

## A SYSTEMS APPROACH TO DEFINING OPERATOR ROLES\*

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Summary

This paper briefly describes the elements of a systems approach for defining the role of the operating crew of a nuclear power plant. A systems approach aims at solving the multifaceted and interrelated problems produced by complex man-machine systems. Through systems analysis and engineering, an organized and systematic approach to the proper allocation of roles between man and machine can be made. This approach is utilized here to develop a methodology for specifying the optimum role of the crew in a nuclear plant system and also defining the internal structure of the crew for the purpose of ensuring the safe and economic operation of the plant.

Introduction

Long before the accident at Three Mile Island, Unit 2, the nuclear industry was aware of the importance of human reliability and operator-plant compatibility in nuclear plant operations;<sup>1</sup> however, the application of human factors engineering in plant design had been minimal. On the assumption that operator training programs had been adequate, the research, development, and application of human factors engineering and advanced diagnostic techniques were considered to be of low economic benefit. Even so, several man-machine related programs were underway prior to TMI-2 at the Electric Power Research Institute (EPRI),<sup>2</sup> the Department of Energy (DOE),<sup>3</sup> Tennessee Valley Authority (TVA),<sup>4</sup> and elsewhere.<sup>5</sup> TMI, however, has changed the emphasis: the unforeseen sequence of TMI events and the inability of the plant operators to recognize them and react accordingly clearly pointed out areas needing improvement.<sup>6-8</sup> Analyses have shown that present equipment layout, designed primarily for normal operating conditions, is not necessarily effective in handling emergency conditions.<sup>9</sup> The human operator, once assumed capable of rationally assessing almost any abnormal situation or plant condition, has been shown to be vulnerable to a multitude of inadequacies.<sup>10</sup> A host of organizations are currently pursuing the development of operational aids to improve plant monitoring, diagnostic and corrective actions, operator-process communication, and operator training.<sup>11</sup> Upgrading of information quality and reduction of information quantity through the application of advanced computer-controlled display and diagnostic systems have been identified as one means of improving crew response during abnormal conditions.

The safe operation of a nuclear power plant depends, of course, on the precise interaction of many systems and components with the plant, including the

operating crew. In the event that a disturbance occurs in the operation, the operator's role is to prevent and/or limit the development of hazardous conditions and equipment damage. The extent to which he can fulfill this role depends on his knowledge of the overall system, the adequacy and relevance of the information available to him, and the availability of control options through which he can respond to that information.

A program now underway at Oak Ridge National Laboratory (ORNL) is designed to examine the operator's role by a systems approach: that is, to perform a systems analysis of the operator's role as it currently exists at nuclear power plants, and then, through systems engineering to define the operator's role as it should be for optimum performance. The status of the program, titled Operational Aids for Reactor Operators and supported by the Nuclear Regulatory Commission, is discussed in this paper.

The systems approach has been well documented<sup>12</sup> and has been successfully applied to high-technology, high-risk industries such as aerospace and aircraft industries. Singleton<sup>13</sup> proposes that the analysis or design of a human-machine system can begin from any of four starting points:

1. Engineering Approach - starts from the characteristics and limitations of the process, instrumentation, and control systems and then considers ways of supplementing or compensating for these by the use of computers and humans.
2. Systems Ergonomic Approach - poses the problem as one of optimal allocation of function between man, machine, and computer.
3. Computer Analysis Approach - starts from the characteristics and limitations of the computer.
4. Psychological Approach - starts from the characteristics and limitations of the human and then considers ways of supplementing and compensating for these by the use of machines and computers.

In defining the role of a nuclear operating crew, we must realize that, for presently operating plants and those planned for the near future, the process machinery is fixed and essentially unalterable. A reasonable approach to defining the crew role, then, would allocate the functions required for support of the plant process to man and computer in an optimum manner so that their combined function would be more effective than either taken separately. Licklider<sup>14</sup> refers to a symbiotic partnership between man and computer. This cooperative coupling would let computers facilitate formulative thinking as they now facilitate the solution of formulated problems and would enable man and computers to cooperate in making decisions and controlling complex situations without servile dependence on predetermined procedures.

Bohr<sup>15</sup> suggests that nuclear plant designers integrate the human operator into the plant.

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Where possible, equipment should be adjusted to the human capabilities and limitations rather than modify human characteristics according to technical requirements. He further suggests that human factors analysts should identify situational conditions predisposing to human error; designers then, by changing these conditions, could reduce the opportunities for errors and ensure that possible errors would have limited degrading consequences. Recently, Corcoran et al.<sup>16</sup> have reviewed the operator's role in nuclear safety and introduced the concept of safety function. A hierarchical approach was taken to derive the safety functions. The systems approach has recently been applied by General Atomics in developing a status monitoring and information system. Their system (called Plant Incident Evaluator or PIE) is based on a top-down approach. The approach described here is somewhat similar to Corcoran, et al.

### Problem Statement

The operating crew of a nuclear power plant manages the integration of the numerous plant subsystems. From that fact two problems emerge: (1) the crew has the potential for either initiating or aggravating a disturbance in plant operation, and (2) operational aids have the potential for either impairing the operators' ability to mitigate a disturbance or increasing the likelihood of his initiating a disturbance. The second problem results from attempting to solve the first. We can be assured that altering the control room structurally or functionally will in itself create new potentials for human error. Designers, therefore, should seek to reduce the overall potential for hazardous conditions by eliminating more latent disruptive problem areas than they create. This can be accomplished by an organized, methodical, and systematic effort.

The systems approach is intended for precisely the sort of multifaceted problems produced by complex man-machine systems. It provides an overall framework that allows all elements of a system and their interrelationships to be characterized in a methodical fashion. The systems approach demands the evaluation of all elements of a system and its surrounding environment, which includes the human element.

The nuclear plant system that includes the operating crew encompasses the whole of the plant: the control room, the process, utility management, and also plant personnel. Integration of operator, control room, and plant systems requires understanding of the individual system components, their relationship to each other, and their combined effect at the system level. It will include an examination of such diverse topics as information flow requirements, human capability, machine capability, plant system requirements, implementation constraints, and crew structure. Crew role and crew structure constitute the framework through which operators interface their uniquely human qualities with the system. Crew role and structure are related as follows: role is the functional relationship between the crew, as a single entity, and the plant; and structure is the internal relationship of the crew. The remainder of this paper highlights current crew role and structure and suggests roles and structures based on a general systems approach.

### Current Crew Role and Structure

The role of the operating crew can be viewed from many perspectives, depending on the state of

the plant and the objective of the next phase of operation. In addition, each organization involved with nuclear power production and regulation describes the role with a different emphasis. Role descriptions can be derived from several sources: (1) operating procedures, (2) plant designers, (3) operator examiners, (4) operator trainers, (5) utility management, and (6) regulators. These descriptions represent different views of the functions currently performed by the crew using existing procedures and equipment. Such differences in descriptions are expected since (1) the charters of these organizations are diverse, and they would naturally place differing requirements and objectives on operator function, and (2) in general, consistent design criteria and objectives have not been applied to control rooms or crew function. By compiling and evaluating role descriptions, the deficiencies can be identified and guidelines for improvement can be developed.

One description of the operator's role, developed by Technology for Energy Corporation (TEC),<sup>17</sup> provides a characterization of an operating crew's function under emergency conditions using the emergency operating instructions (EOI) for a typical pressurized water reactor. TEC determines the operator's role is to be task oriented so that he is limited to specific responses during defined emergency conditions. To carry out his role, he must perform four basic functions: (1) observe the symptoms of an emergency condition, (2) verify the response of the plant systems, (3) terminate emergency conditions, and (4) initiate recovery actions. Thus the operator's current role is the execution of a fixed response that relates a defined set of procedures to the control of the plant. The operator's primary objectives are to ensure the design performance of automatic safety features and to manually control them if necessary to achieve the overall safety objectives.

Nuclear power plant operating crews in the United States are composed of teams of individual operators placed in a hierarchy according to level of training, experience, and responsibility. Individual crew members are not specialized; that is, they receive uniform (not diversified) education and training directed toward developing a general knowledge of the plant. They are expected to be proficient operators of all plant equipment, and therefore, they are interchangeable. The primary responsibility for directing the activities of the crew and ensuring the safe operation of the plant rests on the shift supervisor.\* The assignment of duties to individual reactor operators is at the discretion of the shift supervisor. In a multiunit plant, an assistant shift supervisor is assigned to each unit; he has direct management responsibility for the staff of reactor operators under him. The current structure of the operating crew has no built-in separation of responsibility by function, plant system, or task. An exception is noted, however: the shift technical advisor is educated and trained at a more theoretical level than shift operators. He is assigned technical responsibility, not operational responsibility. The shift technical advisor, shift supervisor, and assistant supervisors are usually required to have a senior reactor operator's license; reactor control operators are required to have a reactor operator's<sup>§</sup> license; and auxiliary operators are not licensed.

\* Also called shift engineer or shift foreman, depending on utility.

\*\* Further information available in NUREG-0731.<sup>18</sup>

The crew structure typical of most power plants represents a management hierarchy as shown in Fig. 1.

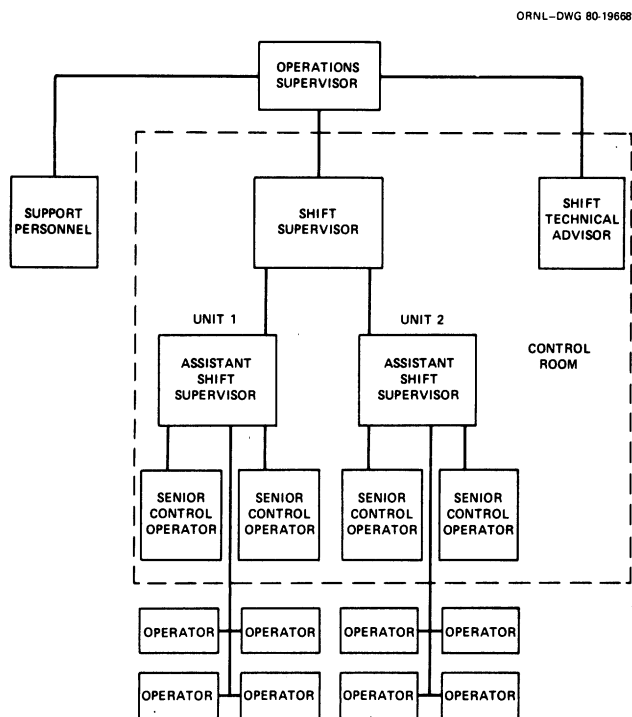


Fig. 1. Line management typical of most power plants.

#### Systems-Based Crew Role and Structure

In defining a crew role using the systems approach, one would begin at the general, most integrated levels and systematically work to the specific, least integrated levels. Identifying and defining the crew interfaces at the general level is necessary to understand the complexity of interactions. The crew interacts in four interface categories: (1) functional, (2) equipment, (3) institutional, and (4) personnel. These interfaces are graphically illustrated in Fig. 2, where the form of interaction or communication is shown in the circles: verbal, visual, written, manual, audio, and olfactory.

The functional interface refers to interaction of the functional characteristics of the process itself and that of the instrumentation, control, and safety systems with the crew. The operator, having a mental model of the plant, interacts with the plant using a knowledge of the system to interpret responses, make decisions, and control interactions and energy flow.

The equipment interface refers to the palpable crew interaction areas: (1) the instrument panels, consisting of the physical displays and controls, and (2) the environment, consisting of the workplace and its condition. In the equipment interface, the operator uses his physical senses and manual abilities.

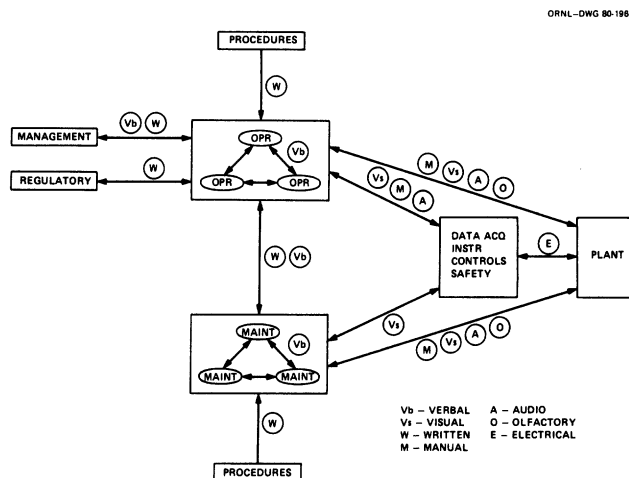


Fig. 2. Interfaces of nuclear plant operating crew.

The institutional interface refers to the crew's interaction with (1) the written procedures and associated training provided by a vendor or utility training organization, (2) the utility management, which advocates an operating philosophy and employee working climate, and (3) the regulatory bodies, consisting of the NRC, labor unions, EPA, and other private and government agencies. The crew learns rules through the institutional interface and applies them to plant operation.

Finally, the personnel interface refers to the human-to-human communication that routinely takes place between two or more operators or between operation and maintenance crews.

From a systems perspective, personnel functions can be defined using a top-down approach. Many perspectives are possible. Without elaboration, one general set of function categories, which applies to normal and off-normal conditions, follows:

1. Administration - refers to activities of record keeping, building security, personnel supervision, and feedback to design groups for future improvements.
2. Systems Supervision - refers to system monitoring, system optimizing, problem anticipating, and problem solving.
3. Manual Intervention - refers to an operator intervening so as to substitute for automatic system control his manual abilities, thus becoming a part of local closed-loop control. This would occur when equipment has failed or become overloaded, or when the plant state has exceeded the design capabilities of the equipment.
4. Communications Coordination - refers to the control of on-site and off-site information transmission. In performing this function, the operator often must translate and compress data.

This general set of function categories can serve as a starting point for a systematic approach that will help develop a well-defined, optimized crew role. Human-machine capabilities,<sup>12</sup> stress behavior,<sup>19</sup> and implementation constraints,<sup>20</sup> discussion of which are beyond the scope of this paper, must also be considered in developing all aspects of the operating crew role.

Effective crew structure relates crew members to each other and to the plant. Crew structure coordinated with a well-defined crew role results in an efficient use of each individual operator's ability. To maximize this ability, crew role and structure should provide a framework that benefits from the diversification of education and training among individual operators. This specialization of talent will help individual operators access specific knowledge about the plant and will help channel information flow to reduce extraneous and competing information.

Crew structure should also provide a framework that integrates the special training and function of individual crew members to accomplish the overall crew role, especially the safety role. A coordinated crew would have a large collective awareness of plant status during unusual situations and would perform consistent, systematic plant status evaluations. They would generate decision alternatives from a broad base of information and would follow a course of action that results in a minimum opportunity for error.

The salient features of a well-structured crew are (1) orderly flow of information, (2) specialization of task, (3) distribution of workload, (4) delegated responsibility and authority, and (5) well-defined man-man and man-machine interfaces. Several methods can be devised for organizing the operating crew. As an example, four different structures are presented here. Though these examples do not exhaust all possible crew structures, and no attempt is made to present them in an in-depth fashion, they do serve to illustrate possible variations. In the first (see Fig. 3), the crew is arranged by physical system; i.e., the structure places responsibility for each major plant system on an individual operator specifically trained for that system. This structure offers a form of task specialization and

distribution; however, intersystem coordination problems should be anticipated with this structure.

The second example, shown in Fig. 4, gives a structure that conforms to the fundamental functional systems of the plant.<sup>21</sup> This structure organizes the crew by high-level system function along the natural boundaries of plant systems which are associated with heat source, heat transfer, and heat sink. The safety functions block refers to the actions recommended by Corcoran:<sup>15</sup> (1) anti-core melt, (2) containment integrity, (3) indirect radioactive release control, and (4) maintenance of vital auxiliaries. The structure is similar to that of Fig. 3, except that physical plant systems are grouped into function categories.

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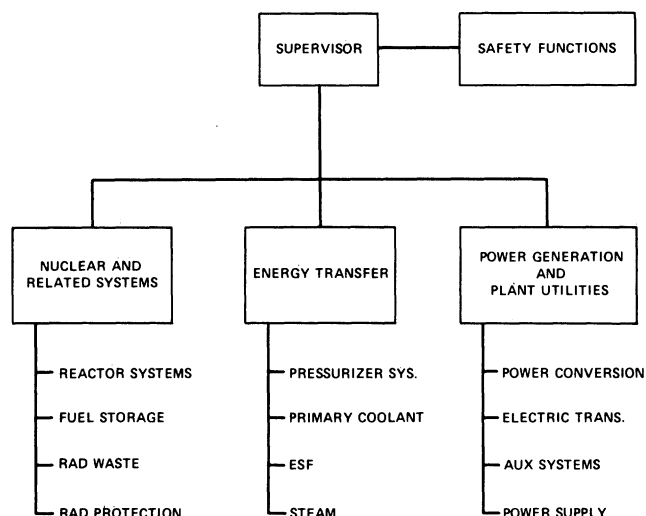


Fig. 4. Crew structure with operators placed in control of bounded functional block (each with distinct operational and safety duties).

Figure 5 illustrates a third structure that is based on the personnel functions as described in an earlier paragraph: administration, systems supervision, manual control, and communication. This organization gives operators specific duties to perform. The physical systems of the plant and their functions are not mirrored in this structure, which may have some operational significance.

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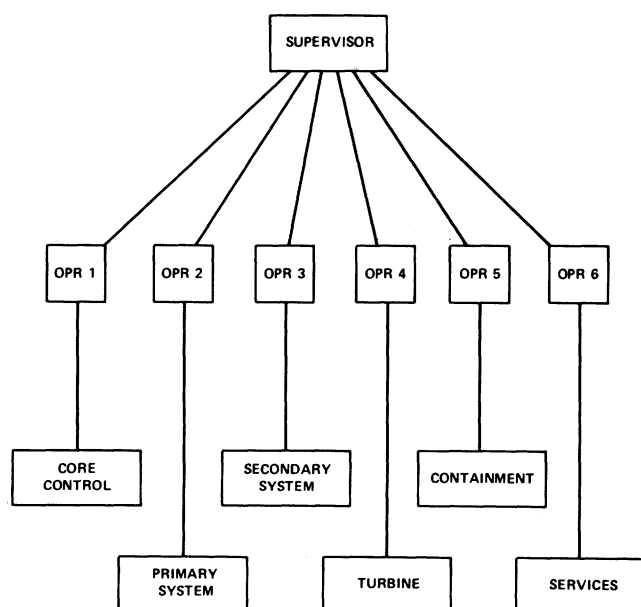


Fig. 3. Crew structure with each plant system under control of individual operators.

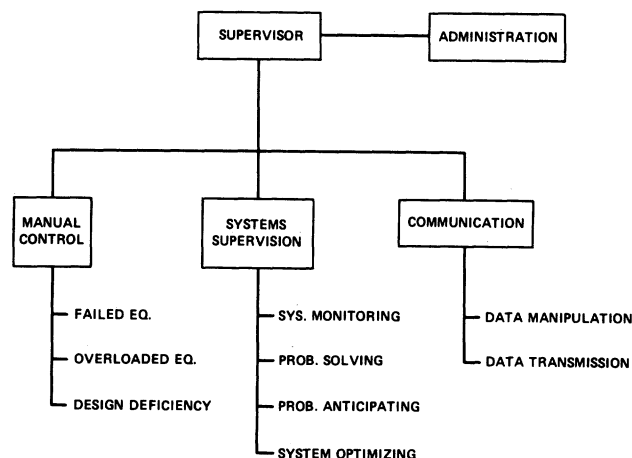


Fig. 5. Crew structure with crew members given specific duties to perform.

Finally, Fig. 6 depicts a hierarchy based on the distinction between system level control and component level control. Basic parts and components are monitored and controlled by the components crew, while the combined effects of these parts and their interactions are monitored by the systems crew. The structure, acting as a filter, diverts data related to the status of elementary parts to one crew and data related to the status of the major plant systems to another crew. The safety monitor maintains a separate perspective on the safety-related status of the entire plant. Problems in precise delegation of responsibility should be anticipated with this structure.

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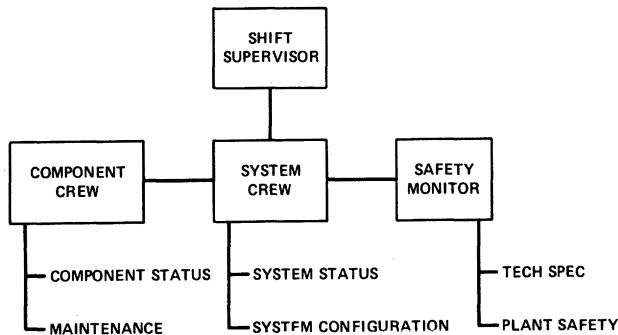


Fig. 6. Crew structure based on a system-component hierarchy that assigns responsibility according to systems complexity.

In the months to come, the ORNL program will evaluate these crew structures and others based on the systems approach. The successes and failures of similar crew structures in other high-technology industries will be examined. A limited quantity of crew structures will be selected and ranked according to their potential improvement on overall nuclear power plant safety. Simulator testing and verification of these hypothetical structures will be required prior to plant implementation.

### Conclusion

Crew role and crew structure form the framework through which individual operators coordinate their efforts to actively influence the course of normal and abnormal events. A well-instructed crew will take advantage of personnel specialization, task assignment, and hierarchical distribution of responsibility. Crew-to-crew and crew-to-system interfaces must be well-defined to eliminate unintentional overlap of responsibility and ambiguity of information. As nuclear systems become increasingly automated and utilize computers in control and safety functions, the systems approach becomes necessary to ensure that new possibilities for error are held to a minimum. The systems approach can be applied to develop an optimized crew role by balancing human, computer, and plant capabilities to meeting the functional requirements of the nuclear power plant. A well-defined role will become the basis for developing design requirements and review criteria for potential operational aids. The systems approach will also lead to an improved crew structure with improved response to

abnormal and emergency situations (i.e., reduced errors, fast response time, and increased diagnostic capabilities) as well as to normal operating situations with improved interaction with maintenance activities. Such an approach will lead us a step closer to the realization of the symbiotic system.

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