the remainder. G. E. will develop display format guidelines, but there is no assurance that either the architect-engineering firm or the utilities will follow these guidelines. G. E. cannot determine diagnostic formats with any finality until the utilities develop their operating procedures. The utilities may retain consultants to help them in formatting displays.

As mentioned above, the first installation of G.E.'s advanced control room will not adopt the Nuclenet configuration. Instead, only two CRTs will be placed at the operator's desk and the remaining CRTs will be on a vertical board, thus requiring a standing operator position. The utility involved has a traditional preference for standing, as opposed to seated, control board operation.

Combustion Engineering (CE) is several years behind G. E. in marketing an integrated advanced control room. C. E. is committed to developing an advanced control room for the TVA but had not developed a marketing approach beyond this commitment at the time of our discussions. C. E. may elect to sell increments of advanced computer graphic displays rather than integrated control rooms. For example, an Arizona utility has on order a control room that was purchased several years ago. As the state-of-the-art has advanced, this utility is considering add-ons to acquire the computer-graphic capability as a supplement to the conventional control room.

C. E. advanced control board concepts are shown in Figures 20-9 to 20-11. The main control room includes the master control console, the auxiliary control and safety



Fig. 20-5. Prototypes of the Nuclenet CRTs currently being developed.

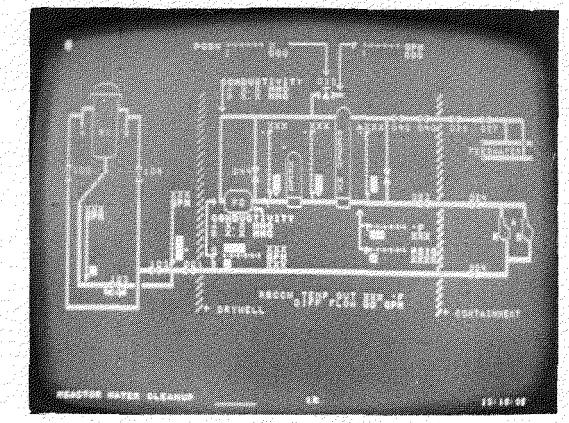


Fig. 20-6. Sample Nuclenet computer-graphic format.



Fig. 20-7. Sample Nuclenet computer-graphic format.

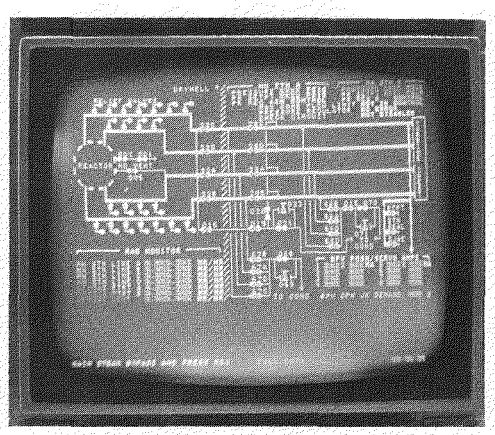


Fig. 20-8. Sample Nuclenet computer-graphic format.

center, and the supervisory monitoring station. The master control console allows a seated single operator to access all information necessary to control the plant. During abnormal situations the console is designed for two-man operation. All alarm annunciation is accomplished through the CRT displays. The operator has ten CRTs on the master control console.

The auxiliary control and safety center is designed to complement the functions performed at the master control console (MCC). These panels include the controls not required on the MCC for normal operation, but which are required in the control room. The auxiliary control center consists of control panels for auxiliary secondary plant functions, control of the station electrical system, control of the switchyard, and any live electrical functions controllable from the plant. The safety center allows the operator to interface with plant protection systems during emergency situations. It contains controls and indicators (CRTs are excluded) to cope with postulated accident conditions that require plant protection system initiation, monitoring, or control .

System reliability is provided by a remote data multiplexing system that eliminates system failures due to single component, subassembly, or subsystem failures. The plant is served by two independent multiplexing data strings, each equipped with dual central control units and dual data busses.

In addition to the conceptual designs shown above, C. E. has developed some early mockups shown in Figures 20-12 and 20-13. Also an active CRT display format development program is underway (see Figure 20-14). A special color coding scheme has been developed as follows:

Color	Use
Black	Display background
Blue	Nonessential or noninformation bearing data
Cyan	Essential or information bearing numeric data or text
Green	Off, deenergized, closed, normal
Red	On, energized, open, bypassed
White	Intermediate between red and green
Yellow	Caution, attention required
Magenta	Danger, immediate action required.

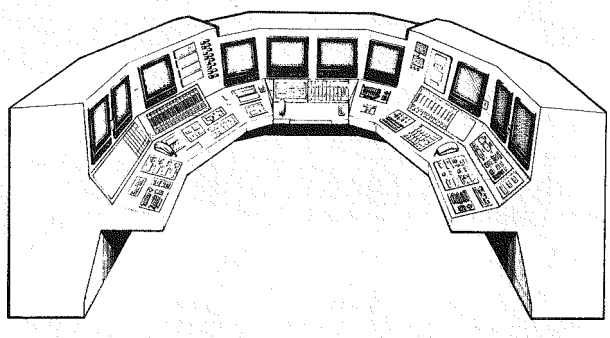


Fig. 20-9. CE advanced master control console.

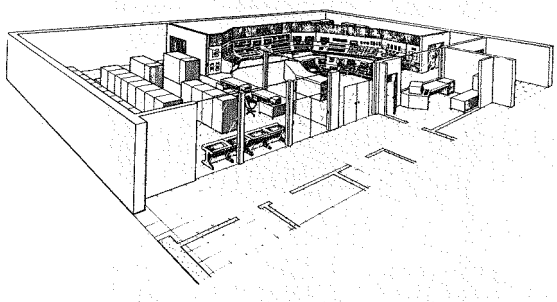


Fig. 20-10. CE single level control room.

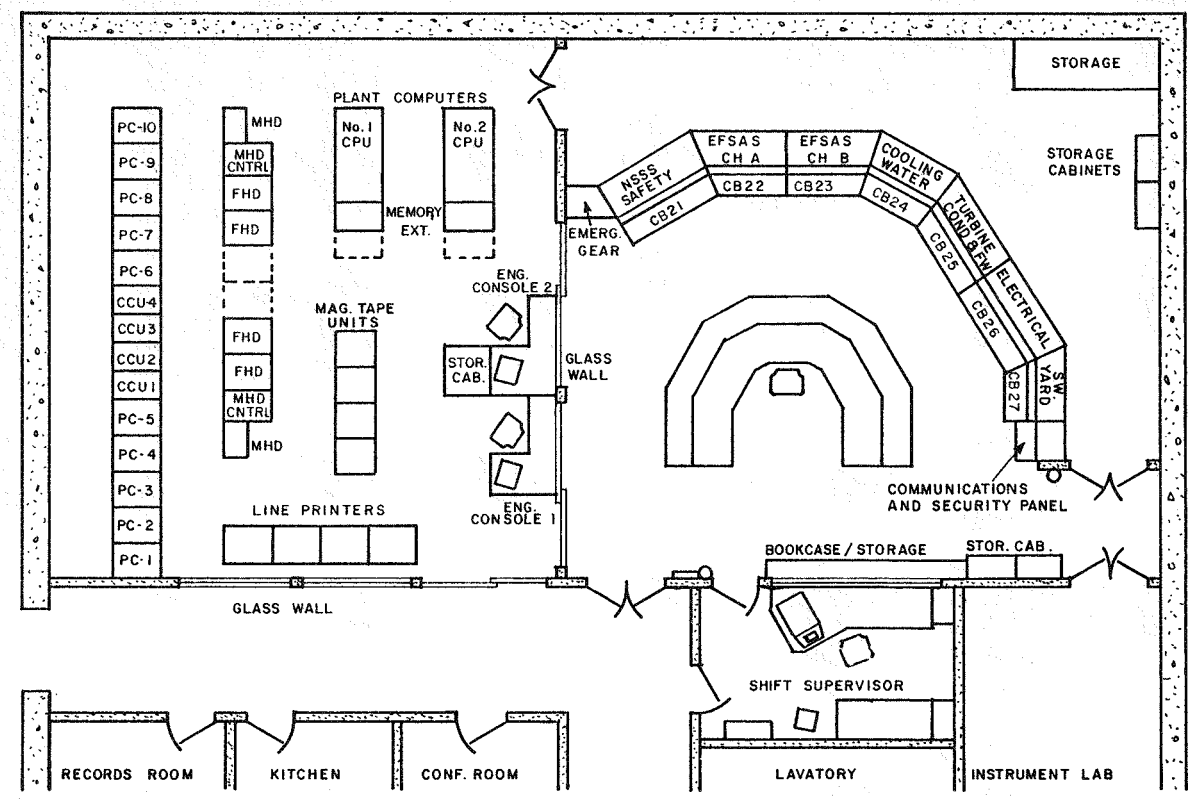


Fig. 20-11. Single level control room.

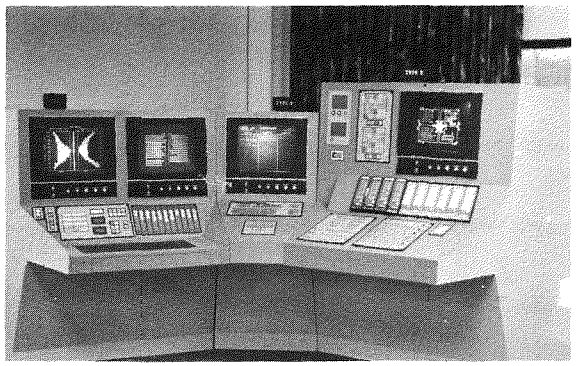


Fig. 20-12. Early Combustion Engineering mockup of advanced control-display concepts.

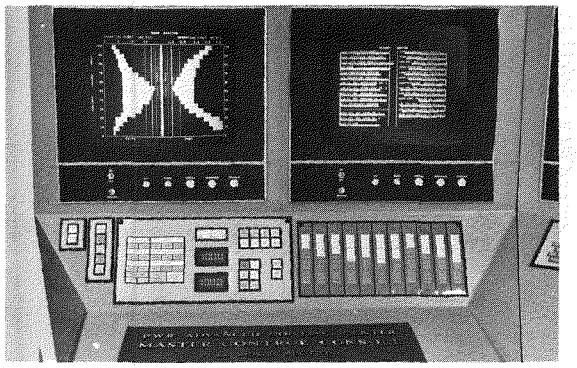


Fig. 20-13. Mockup of C. E. CRT formats.



Fig. 20-14. Prototype C. E. CRTs showing format development activities.

This color code attempts to preserve present Red/Green conventions and introduces a distinctive magenta color for danger indications.

Babcock and Wilcox (B&W) advanced control room design concepts are at about the same stage as those of CE. B&W is developing several different advanced control room approaches, one for the Washington Public Power Supply System and another for TVA. B&W is not marketing a single advanced control room concept such as Nuclenet. B&W developed a complete mockup of the Washington utility control consoles and backboards (see Figure 20-15) which utilized four computer driven color CRTs not including turbine functions. The design philosophy is that no plant systems are dedicated to a single CRT but rather are available for call-up by the operator on any of the CRTs. However, one CRT will probably be reserved for alarms.

The advanced control room for the TVA Bellafonte unit follows a completely different approach. It will be wholly mimicked in format and design. The main console will be more than 40 feet long, and some of the engineers consider this a "design headache." It will be interesting to determine the operators reaction to this control room and the eventual record of operator errors. We predict, based on discussions in Section 5, that this type of room would be easier to train operators on and would result in fewer human errors.

B&W advanced control room designers complained about the lack of any applicable human engineering standards for this activity. They were doing their best with some old military standards and a graduate student's thesis on human engineering. They were quite vocal on some A&E contractors and utility decisions based primarily on cost or personal preference. One example was the continued use of the large pistol grip switches which are exorbitant users of panel space.

At the B&W Research and Development Laboratory, there was an active program on color CRT parameters and various types of display formats (see Figure 20-16) A detailed specification had also been written on this topic and B&W is returning to the military convention of using red for abnormal or warning and green for a normal operating condition. They are also conducting research on display reaction time, bar chart labeling for rapid readability, color discrimination, and optimum line crossing layout.

Westinghouse is investigating and planning to market in the near future a variety of advanced control room design approaches including optimized conventional design

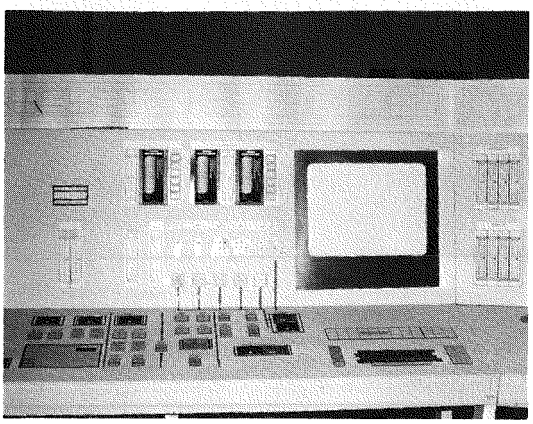


Fig. 20-15. Babkcok & Wilcox mockup of advanced control console.

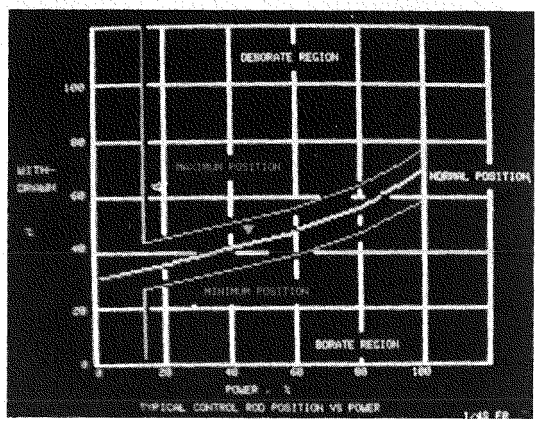


Fig. 20-16. B&W format for advanced control systems.

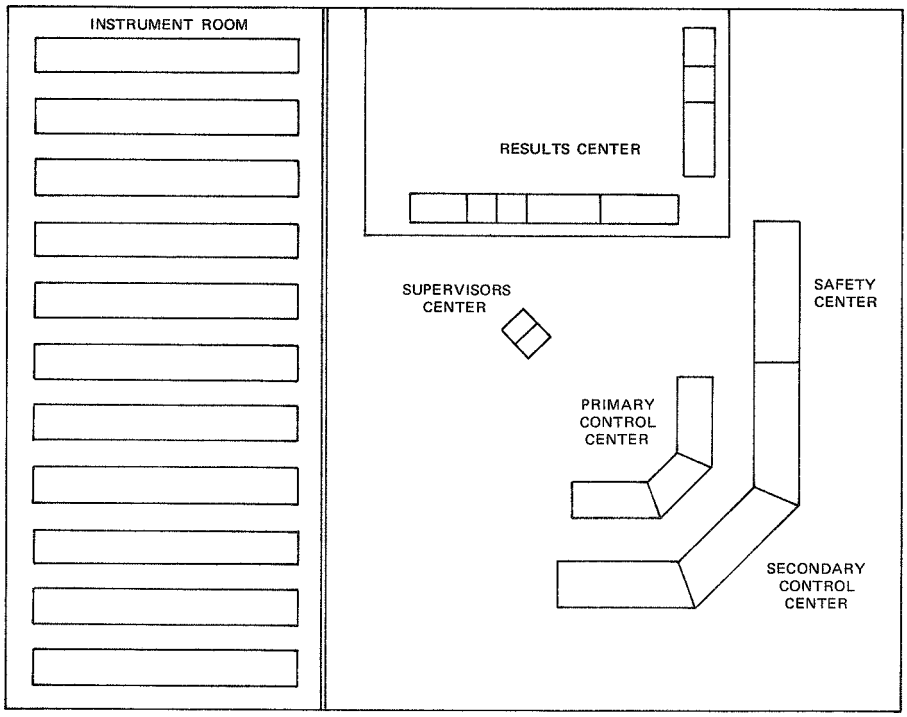


Fig. 20-17. Westinghouse advanced control room design.

techniques, reduced-size versions of conventional approaches, and computer-generated visual display approaches. A classification study has been conducted to determine the frequency of use of control board elements within the various operational modes. Based on this study, control board components have been classified as belonging in either primary or secondary control board areas. Also, video tapes have been prepared of simulated operations (e.g., hot shut-down to full power and back). A review of these tapes by means of link analysis techniques has indicated improvements in the general arrangements of the boards for future designs.

Based on these activities preliminary designs are being formulated such as the concept shown in Figure 20-17. A mockup of this concept is being constructed; that for the primary control center already completed. This mockup is being reviewed by operations personnel, control board design engineers, and human factors specialists.

A program has been initiated to develop CRT formats for advanced display concepts. A team approach to this task is being utilized in developing these advanced displays.

The primary control center (PCC) shown in the foreground of Figure 20-17 will house all controls and displays required for normal power operations. The secondary control center (SCC) in the background will accommodate all other required instruments, recorders, and controls other than those that are safety related. The safety related components are assigned to a safety center. The results center is the location for recording system data, e.g., results of core calculations. A CRT display with an interactive keyboard will provide plant personnel with the capability to modify the display systems or computer programs. This center will also include an engineering station which can call up information from any of the primary control center CRTs.

The supervisor's center is located to provide visual contact with the PCC and safety center. This station will have a CRT readout display with the ability to access any display available at the other control centers.

Separation of control-display elements into primary and secondary areas can be troublesome because the operator is then sometimes required to be in two places at once. Westinghouse hopes to avoid this problem by means of allowing call-up of secondary area information in CRTs located in the primary control center console.

These designers also hope to provide direct visual access to the SCC from the operator's position at the PCC. Based on our observations, this will not be easily accomplished.

OPERATOR AND TRAINER ATTITUDES TOWARDS ADVANCED CONTROL ROOM TRENDS

Operators were queried about their attitudes toward advanced control room trends. The following question was asked: "From all indications, future generation control panels will rely heavily on computer-generated cathode ray tubes or TV screen type displays for the display of information to operators, thereby minimizing the use of extensive arrays of fixed meters and indicators. Do you favor this trend? What advantages and disadvantages do you foresee from an operation standpoint?" The attitudes of operators and trainers regarding advanced control room concepts were divided between those who were frankly apprehensive regarding any computer-based control board concept and those who saw the trend towards computer-graphic displays as a good one, but only as a supplement to their existing dedicated control-display system. A small minority endorse future control room concepts and some took a "wait and see" attitude.

Much of the negativism toward future concepts stems from operator experience with present computers. As noted in Section 4, a major problem noted in four of the five plants visited is the notorious unreliability of control room computers and lack of adequate operation training in the characteristics and operation of computers. These experiences have colored the expectations of the operators with regard to advanced control room concepts.

A second major concern is that the CRTs will not be able to deliver in an expeditious manner all of the information now simultaneously available to the operator, i.e., the operators and trainers anticipate an information retrieval problem in accessing all the data that the computer generates and stores. The operators feel that they can more effectively take the pulse of the plant and diagnose abnormalities by scanning the present displays than by trying to call up selective CRT presentations.

On the other hand, some operators saw advantages of reduced control room size. Others saw the value of computer-graphic displays in diagnosing abnormal events and as a supplement to existing dedicated instruments. A few mentioned the possibility of using the computer to call up reference diagrams, in lieu of searching through prints, and using CRTs to display emergency procedures.

Some sample comments which follow support the above summary:

- I would love to see everything we have placed on one to three CRTs. But the basic parameters (dedicated displays currently available) need to be there at all times. I would use the CRTs as a tool and a backup. I wouldn't like CRTs as the primary display.
- I am not in agreement that CRTs should displace a lot of meters. While the CRT has the advantage of a centralized place to display a lot of parameters, the disadvantage is that you may decide to watch the wrong parameters.
- I'm skeptical. I don't think that the reliability of computers is that good. Total computer failure will knock everything out. In a real emergency you would have to rely on a secondary analysis of unfamiliar indications.
- As it is now, any trained person can walk around the control room and know what is happening. In a CRT system, only the one individual with his hands-on the system would know the complete status.
- The cause of a disturbance registered on one part of the board may be found by observing an indicator on some other, perhaps more remote, part of the board. A CRT could reduce the probability of detecting a remote cause--information would not be readily available for the scanning activities required to detect remote causes.
- It is easier to select information from a panel of indicators than to select a particular parametric value from a CRT page of values.
- The computer must be 100% reliable before it should replace anything--and this is unheard of.

SUMMARY

It was hoped that future control rooms would avoid the human factors problems observed with present generation control rooms. Our brief look at future concepts is less than totally reassuring. While there are indeed some distinct advantages associated with control rooms based on computer-graphic displays, we cannot conclude that the man-machine interface will be any better than what currently exists. In fact, the operators may be correct in their great pessimism concerning trends in control room design.

Advanced control room designers are proposing and successfully marketing essentially unproven systems. Substantive data on the adequacy of the man-machine interface has not been developed on any advanced control room simulator. The design organizations speak of simulators solely for future operator training purposes. In our view, which is based on military and space experience, no transition as dramatic as is being proposed, and with so many open human factors questions, should be attempted until the man-machine interface is proved effective. It is somewhat surprising to note the eagerness of utilities to spend additional millions for advanced control room concepts without solid evidence of their worth.

While some excellent human factors attention is being provided to anthropometric considerations, maintainability, and the detailed design of CRT formats and console layouts, no in-depth analyses of the operator's functions and tasks are being conducted as the basis for advanced designs. No empirical studies are being performed to verify the ease of data retrieval, and no formal or definitive comparisons between the old and the new are underway to demonstrate the relative advantages of future designs in terms of reduced operator errors, increased operator efficiency, or reduced training and selection demands on the utility.

The present lack of any standardization among control rooms is likely to persist unless present trends are somehow reversed. For example, each of the advanced designs reviewed has developed its own color code for CRT graphics. With the control room vendor, the architect-engineer, the utility, and assorted consultants each having responsibility for a segment of the CRT pages, what is the likelihood that the 200 pages will have standardized color codes, symbology, abbreviations, etc.? In the case of one future plant, a sit-down console concept was changed to a standing operation because of an intuitive feeling that a standing operator is somehow more effective than a sitting operator. The orientation of the master control console with respect to auxiliary consoles and safeguards panels differs from design to design. Does it make sense to separate the safeguards features from the master control console? This was a severe disadvantage in one of the control rooms reviewed in this study.

Advanced control room designs offer great promise in reducing control room size so that it is normally manageable by a single operator. The computer graphics have the potential to provide the operator the system insights now offered by mimic panel arrangements which operators strongly favor. Computer-based advanced control systems potentially offer another capability which is apparently not being included in the systems reviewed. One of the major problems that the operator presently encounters is the need to piece together or integrate many discrete bits of data or symptoms to form an accurate diagnosis of a system problem so that correct remedial action can be taken. This is currently a formidable task and operators vary widely in their ability to perceive and piece together events occurring across expansive control boards. Associated alarms may sound as much as an hour apart and it is difficult for an operator to make such relationships. The advanced control systems, with their extensive computer capabilities, could do much to facilitate this task. For example, the computer could be programmed to recognize and integrate patterns of symptoms and offer the operator probable causes in order of priority or probability along with recommended actions. Decision analytic techniques which are

finding increasing application in complex command and control centers should be reviewed and evaluated for feasibility in the power plant control room. Decision aids should be developed and incorporated in all phases of plant operation to provide an optimal integration of system information with the required assessments and judgments of the experienced operator. Design efforts are being devoted to the means of displaying information to the operator, but little or no effort appears to be devoted to the overwhelming task of integrating and evaluating this abundance of data. None of the advanced concepts reviewed offers the operator malfunction diagnosis or decision-making aids such as fault trees, decision logic structures, checklists, template analyses, conditioned assessment models, multi-attribute utility models, or Bayesian probability models. Human factors research indicates that man is a poor processor of information and advanced control room concepts should begin considering ways of alleviating the information processing burden that currently rests on the power plant operator.

Other industries have successfully turned to such advanced design approaches. As one designer observed, "This is the last major industry not to go to CRT-computer control-display concepts." However, before we can be sure that a successful and painless transition can be made between the present and future control rooms, some basic questions should be asked:

- How well can the operator monitor system status with advanced versus conventional control-display arrangements?
- How effectively can the operator respond to system abnormalities with advanced versus conventional control-display boards?
- Which of the alternative CRT formattting approaches being developed are most effective from the man-machine interaction viewpoint?
- For what period of time can an operator be expected to continuously monitor flickering CRT displays without undue fatigue? Is it reasonable to expect the operator to sit before such displays for 16 hours in the event that his relief does not show up?
- How effectively can control functions be integrated with the various CRTs available? While alternate displays can be moved from CRT to CRT, the present control concepts are in fixed positions. Have candidate control concepts such as light pens been thoroughly evaluated?
- Has the arrangement of primary and secondary consoles been based on functions and task analyses and validated through mockup and simulation verification exercises?
- Is room illumination consistent with the special demands imposed by CRT displays?
- Have alternative data retrieval approaches been examined empirically and has the operator been provided ready, error-free access to all the data available?

- What special demands will be required of the utility to maintain and reprogram the computer data system?
- What is the optimal arrangement of the advanced control room--communications equipment, visitor provisions, egress-ingress pathways, etc., that would be commensurate with the advanced control consoles being developed?
- How readily can the existing pool of licensed operators make the transition to advanced control room concepts?
- What implications do the advanced control room concepts hold for training and retraining programs?
- Are the selection criteria currently applied in recruiting control room operators applicable to operators for advanced control rooms?

Section 21

CONCLUSIONS AND FUTURE STUDY NEEDS

This study reviewed five nuclear power plant control room designs from the human factors engineering standpoint. We have attempted to show that in many respects, some minor and some major, the control rooms are not optimized to promote reliable, effective, and safe operator performance. Control rooms are complex and tend to maximize rather than minimize the training and selection burden on the utilities. Despite extensive training programs, highly motivated and capable operators can and do make costly errors.

The nuclear utility industry finds itself in the same situation that the military found itself during World War II: the consequences of human operator error were so severe that attention to training and selection were not sufficient to guarantee effective man-machine performance. Human factors engineering was developed to help minimize the probability of operator error by tailoring the workplace to the abilities and limitations of the operator, especially when anomalous and stressful situations occur. In recognizing the fallibility of humans and the failure of extensive training and careful selection to preclude operator errors, this industry favors increasingly automated system responses to system anomalies. There are obvious limits to the extent that automation can substitute for operator judgment. As the control systems become increasingly complex and automated, it is more difficult for the man to effectively intervene manually when automated systems fail. Automation will not eliminate the man from the system any more than we have eliminated the pilot from the Boeing 747 cockpit. Automation will require other human engineering approaches in providing an effective man-machine interface.

What can or should be done to reverse the picture given by the preceding pages and introduce human factors principles into the control room? In discussing this question with many individuals in the industry, several points of view emerged. One training director at a simulator training center said: "A good operator can operate any board. The job is boring so the board creates a challenge. If the board is too straight-forward or 'human engineered,' then the operator will lose his edge." This view regards the operator as infinitely adaptable to any control room design.

Others see the need for human factors attention to control room design but have no real understanding of the scope or content of this discipline. As one individual put it: "Human engineering is treated as a black art."

Another view holds that our findings present only one side of the picture, namely, the man-machine interfaces observed in operational control rooms and simulators. Had the study focused on the constraints (standards, regulations, criteria, hardware availability, schedules, etc.) presently placed on the control board designer, we might have had a better understanding of how the control boards came to be as they are. There may be much truth in this view and it suggests that future effort should be directed at reviewing these constraints to determine the extent to which operator effectiveness factors may have been traded away in the interests of other pressing concerns.

Designers that we have spoken to in the course of this study have sensed the need for human factors data to apply in the formulation of control boards, but have not always been successful in finding the data to fit their specific needs. They generally bemoan the lack of human factors information in a readily usable format and have little use for vague generalizations that state lofty human factors objectives.

We conclude that a detailed set of human factors standards must be developed and must receive industry-wide acceptance. These standards will not guarantee a standardized control room, which is probably an unrealistic expectation. Rather, such standards will promote a uniform and systematic set of guidelines based on a concern for human factors issues and design considerations. Adoption of these standards will eliminate some of the major deficiencies noted in this report, e.g., operator stations that require the operator to sit with his back to the control boards, meters placed beyond visual access limits for fifth percentile operators, lack of functional grouping and demarcation of panels and subpanels, inconsistent color coding of displays, and lack of shape or other coding of identical controls placed side by side.

However, detailed standards that are acceptable to all segments of the industry will not be developed overnight. Furthermore, human factors standards will have greater relevance to the control room of the future than to existing operational control rooms. In the interim, it is hoped that this report may serve as the starting point for a reexamination of control rooms. A major follow-on study area proposed

is an examination of existing control rooms with the objective of developing reasonable and cost-effective remedial measures to upgrade the control room from the human factors standpoint.

While it is easy to fault existing designs, it is quite another matter to retrofit these designs to solve the problems encountered. Some problems such as inefficient labeling practices and the lack of meter band coding lend themselves to solutions at a minimum cost and no interference with ongoing operational activities. Other changes, such as the redesign of especially troublesome panels, will have to be made when the plant is down for scheduled refueling. In any case, a hard look should be taken at what can be done along with the costs and associated benefits involved. This effort would require the support and cooperation of the operational and engineering staffs of some representative plants to determine what is reasonable and cost-effective. This follow-on study should produce a guide that all utilities could apply in evaluating the human factors aspects of their control rooms and adopt remedial measures where indicated. The guide would specify detailed techniques for improvements in the following areas: safeguards to preclude accidental activation of controls, techniques for functional demarcation of related groups of panel elements, recommended shape coding practices for controls and color coding for displays, improvements in meter scaling and coding, guidelines for control of environmental factors, etc.

While the foregoing study recommendation would focus on the need to enhance existing control room designs, a more fundamental need exists for a comprehensive human factors design guide which would structure the control room from concept to operation in accordance with human factors engineering principles. Such a design guide would provide the analytic and design tools for shaping the control room to accommodate the needs, capabilities, and limitations of the operator in the interests of safe, reliable, and effective operator performance. The guide would include the following topics. (1) The role of the operator, (2) The informational needs of the operator, (3) Control options, (4) Control room arrangement, (5) Control board configuration, (6) Control panel designs, (7) Display selection and format criteria, (8) Control selection, (9) Warning-annunciator system design, (10) Prevention of accidental activation of controls, (11) Labeling practices, (12) Control display coding practices, and (13) Design verification by means of mockups and simulation.

The development and application of these guides would further the development and refinement of human factors standards that might gain industry-wide acceptance.

Beyond the development of design guides and standards, research should be initiated to develop a data base that describes the control room operator and man-machine interfaces. Very little is known, in a formal scientific sense, regarding the nuclear utility operator compared to the astronaut population, the military man, or the FAA controller. Some of the research topics that would provide data of use to designers and utility decision-makers are provided below. It is recognized that some of these research topics may not be within the scope of EPRI's charter responsibilities.

- Major selected control board panels should be reconfigured in terms of human factors engineering criteria and an evaluation of operator performance should be conducted comparing existing panels with human engineered layouts.
- A definitive comparative evaluation should be conducted to determine the relative advantages of conventional versus advanced, computer-based control board concepts.
- An investigation should be conducted of decision-aiding techniques, such as fault trees, that might help the operator to identify, integrate, and assess presently scattered discrete bits of information.
- A human factors review of the auxiliary operator's role, his interaction with the control room operation, and the man-machine interfaces associated with the auxiliary operator's tasks should be reviewed.
- Investigate nuclear power plant communication system needs to develop recommendations for facilitating normal and emergency control room operator contacts with other plant personnel.
- Review nuclear power plant hardware systems against ease-of-maintenance criteria; determine adequacy of maintenance instructions and procedures and evaluate training and selection methods for maintenance personnel.
- Investigate how best to utilize existing computer capabilities in operational control rooms and delineate training requirements to enhance the operator-computer interface.
- Review approaches for presenting procedural information in a timely and efficient manner.
- Survey non-U. S. approaches to control room design and human factors issues.
- Review techniques developed in other contexts for enhancing operator vigilance, including a consideration of boredom and stress factors.
- Analyze performance degradations associated with shift transition schedules and overtime demands to develop recommendations for effective scheduling of operators.
- Determine the anthropometric ranges of control room operators.
- Develop human reliability estimates for representative normal and emergency operator tasks.
- Determine the relative effectiveness of single unit versus multi-unit control rooms.

- Establish the relative merits of alternative panel layout approaches, (e.g., mimic versus conventional functionally grouped panels) in terms of operator response times and error rates.
- Determine the need and mechanisms for applying organizational effectiveness techniques in alleviating adversary relationships between management and operators and substituting effective communication channels and goal reconciliation approaches.
- Examine the content of training curricula in relation to operator performance requirements to establish the best mix of theoretical and operational training.
- Define the operator's task, required skills and background factors, to establish selection criteria and valid selection methods for future operators.
- Extend the human factors methodology developed for the present study to an examination of the operator-control room interfaces in the fossil fuel plant.

REFERENCES

1. Austin, R. C., L. E. Kanous and J. D. Starkweather, A Task Force Approach to Control Room Planning, Proceedings of the American Power Conference, Chicago, April 23-25, 1968, Vol. 30, pp. 1228-1239.

2. Dickey, D. E., A Human-Engineered Reactor Control Panel, Nucleonics, 18(12): 80-81 (December 1960).

3. Fitzpatrick, R., D. W. Dysinger and V. L. Hanson, The Performance of Nuclear Reactor Operators, American Institutes for Research, AIR-491-9/68-FR, September 1968.

4. Evaluation of Incidents of Primary Coolant Release From Operating Boiling Water Reactors, Atomic Energy Commission, Directorate of Regulatory Operations, Office of Operations Evaluation, October 30, 1972.

5. Hanauer, S. H., Control Room Standardization: A Safety Goal, IEEE Transactions on Nuclear Science, February 1974, Vol. NS-21, No. 1, pp. 957-958.

6. Kaiz, G. H., Control Panel Design--An Additional Impact on Plant Operations, paper presented at the Conference on Reactor Operating Experience, Reactor Operations Division of the American Nuclear Society, August 3-5, 1975, Albuquerque, N. M.

7. Power Plant Operator Selection Methods, Electric Power Research Institute, Conference Proceedings, EPRI SR 28 Special Report January 1976.

8. Raudenbush, N. H., Human Engineering Factors in Control-Board Design for Nuclear Power Plants, Nucl. Safety, 14 (1): 21-26 (1973).

9. Raudenbush, N. H., Evaluation of Operator Response at a Miniaturized Control Board of a Large Nuclear Power Reactor, MS Thesis, North Carolina State University, 1971.

10. Reactor Safety Study; An Assessment of Accident Risks in U. S. Commercial Nuclear Power Plants, U. S. Nuclear Regulatory Commission, WASH-1400 (NU REG-75/014), October 1975.

11. Seidenstein, S., Time Stress and Human Performance, Lockheed Missiles and Space Report, May 1975, Sunnyvale, California.

12. Seminara, J. L., & R. L. Ketcham, "Combatting Confusion in Control Panels," Machine Design, April 1968.

13. Seminara, J. L. & James K. Gerrie, "Effective Mockup Utilization by the Industrial Design--Human Factors Team," Human Factors Journal, August 1966, Vol. 8, No. 4, pp. 347-359.

14. Seminara, J. L., "Warning-Systems Design," Machine Design, September 30, 1965, pp. 106-116.

15. Seminara, J. L., and S. O. Parsons, "Seventeen Ways to Stop Control Accidents," Control Engineering, November 1964.

16. Seminara, J. L., and S. O. Parsons, "Display Systems Design," Machine Design, November 7, 1963.

17. Seminara, J. L., "Designing Meters For Maximum Reading Efficiency," Design News, May 22, 1961.

18. Seminara, J. L., "Designing Labels For Efficient Reading," Design News, May 9, 1960.

19. Seminara, J. L., "When Equipment Says It In Color," Product Engineering, September 14, 1959, pp. 51-54.

20. Seminara, J. L., "Control Identification," Machine Design, June 25, 1959, pp. 137-139.

21. Swain, A. D., Preliminary Human Factors Analysis of Zion Nuclear Power Plant, October 1975, Sandia Reliability Division, Sandia Laboratories.

22. Verna, B. J. (Publishers), Nuclear Power Experience, Vols. PWR 1 and 2, BWR 1 and 2, Los Angeles, California.

Appendix A

HUMAN FACTORS ENGINEERING CRITERIA DEVELOPMENT REFERENCE LIST

GENERAL TEXTS & PUBLICATIONS

Applied Ergonomics (British Journal).

Bennett, E., Degan, J., and Spiegal, J. (eds), Human Factors in Technology, McGraw Hill, New York, 1962.

Biberman, B. M., Perception of Displayed Information, Plenum Press, 1973.

Chapanis, Alphonse, Man-Machine Engineering, Wadsworth, Belmont, CA, 1965.

Chapanis, Alphonse, Research Techniques in Human Engineering, The John Hopkins Press, Baltimore, 1959.

Damon, A., Stoudt, H. W., and McFarland, R. A., The Human Body in Equipment Design, Harvard University Press, Cambridge, Mass., 1966.

DeGreene, Kenyon, Systems Psychology, McGraw-Hill, New York, 1970.

Dreyfus, Henry, Designing for People, Paragraph Books, New York, 1967.

Dreyfus, Henry, Symbol Sourcebook, McGraw-Hill, New York, 1972.

Ergonomics (British Journal).

Fitts, P. M., and Possner, Human Performance, Brooks/Cole Publishing Co., Belmont, CA, 1968.

Fogel, L. J., Biotechnology; Concepts and Applications, Prentice-Hall, Englewood Cliffs, New York, 1963.

Fraser, T. M., Philosophy of Simulation in a Man-Machine Space Mission System, National Aeronautics and Space Administration, Washington, 1966.

Gagne, R. M. et al., Psychological Principles in System Development, Holt, Rinehart and Winston, New York, 1961.

Harris, D. H. and Chaney, F. B., Human Factors in Quality Assurance, Wiley, 1969.

Human Factors (Journal of the Human Factors Society).

Johnson, E. G. and Corliss, W. R., Human Factors Applications in Teleoperator Design and Operations, Wiley, 1971.

Journal of Aerospace Medicine.

Journal of Applied Psychology.

Kryter, Karl, The Effect of Noise on Human Performance, McGraw-Hill, N.Y., 1970.

McCormick, E. J., Human Factors Engineering, McGraw-Hill, N.Y., 1970, 3rd Ed.

Meister, David, Human Factors; Theory & Practice, Wiley & Sons, N.Y., 1971.

Meister, David & Rabideau, G. F., Human Factors Evaluation in System Development, John Wiley, N. Y., 1965.

Murrell, Ken, Human Performance in Industry, Reinhold, N. Y., 1965

SID Journal (Journal of the Society for Information Display).

Singleton, W. T. et al., The Human Operator in Complex Systems, Taylor and Francis LTD., London, England, 1967.

Woodson, W. E. & Conover, D. W., Human Engineering Guide for Equipment Design, McGraw-Hill, N. Y., 1963.

SPECIFICATIONS

MIL-D-2623A Qualitative and Quantitative Personnel Requirements Information (QQPRI) April 1961.

MIL-H-46895A Human Engineering Requirements for Military Systems, Equipment and Facilities, May 1972 (Tri-Service).

MIL-STD-470 Military Standard Maintainability Program Requirements for Systems and Equipment, March 1966.

MIL-H-XXX- Personnel Subsystem/Human Factors Test and Evaluation (Unpublished Air Force Specification, 1971).

OPNAV INST 39008 Planning Procedures for Navy RDT & E Program.

REGULATIONS

AFP 80-14--Test and Evaluation.

AFP 800-15--Human Factors Engineering and Management, October 1974.

STANDARDS

MIL-STD-1472A--Human Engineering Design Criteria for Military Systems, Equipment and Facilities.

Occupational Safety and Health Standard, Dept. of Labor OSHA, Federal Register, Vol. 37, No. 202, October 18, 1972.

HANDBOOKS

DH 1-3 AFSC Design Handbook--Personnel Subsystems.

DH 1-X AFSC Design Handbook--Checklist of General Design Criteria.

DH 2-8 AFSC Handbook--Life Support.

Data Book for Human Factors Engineering, Vol. 1 Human Engineering Data, NASA-Ames Research Center, November 1969.

NASA Bioastronautics Data Book, NASA SP-3006, 1973.

Navships Display Illumination Design Guide, Naval Electronics Laboratory Center, TD 223, July 1973.

Human Engineering Guide to Equipment Design, Joint Army-Navy-Air Force Steering Committee, 1972.

Handbook of Instructions for Ground Equipment Designers, AFSCM 80-5, August 1963.

Human Factors Reference for Designers of Ground Handling Equipment, Lockheed Missiles & Space Co., Human Factors Staff, January 1962.

Human Factors Reference for Missile Designers, Lockheed Missiles & Space Co., Human Engineering Staff, November 1967.

Human Factors Reference of Facility Designers, Lockheed Missiles & Space Co., Human Engineering Staff, February 1969.

Human Factors Reference for Designers of Electronic Checkout Equipment, Lockheed Missiles & Space Co., Human Engineering Staff, October 1973.

Appendix B

STRUCTURED INTERVIEW QUESTIONNAIRE ADMINISTERED TO OPERATORS AND TRAINERS

OPERATIONAL CHARACTERISTICS OF NUCLEAR POWER PLANT CONTROL ROOMS

STRUCTURED INTERVIEW

We are doing a study for the Electric Power Research Institute to determine how good present day nuclear power plant control rooms are from an operational standpoint. The purpose of the study is to determine what groundrules should be used in designing control rooms for future generations of nuclear power plants. Perhaps the best source of information in terms of improving control room designs and avoiding the mistakes of the past is to talk directly to the people who have to operate control rooms on a day-to-day basis. That is why we have asked for this interview with you.

Let's pretend that you are talking with the man who was responsible for the design of your control room. He is about to embark on the design of another generation of control rooms and he wants your frank advice. What guidance would you give him? I'm going to ask you a number of questions to help me design a control station that takes into consideration the needs of the operator for the most effective possible operation of the future control room.

Before we start, let me assure you that we are not interested in criticizing your present control room and that your responses will be kept confidential. The results of these interviews will be presented in summary form to the utility industry and no individual control room will be singled out for any negative comments. We are simply interested in highlighting any categories of design errors that may have been made in the past so that they can be avoided in the future. We are also interested in retaining the good features of present day control rooms.

BIOGRAPHICAL DATA

YOUR POSITION (e.g., Senior Control Operator) _____

YEARS OF NAVY NUCLEAR EXPERIENCE: _____

NATURE OF NAVY NUCLEAR EXPERIENCE: _____

YEARS OF FOSSIL FUEL PLANT EXPERIENCE: _____ TYPES OF EXPERIENCE: _____

_____

YEARS OF COMMERCIAL NUCLEAR POWER PLANT EXPERIENCE: _____ TYPES OF EXPERIENCE: _____

_____

OTHER NUCLEAR PLANTS THAT YOU HAVE WORKED AT: _____

_____

DATE OF FIRST LICENSES: _____ RO _____ SRO

YOUR AGE: _____ YOUR HEIGHT: _____ YOUR WEIGHT: _____

EDUCATION: _____ YRS HIGH SCHOOL _____ YRS COLLEGE OR UNIVERSITY

TOTAL CAREER WEEKS OF SIMULATOR TRAINING (WHICH ONES) _____

_____

THE CONTROL ROOM

1. Nuclear plant control rooms vary considerably in size. How would you describe your control room size with regard to effective plant operation? Is it too large, too small or just about right? Please comment on problems in this area.

2. Are there any problems of an environmental nature which detract from effective operations in your control room, e.g., heat, ventilation, humidity, illumination, noise, distractions from visitors or excessive plant personnel, etc.? Let's take them one at a time.

   Ventilation: Yes _____ No _____ (If Yes, please describe).

   Temperature/Humidity: Yes _____ No _____

   Illumination: Yes _____ No _____

   Noise Levels: Yes _____ No _____

   Excessive Traffic through Control Room: Yes _____ No _____

   Distractions from Visitors: Yes _____ No _____

General Appearance Factors (Wall colors, decorations, etc.) Yes _____ No _____

Other Environmental Factors, e.g., nature of the floor surface.

3. Tech Spec Requirements indicate that a minimum of _____ operators must be in the control room at all times. In your opinion, what is the minimum number of operators that are actually needed to effectively operate your control room: during normal operations _____, during start-up _____, during serious casualty modes_____.

4. Is the control room arranged in such a manner to allow effective operations with the minimum required number of operators during normal and off-normal operations?

5. Can the status of your plant be monitored from one central position or is the operator continually moving about the control room to assess system status? What are your preferences in this regard?

6. Are specific stations established for the operators and watch foreman? ____Yes _____No. Have the operator and supervisor stations within your control room been arranged most effectively so that coordinated actions can be taken in conducting normal and emergency operations? If not, please describe problems.

7. The operator has need to communicate effectively with others in the plant. What improvements, if any, are required with regard to your communication system?

8. Have eating and toilet facilities been located for maximum operator convenience? How long does it take an operator using these facilities to return to the control room in the event of a casualty? _____ Minutes. How long can an operator leave the main portion of the control room without calling for a replacement? ____ Minutes.

9. How many generating units do you presently operate? If you operate two or more control stations, are they: _____ IDENTICAL, _____ NEARLY IDENTICAL, _____ MIRROR IMAGES OF EACH OTHER, _____ DISSIMILAR

If applicable, please describe any problems in shifting from one control station to another.

10. Have the control panels in your control room been placed in an arrangement that is logical for normal and emergency operations? If not, how could the placement of panels be improved?

11. Within each specific panel in your control room, have related controls and displays pertaining to individual subsystems been grouped logically and distinctively?

12. Does your control room include instrumentation, controls and displays which are unnecessary for you to do an effective job? If "YES", please provide examples.

13. Does your control room lack important instrumentation, controls and displays which would help you do a more effective job? Examples please.

14. Does your control room make use of mimic or graphic/pictorial panel arrangements and do you favor the use of such control panel designs?

15. Are important displays generally placed where they can be read easily? Examples of problems please?

16. Are important controls generally placed where they can be reached with ease? Examples of problems please.

17. Have controls been selected and oriented to minimize accidental disturbance of control settings? Please describe examples of problems in this area.

18. Have groups of controls which are identical been coded in any way to permit the operator to readily distinguish between them? To what extent do you find yourself reaching for the wrong control or mistaking the identity of an indicator light or meter? Please describe problems, if any.

19. To what extent do operators in your control room find it necessary to add or modify labeling, code meters, add mimic lines, protect certain controls from accidental activation, or otherwise modify the panels to make operation easier?

20. Have major panels, sub-panels and panel elements been labeled clearly and consistently to facilitate identification of control rcom elements? Please describe problems, if any.

21. In your opinion, are too many or too few functions performed automatically by your system in controlling abnormal events, i.e., should the operator have greater or less control of the system in the initial response to abnormalities? Can you provide examples where direct control by the operator, in place of automatic system response, would be preferable? Are there examples where automatic system response would be preferable to manual control?

22. What functions does your computer perform to assist you in operating the control system? How useful and reliable is your computer? What changes or additions in computer usage would you like to see? Are operators adequately trained to use the computer?

23. From all indications, future generation control panels will rely heavily on computer-generated Cathode Ray Tubes or TV screen-type displays for the display of information to operators, thereby minimizing the use of extensive arrays of fixed meters and indicators. Do you favor this trend? What advantages and disadvantages do you foresee from an operational standpoint?

ANNUNCIATOR/WARNING SYSTEM

24. Has the annunciator/warning system in your control room been designed so that you can immediately determine when an abnormal event has occurred and its specific nature? Describe problems, if any, please.

25. When an abnormal occurrence takes place, does your control board provide all the necessary information in the right format to allow you to readily diagnose problems and take corrective action? Describe problems please.

26. When your system reacts automatically to an abnormal condition, do you have any problems in determining what has happened and/or verifying that automatic system response has been effected properly? Examples of problems.

27. Have warning/annunciator lights been clearly and consistently color coded so that you can immediately determine whether the system is in a normal or abnormal state? Please give examples of any problems.

28. Are the auditory warning signals differentiated to provide different meanings such as the seriousness of the problem or refer you to the specific control panel(s) involved?

29. To what extent does your control room present you with "false alarms" or nuisance alarms that you have to learn to ignore? Please describe problems, if any.

30. Is your alarm system designed so that you are not expending an "unreasonable" amount of effort in silencing or acknowledging alarms?

PROCEDURES/DOCUMENTATION

31. Are your procedures sufficiently detailed and clear to permit effective operation of your control room? If "NO", please describe how procedures could be improved.

32. Is the operator required to commit an unreasonable number of procedures of an emergency nature to memory? If so, what measures could be taken to help the operator?

33. In general, is too much or too little emphasis being placed on procedures and "doing things by the book"? Please comment regarding your opinion.

34. Are your emergency operating procedures easily accessible? Is there a need for more efficient means for presenting such emergency procedures to the operator in a more timely manner?

35. Are your emergency procedures designed so that there is a clear definition and division of responsibilities among control room operators in dealing with off-normal events or is there a duplication of coverage or other problems?

36. Do your record keeping tasks (log entries and reading of parameters) interfere with your operational duties, especially during responses to serious off-normal conditions? If yes, what improvements can you recommend?

SELECTION/TRAINING

37. In your opinion, in what ways could the control room be redesigned to reduce the time it takes to learn to operate the control board?

38. To what extent do you feel that the classroom theoretical training and operational training required to successfully pass the NRC licensing examinations is related to effective operational job performance?

39. What major changes in the training programs for ROs and SROs do you recommend to improve the quality of operator training and reduce training time?

40. What opinions do you hold regarding requalification training for ROs and SROs? Does this required training pose any problem?

41. In your opinion, how useful are control room simulators for training purposes to prepare ROs and SROs for operation of your plant?

42.a What three qualities or characteristics would you personally look for in selecting successful candidates for operator training?

b What three major qualities or characteristics do you feel are representative of the less successful operators in your experience?

SHIFT WORK/OVERTIME

43. Would you prefer a different shift schedule than the one you presently have?

44. Have you observed any problems associated with watch turnover? Please describe any control station turnover problems.

45. Have you noticed any negative effects on operator performance which can be attributed to changing from one shift to another, e.g., going from day shift to the midnight shift?

46. How many hours of overtime do you typically work over a period of one year? Have you noticed any problems associated with operators working extensive periods of overtime?

47. Have you observed any personal problems that operators are experiencing which result from shift work and/or extensive overtime demands?

GENERAL

48. Based on your operational experience, cite one example of an operator error, accident or near accident with serious or potentially serious consequences. Describe the specifics of the case and indicate how the situation could have been averted through either improved control room design, improved procedures, or special training provisions.

49. Based on your operating experience with your control room, cite one example of a particular control, display, panel, warning device, etc., which is not "human engineered" or is poorly designed from the operator's standpoint, and has or could lead to a malfunction or operator error.

50. Now think of an example of a particular display, control, label, panel layout, warning device or other control room feature which is well "human engineered" and which might have prevented a serious or potentially serious accident or operator error. Please describe this equipment with particular emphasis on the features which make it desirable from an operational standpoint.

51. The reactor operator's job has been described as consisting of "hour after hour of debilitating boredom interspersed with periods of abject terror."

A. Assuming that there is some degree of truth to this statement, what can be done to relieve the routine or boring aspects of the operator's job?

B. What can or should be done to relieve periods of intense stress?

Appendix C

PROCEDURE EVALUATION CHECKLIST

		Yes	No
1	Is the print at least as large as standard typewriter print?		
2	Is there a margin at least 1/2 inch around each page?		
3	Are foldout pages avoided where possible?		
4	Has the need to rotate pages been avoided where possible?		
5	When rotation is needed is the top at the bound edge?		
6	Are all graphs and tables properly labeled?		
7	Does a vertical line or 1/4 inch minimum line separate columns?		
8	If interpolation is required are graphs (not tables) used?		
9	Is presentation of graphs and tables consistent throughout?		
10	Are numbered grids in graphs darker than unnumbered grids?		
11	Are pages numbered X of X for recognition of missing pages?		
12	Is a last page for last item, sentence, or word avoided?		
13	Are all applicable documents listed?		
14	Has a tabular format been used for the methods section?		
15	Have warning/precautions been inserted immediately preceding applicable steps or procedure?		

	Yes	No
16 Have aids been described where data reduction is required?		
17 Have subtests and subtasks been set off with separate headings?		
18 Have checklists been provided for lengthy prerequisites, tests, or complex tasks?		
19 Have all prerequisites been inserted immediately preceding applicable sections?		
20 Is the need for reference to other documents minimized but completely stated within the procedure?		
21 Is the procedure identified by:		
Title?		
Applicability (if not in title)?		
Revision date?		
Approval status?		
Indexing designation/code?		
22 Has peak stress been used, i.e., capitalization or underlining?		

	Yes	No
23 Have critical control settings been adequately stated?		
24 Have illustrations been used to replace long descriptions?		
25 Have limits been clearly stated in quantitative terms?		
26 Do quantities and dimensions correspond to referenced displays and documents?		
27 Do terms and nomenclature match exactly common use and equipment labels and legends?		
28 Have uncommon abbreviations been eliminated?		
29 Is language simple, concise, and unambiguous?		
30 Is the sequence of steps logical and accurate?		
31 Are instructions for emergency shutdown provided and not just referenced?		
32 Are decision making cues clearly stated?		
33 Are unnecessary memory recall requirements avoided?		
34 Are violations of human capabilities avoided?		
35 Is the location or source of required information or action self-evident or clearly stated?		

	Yes	No
36 Are procedures logically and accurately filed and identified for easy locatinn?		
37 Are procedures located for quick access?		
38 Is the level of detail adequate to avoid omission of steps?		
39 Is formatting neat, simple, and consistent across procedures?		
EMERGENCY PROCEDURES: Are following sections or items included:		
40 Symptoms, e.g., alarms, conditions, probable magnitudes, which identify this procedure?		
41 List of probable automatic actions?		
42 Immediate operator action? (which includes):		
43 Confirm/ensure automatic action functions?		
44 Caution to avoid switch to manual unless automatic operations is confirmed failed?		
45 Reminder(s) for proper monitoring of automatic systems placed in manual?		
46 Steps to ensure core cooling and safety?		
47 Proper notification of plant personnel?		

	Yes	No
48 Ensure reactor coolant system integrity?		
49 Confirmation of adequate source of power?		
50 Confirmation of or steps to control containment and exhaust systems to prevent radioactive release?		
52 Subsequent actions? (which includes):		
52 Steps to bring conditions back to normal or long term stability?		
53 Is level of detail written to allow flexibility in sequence of events but to avoid omission of steps?		
54 Is the need for calculations and conversions avoided?		
55 Is supplemental background information separated from the body of procedures?		