The Organization and Management of Nuclear Power Plants

by

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ABSTRACT

Nuclear power plants are a controversial technology. The future of the industry depends on the ability to manage efficiently and safely, and to effectively manage organizational change as new technologies and practices are introduced and disseminated. This paper provides a conceptual framework and discussion of the management and organization of nuclear power plants around three questions: (1) How should nuclear power plants be organized and managed to ensure that they are operated most safely and efficiently? (2) What does an understanding of the organization and management of nuclear power plants tell us about how they change or resist change? and (3) What indicators or measures of various characteristics and processes of nuclear power plants are needed in order to address the above questions? We review existing literature on the organization and management of nuclear power plants, and suggest how we would structure a research project to address the above questions.

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INTRODUCTION

Nuclear power provides 17% of the world's electricity, including 20% of U. S. electricity generation (and 70% of France's). Yet, controversy continues to surround the industry. Supporters argue that technology and engineering practices have achieved suitable safety and efficiency levels after decades of experience. The contained effects of the accidents at Three Mile Island and Chernobyl are looked upon as proof that the system works (under almost worst-case scenarios), and that fossil fuel alternatives are far more dangerous (Blix, 1989). The problem, they say, lies in the public's fear of anything nuclear, demand for a level of safety beyond that in other energy industries, and the resultant climate of intense government regulation (Koutz, 1989).

Yet, this positive view of the industry is contested by those who argue that nuclear power generation is inherently so complex and interlinked that accidents are inevitable (Perrow, 1984), that there are some poorly run plants, that U. S. plants are not as well run as those in several other countries (Hansen et al., 1989), and that the industry focuses on performance

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indicators that portray it favorably rather than on safety behaviors that are more questionable (Marcus et al., 1989). In particular, variations in safety and efficiency seem attributable to organization and management rather than to technology.

This paper provides a conceptual framework and discussion of the management and organization of nuclear power plants. Our objectives are summarized by two questions: (1) How should nuclear power plants be organized and managed to ensure that they are operated most safely and efficiently? and (2) What does an understanding of the organization and management of nuclear power plants tell us about how they change or resist change? The latter question presumes that achieving and maintaining excellence depends upon a continual process of change. To answer both questions, we need to address a more proximal one: What indicators or measures of various characteristics and processes of nuclear power plants are needed in order to address the above questions? Therefore, this paper is directed at the problem of indicator development as a basis for empirical research.

To discuss this problem effectively, we first present arguments for the importance of nuclear power plants as worthwhile objects of study. Following, we suggest organizational change and learning as windows through which we present our conceptual and theoretical approach to NPPs as organizations. We then review existing literature on the organization and management of NPPs, and suggest how we would structure a research project.

WHY STUDY NUCLEAR POWER PLANTS?

There are three reasons why nuclear power plants (NPPs) appear to be appropriate for organization-based study: they are a major public concern and social issue, they are particularly difficult to manage, and performance seems especially sensitive to management and organizational practices within the context of a relatively uniform and mature technology (excepting some Soviet reactors).

Public Safety and Confidence

NPPs represent a high-hazard technology. That is, if a complete failure of a nuclear power plant were to occur, there is some probability that there would be considerable injury and loss of life. Although the probability of catastrophe may be low, the public has a high dread of nuclear accidents (Fischhoff et al, 1981). Mistakes and accidents in the nuclear industry have been well-publicized, and public confidence in the competence and selflessness of the industry is low in most of the world. This high hazard, low confidence industry therefore poses an interesting and socially-relevant forum for investigation.

An Extreme Management Task

Second, NPPs are extremely difficult to manage. This arises from the highly demanding nature of both their internal and external environments. Perrow (1984) sees the problem of internal management as a product of complexity and tight coupling of the power plant technology. First, the technology is so complex that it is inherently unknowable. Because many events occur invisibly and are not immediately comprehensible, no individual or organization can get such a complete understanding of the operation of the system that its behavior becomes completely predictable. Second, the individual components of the systems are very highly coupled because of fixed sequences, critical timing elements, little slack, and few buffers and substitutions. Therefore, the failure of any individual component in a system can lead to rapid changes, and often failures, in other components. Operators, with their faulty mental models, are likely to misinterpret the events and exacerbate the problems. When these two characteristics, high complexity and high coupling, are brought together, NPPs are seen as highly susceptible to "system accidents," simultaneous and unpredictable failures of interdependent systems.

To make matters worse, the external environments of NPPs are both extremely demanding and highly constraining. The plants are subjected to an aggressive regulatory environment of government agencies, utility groups, and insurers, and to intense scrutiny by public interest groups, media, and others. These groups make strong demands on the organization, place severe restrictions on its management and ability to obtain income, and bombard it with information. For example, such extreme scrutiny and anxiety may lead plant managers to enhance safety at the cost of efficiency by having redundant systems, shutdowns in response to minor problems, and so forth. But, safety may be eroded as well if low public opinion leads qualified people to refuse to work for NPPs or leads utilities to deprive plants of resources since they are in a declining sector. Yet, openness to the environment is important because other plants are having operating experiences which may provide vital information for future safety.

The recognition of the difficulties in managing plants leads to three alternative prescriptions. At the pessimistic end, Perrow (1984) argues that nuclear power plants are so complex and highly coupled, and the potential hazards so great, that safe learning is impossible. Underlying this is the assumption that learning occurs when there is a mismatch between system performance and our expectations (Argyris and Schon, 1978). For example, we might learn that we need positive indicators of valve position rather than temperature readings that are too easily misinterpreted (which happened at TMI). In the case of a nuclear power plant, such trial-and-error learning could involve a serious accident and, hence, unnecessary risk.

On a more optimistic note, Wildavsky (1988) argues that much learning occurs through the understanding of minor mismatches in performance. Therefore, performance improvements can occur without major incidents or accidents. He exemplifies his argument by tracing the histories of technologies such as fuel pipelines, which were once considered very dangerous but are now thought relatively benign.

The regulatory community (e.g. IAEA, 1988) argues that while the technology may not be completely knowable, it is possible to construct a series of independent (de-coupled) organizational and technological barriers which will contain an accident. If the probability of each barrier being violated is low enough, then the cumulative probability of accident will be very low. This approach, known in the industry as "Defense in Depth," is consistent with Perrow's recommendations for increasing safety by reducing high coupling.

However, the fact remains that the management and organizational designers of NPPs face a more difficult task than other organizations which are less complex and/or more loosely coupled, in which small mistakes or problems cannot mushroom into events with catastrophic potential for the company and the public. LaPorte and Consolini (1989) consider "failure-free performance" to be a key challenge for organizational theory. The study of NPPs, therefore, is a study of organizations "at the edge," coping with extreme demands.

Performance Depends on Management Rather Than Technology

The final reason why nuclear plants are empirically very interesting is that there is considerable variation in safety and performance that is hard to attribute to the basic technology. Most Nuclear Steam Supply Systems (outside the centrally-planned economies) are built around light water reactors and are manufactured by one of a few manufacturers. Similarly, there is relatively little variation in the designs of the Balance of Plant (turbines, generators, etc.). However, each plant may be a unique combination of design and components, with the degree of diversity in the technology varying from country to country and utility to utility within countries. The U.S., with its large number of utilities and early entry into the industry, has the highest diversity. France, with one utility, uses one design for each generation of reactor in service. Finland, presumably for political reasons, has two U.S.-designed reactors and two designed in the U.S.S.R.

However, studies indicate that much of the variability in performance cannot be attributed to variations in the basic technology itself. For example, Swiss and Japanese plants operate at very high efficiency (power production as a percent of potential production), and have very few unplanned outages or other safety incidents. Within each country, the various plants operate at very similar levels of efficiency and safety, although their reactors vary substantially in design (Beckjord et al., 1987).

Furthermore, performance variations cannot all be explained by variations in the external environment such as the form of regulation. For example, Beckjord et al. (1987) found that the U.S., with as many light water reactors as the rest of the world combined, had as much variance in operational performance (measured as mean and variance in % availability) as the other five countries they studied, indicating that regulation cannot be explaining performance differentials. Furthermore, they found that differences in regulatory structure were not terribly great anyway.

This does not mean, however, that objective circumstances are completely irrelevant. Some technology effects have been observed. Samanta et al. (1988) found that different reactor designs had different inherent sensitivity to operator error. They found that Babcock and Wilcox reactors were much more sensitive to differences in the probabilities than those of other vendors, although their study is difficult to interpret because of a methodological artifact. Beckjord et al. (1987) and INPO (1988) both found differences in the performance of pressurized vs. boiling water reactors. A generation of Soviet reactors lacking emergency core cooling systems and effective containment are very sensitive to error, as we discovered at Chernobyl.

Institutional effects have also been observed. Lester (1986) found that the high horizontal disaggreggation and low vertical integration of the nuclear power supply industry led to diminished economic performance and learning both in construction and operation of plants. Lester and McCabe (1988) found that industrial structure, especially the level of disaggregation, had an effect on French and U.S. utilities' ability to learn.

Regulatory institutions may also matter. Suzuki and Hansen (1988) found that various elements of safety regulation in the U.S. and Japan affected safety performance. For example, the presence of MITI enabled standardization of designs and approaches, and this affected performance. Beckjord et al. (1987) found that the U.S. was the only low-performing country that did not appear to be learning how to operate its plants better with time, and implied that the problem may arise from the high level of antagonism between the various actors in the U. S. industry.

Thus, despite the importance of technological, economic, and institutional factors, it appears that significant performance variability is due to management and organizational factors. If that is the case, then we need a model of NPP performance that includes management and organizational factors, and a model of organizational change that would guide efforts to improve plant performance. In the next section, we argue that models of performance and models of change are closely interrelated.

LEARNING AND CHANGE

Changes in plant practices and policies require a process to get from the current situation to the new one (Schein, 1980). Nuclear plants change continually, as do all organizations, yet some kinds of changes are quite difficult to make. We need to identify the change process in nuclear plants, including barriers to change, and strategies to overcome these barriers. It is quite interesting, for example, that U. S. plants are disinterested in the practices of European and Japanese plants, whereas those countries regularly seek new information from the U. S. Our Japanese colleagues report that the Europeans are regular visitors at their plants, but the Americans never come there. In part, this reflects the traditional role of the U. S. as the source of nuclear technology. However, that parochial attitude is now outdated as foreign nuclear industries surpass the U. S. in size and performance, and may become the source of new technology and new management practices.

The problem of learning has been described by Marcus, Bromily, and Nichols (1989). They note that the Bhopal, Challenger and TMI accidents were preceded by adequate warnings that something was amiss. Bhopal was preceded by two phosgene leaks at the site, Challenger was preceded by Roger Boisjoly's appeal that the O-rings could fail, and TMI was preceded by Davis Besse. In reflecting on TMI, GPU President Herman Dieckamp said, "To me that is probably one of the most significant learnings of the whole accident [TMI] the degree to which the inadequacies of that experience feedback loop... significantly contributed to making us and the plant vulnerable to this accident" (Kemeny, 1979a, p. 192). Marcus et al. note that "One can examine almost all recent disasters and find that warnings were given but not heeded. ... The fact is that problems that lead to major tragedies may not be appropriately recognized. It is hard to distinguish the true `signal' from the `noise'" (p. 116).

The essential problem with learning is that it takes place against a background of expectations and current understandings. That is, for people to detect a mismatch between their assumptions about the nature of the system and the actual system, they have to have a working "mental model" of the system they are operating. However, as we noted above, Perrow (1984) argues that many accidents occur through unexpected interactions in complex, highly coupled, systems. The fundamental implication of this argument is that the technology is inherently unknowable. That is, we cannot construct a valid model of the technological system. If his argument is correct, it follows that it is impossible to differentiate the noise from the signal and, therefore, it is impossible to learn.

Rather than suggesting that learning in this case is a problem of information processing, we think it is worth investigating whether or not the signal and the noise are virtually inseparable. There is so much noise and so little signal, and the cognitive model is so ill-defined, that a mismatch cannot be detected. In this case, both safe management and learning require noise reduction. Safe management require noise reduction because it is otherwise impossible to know whether or not ominous signals have been attended to. Learning requires noise reduction to increase the ratio of signal-to-noise in the hope that the signals which define the boundary of the known part of the technology might be detected. (Embedded in this is the assumption that there is no misinformation flowing around which, if heeded, would do damage to the organization.)

Given this, a good management strategy minimizes the amount of information flow (by reducing the amount generated, not by censoring it) and maximizes the organization's ability to absorb it. Information flow into the organization can be minimized by careful management of the external environment (e.g. Maine Yankee's strategy of meeting regulators' needs immediately so they do not have to be dealt with multiple times and so the regulators do not have to go into the organization looking for problems). Information flows within the organization are minimized by such things as reducing maintenance backlogs. Barriers to information flow are removed by allowing for smooth flow of information into the organization and development of systems to deal with it. Internal barriers are removed by ensuring smooth interfaces between units.

THE DEVELOPMENT OF A MODEL OF NUCLEAR POWER PLANT PERFORMANCE

The development of an approach to the study of NPPs demands a more specific understanding of NPPs as structured entities responding to internal and external forces and objectives. Marcus et al. (1989) provide a framework for linking management and organizational factors to performance (their own focus is safety, but it is rather simple to extend this to performance in general). This framework separates causal factors, intermediate outcomes, and safety (or performance in general). The causal factors are environment (region, resources), context (technology), organizational governance, organizational design, and emergent processes (learning, culture, cross-functional relations, training, attitudes, stress, etc.). The intermediate outcomes are efficiency, compliance to normative prescriptions, quality of construction and operation, and innovation. The safety indicators (scrams, significant events, etc.) are the final outcomes.

We believe that there are five issues that must be considered in evaluating the relationship between organization and management of NPPs and operating efficiency:

1. The impact of the external environment (society, technology, industry, regulators, etc.) on organizational characteristics;

2. The way in which the organization defines its objectives (in relation to both external and internal constituencies);

3. The way in which the organization sets up people, tools, and tasks in order to accomplish its objectives;

4. The processes by which members of the organization enact behavior within this structure (within and between organizational units) in order to accomplish organizational and personal objectives; and

5. The ways in which the organization reactively or proactively initiates and implements change in any of the above elements and relationships.

We will first look at the issue of objectives and performance, and try to understand how to consider multiple system goals (beyond just one goal such as safety), building on the work of Osborn et al. (1983; Marcus et al., 1989). Secondly, we will develop an approach to the management and organization of NPPs based on open socio-technical systems models, arguing for interdependence among technology (the application of knowledge to do work, Rousseau, 1979), human factors, social interactions, and external demands and resources. Third, we will look closely at the structure and processes of organizations, and argue that the ability to learn underlies long-term success. However, the very high complexity of nuclear power plants makes this very difficult; organizational practices and procedures implicitly establish or block this process. Finally, we look at how the various components of this model can be measured, in terms of indicators.

Objectives and Performance

Organizations have multiple objectives which they use to define their relationship to both their external environment (Pfeffer & Salancik, 1978) and their core technology (Thompson, 1967). Common strategic objectives include maximizing shareholder wealth, return on equity, and growth (measured in various ways), minimizing risk, and achieving industry primacy. These objectives, and the relative weight they are accorded, can be both long and short term, can vary from organization to organization, and can vary within organizations over time. This raises two questions: First, what are the objectives of nuclear utilities? and, second, what happens when they are accorded differential priority?

The most obvious goal of a nuclear plant is to generate electricity. Most observers of the nuclear industry infer two other goals: financial performance and safety. In a country with a nationalized industry, power generation (availability) could be the primary goal, with cost control and safety as secondary goals or constraints. In the U. S., private utilities may view long-term financial performance as the real goal, with availability and safety as necessary sub-goals.

A recent trend has been to make safety the key objective.

Suzuki and Hansen (1988) found that stronger emphasis on safety as an organizational objective led to improved safety performance in Japan, when compared to the U.S. The IAEA (1988) argued that nuclear utilities need to develop a "safety culture." Clearly, this is a statement that safety should be a primary objective of utilities, and that the strategy to achieve safety should become implicit in all activities, ie., part of the culture. The nuclear industry has made careful lists of the performance objectives for NPPs. For example, INPO (1987) provides descriptions of the proper goals and criteria for organizational structure, management involvement, maintainance, human resources, and other functional departments or areas within plants. However, these tend to be lists of desirable characteristics without detail on how to achieve them or how to prioritize among them.

More useful for our purposes, however, is the work of Osborn et al. (1983) who argued that the goals of safety and profitability are best pursued through four sub-goals or operational goals: quality, innovation, efficiency, and compliance to normative prescriptions. They could not make an empirical causal link because there have been too few serious incidents (examples of non-safety) to make any real tests. Marcus et al. (1989) argued that a safe organization is one which manages to actively pursue these simultaneously. Their analysis of the management problem for nuclear power plants then becomes one of trade-offs among objectives and innovative solutions for managing multiple objectives.

We can not, however, specify how best to make these trade-offs. For example, long-term good performance depends on a balance between compliance with good practices, thus avoiding degeneration and complacency, and innovation to adapt to changes and make the achievement of objectives easier over time. Mintzberg (1988) argues that managers have to deal with the contradictions between "machine-like compliance" demanded by the standard operation and maintenance of NPPs, and innovative responses to unexpected occasional problems requiring communication with a professional layer of engineers. Marcus et al. (1989) suggest that good performance may foster routinization and complacency and thereby reduce future performance, and that enhanced safety may come at the cost of efficiency in the short run but increase efficiency (and profits and other outcome measures) in the long run.

We would expect that organizations with differences in the relative weight of objectives would differ in their relative performance with regard to those objectives. For example, Osborn and Jackson (1988) inferred that utilities with a higher dependence on nuclear power for organizational survival would accord safety a higher priority. They postulated, and found, that such utilities ran NPPs with better safety performance.

However, the above research and the previously-reviewed research on environmental and technological predictors of performance, give little insight on <u>how</u> these factors result in good or poor performance. How, for example, is innovation achieved through changes in the technology (e.g., making it more linear and less tightly-coupled, Perrow, 1984) and in the organization (e.g., culture, management practices)? We argue that the understanding of NPPs requires specification of the nature of organizational structures and processes that play crucial roles in plant performance. It is to this topic that we now turn.

Organizations as Systems

Organizations translate their strategic objectives into a structure (Chandler, 1962) subject to the constraints of their core technology (Thompson, 1967) and their environment (Pfeffer & Salancik, 1978). Over time, as a result of learning, they may attempt to modify both the core technology and the environment to make their tasks easier.

However, when considering these elements, it is important to realize that it is impossible to fully understand social and technological phenomena independently. The plant must be seen as a co-evolving system of mutually inter-dependent social interaction and technology, as symbolized in Figure 1. For example, lengthy procedure manuals that routinize or "script" operator interventions have dual effects: operator error is reduced where proper responses to known scenarios can be built into the equipment or the procedure manuals, but operator error may be increased if the increased boredom and unattractiveness of the job lead to a less motivated and less skilled operator team which may be less capable of dealing with "non-scripted" emergencies.

Time and again, efforts to improve organizational performance by introducing new technologies have produced disappointing results. Instead, it is the combination of new technologies _and_ new patterns of training and coordination that seem to make the most of new opportunities (e.g. auto industry use of automation and robotics, MacDuffie & Krafcik, 1989). Organizations systematically underestimate what has to be done to make technological innovations pay off (McKersie & Walton, 1989).

It is also impossible to separate completely the "structure" of organizations, expressed as formal roles, functions, and procedures, from the "processes" by which the work of the organization is "enacted" (Weick, 1979). Even as organization designers and engineers try to embody their objectives in a pre-planned structure (a more detailed version of Figure 1), the informal organization or "emergent processes" represent a level of detail or time-scale of action that cannot be ignored (i.e., behaviors that occur within the subsystems in Figure 1 and across the "interfaces" between subsystems). Although we will discuss structure issues and process issues as if they were two topics, this apparent separation is for communicative efficiency.

Core and periphery. Although organizations must "fit" their technology, environment, and strategy, different parts of an organization fit in different ways. As Thompson (1967) argued, a central part of the organization is built around its core technology and the necessary interdependencies in the transformation of inputs to outputs. For NPPs, that core technology is the sequence of nuclear reaction, steam generation, and electric power production. The core organizational units of the plant are operations, engineering, and (somewhat less obviously) maintainance.

The organization surrounds that core with input and output activities essential to its functioning, but decidedly secondary in importance, such as health physics and personnel. The organization carries out these secondary input and output activities, rather than purchasing services and materials on the market, to buffer the core from fluctuations in the environment (e.g., suppliers, customers, regulators, shareholders, and competitors) which would otherwise interrupt core production (c.f. Williamson 1975). For example, a unit such as public relations can buffer the organization from public opinion by running a visitors´ center to educate the public about nuclear power and environmental issues.

The more important input/output functions are "transformative" activities (Cebon, 1990) that attempt to produce the best possible match between the core and the environment (Lawrence & Lorsch, 1967), by exchanging relevant information and resources (including people) with the environment. Less important input/output functions are "peripheral." Some peripheral functions such as security can be purchased from suppliers rather than directly managed. Which input/output functions are in transformative positions depends upon organizational strategy, given constraints placed on the organization by its institutional environment (DiMaggio & Powell, 1983; Pfeffer & Salancik, 1978) and the core technology. As safety is elevated in importance, we expect to see the organization becoming more responsive to the legitimate safety concerns coming from the environment. For example, we might see a cooperative rather than an adversarial relationship developing with the NRC.

Coordination and structure. Organizational units are created by grouping together people who must interact the most and are reciprocally interdependent (require extensive information from each other or exchange physical resources). Therefore, each input/output activity is likely to be the responsibility of a particular unit (Thompson, 1967; Nadler & Tushman, 1988). These units will be linked in ways that minimize communication difficulties (Galbraith, 1977; Malone & Smith, 1988).

However, for organizations with multiple and competing objectives, such as safety and efficiency, there may not be one best arrangement of communication paths among organizational units (cf. Arrow, 1970). Such an organization needs multiple communication paths, making the nature of interaction across the interfaces between units important and difficult to manage centrally. That is why the decentralized, networked organization is becoming a more prominent form (Galbraith & Kazanjian, 1988).

However, the same complexity can lead to situations in which key systems are the joint responsibility of several different people without clear lines of authority, resulting in numerous meetings to negotiate accountability and implementation of change. One utility, for example, has a fire protection officer at each plant, but also a fire protection engineer, a fire protection program manager, and a fire protection matrix manager at the utility, as well as electrical engineering and project engineering managers. It is not clear who is in charge, or how to implement new programs (presumably another project engineer would be appointed, who would have to negotiate with all the other interested parties, but who would not have authority nor accountability for changes).

Organizational Processes

If we consider our definition of process - the way people carry out tasks in order to accomplish objectives - then it is reasonable to classify organizational processes by their relationship to the components of the definition. This suggests categories such as the following: (a) the processes by which people are brought into the company, the characteristics they thereby bring with them, and the way they are socialized and trained; and (b) the procedures established to define and carry out tasks, including assigning people to various roles. Note the assumption that people carry out organizational procedures: if a group does something, it is the people in the group that actually perform activities.

Selecting and managing people. The career paths of plant personnel in U. S. plants tend to be very different from comparable ones in Europe and Japan. For example, U. S. operators tend to be high-school educated, and to have come through trades such as electrician and machinist. Many received their experience in the nuclear Navy; other personnel were promoted from fossil fuel plants into better-paying nuclear plants. Although operators receive formal training and licensing, their education may not be sufficient for the demands of unusual or emergency situations. They may not understand the underlying physics of the plant and, as was the case with Three Mile Island, may use a faulty "mental model" of the plant in responding to problems and thereby exacerbate the situation. In contrast, plant operators in many European countries (e.g., Switzerland) get specialized technical training through educational tracks that take a very different approach to "vocational" education. Such technical workers are much more sophisticated, and much closer in status to engineers, than is the case in this country. This affects both the available know-how to run the plant, and the relations among various functional groups in the plant.

Organizational processes are enacted by people whose characteristics influence and are influenced by the organization. For example, the culture of an organization consists of artifacts such as behaviors and physical objects, beliefs and values, and underlying basic assumptions that are usually outside awareness

(Schein, 1985). U. S. NPPs are a meeting place of several cultures: The "engineering" culture of the designers and builders of the plant, the "fossil fuel plant" culture that produced many of the control room and maintenance personnel who transferred to the more glamorous and better-paying nuclear plants, the blue-collar machinist-electrician culture, the "Nuclear Navy" culture, and so forth. These cultural groups have substantial differences in education, status, skills, and modes of work. For example, Eagan (1982) contrasts the engineering world as one of the "mind" while the operators deal with feedback of the "hand." In at least some plants, members of each group tends to think that they alone know how to "really" operate the plant: communication may be strained or misleading; cooperation may be difficult to obtain. For example, operators may have little say in configuring the plant or dealing with problems, and the engineering solutions may be unrealistic and/or resisted by the plant culture.

Managers are known to differ in the underlying assumptions they make about the competency and motivation of various groups of employees. For example, "Theory X" managers (McGregor, 1960) make management responsible for motivating and controlling workers who are assumed to be self-interested. In contrast, "Theory Y" managers believe that workers want to participate and contribute, and management should strive to encourage workers to develop their skills.

Such managerial assumptions, when shared, become embodied in organizational incentives and control systems. NPPs can be run as "low trust" organizations that want the operators (and others) to follow the book, let the automatic systems run the plant until the right procedures are located, respond only to symptoms, check and double check everyone's actions, and so forth. Or, they can be run as "high trust" organizations that rely on the personnel to take initiative, innovate, diagnose underlying causes, and exercise their discretion. The culture of the organization thus will be reflected in the kind of personnel it attracts and socializes, and the kind of learning it encourages and permits.

Procedures for task accomplishment. There are many different ways to accomplish what appears to be the "same" task. Many plants seem to operate in a passive mode, somewhat homeostatic, unchanging unless forced to change by an accident at the plant, a major event such as TMI, or prodding by the NRC. On the other hand, both Connecticut Yankee and Maine Yankee are very proactive in their dealings with the NRC. They have created procedures to find small problems before they become big problems, which involves open channels of communication within the plant and between the plant and the outside world. A sincere commitment to safety (a "safety culture") would presumably reward or recognize people who identify problems, even if these lead to plant shutdowns, rather than trying to avoid problems in order to keep "steaming" (ie., running the plant until planned shutdown; note that the recent Japanese accident involved a problem that emerged a few days before planned shutdown, Mainichi Daily News, 1989).

As a good example of activities carried out between people in the same unit, consider shifts of operators in control rooms, who are generally constituted as teams who train and work together. Team members are rotated together from shift to shift, and train together on simulators. Team performance therefore depends not only on individual training and competence, but also on the team's ability to share information and duties. Further, performance depends on managing the interface between the team and others outside the control room who provide information and carry out activities such as investigation, maintainance, and so forth.

As an example of processes that act across unit boundaries, consider the problem of managing the flow of information across the organizational boundary. Information about technical developments and operations experience must flow into the plant and have impact, in order to avoid the TMI situation in which accident precursors in other plants were not communicated to the TMI operators. Similarly, information about the plant must flow outward to the owners, NRC, INPO, and public. The continued ability of the plant to attract resources (money, personnel) depends on their management of this information flow.

Indicators of Management and Organizational Factors

As we have discussed, the detailed studies of TMI concluded that management and organizational factors (at plant and institutional levels) are associated with safety. More recent studies draw the same conclusions (e.g., Ryan, 1988; Morey & Huey, 1988; Reason, 1988; Hansen, et al., 1989). Although NPPs, INPO, NRC and others collect enormous amounts of data, good indicators of management and organization are not yet available. Even good data on staffing, budgets, and organizational charts do not exist (Marcus et al., p. 93).

Discussing performance indicators, Marcus et al. (1989) suggest that "the limitation of these indicators is that they have been developed incrementally over time to deal with specific issues as they have arisen and are not part of a broader logical framework" (p. 23). For the most part, efforts have focused on developing indicators that are easily available, "objective," comparable among plants, and quantitative. Thus, for example, Olson et al. (1988) operationalized "management" as generic issues backlog, procedure LERs (Licensee Event Reports), and administrative LERs. In fact, this seems to be measuring something by its presumed effects: LERs are a result of management (and other things), not a "measure" of management.

In contrast, serious management reviews involve more subjective and process-level information. For example, the NRC conducts in-depth on-site management and organizational analyses examining twenty variables (e.g., communications, attitudes and morale) through systematic interviews and a data collection instrument (see Marcus et al., pp. 68-69). These seem to form an implicit theory (or, at least, a checklist) of NPP functioning. Some interview questions are directly tied to predefined management problems such as lack of follow-up on improvement programs, problems resolving conflicting resource demands, and emphasis on production over safety and quality. Marcus et al summarize a useful direction to indicator development in Appendix 3.1, drawing on interviews with NRC staff.

No matter how "objective" the indicators appear to be, there is unavoidable incompleteness that is exacerbated by the apparent scientific respectability of quantitative indicators. The nuclear power industry (e.g., INPO) concentrates on final outcomes (e.g., accident rates, scrams, radiation releases) because the industry has done very well when measured in *this* way, and because the regulation of outcomes permits the industry considerable freedom (Marcus et al., p. 70). However, the NRC is increasingly concerned with safe *behaviors* rather than safe *outcomes*, and seeks to identify and regulate management behaviors and organizational conditions that are safety-relevant.

RESEARCH PLAN

The Goal of Understanding

Prior research on the issue of organization and management of NPPs has generally focused on documentation of best practice and quantitative empiricism. Best practice reports from "successful" plants try to incrementally improve technical, procedural, and managerial practices. However, lacking a comprehensive model of the plant as a whole, including the processes or mechanisms by which various procedures affect desired outcomes, we may fall prey to two kinds of errors: (1)

assembling best practices of various sorts that do not work well in concert, and (2) failing to go beyond available examples because we do not understand the relationship between problems and their solutions. Predictive models that compare quantitative indices of performance against various organizational, technical, financial, and contextual variables tend to measure structure and outcomes but not process (because process is hard to measure), and treat performance as an additive sum of these variables, again failing to represent or understand the complex dynamics of plant management.

Instead, we seek to develop a deeper understanding which builds upon such predictive relationships, but seeks a more comprehensive and process-oriented view of NPPs. We believe that a thorough understanding of NPPs arises through the accumulation of detailed knowledge of operating plants, and the assembling of such information into a framework or conceptual model of the plant and how it learns.

We recognize the need to represent our understanding of NPPs in compact form, possibly as a quantitative model or a computer simulation. However, we believe such models presuppose a level of understanding: as Campbell (1979) has said, "science depends upon qualitative, common-sense knowing" (p. 50). In short, we cannot merely accept the quantitative indicators that NPPs already collect for various financial, regulatory, and management reasons, but rather permit new indicators to emerge along with theory. The same view is repeatedly found in prior organizational research in NPPs (e.g., Marcus et al., 1989).

Indicators

The overall plan of research is to identify and/or develop indicators of critical NPP organizational components. We presume that these indicators would differ markedly from what is currently available in two ways: first, there would be more emphasis on the portion of plant behavior labeled "emergent processes." Marcus et al (1989) left this as a catch-all category that had few objective, readily-available, indicators. We find emergent processes to be central to our understanding of plants. Second, we would include indicators that are qualitative or more difficult to obtain. Several scholars argue that perceptions are critical for analyzing NPPs as organizations (Marcus et al., 1989, p. 55; Weick, 1988). Our goal is understanding rather than the implementation of a universal assessment system (as NRC and INPO must achieve). Therefore, we can afford to strive for a theoretically-rich set of indicators that may be impractical for other purposes. However, we would hope that our indicators could be adapted for other purposes in the future.

Once these indicators were developed, we would "instrument" some NPPs for a period of time capable of witnessing an entire fuel cycle and possible technological and organizational changes (or failed change efforts). "Instrumentation" would include readily-available and quantitatively precise data, but would also include information that could only be obtained by questionnaire, interview, on-site observation, or electronic instrumentation (e.g., video recording). This intensity of data collection implies studying a small number of plants observed for two or three years. The plants would be chosen for their informativeness, such as a plant with an outstanding reputation, a plant trying to change its management in order to be more efficient and more safe, or a plant with a very different approach to effectiveness (perhaps a Swiss or Japanese plant).

Indicator Development

Along with reviews of the literature specific to NPP and relevant areas of organizational studies, the process of indicator development would involve:

(a) Interviews with experts who understand NPP functioning in substantial detail. For example, there are site-visiting teams used by the NRC and INPO to assess plant performance. These teams use objective data, interviews, and direct observation, filtered through their broad experience base, to determine plant performance. Interviews would seek to determine their models of plant functioning and their beliefs and insights about indicators. It would be desirable to accompany such teams on actual site visits.

(b) Retrospective case studies of particularly informative plants. For example, we visited Connecticut Yankee because their performance had deteriorated after many successful years, and then improved after a change in management. Our interviews with managers and plant personnel suggested what they believed to be the key reasons for poor and good performance, and the "people management" techniques that they used to affect performance. Similarly, we visited Maine Yankee to ask them how they had managed to remain a top-performing plant for so long. Part of the answer seems to lie in the way they manage external relations with the NRC and the public.

(c) Fieldwork in NPPs. Observation at one or two carefully-chosen plants will be carried out by faculty (and possibly doctoral students) who will spend considerable time on site for a 3 to 6-month period. Collaboration with knowledgeable insiders (on-site personnel) is essential to this effort, and this collaboration would include two possible forms: (1) reliance on expert informants to offer their knowledge and access to various documents and other personnel, and (2) identification of a group of insiders to be trained in observation and act as a research team (in addition to their regular duties). It would be desirable to have this level of collaboration because insiders have technical and organizational knowledge and access that outsiders can achieve only partially after considerable time.

(d) Survey of MIT Nuclear Engineering Graduates. The Nuclear Engineering Department at MIT has been a central source of trained personnel for upper-echelon technical and managerial positions in the nuclear industry. The Department has been in operation for over 25 years, and has produced hundreds of graduates who have positions throughout the industry (including CEO and Vice-President) and in many different countries. A mailed questionnaire to these graduates would produce a tremendous amount of useful information about their specific plants and utilities, the issues they see, their ideas about change processes and indicators of organizational characteristics, their beliefs and values, and so forth. Since the questionnaire would originate from MIT, we would expect a high response rate and substantial candor and effort.

(e) Simulator experiments. Improvements in operator skill and in control room design is traceable, in part, to the increased use of simulators. Highly realistic mock-ups of control rooms, with computer-driven displays that model the responses of a real reactor, offer a way to teach operators, and to test new procedures and instrument designs. They also offer an opportunity to experiment with group processes in a controlled environment, and to develop indicators of group functioning apart from "performances" (e.g. how they handle a steam tube rupture). It would be possible to look at extreme situations such as understaffed control rooms, and to compare the thoughts and feelings of operators in actual control rooms vs. simulators (actual control rooms are boring but have real consequences, simulators have a flurry of activity but no real danger and no night shifts).

Indicator Content

As we explained previously, the study of organizational life requires that we examine key functional units, the relationships within the units and between units, and the ways in which learning and change occur or are inhibited. We anticipate that a very broad range of indicators will be developed to measure plant characteristics such as organizational structure, typical career paths, culture, and mental models, and organizational processes such as standard operating procedures, communication patterns, exercise of power and accountability, learning and change, problem finding, planning, and risk assessment.

The measurement of these indicators would be based on a variety of methods, not limited to readily-available quantitative information of the sort already reported to INPO and the NRC. For example, measures of culture would undoubtedly involve on-site observation and intensive interviews with a broad spectrum of plant personnel. Communication patterns would be assessed through self-report inventories of daily activity (with whom one interacted, through what channels, and what was the content) at randomly-selected days (Allen & Cohen, 1969). Mental models are measured by asking respondents to diagram workflows, communication patterns, and event contingencies (ie., their "theories" of the plant and the organization). Nuclear plants are continually assessed for various low probability events. Techniques such as fault-tree analysis are used to estimate the likelihood of various types of problems, and these analyses are used to guide policy and procedures in the plant, and to communicate with various constituencies (e.g., regulators, the public). In short, we are likely to use a broad variety of techniques, and hope to develop new techniques that fit the concepts being measures.

Project Management

The NPP Indicators Project would be managed by a faculty member acting as Project Director. The Project Director would be in charge of overall management (with the assistance of a staff Project Manager), and the linkage between specific research projects and the goals of the overall Indicators Project. The Project Director would act as Chair of the Research Board, consisting of all faculty participating in research within the Project (anticipated to be 4 to 6 people).

The Project would be assisted by an Advisory Board of academics from relevant social science, management, and engineering disciplines (examples of people we would ask are Karl Weick, Henry Mintzberg, Todd LaPorte, Alfie Marcus, Olsen, Andy VandeVen, Larry Hirschhorn, Chick Perrow, Peter Manning, others from Nuclear Engineering, Economics, Accounting, Operations Management) and industry experts (NRC, INPO, utilities). The size of the Advisory Board would be approximately eight people.

Along with the faculty investigators on the project, we would anticipate having a visitor each year such as Peter Manning or Alfie Marcus to conduct their own research and assist ongoing projects.

We anticipate having an Annual Conference of the project personnel, Advisory Board and sponsors to discuss objectives, plans, and progress. From the second year onward, this Conference could be expanded to a research conference for those concerned with the management of high reliability and high technology systems such as NPPs.

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APPENDIX

HISTORY OF CONCERN FOR SAFETY IN NUCLEAR POWER PLANTS

The most useful way to understand the nuclear industry and the nature of organization and management in the industry is to have a brief historical outline.

Early History

The nuclear industry traces its development to the Manhattan Project's first controlled chain reaction on a squash court at the University of Chicago in 1942. By 1946, the Project had built the first peacetime reactor at Oak Ridge National Laboratories. The Atomic Energy Act of 1946 converted the Project into the Atomic Energy Commission, which continued reactor development as a military effort focused on weapons stockpiles. At the instigation of Hyman Rickover, the Navy developed a nuclear-powered submarine lauched in 1955 with a small pressurized-water reactor (PWR) built by Westinghouse.

Early in the Eisenhower Administration, the government began to push for industrial powerplants. The Navy large reactor program was canceled and the large PWR project was rechannelled to powerplants. The AEC began a 5-year demonstration testing five types of reactors, including the Navy PWR and a boiling-water reactor (BWR) developed at Argonne National Laboratory and adopted by General Electric.

The Atomic Energy Act of 1954 permitted industry to "use and process" nuclear material, thus shifting the government role from monopoly to regulation. However, industry was still unwilling to take financial risks, so the AEC established a system of subsidies until 1963. The first commercial NPP went into operation in 1957. By 1963, the workability of both PWRs and BWRs was established, 13 "turnkey" projects were ordered from GE and Westinghouse for various utilities, and 27 other plants were ordered from various vendors. Expansion continued through the 1960s, with growing numbers of plants, and increased size of plants.

A 1967 report showed that containment in the new larger units could not be assured in the event of a core meltdown, and the AEC began to shift from accident prevention to accident mitigation and quality assurance. Environmental activism began to slow construction of new plants. Charges of conflict of interest resulted in the AEC being split in 1974 into the Energy Research and Development Adminsitration (to promote nuclear power) and the Nuclear Regulatory Commission. Increased regulatory demands, tight capital markets, and decline of electric consuption growth in the 1970s led to deep uncertainty in the industry, capped by the Three Mile Island (TMI) accident in 1979.

Three Mile Island

TMI illustrates the Perrow-style nightmare of a system accident. A minor failure in the non-nuclear feedwater loop resulted in increased pressure and temperature in the primary loop that cools the reactor. The pressure relief valve automatically opened but remained stuck in the open position, permitting a loss of coolant through the open valve. Because there was no positive indicator of valve position and there was a history of misleading temperature readings due to small leaks, operators erroneously believed the valve was closed for two hours. Following their training, they attempted to maintain proper pressure in the system without "going solid" or filling the pressurizer with water. Unfortunately, because of steam bubbles in the pressurizer, pressure remained high although the level of coolant was actually low. The operators discounted high temperature readings that were known to fluctuate even under normal conditions. Since the operators were preventing emergency systems from pumping more coolant into the system, the core was uncovered and had no way to dissipate its heat, the zirconium fuel rods reacted with steam to create hydrogen gas and weakened fuel rods which ruptured, and serious damage resulted.

Although TMI can be traced to a combination of physical malfunctions and operator misdiagnoses that overrode safety systems, the true causes are more complex. The operators were doing what their training told them to do, and what the vendor (Babcock and Wilcox) recommended. The fact that they did not understand the events unfolding was at least partly due to their lack of training for this scenario; in short, their "mental model" of the plant and accident scenarios was deficient.

Yet, there is an even deeper cause: there were precursor events at TMI and other plants that should have led to changes in equipment, procedures, and training in time to prevent the accident. Virtually identical "transients" involving stuck-open pressure-relief valves occurred in 1974 at a Westinghouse reactor in Switzerland, and in 1977 at a very similar Babcock and Wilcox plant in Toledo (Davis Besse). The Davis Besse accident was thoroughly analyzed by Toledo Edison, Babcock and Wilcox, and the NRC. They knew that the valve could stick open, that level readings could be erroneous, and that the dangers of "going solid" were mild compared to the risk of uncovering the core, but none of this information was communicated to Metropolitan Edison (the owners of TMI) or the operators at TMI.

Underlying this lack of communication and failure of organizational learning were several factors: the NRC focused primarily on reactor design review rather than reactor operations; the thousands of reports going to the NRC were hard to analyze, difficult to diagnose and classify, and were not systematically reviewed for safety problems; utilities did not share information about safety-related operational problems among themselves or with vendors; vendors were inconsistent in monitoring operations in plants they had built.

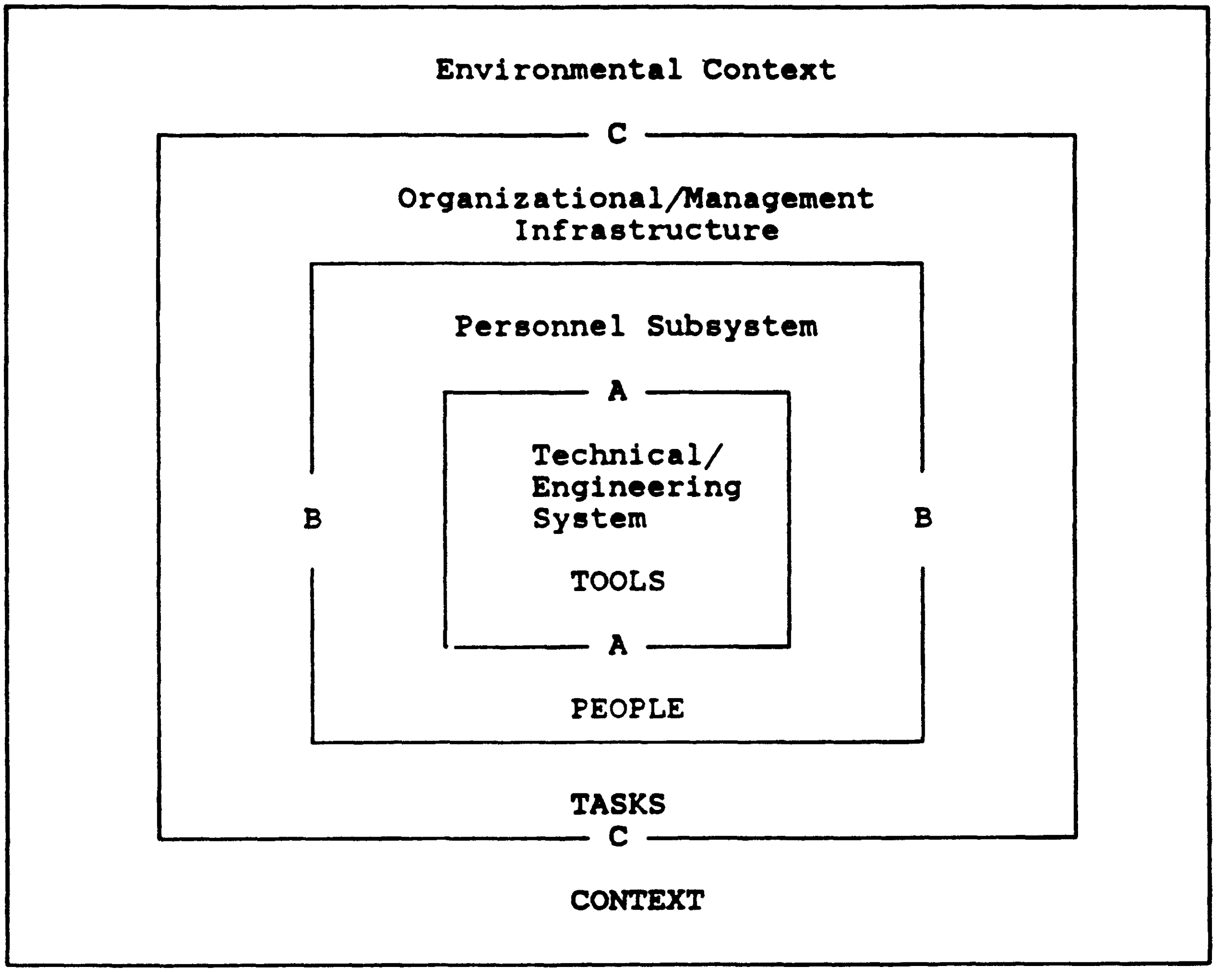
Post-TMI

It is unfortunate that it takes a disaster like TMI, or Challenger, to create reforms. TMI was intensively analyzed (Kemeny et al., 1979, Rogovin & Frampton, 1980) and significant change resulted. NRC internal organization and reporting requirements changed, including NRC on-site personnel at each plant. The industry created the Institute of Nuclear Power Operations (INPO) to collect and analyze information, train and accredit operators, evaluate plants, promote innovations, disseminate information, and so forth. New operating procedures were instituted including technically-trained personnel in the control room, new training requirements for operators, far more detailed operations manuals, new training procedures with increased use of simulators, more intensive and useful reporting requirements to the NRC and INPO, specific changes in equipment to prevent a TMI-type accident, and many other innovations.

The net result of all this effort has been beneficial. Reactor operations have become the focus of attention (no new U. S. reactors have been designed in many years!). Far more information is being exchanged among plants, utilities, vendors, and regulators. According to INPO, performance of NPPs on safety and efficiency criteria have steadily improved during the 1980s. For example, unplanned automatic scrams while critical have declined from 7.4 in 1980 to 2.1 in 1988. However, although the average "health" of the industry has improved, several key issues remain: is the industry healthy enough, given the desire to reduce risk in this industry; do the indicators of health tell the whole story with sufficient accuracy; and what can be done with the minority of plants that are clearly deficient on many indicators?

Figure 1

Components of A Socio-Technical System



Note: Adapted from Shikiar (1985) and Moray and Huey (1988)