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SCIENCE DIRECT

Reliability Engineering and System Safety 89 (2005) 331–345

RELIABILITY ENGINEERING & SYSTEM SAFETY

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Characteristics of organizational culture at the maintenance units of two Nordic nuclear power plants

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Received 21 May 2004; accepted 8 September 2004
Available online 10 November 2004

Abstract

This study aims to characterize and assess the organizational cultures of two Nordic nuclear power plant (NPP) maintenance units. The research consisted of NPP maintenance units of Forsmark (Sweden) and Olkiluoto (Finland). The study strives to anticipate the consequences of the current practices, conceptions and assumptions in the given organizations to their ability and willingness to fulfill the organizational core task. The methods utilized in the study were organizational culture and core task questionnaire (CULTURE02) and semi-structured interviews. Similarities and differences in the perceived organizational values, conceptions of one's own work, conceptions of the demands of the maintenance task and organizational practices at the maintenance units were explored. The maintenance units at Olkiluoto and Forsmark had quite different organizational cultures, but they also shared a set of dimensions such as strong personal emphasis placed on safety. The authors propose that different cultural features and organizational practices may be equally effective from the perspective of the core task. The results show that due to the complexity of the maintenance work, the case organizations tend to emphasize some aspects of the maintenance task more than others. The reliability consequences of these cultural solutions to the maintenance task are discussed. The authors propose that the organizational core task, in this case the maintenance task, should be clear for all the workers. The results give implications that this has been a challenge recently as the maintenance work has been changing. The concepts of organizational core task and organizational culture could be useful as management tools to anticipate the consequences of organizational changes.

Keywords: Organizational culture; Maintenance work; Safety culture; Organizational assessment; Work psychology; Task analysis

1. Introduction

The term *safety culture* was introduced into common usage after the Chernobyl nuclear accident in 1986 [21]. The main reasons for accidents were proposed to be not only technical faults or individual human errors. It was suggested that management, organization and attitudes also influence safety for better or worse. In a 1991 report INSAG [21] defined safety culture as follows: "Safety culture is that assembly of characteristics and attitudes in organizations and individuals which establishes that, as an overriding priority, nuclear plant safety issues receive the attention warranted by their significance." [21: p. 1]. The demand for 'a proper safety culture' quickly became a (more or less explicit) requirement by the regulatory authorities, first in the nuclear field and gradually also in other safety-critical domains (e.g. offshore drilling industry, railway industry). For an overview of the field see e.g. [9,15,34,50].

The concept of safety culture was coined partly because of a need to assess the operating risk associated with the overall functioning of safety critical organizations [21]. Sorensen [50] nevertheless criticizes the approach taken by INSAG towards the safety culture concept: "The fundamental problem with INSAG's approach to safety culture is that it specifies in great detail what should be included, but provides little guidance on overall criteria for acceptability. Furthermore no link is made (or even seems possible) between safety culture as INSAG defines it and human performance or human reliability. A positive relationship is simply assumed." [50: p. 191].

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doi:10.1016/j.ress.2004.09.004

Sorensen's (and other's, see e.g. [34,39]) critique concerning INSAG's approach to safety culture brings up two important issues. First, the term safety culture was expected by the 'risk' community to help explain the causes and probabilities of human errors that affect the operating risk. But the concept was adopted from an entirely different scientific tradition than that commonly used in safety science. The lack of criteria for acceptability or evidence of causal links stems partly from the tradition in ethnographic culture study. The ethnographic culture tradition is basically descriptive in nature and its researchers do not aim to assess the 'goodness' or 'badness' of cultures [1,48]. Sorensen concludes "although INSAG has borrowed the term "culture" from either anthropologists or the organizational development community (who in turn borrowed it from anthropologists), the INSAG publications make no reference to the bodies of literature in those fields… Nevertheless, suggestions that "culture" might help explain organizational behavior, and that management and organizational factors could influence safety performance, both predated INSAG's introduction of the term 'safety culture'" [50: p. 191].

Also, management and organizational 'factors', have received considerable attention in organizational research, where the dominant focus is on corporate performance. Starting in the late 1970s, traditional mechanistic management models were repeatedly found to be inadequate and to tend to neglect issues associated with knowledge about human nature. A new concept was needed to describe and explain the individuals' actions in an organization so that the effectiveness of the organization could be improved [2]. Organizational culture was suggested to be such a concept. Despite the almost immediate popularity of the organizational culture concept, no clear and widely accepted definition of the concept has emerged [27,46,48]. Also the evidence of a link between organizational culture and effectiveness is tentative at most [56]. The reasons for this state of affairs are numerous, and stem, e.g. from different conceptualizations of organizational culture and effectiveness, and from problems in assessing culture and performance independently [42,56].

Cultural approaches are particularly interested in meanings and the generation of these meanings in organizations [1: p. 106]. The meanings that the personnel relate to the demands of their work are of special interest from the perspective of the present authors. These meanings are assumed to be constructed in interaction with other members of the organization as they are trying to maintain the internal cohesion and external adaptation of the organization [31,46]. Cultural approach thus emphasizes collective issues (and those issues that should be shared) over e.g. individual decision making. Individuals act and make decisions in a social context. The effect of this context can be so strong that the individual is not even aware of making a decision—choosing between alternative ways of acting [1: p. 118,42].

We define organizational culture as a learned way of responding, or a solution, to the demands of the organizational core task [31,42,46]. A solution, however, is not final or unambiguous since organizational culture includes the process of formation and reformation of the abovementioned solution. This also means that the organizational culture as we define it includes dysfunctional solutions, dissent and conflicts of interests, as well as the attempts to solve or cover these [31: p. 292]. This process, which has close connections to Weick's [55] concept of sense-making, may be perceived as the essence of an organizational culture. Weick has described this continual and collective reality-building process constantly taking place in the organization. In this process, the meanings of various events are deliberated and a common view is formed based on perpetually incomplete information [55]. It seems reasonable to state that the influence of this phenomenon is crucial to acknowledge in safety-critical environments. This is especially the case in activities where large groups act with some degree of autonomy, performing different tasks, but having a common goal for their work and a need to co-operate in a number of situations. All these characteristics apply to, e.g. maintenance, technical support organizations, the construction industry and health care.

Maintenance of a nuclear power plant is a complex activity characterized by many coupled subsystems, uncertainty in the data available to the workers, mediated interaction via various tools and potentially high hazards [52: p. 14–17], see also [33]. In addition, recent changes in society (changes in the age structure and values towards work, utilization of new technologies, deregulation of the electricity markets, emphasis on outsourcing noncritical functions, etc.) have set new demands on the nuclear power plants [25,54]. The competence in maintenance consists of different technical fields but also requires strategic understanding as well as practical handicraft skills. For example in annual outages, the maintenance organizations have to schedule and plan hundreds of work packages requiring multiple technical disciplines [5]. In addition to that, all the tasks have to be coordinated with the operations and done according to organizational procedures. Despite the organizational challenges, the human factors research has focused mainly on occupational accidents [53], human errors [35,37] or reliability of individual task performance, e.g. probability of detecting flaws by non-destructive testing. Due to the diversity of the maintenance tasks and the numerous competence requirements, focusing on a single task (e.g. electric installation), special situation (e.g. outage) or a single psychological problem (e.g. memory overload) can only partially explain maintenance as a job.

Culture approaches share a relation with many systemic approaches that focus on the adaptive potential of a culture/system [42]. Safety of an organization is suggested to be related to the ability of the organization to cope with changes (its adaptive potential)—in order to explore this issue it is essential to get hold of, e.g. the general values and orientations in an organization that transcends the specific focus on safety [28,31].

The cultural approach to maintenance work raises a number of important questions: To what extent do the personnel perceive maintenance as a safety-critical activity? Do the personnel feel that the maintenance of a NPP is demanding? How to maintain the safety and reliability of maintenance activities when conducting organizational changes? What aspects in the organization contribute to the experience that the worker is able to cope with his tasks and experiences his work as meaningful? What kind of cultural features are required for reliable maintenance in NPP? Our hypothesis is that due to the social complexities of the maintenance work, the cultural features and the challenges related to safety and reliability variy between the different maintenance organizations. On the other hand, the content of the work and the objectives of the maintenance organizations should be quite similar. Thus, the second hypothesis is that there are common dimensions in how the maintenance personnel experience their work independent of their organization. These hypotheses are considered in two case studies, where the aim is to identify the cultural similarities and differences related to the above-mentioned questions.

2. Methods

2.1. Research strategy

The study aimed at characterizing and assessing the organizational cultures of Nordic nuclear power companies' maintenance units The research focused on two NPP maintenance units, Forsmark (FKA) in Sweden and Olkiluoto (TVO) in Finland. Both companies can be considered as high reliability organizations [24,44] by showing a good performance record and few incidents. We aimed to illustrate how the identified cultural features might affect safety and efficiency in the case organizations.

The cultural assessment was made by the means of maintenance core task modeling—a strategy that has already been used in our previous studies [29,31,40]. This approach has been titled 'The Contextual Assessment of Organizational Culture (CAOC)' [31,40,42]. The methodology utilizes two concepts, organizational culture and organizational core task (OCT). OCT refers to the shared motive of the activity of the organization and to the requirements for and constraints of the organizational practices [42] (Fig. 1).

The theoretical OCT model was used in evaluating the characteristics of the organizational culture (Fig. 1). We aimed at identifying the strengths and weaknesses of the case organization's culture in relation to its core task. The focus of the assessment was not on explaining causal relations to objective measures (e.g. occupational accidents or number of common cause failures). Instead, we strove to anticipate the consequences of the current practices, conceptions and assumptions in the given organizations to their ability and willingness to fulfill the OCT [42]. However, the purpose of this article is not to evaluate which organization is better, but to raise issues that require attention in the organizations. When evaluative statements are made, the criteria are formed on the basis of the core task model: Even though the practices differ, they may both be as effective from the perspective of the maintenance core task [42].

The methods utilized in the study were organizational culture and core task questionnaire (CULTURE02) and semi-structured interviews [40,41]. We propose, along with many others [27,45: p. 206], that one of the best ways to study organizational culture in complex sociotechnical systems is to use both qualitative and quantitative methods, since we strive to understand the unique organizational culture in question and also to compare the profiles of similar organizations and identify subcultures within the organizations.

2.2. Criteria for the assessment: the core task of maintenance

Maintenance activity is viewed through a conceptual model of the demands of the maintenance core task. This model has been conceptualized in our previous studies [31,40]. The model has been further iterated by the participating researchers (the authors) and in discussions

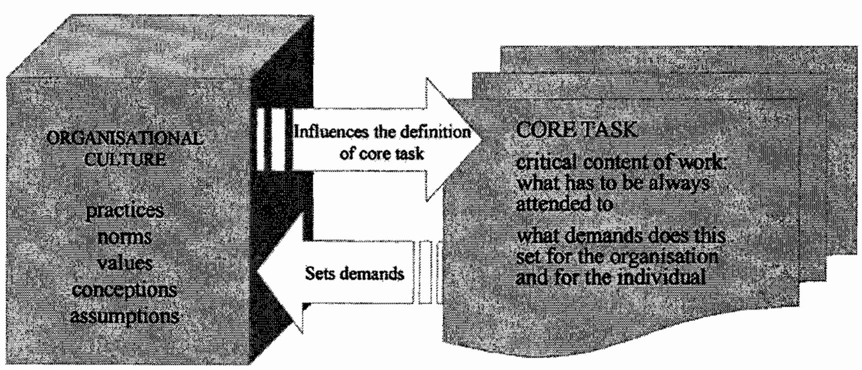

Fig. 1. The central concepts of CAOC methodology, from Reiman and Oedewald [40].

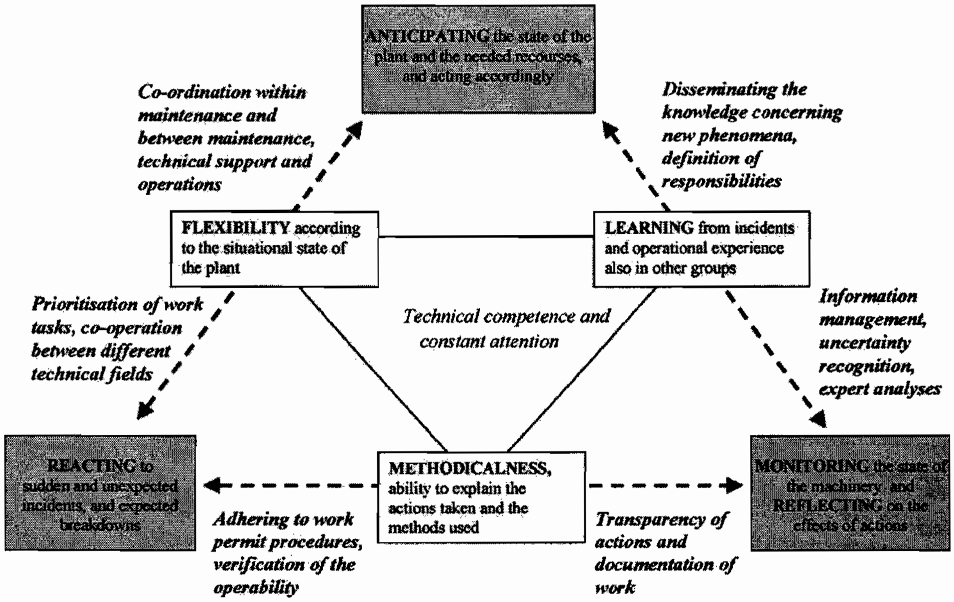

Fig. 2. The model of the demands of the maintenance core task, adapted from Oedewald and Reiman [31].

with maintenance experts from TVO. The model aims at presenting a general framework of the demands of the maintenance work. The model serves as a starting point for the discussion of organizational practices and strengths and weaknesses of the culture [31].

The model depicts maintenance as balancing between three critical demands: *anticipating*, *reacting*, and *monitoring and reflecting* (Fig. 2). In addition to the critical demands, three instrumental demands that facilitate the fulfillment of the critical demands, have been extracted; *flexibility*, *methodicalness* and *learning*. Working practices related to the fulfillment of the critical demands are also depicted in the figure.

The model depicts knowledge creation and problem solving activity as being inherent in the maintenance task and brings thus the demands of the maintenance work closer to those of knowledge work. Simultaneous multiple and parallel tasks, some of which are independent and some which are dependent on one another present a challenge to the maintenance work. Individual maintenance activities (e.g. corrective maintenance) can be modeled linearly as a work process starting from planning and ending in documentation of the work [3]. The OCT model, however, depicts the demands of the activity in the entire organization. The different activities and technical disciplines have to be coordinated in the daily work in a manner that also ensures the creation of new knowledge concerning the (changing state of the) plant.

2.3. The case organizations

2.3.1. Olkiluoto maintenance

TVO's organizational structure was reformed in January 2003, after the main data collection. The new organization comprises five departments: *Operation* responsible for the operation and maintenance of units OL1 and OL2, *Project* responsible for the construction of the fifth NPP in Finland (OL3), *Engineering, Finance* and *Corporate resources* [51]. Approximately 120 employees work with issues related to maintenance in the operation department. The case study concentrated on the two offices of the operation department in charge of the maintenance at Olkiluoto: The office of mechanical maintenance and the office of electrical and I&C maintenance. These offices changed little in the 2003 reorganization.

The offices consist of a number of groups with a group manager, foremen and technicians. The group manager also attends to the duties of the foremen. At TVO, a system of equipment responsibility areas has been used to organize the work since the middle of the 1990s. At the same time, a comprehensive new information system was taken into use to organize the work, store plant-related information and plan the maintenance activities on a short- and long-term basis. The system of equipment responsibility means that the foreman or the group manager 'owns' the particular equipment group and plans, e.g. the program of preventive maintenance and budget for the machinery. The owner of the equipment plans all the maintenance activities conducted for the corresponding equipment, irrespective of the type of maintenance (electrical, mechanical, instrumentation) required. The owner utilizes experts of the other fields to accomplish this.

2.3.2. Forsmark maintenance

The maintenance function at FKA lay in the aftermath of a major reorganization at the time of the data collection. Before the reorganization, maintenance activities were distributed so that each of the three nuclear power stations had their own dedicated maintenance support-organization. Control was previously exhibited in terms of a line organization within each station-specific maintenance organization. In the new maintenance organization, the previous functions were centralized into a single maintenance unit and a matrix organization was introduced. A total of 180 employees work in the new unit.

Four 'business areas' (Operative maintenance, Maintenance projects, Installation, Analysis and development) controlled and implemented operative maintenance projects that were ordered from the stations at the site (with a lot more 'business' flavor than previously). Responsibility for the execution of the various maintenance projects was, in the new organization, separated from the responsibility for the maintenance resources (the matrix). As usual in a matrix organization, the operative personnel had several 'bosses'. A technician could conduct work at request from several business areas under the manager from that area. The line manager 'sells' the technician to the particular business area that needs the resources. In Spring 2003 there was again a change in the maintenance organization. The matrix type was discarded in favor of a more traditional line organization; the centralization aspect was retained, however.

2.4. Description of the methods and data collection

2.4.1. CULTURE-questionnaire

The questionnaire consists of four different measuring instruments: measure of the perceived values, measure of the psychological characteristics related to work, measure of the personnel's conceptions of the organizational core task and measure of the ideal values of the organization. The questionnaire consists of about 100 multiple choice questions and two open questions. The open questions are phrased as follows: "What are the strengths of the maintenance activities at X" and "What are the weaknesses of the maintenance activities at X" (X being the plant in question). The questionnaire was piloted at a Nordic NPP [40,41]. The current version was tailored and translated into Swedish in three meetings together with the researchers (the authors).

The respondents were assured that the responses would be handled confidentially and that the results could not be traced back to the individual respondents. In Finland, each questionnaire was addressed directly to the personnel with a sealable envelope, preaddressed to the research institute. In Sweden, the questionnaires were distributed at six section meetings and completed individually by each participant. Ten questionnaires were returned by mail by subjects who had not participated in the section meetings. Eighty-four responses were obtained from TVO (with a response rate of 60%), and 132 responses from Forsmark (with a response rate of 72%). The missing values were replaced by mean scores, after making sure that the missing values were random and no respondent had more than 20% missing in a given section. This criterion was not fulfilled by one respondent in Section B, and by two in Section D, and hence their values were not replaced.

2.4.1.1. Measures of workplace values (perceived and ideal), sections A and D. According to Cameron and Quinn's [6] Competing Values Framework, organizations can be typified into four dominant culture types (see also [36]). In a *hierarchy-focused* culture, procedures govern what people do and stability, predictability and efficiency are considered as long-term concerns of the organization. A *market culture* values productivity and competitiveness by emphasizing external positioning and control. The workplace is result-oriented. A *clan culture* values cohesion, participativeness, teamwork and commitment. An *adhocracy* culture has the fostering of adaptability, flexibility and creativity as a major goal. Readiness for change is advocated [6,36].

Thirty-four items, each rated on a six-point scale (from 'completely disagree' to 'completely agree'), were related to the values typically manifested in organizations (e.g. 'flexibility', 'economic efficiency'). The values were initially selected on the basis of Cameron and Quinn's [6] Framework and previous studies [38,40,41]. The instruction was to mark how much the respondent felt that the given values were endorsed in the respondent's section. The respondents were also asked to select their ideal values in the final (D) section of the questionnaire, with the same 34 items and the same six-point scale.

2.4.1.2. Measure of conceptions of one's own work (B-section). Thirty-two questions, each rated on a six-point scale, addressed the conceptions concerning one's own work and the organization. According to Hackman et al. [16–18], see also [11], high job motivation and high quality of the work performance can be acquired if the worker can achieve the following three psychological states:

- the work must be experienced as meaningful;
- the worker must experience that he is personally responsible for the work outcome;
- the worker must be able to determine how his efforts are coming out, what results are achieved and whether they are satisfactory.

The questions were initially formed on the basis of the above-mentioned theoretical model and previous organizational culture studies [38]. The pilot study [41] identified a fourth psychological 'state', sense of control [22,26]. Questions measuring this concept were also included in the B-section.

Three personal work-related scales were identified in the pilot study: perception of the working climate, attitudes toward the management and personal development orientation [41]. Questions related to these scales were included in the B-section of the questionnaire.

2.4.1.3. Measure of the maintenance core task (C-section). Twenty-three items, each rated on a six-point scale, related to the general demands of the maintenance work at a nuclear power plant. The questions were initially formed on the basis of interviews and workshops with maintenance experts from the pilot organization, and they were tailored on the basis of the pilot study [31,41]. The maintenance core task model that was constructed in the previous study identifies three critical demands of the maintenance task: anticipating, reacting and reflecting/monitoring (Fig. 2). The measure aimed at grasping the features of the maintenance task that are common to the entire organization. The measure included questions such as 'knowledge sharing is imperative to effective maintenance', 'close co-operation between different technical fields is required in order to be able to carry out the maintenance tasks', and 'unexpected things happen unavoidably in maintenance activities'.

2.4.2. Interviews

The participating researchers (authors and Irene Eriksson from Mälardalen University) formed the interview questions in concert CAOC-methodology [42] and previous studies [31,40] served as a background for the questions. The interview themes were as follows:

- Own job (the content, motivating and demanding features, nature of expertise, changes in work);
- Maintenance task (goals and critical demands);
- Organizing of maintenance activities (pros and cons of current organizational structure, co-operation between different technical fields);
- Organizational culture (stories, climate, subcultures).

Twenty interviews were conducted at TVO, ten in fall 2002 and 10 in spring 2003. At Forsmark, 12 interviews were conducted during fall 2002–spring 2003. The interviews were transcribed and used for an analysis of the typical features of the organizational culture, based on grounded-theory [7]. The interviews were also used as an aid in the interpretation of the survey results.

3. Results

3.1. Descriptive statistics and factor solutions for the survey

Table 1 depicts the demographic variables and their descriptive statistics. In addition to the demographic information, several covariates were included in the survey. Generic satisfaction with one's work was measured with one question 'I am generally satisfied with my work'. Job motivation was measured with the question 'My work is motivating'. Job stress was measured with the question: 'My work is stressful', and the sense of coping with one's tasks with question 'I can cope with my tasks'. All four questions were included in the B-section of the survey.

As shown in the table, only tenure, job stress and the perceived proficiency value differed significantly between the plants. Job stress and the perceived proficiency value received higher mean scores at Forsmark, whereas average tenure was higher at Olkiluoto.

The primary data was factor analyzed by the principal components method [19]. Results of the pilot study [41] were used in defining the hypothesized factor structure for the survey data. Four variables were removed from A and D-sections due to technical problems in the translation (see Section 2.4.1). A four-factor solution of the A-section was obtained on the basis of eigen values over one, which explained 58.9% of the total variance of the questions. The initial solution was rotated by the Equamax method, similarly to the pilot study. A five-factor solution of the B-section was obtained on the basis of scree plot and it explained 57% of the total variance of the questions. The initial solution was rotated by the Varimax method. A five-factor solution of the D-section was obtained on the basis of scree plot, which explained 54.3% of the total variance of the questions. The initial solution was rotated by the Equamax method. Factor scores from all solutions were formed by the regression method. The factor scores were used as dependent variables in subsequent analyses. Also summated scales were formed from the highest loadings in order to compare the unstandardised mean scores.

Table 1
The demographic information and the modes or mean scores and standard deviations in the entire sample and F-scores and significance levels from the analysis of variance with the plant as an independent variable

Variable	Scale	Categories	Mode/mean	Standard deviation	F score	Sig.
Age	Ordinal	5	Mode = 46–55 (4)	1.03	0.29	0.590
Position	Nominal	5	Mode = technician (1)	–	–	–
Section	Nominal	Varied	–	–	–	–
Tenure	Ratio	n.a.	$M = 17.6$	10.09	13.33	0.000
Time in same task	Ratio	n.a.	$M = 13.8$	8.39	2.15	0.144
Job satisfaction	Ordinal	6	$M = 4.39$	0.97	2.32	0.129
Job motivation	Ordinal	6	$M = 4.33$	0.97	0.12	0.728
Job stress	Ordinal	6	$M = 3.65$	1.16	5.98	0.015
Coping with tasks	Ordinal	6	$M = 4.74$	0.84	3.20	0.075
Proficiency value	Ordinal	6	$M = 4.69$	1.04	8.51	0.004

The summated scales and factor scores were formed as follows.

3.1.1. A-section

1. Wellbeing and development values (e.g. wellbeing of personnel, openness for new ideas, efficient work tasks, cooperation).
2. Goals and feedback values (e.g. feedback, well-defined tasks, goal setting, learning).
3. Safety and rules values (e.g. occupational safety, rule following, carefulness, collective responsibility).
4. Financial values (e.g. cost-effectiveness, financial objectives).

3.1.2. B-section

1. Knowledge of expectations concerning one's own work (e.g. I have a clear picture of my responsibilities, I know on what basis my work is assessed).
2. Meaningfulness (e.g. I feel that the work I am doing is important, My job tasks are varied).
3. Development orientation (e.g. I actively develop my skills, I generally enjoy challenges in my work).
4. Sense of control and personal responsibility (e.g. I always have enough time to do my job carefully, I make sure that my tasks lead to the desired outcomes, I am able to influence the quality of my work).
5. Communication and climate (e.g. My superior gives me constructive feedback, The working climate in my group is good).

3.1.3. D-section

1. Goals and feedback values (e.g. feedback, well-defined tasks, goal setting).
2. Safety and wellbeing values (e.g. wellbeing of the personnel, occupational safety, learning).
3. Effectiveness values (e.g. cost-effectiveness, efficient work tasks).
4. Procedures and rules values (e.g. rule following, collective responsibility, systematic way of work).
5. Development and change values (e.g. openness for new ideas, questioning old beliefs).

In the A-section, four scales were formed in comparison to the six dimensions identified in the pilot study. The development and wellbeing values were considered as being one dimension, as were the safety and rule related values. At the pilot study, they formed their own factors. The goals and feedback dimension combined the values related to both management activities (goal setting) and to personal activity (learning) in a manner that did not come up in the pilot study [41]. At the ideal value section (D), the development and change values formed their own factor, approaching the structure in the pilot study.

In the B-section, the knowledge of expectations resembles the feedback scale at the pilot unit, but it emphasizes more the structural aspects of the work itself in the sense of communicating the expectations to the workers. The new dimension that was identified at the pilot study, sense of control, blended with the sense of personal responsibility scale in this sample.

The difference between the solutions in the A and D-sections is noteworthy. Especially interesting is the connection of safety values to rules in the perceived values section and to wellbeing in the ideal values section. This implies that safety is currently seen as being related to rule following, procedures and collective responsibility (possibly manifested in procedures and instructions), but the maintenance personnel would prefer safety to be related more to the general wellbeing and cohesiveness of the organization. The summated scales and their mean scores are shown in Table 2.

Table 2 shows that safety and rules values had the highest mean scores in the perceived values section, whereas financial values ranked the lowest. Meaningfulness of work, sense of control and personal responsibility and development orientation all received quite high mean scores. At the ideal values section, goals and feedback had the highest mean scores. The value statements of the CULTURE-questionnaire did not, however, include the plausible goals

Table 2
The summated scales, number of items, reliability coefficients, mean scores and standard deviation (SD)

	No. of items	Alpha	Mean	SD
Values				
Wellbeing and development	11	0.92	4.12	0.85
Goals and feedback	8	0.89	4.15	0.85
Safety and rules	7	0.83	4.50	0.75
Financial	3	0.67	3.88	0.91
Psychological characteristics				
Knowledge of expectations	5	0.87	3.96	0.94
Meaningfulness	4	0.79	4.43	0.77
Sense of control	6	0.75	4.49	0.63
Development orientation	4	0.68	4.51	0.64
Communication and climate	4	0.72	4.15	0.81
Ideal values				
Goals and feedback	8	0.82	4.87	0.56
Safety and wellbeing	6	0.77	4.28	0.91
Effectiveness	4	0.74	3.97	0.78
Procedures and rules	5	0.76	4.42	0.76
Development and change	5	0.73	4.73	0.62

In all the scales except two, the reliability coefficients (Cronbach's alpha coefficient, see e.g. [13: p. 256]) were over 0.70 which is usually considered as acceptable for reliable interpretations [19,30]. The total N for the analysis was 216 in the values section, 215 in the psychological characteristics section and 214 in the ideal values section.

of a power plant, such as nuclear safety, reliability of power generation, profit or shareholder value. Thus, the high mean score of the goals and feedback variable does not indicate which specific goals are deemed as important. Neither does Table 2 show the possible differences between the plants in the mean scores. It is necessary to further analyze the conceptions of the personnel about the goals and demands of the maintenance task with the use of interview data. Prior to this, the statistical differences between the plants are explored in order to illustrate the similarities and differences in the cultural features.

3.2. Plant specific analyses of the survey

The factor scores were used to inspect the differences between the plants (see Table 3).

It can be noted from Table 3 and the mean scores in Table 2 that the values related to safety and rules were perceived to be high at both plants. Also, meaningfulness of work was high and showed no statistically significant differences between the plants. Knowledge of expectations is much lower at FKA, which could explain the result that goals and feedback are more strongly emphasized as ideal values there than at TVO. Safety and wellbeing is, on the other hand, more strongly emphasized as an ideal value at TVO, and wellbeing as being currently valued significantly less at TVO than at FKA.

ANOVA was conducted with the factor scores as dependent variables and the task in the organization as an independent variable separately for both plants. At TVO, the perceived goals and feedback values differed ($F(7,76)=2.14$, $p=0.049$) with the technicians scoring lower than the foremen or managers. Also the ideal values of procedures and rules differed ($F(7,76)=2.42$, $p=0.027$), with managers emphasizing it less than technicians (Bonferroni post hoc test $p=0.013$). Furthermore, communication and climate differed on the basis of the task in the organization ($F(7,75)=2.75$, $p=0.013$), with the foremen scoring lower than others. At FKA, only the knowledge of expectations differed between the task groups ($F(8,123)=2.84$, $p=0.006$), with the managers scoring higher than others. Of the covariates, at both plants only the experienced work stress differed between the tasks ($p<0.05$). At FKA, the managers scored higher, and at TVO, the foremen scored higher.

Table 3
Summary table of ANOVA with the factor scores as dependent variables and the plant as independent variable

	df	*F* score	Sig.	Higher score
Values				
Wellbeing and development	1.214	39.724	0.000	FKA
Goals and feedback	1.214	14.337	0.000	FKA
Safety and rules	1.214	1.235	0.268	–
Financial	1.214	25.026	0.000	TVO
Psychological characteristics				
Knowledge of expectations	1.213	22.453	0.000	TVO
Meaningfulness	1.213	0.019	0.892	–
Sense of control	1.213	10.267	0.002	TVO
Development orientation	1.213	0.364	0.547	–
Communication and climate	1.213	0.006	0.939	–
Ideal values				
Goals and feedback	1.212	18.368	0.000	FKA
Safety and wellbeing	1.212	5.206	0.024	TVO
Effectiveness	1.212	0.127	0.722	–
Procedures and rules	1.212	39.697	0.000	FKA
Development and change	1.212	2.939	0.088	–

Table 4 depicts the plant-specific correlations of the factor scores to ordinal and ratio scale covariates.

Table 4 indicates that sense of control relates positively to job satisfaction at FKA but not at TVO. Development orientation correlates positively with job motivation but not with job satisfaction. The proficiency value correlates positively with structure at TVO and with meaningfulness at FKA. Also, the ideal value of proficiency is connected to both the safety and wellbeing and procedure and rules values at FKA, but at TVO it only has a slight (non-significant) negative correlation to the development and change values.

The core task section of the survey was inspected next. The sharing of knowledge as well as anticipation and planning were commonly seen as important requirements of the maintenance core task at both plants. The questions that suggested bypassing the bureaucracy in the name of efficiency scored very low at both plants. On the other hand, both plants also scored low on questions that suggested that rules relieve of personal responsibility or that it is enough to merely follow the instructions in unanticipated situations.

Significant differences between FKA and TVO were found in questions that concerned, e.g. the ability to know the consequences of the maintenance activities in advance, and the way of dealing with uncertainty. At TVO, the personnel were more confident about the consequences of the various daily maintenance tasks (e.g. question 'it is possible to predict the effects of various maintenance activities', $F(1,214)=6.5, p=0.011$). They also emphasised that 'if you are uncertain you should do nothing' ($F(1,214)=28.6$, $p<0.001$). Furthermore, they did not see a contradiction between economy and safety, as the personnel at Forsmark did ($F(1,214)=21.0$, $p<0.001$). The responses to questions concerning the role of rules and instructions also differed between the plants. At TVO, the personnel did not see a need to interpret the rules, whereas at Forsmark, where the personnel perceived more uncertainty they also stated more strongly that the 'rules have to be sometimes interpreted' ($F(1,214)=12.6$, $p<0.001$).

Table 4
Correlations (Pearson's r) between the factor scores and covariates at Olkiluoto (TVO) and Forsmark (FKA)

	Age		Tenure		Same task		Job satisfaction		Job motivation		Work stress		Coping with tasks		Proficiency value	
	TVO	FKA	TVO	FKA	TVO	FKA	TVO	FKA	TVO	FKA	TVO	FKA	TVO	FKA	TVO	FKA
Values																
Wellbeing and development	0.138	0.038	0.124	0.074	−0.033	−0.025	0.309**	0.129	0.285**	0.307***	−0.040	−0.043	0.044	0.015	0.334**	0.450***
Goals and feedback	−0.020	−0.051	0.082	0.002	−0.155	0.017	0.492***	0.171*	0.512***	0.203*	0.112	0.050	−0.008	0.177	0.482***	0.278***
Safety and rules	−0.172	0.055	−0.192	0.119	−0.182	0.018	0.121	0.109	0.106	0.046	−0.038	0.053	0.058	0.044	0.451***	0.291***
Financial	0.121	0.110	0.240*	0.095	0.063	0.057	0.059	0.084	−0.002	0.237**	0.003	0.042	0.033	0.067	0.121	0.133
Own work																
Knowledge of expectations	0.025	0.346***	0.115	0.297***	0.118	0.147	0.292**	0.268**	0.325**	0.248**	0.112	0.178*	0.157	0.328***	0.340**	0.087
Meaningfulness	0.249	−0.138	0.335**	−0.036	−0.028	−0.101	0.476***	0.477***	0.624***	0.622***	0.192	0.215*	0.186	0.055	0.116	0.371***
Sense of control	−0.175	−0.074	−0.166	−0.060	0.086	0.031	−0.057	0.367***	−0.087	0.245**	−0.244*	−0.372***	0.266*	0.325***	−0.066	0.00
Development orientation	0.000	−0.170	−0.231*	−0.202*	−0.164	−0.164	0.173	0.133	0.225*	0.259**	0.189	0.093	0.392***	0.298***	0.083	0.201*
Communication and climate	−0.203	−0.051	−0.111	−0.002	−0.324	0.028	0.226*	0.384***	0.058	0.289***	−0.177	−0.102	−0.224*	0.056	0.265*	0.287***
Ideal values																
Goals and feedback	0.236*	−0.080	0.063	−0.041	−0.114	−0.14	0.182	0.171	0.246*	0.244**	0.145	0.056	0.217*	0.189*	0.017	0.284***
Safety and wellbeing	−0.013	−0.221*	0.054	−0.166	0.139	−0.03	−0.149	0.161	−0.151	0.260**	0.021	−0.073	−0.036	0.109	−0.070	0.237**
Effectiveness	−0.007	0.126	0.025	0.105	−0.116	0.06	0.270*	0.292***	0.398***	0.304***	−0.029	0.090	0.240*	0.228*	0.346***	0.036
Procedures and rules	−0.080	0.190*	0.039	0.104	0.031	0.224*	−0.066	0.205*	−0.091	0.114	−0.214*	0.062	−0.150	0.122	−0.056	0.126
Development and change	−0.224*	−0.174*	−0.096	−0.086	−0.043	−0.087	−0.038	0.044	−0.128	0.215*	−0.118	−0.073	0.019	0.073	−0.204	0.168

*$p<0.05$, **$p<0.01$, ***$p<0.001$. Note that number of respondents vary in TVO sample from 74 (same task), 77 (tenure), 80 (age) to 83 in the rest of the variables, and at FKA sample from 122 in tenure and same task to 129 in age and 132 in others.

The results thus suggest that knowledge sharing, planning and anticipation and personal proficiency are considered as important requirements of the maintenance task in a NPP. However, at TVO the personnel experienced less uncertainty in the maintenance work itself. They approached the work more through routines and formal procedures than Forsmark did. There, the uncertainties of the sociotechnical systems were more apparent and the personnel also emphasized the maintenance work more as a learning and problem-solving task.

The strengths and weaknesses of the maintenance culture were asked in the survey. At TVO the personnel saw their strengths mainly in the know-how and experience of the workers (57 respondents out of 59 raised either know-how or experience as the main strength) and in the attitude and motivation (responsibility) of the personnel. Also, viability of the organization (ability to react to problems, methodicalness, flexibility) was emphasized, as were good tools and procedures and the good condition of the plant. The current age structure of the personnel and inadequate attention paid to the problems of knowledge retention were perceived as central weaknesses. Furthermore, leadership and personnel values of the organization were experienced as needing improvement.

At FKA, the need for clarification of the new organizational structure was the most acute problem according to the respondents (30 persons out of 76 raised this issue explicitly). Also cooperation between the work groups and the quality of leadership were raised as needing improvement. It is possible that these stem in part from the reorganization, together with the unclear division of labor that 10 persons raised as needing improvement. Only one person raised the age structure and knowledge retention as problems needing attention. Communication and cooperation within the work groups was experienced as working well at FKA. A few employees explicitly raised the safety thinking as a strength and a few emphasized the managerial and leadership aspects.

3.3. Conceptions of maintenance work—results from interviews

Interviews were used to illustrate how the personnel perceived and conceptualized their own work and the maintenance task. The interviewees were first asked about what motivates them at their work. The results show that the answers varied in content between the plants. At FKA, the personnel were motivated by new learning opportunities, technical problem solving, fault situations, and also by good colleagues and the social aspects of the job. At TVO the personnel experienced more meaningfulness from non-events, smooth functioning of the plant, and of being 'the best in the world', but also special situations, wage and the social climate motivated at TVO as they did at FKA.

The most demanding aspects in the interviewees' jobs were asked. In the analysis of the interviews, based on grounded theory, qualitatively different categories emerged. The categories resembled the findings of the survey. At TVO, the following categories emerged:

- nothing special ('I have to admit that I don't know', 'I've been here for so long that nothing is anymore', 'routine-like, normal work-work') (4);
- personnel relations (4);
- special situations, e.g. outage, modifications (4);
- the achievement of certainty and the endurance of strain ('so you don't start to rush', 'safety requirements… that the work's done correctly', 'fault repairs…gets you thinking') (3);
- other things related to the maintenance of expertise, e.g. language skills, deteriorating eyesight (3);
- knowledge of the machinery ('upgrades and modifications', 'to know these machines') (2).

At FKA, the following categories emerged:

- prioritizing the tasks, work load (6);
- seeing the goals, trust in the management ('purpose of the reorganization') (4);
- social demands (3);
- technical competence (2).

At TVO, feedback was considered as a mostly negative indication, that something had been done poorly. Positive feedback was rare according to the personnel. On the one hand, the personnel emphasized that they themselves usually knew whether or not the particular job had been done well. On the other hand, some people felt that the culture is somewhat problematic in the sense that high quality performance is taken for granted. This leads to the practice in which high quality is an assumption and positive feedback is not given, but mistakes and poor quality immediately gets attention from the managers.

At FKA, current maintenance organization evoked mixed feelings. Several interviewees complained about the matrix form and found it confusing. On the other hand, there were also signs that the new organization had led to a broader scope of work tasks and to positive challenges in one's work. On the downside there were indications that the new maintenance organization had led to negative changes in the perceived ownership for the technology—previously the maintenance organization had been separate for each of the three stations. Several of the interviews included indications of a general cost pressure that affected the maintenance organization: 'it is talk about costs all the time' and 'costs have got a too high focus'. On the other hand, several of the interviewees said that they were personally strong in their ambition to keep the plant in a state of high quality.

3.4. Summary of the main results

The main characteristics of the maintenance cultures are summarized in Table 5. From the table it can be noted that

Table 5
Summary table of the main results from the case studies

Plant	Workplace values	One's own work	Perceptions of organization	Perceptions of maintenance task	Perceptions of development targets
TVO	Safety values highest, cohesiveness values lowest, also financial values quite high, safety and wellbeing values emphasized most as ideal values	Meaningfulness of work high, mostly routine work with few demanding aspects, workload experienced as high by the foremen	Sense of pride in the plant, the company and in one's own expertise. On the other hand, criticism of leadership and communication practices within the maintenance	Clear, few uncertainties, procedures and information systems central, planning and anticipating emphasized, emphasis on the systematicalness demand of maintenance	Change of generation and the transfer of existing knowledge to newcomers, management and leadership, employee wellbeing
FKA	Safety values highest, financial values lowest, goals and procedures related values emphasized most as ideal values	Meaningfulness of work high, technical problems experienced as both demanding and motivating	Organizational structure experienced as unclear, cost pressures experienced as stressing, climate in work groups good	Uncertainties perceived in the maintenance task itself, planning and anticipating emphasized, learning emphasized as being critical in maintenance	Clarification of the organization, cooperation, leadership

the maintenance units at TVO and FKA had quite different organizational cultures, but they also shared several issues and conceptions.

Safety was highly valued at both plants, and in that sense they both had strong safety cultures. Otherwise the cultural features were quite different, and thus it seems that the means of maintaining high safety differ. The reasons for the similarities and differences in the cultural features are considered further in the discussion section. Also, the implications of the cultural features to safety and reliability of the maintenance units in the long run are debated.

4. Discussion

4.1. Case organizations and the maintenance core task

It was common to both plants that at a general level the goals of the maintenance task were considered to be very clear; maintenance is a prerequisite for reliable production of electricity. Knowledge sharing, long-term planning and anticipation of the plant condition were considered as important requirements for the maintenance task. However, critical attitudes towards the management and the values prevalent in the organization existed at both plants. The task groups within the units also differed in their perceptions of the organization. The shop floor workers were more critical in their attitudes, which is quite common in organizations, see, e.g. [6,20,41: p. 877].

In order to be reliable and effective, the case organizations have developed different strategies for coping with everyday challenges. The fact that organizations with the same task develop distinct ways of acting has also been discussed by Bourrier [4,5]. We try to evaluate the relation of these different strategies to the safety and reliability of the plant with the help of the core task model [31]. Our conception of organizational reliability is not restricted to compliance with procedures or absence of human errors. The aim is to anticipate the direction of the evolution of the organization [42].

A central finding in terms of organizational reliability is that at TVO, the maintenance personnel experienced less inherent uncertainty in the maintenance task itself. They approached the work more through procedures and routines than the personnel at Forsmark did. At TVO, the maintenance work itself was experienced as quite routine-like and the personnel had difficulties in identifying any challenging aspects in their own tasks. It was pointed out that the plant is well-functioning and everybody has sufficient competence to get along with his daily tasks. The focus of the maintenance organization had for some time been in anticipating the plant condition and conducting preventive maintenance accordingly. This has both advantages and disadvantages. At TVO, where organizational procedures and information systems have been intensively developed to facilitate the anticipation, the personnel also saw the overall goals of the organization and their own contribution to them more clearly than at FKA. Anticipating the plant condition was dependent more on the methodicalness of the current activity than on critical reflection or questioning of the existing approaches. This works efficiently as long as the existing approaches are adequate and are seen as tools and not as mere aims. Understanding and verification of the accuracy of the data in the computerized maintenance programs is not easy either when the fulfillment of the program is considered as an aim as such. Thus, for example, an accidental deactivation of the periodical testing program for some equipment might go unnoticed. At the moment this is compensated by the high personal competence and experience of the workers who know the safety significance of the equipment. It can be concluded that the culture at TVO currently focuses more strongly on the fulfillment of the critical demand of anticipating than the other demands of the maintenance core task (see Fig. 2).

At FKA, the uncertainties of the sociotechnical system were more apparent and the personnel also emphasized the maintenance work as learning and problem solving task. Reflectivity and learning (Fig. 2) were currently pointed out as being critical to achieving the goals of maintenance since many workers had new responsibility areas. Currently, this may lead the personnel to question the practices and procedures previously taken for granted. Even some latent failures could be spotted with 'new eyes'. The prioritizing of tasks and managing of the increased workload were seen as demanding since the workers lacked the overall picture of the goals of the plant and of the organizational responsibilities. In order to manage the situation, the social aspects of the organization were emphasized by the personnel (e.g. good team spirit). In the long run, however, this kind of a situation is stressful and unmotivating to the personnel. Furthermore, gathering and interpreting systematic information of the entire plant condition is extremely demanding in the current situation. This may lead to increased events because the knowledge concerning the plant's state either does not exist or is not shared sufficiently. The culture of the FKA was in transition. In practice, the organization was currently focusing on the reacting demand. The significance of the demand for reflecting was emphasized. Nevertheless, the change in the organizational structure also changed the means of reflecting more from formal to informal networks.

The reasons for the differences in the emphases of the core task demands stem partly from the different situations within the case organizations. Forsmark was in the aftermath of a major reorganization, and it is thus expected that learning requirements would be emphasized. A future challenge for both plants is to take into account all the critical demands of the maintenance core task. Otherwise the maintenance cultures can develop assumptions that disregard some of the demands, concentrate on only some of the criteria and measure the effectiveness of maintenance in relation to these criteria.

4.2. Working in complex organizations—typical features and challenges

The research gave implications about the common features of work in complex organizations. We propose on the basis of this case study and Ref. [41] that the work in these systems could be characterized along the following psychological dimensions (cf. Table 2):

- Structure (manifesting as knowledge of expectations).
- Communication climate.
- Experienced control over one's own work.
- Meaningfulness of work.

We define *structure* as the degree to which people feel that goals, tasks and responsibilities are well defined. New information technology and the new forms of organizing work (e.g. outsourcing) are not only changing the structure, but also the nature and requirements of the maintenance work (see also [8]). This seems to happen in quite a similar way to what Zuboff [58] noted happening in the late 1970s in the process control task in industrial work.

The current focus on strategic optimization and new information technology can threaten the traditional conception of proficiency (based on handicraft skills and experience) among the personnel. The new expectations created by the new technology are not congruent with the old cultural conceptions of a skilled worker. The personnel do not want to see the machinery as merely numbers on a computer screen or data base, but as concrete objects to work and play with (cf. [58]). This means that when new structural solutions are introduced, the other dimensions of the work, communication climate, sense of control and meaningfulness also have to be taken into account. It was noted in the pilot study that the personnel with longer tenure saw the maintenance organization as more change-oriented than the newcomers did. Implications were also found that the employees with longer tenure did not like the changes that they perceived [41: p. 883].

Introduction of complex and large matrix organizations, such as in the case of Forsmark, makes it more difficult to structure the communication. In fact, the more 'matrix' used, the more important communication seems to become for supporting the functioning of the matrix. To some extent this increased need seems to counteract the efficiency benefits looked for in the matrix arrangement (cf. [57: p. 143]). Communication practices also appear to be more and more abstract and in some sense also to have less of a face-to-face nature in today's workplace. Orr [32] noted that the technical knowledge of the machine repairers was strongly dependent on face-to-face encounters between the repairers and on the task-related stories that they shared in the meetings (cf. [55: p. 127]). Due to confusion in the organizational structure, the technicians emphasized the meaning of face-to-face communication at FKA. In the study, the communication climate was found to correlate positively with job satisfaction, but negatively with the sense of control at TVO (see Table 4), suggesting that the quality of communication is more important than its quantity. Hence the term *communication climate*.

Experienced control means the degree of personal sense of coping with the tasks and the demands that they set (cf. [22,26: p. 65]). The sense of control was quite high among the maintenance personnel (cf. [41: p. 882]), especially at TVO. This is partly explained by the more stable situation at TVO and the higher average tenure. Long tenure or experience as such does not, however, guarantee competence (cf. [23]). New technology sets new requirements (cf. [8: p. 979]), which means that some of the old habits have to be unlearned. The longer the habits have been in use, the more difficult the change. Long tenure can also lead to routinization [37: p. 105]. Experience is then no longer a benefit, but can actually be a source of errors when the work and its outcome are not actively reflected upon (experienced control is too high). At the same time a change of generation is happening. This means that some of the cultural values and artefacts (e.g. emphasizing certainty and talking about proficiency as something taken for granted) have to change. The newcomers should achieve a realistic sense of control based on one's own skills and abilities and on the demands of the work.

Meaningfulness is a complex psychological state resulting from several dimensions, such as the content and variation of the tasks and the feeling that the work is important and leads to personal development (cf. [11,18]). Meaningfulness was in the present study found to exhibit a high, significantly positive correlation with job motivation and job satisfaction. Maintenance work appeared to produce a feeling of meaningfulness when there are technical problems to solve with safety significance and time pressure (see also [43]). This is a paradox in the sense that one of the goals of maintenance is to avoid problems and keep the technology running reliably. If one assumes that the technology in the future can be made more reliable and fewer problems will occur, then this could be a challenge for the personnel to retain meaningfulness of the work. The maintenance task should be focused on maintaining the entire plant, not some individual pump or valve. In other words, we propose that meaningfulness in one's work should be connected to the organizational core task (cf. [41: p. 884]). One possibility for enhancing the meaningfulness of the maintenance work is to try to give the maintenance workers more opportunities to participate in the various modernization projects [8].

The connection of meaningfulness to the task itself and the gradual shift of the source of meaningfulness (e.g. to social relations) in change situations are important phenomena to take into account when considering the overall reliability of the system. An interesting dimension that does not come up directly from the present data is *sense of personal responsibility* [16,18,41]. The sense of personal responsibility can be hypothesized to refer more to the internal state of motivation and a feeling of being personally accountable for the results of one's actions. In nuclear power plants, the achievement of a sense of personal responsibility is complicated by strict rules, procedures, and a tendency to emphasize shared responsibility and collective action instead of individual action [18: p. 75,41,44: p. 1554]. An ambiguous sense of personal responsibility could lead to overemphasis of the formal structural features of the organization as a source of sense of control and meaningfulness. Responsibility would then mean that you do what is formally required, not what would be felt personally as a sensible course of action in the given situation. Personal responsibility is thus not directed towards the fulfillment of the organizational core task, but towards the fulfillment of the subtasks and subgoals that the given actor is directly accountable for.

4.3. Implications

The results provide some insights into the discussion on organizational culture and reliability. We would like to see the results contribute both to the academic discussion on measuring safety culture as well as to the safety analyst's challenges in evaluating organizational performance. The main motivation of the study was, however, to create knowledge that the case organizations themselves could utilize.

When considering organizational culture, one should take into account that contradictions and different points of view may exist within the organization in question [1,27]. Another premise is that these differences are not a priori 'bad'. The homogeneity of the culture (widely shared conceptions and assumptions) as such is thus not always a criterion for good culture (which is often an implicit assumption in the safety culture research). The starting point of all evaluation is the demands of the work, i.e. the core task of the organization. Thus the demands of the OCT dictate whether or not certain cultural features (e.g. differences in opinion) are good, bad or insignificant for the effectiveness of the organization [42]. For example, different opinions can facilitate discussion and be adaptive in fulfilling the demands of safety and reliability. The demands of the task create the boundaries within which the activity has to 'sail' (in contrast to 'drift', as depicted by Snook [49]). Practical drift means gradual local optimization of the working practices, which does not necessarily take the entire organization into account [49]. The OCT model could be used as a starting point in the analysis of deficiencies in specific work processes [3,29].

If the case organizations were analyzed from the traditional viewpoint of safety culture, the attention would probably focus on the safety values or on the safety record of the plants. From that perspective, the plants would probably be categorized as 'well performing' plants. We state that despite the good performance, both organizations have challenges in fulfilling the organizational core task and thus maintaining plant reliability in the future. For example, implementation of new technologies or new management philosophies and a gradual change in the maintenance task have led to a work overload in some personnel groups. This kind of a situation includes the risk that the employee experiences too low a sense of control or learns an unhealthy strategy of focusing solely on issues that are measured or that the management attends to. Measuring safety attitudes does not necessarily show these phenomena since, for example, implementing new technologies or practices is usually presented as an investment for the future, an upgrade [57: p. 141]. In fact, they can be seen as (and they usually are) an indicator of a strong safety focus for the part of the management.

Our study also gave implications that organizational changes do not seem to affect the safety climate or safety culture as defined by the employees valuing safety. Instead, the changes affect more the psychological work characteristics, such as meaningfulness of work and sense of control. Changes that seem to endanger safety are experienced as highly stressful, especially since safety remains highly valued. Developing only the safety values and safety attitudes of the organization is thus not beneficial, since the safety attitudes are at least as high as before the change (most likely even higher). Still, incidents can be caused by, e.g. unclear organizational structures, lack of communication, or low sense of control among the workers.

The model of the work features depicted above (see Section 4.2) offers a preliminary structure of psychological issues directly or indirectly related to safety and reliability of complex sociotechnical systems. For example, events (incidents and accidents) could be understood more deeply with the concepts depicted in the model combined with an understanding of the demands of the particular work [29, 57]. Meaningfulness of work or sense of control, which affect the decision making in everyday work, are seldom considered in event investigations [14: p. 99–100]. However, work pressure and workload are included in most safety culture instruments, see [10]. Our purpose is not to suggest that events should be characterized only by mental states; rather it is suggested that by asking about the mental states of the personnel one can achieve an understanding of how the working conditions and the organizational factors influence the actions of the personnel [12: p. 151].

The results can be used in redirecting how the managers perceive their organization. Especially the way of conducting the case studies from 'bottom-up' created for the managers new insights into their own organization. Managers are as much a part of the culture as the workers are. Their ability to become aware of and question the cultural assumptions is thus limited. The study helped to enrich the language that the managers and the personnel used for talking about their organization and their task [31]. This was noted especially at TVO, where two seminars were held on the basis of the results for the entire maintenance personnel. The study offered neutral concepts ('organiz-organizational core task', 'cohesiveness', 'sense of control') with which to tackle issues that had previously been too sensitive to question, allowing the personnel to engage in dialogue with each other. In a dialogue, the cultural values and assumptions can be confronted and a common understanding can be built [31,47]. We propose that the starting point of the dialogue and the value creation should be the core task of the organization. Values are experienced as meaningful when they are clearly connected to the work itself.

Many of the issues that are discussed in this article are relevant from the perspective of change management. Anticipation, certainty and stability are central features in high reliability organizations [31,41,44]. Change seems to endanger all of these, and thus change situations are demanding and experienced as stressful. Resistance to change on the part of the personnel can actually reflect the strong commitment to safety that they feel is in danger in the new situation. This requires better communication of both the goals and the methods of change to the personnel. Furthermore, the managers would benefit from listening more to the ideas of the field workers since they usually know the plant best. As stated by Woods and Cook, changes in complex systems are "opportunities to learn how the system actually functions" [57: p. 142]. The CAOC methodology aims to provide the means for anticipating the functioning of these systems so that poorly functioning systems need not fail before their dynamics are understood [42].

Acknowledgements

The authors wish to thank the participating maintenance organisations and their personnel for excellent co-operation, openness, and commitment to the research project. The project was funded by the Nordic nuclear safety research (NKS). Additional funding for the writing of this article was received from SAFIR Safety of nuclear power plants—Finnish national research programme 2003–2006.

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Reliability Engineering and System Safety **38** (1992) 157–171

A framework for assessing influence of organization on plant safety

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A framework is introduced which hierarchically describes the elements of plant safety. This framework includes two structures called the 'diamond tree' and the organization field model. The former describes the functional hierarchy of plant safety, including the role of operators and plant management. The latter describes the behavioral aspects of the organization related to the management and operation of the plant. A brief description of the expected use of this framework in the assessment of plant safety is presented.

INTRODUCTION

In the past, safety analysis in nuclear plants has been performed mainly by considering the physical aspects of accident sequences. That is, the role of organization and its behavioral characteristics have been mainly neglected. However, the root-causes of a number of major incidents in nuclear and other industries can be traced to the role of the organization. Examples include the Three Mile Island (TMI), Chernobyl and Bohpal accidents. Several attempts have been made to address this issue. These include work by Marcus & Nichols[1] in which the role of organization factors in safety performance in nuclear power plant is studied; work by Wreathall & Appignani[2] on the effectiveness of maintenance at nuclear power plants which concludes that those that investigate problems and remove them by hardware or procedural changes are likely to present smaller hazards. Wu *et al.*[3] describe the role of organization as it relates to probabilistic safety analysis.

Due to the complexity of the problem, an opportunity exists to hierarchically describe the elements of plant safety by decomposing it into smaller problems, the solutions to which are easier. As an example, the influence of organization on plant safety can be described by showing how human action influences the availability of equipment by reducing the mean time to repair once it fails. In this paper, a framework has been developed based on which the role of organization, its people and their interactions with plant equipment and, ultimately, plant safety can be shown.

Although the framework described in this paper has been developed as a tool to integrate and discuss the relevance of the current performance indicators in use or in development by the U.S. Nuclear Regulatory Commission (NRC), it can be equally used to address the impact of organizations on plant safety. In this paper we have addressed how the framework is developed, and how it is anticipated to be used for safety analyses. Therefore, in this paper we have mainly focused on describing the framework and defining issues related to its use. Some preliminary results regarding the use of this framework in the assessment and integration of performance indicators are also briefly discussed.

STRUCTURES OF THE FRAMEWORK

Two major parts of this framework are 'diamond trees' which show in a hierarchic fashion the elements

Reliability Engineering and System Safety 0951-8320/92/$05.00

of plant safety, and the 'organization field model' which describes the role of organization and its behavioral elements. These structures are described in more detail in the following.

The diamond tree

The diamond tree is a rigorously structured top-down, success-oriented tree that describes a nuclear plant and its operations. It is human nature that when we face complex problems we tend to decompose them into smaller abstract sub-problems whose solutions are within the realm of our knowledge.[4] Diverse, complex systems have traditionally posed difficulties in understanding them and describing their properties. Hierarchic decomposition is a means of describing elements of such systems.[5]

Hierarchic representation has two connotations, structural and functional. The structural hierarchy is reasonably simple and straightforward. The relationship between basic components of a system when hierarchically shown represents a structural hierarchy. An example includes organization charts. The functional hierarchy, on the other hand, brings a much richer definition of a complex system. It shows in what ways the functions of the system influence and fulfill the achievement of the objective of the system. In reality, the structure and functions of a system are inseparable. The structure, however, serves as the basis for analyzing the functions.

The diamond tree representation is an outgrowth of previous work.[6] Additionally, research sponsored by US Department of Energy used the hierarchy decomposition concept and performed a variety of related methodological developments. For example, Hunt & Modarres[7] have described the concept of goal tree for solving risk management problems. The goal tree concept and rules of decomposition in hierarchies are described in this paper. The same rules are equally applicable to Diamond Tree. These rules are discussed more thoroughly in Ref. 8. The concept of decomposition has been applied to a number of problems including allocation of reliability in a design or improvement process[9] and in explaining nuclear plant containment integrity.[10] Also, the foundations of using the goal tree concept including the role of plant organization is discussed in Ref. 11. The diamond tree is therefore a goal tree which is further expanded to include elements of organization. Generally the process of developing a diamond tree involves identifying the following:

- a precise statement of the plant's principal objective, for example, plant safety; and
- functions that must be satisfied to achieve that objective.

In turn, the functions that assure achievement of the objective are detailed, thus providing a description of the plant in terms of its functional requirements for operation.

Further development of the tree identifies the relationships between hardware components and the plant functions which they support. This can be shown either in the form of a success tree or success paths showing combinations of equipment that satisfy a function. Understanding these relationships provides a basis for highlighting those aspects of plant operation which are essential to safety.

Finally, the method establishes the relationships between human activities and hardware performance. Human activities are usually recognized as affecting hardware performance by actions that change the equipment's performance: e.g. by starting, stopping, modulating, etc. However, human action also affects the quality of performance through maintenance activities and through equipment monitoring. These actions are supported through plant programs which involve items such as maintenance programs, quality assurance and training programs. (Another dimension of human action involves the behavioral aspects which is later described by the organizational field model.)

Since the plant programs are implemented and monitored by the management, and the management style and the company policies are initiated by the chief executive officer (CEO), the development process converges at the CEO. Figure 1 depicts the general layout of a diamond tree. On the right-hand side of the figure, the role of each level of the diamond tree in supporting the 'objectives' are shown.

Since the diamond tree is an integrated representation of the plant, such a description provides a structure within which many decisions concerning plant operation can be made. For example, by describing the role of equipment, human activities, or

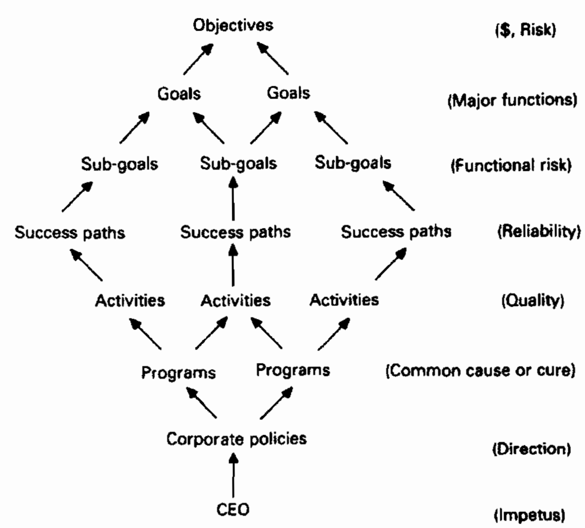

Fig. 1. Diamond tree with organization hierarchy.

programs and their relationship to plant safety. The discussions can cover the complete range of issues from design to maintenance or operation of an existing plant or one under design. The hierarchy also provides the ability to quantitatively evaluate the decision. This will be briefly discussed later in this paper.

As an example of the conceptual form of diamond tree shown in Fig. 1, consider the diamond tree for a typical pressurized water reactor. The top part of the tree is shown in Fig. 2 with an objective of describing items that 'influence plant safety'. The upper half of the diamond tree will be explained first.

Plant safety includes both non-nuclear-related and nuclear-related safety issues. Non-nuclear-related issues are normal industrial safety issues which are

(a)

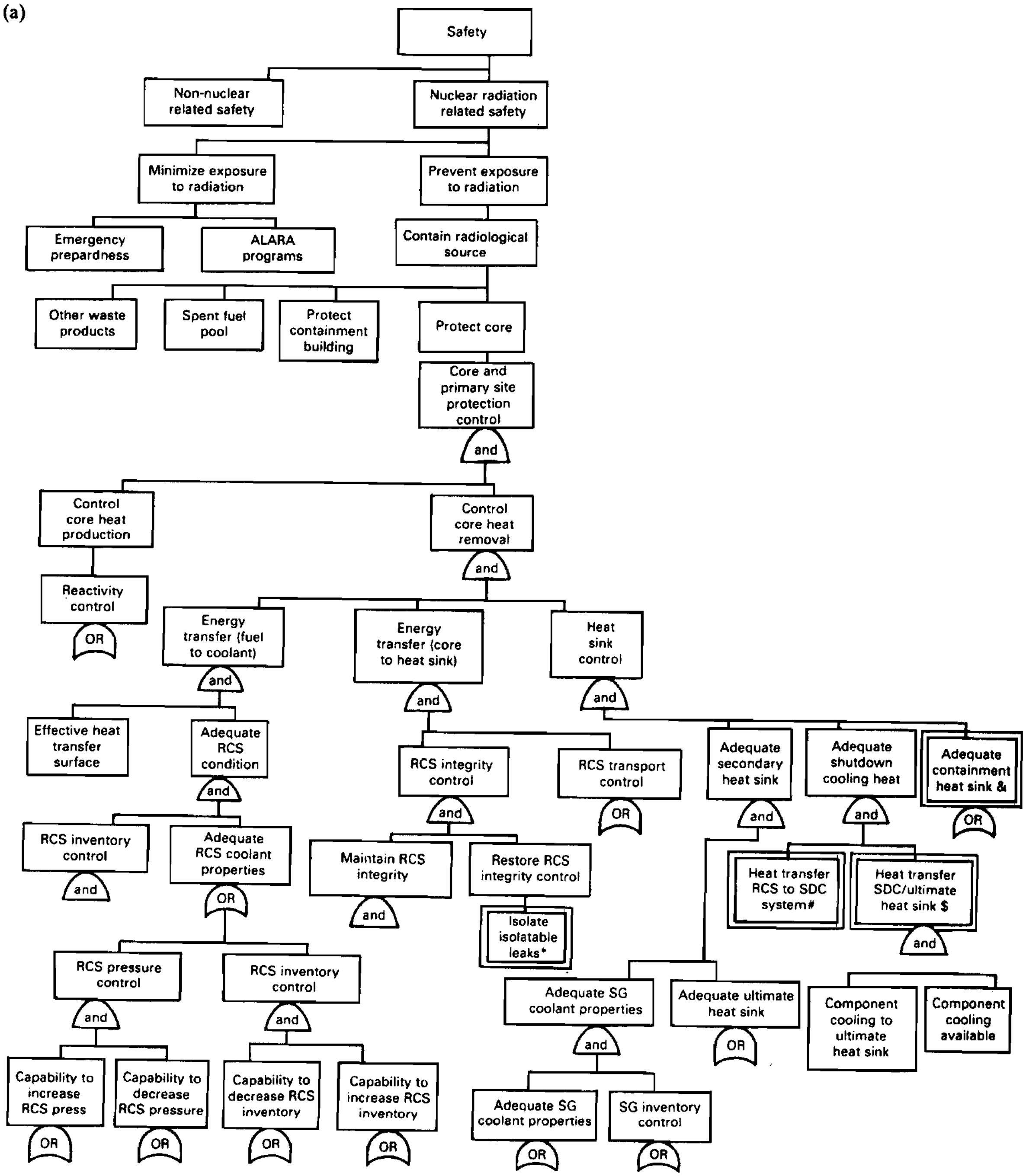

Fig. 2. (a) Diamond tree for a PWR; (b) expansion for RCS transport control.

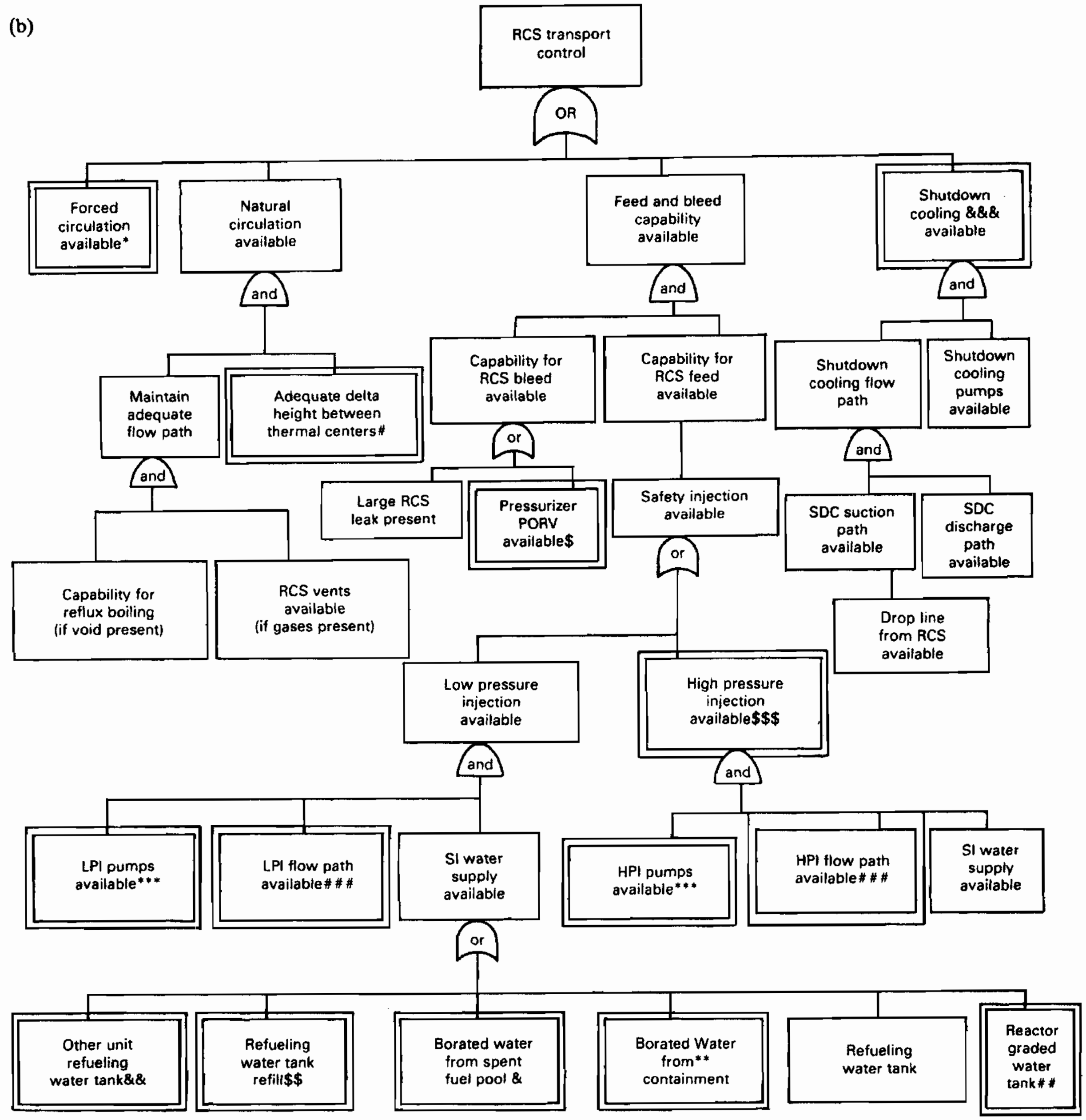

Fig. 2.—(*continued*)

not further expanded here. Minimizing radiation exposure can be accomplished by either emergency preparedness or ALARA programs.

Preventing radiation exposure includes containment of radiological sources and control of the location and procedures followed by workers within a radioactive environment. Means of radioactive containment (defense-in-depth philosophy) should be considered as subfunctions of this function. These are core and primary-side protection control, containment integrity, spent fuel pool safety, and waste product processing and storage protection. Since all radiation sources other than the core are relatively small, the focus of development has been on protection of the reactor core.

There are two important elements in maintaining core protection. These are prevention of challenges to the core and protection of the core given a challenge. These are heat production and heat removal functions from the core. The decomposition continues to a point where the so-called critical safety functions are shown. Further decomposition of these functions shows the role of safety systems and then components. The components can be shown together such that various success paths can be described.

Each system or subsystem is shown at least once in the upper part of the diamond tree. Some of these systems support more than one function in which case they may be shown more than once.

The upper half of the diamond tree ends with plant hardware and operator actions. The lower half explains ways that the performance of these items are achieved and it shows the role of the operators who 'support' this hardware. Since the types of activities and programs that support plant hardware are essentially the same, one generic model for the lower part of the diamond tree can be developed. This starts with 'Item Performance', which can be decomposed into corresponding support functions, activities and programs. 'Item' here refers to each of the lowest level boxes in the upper part of the diamond tree. It should be noted that although performance of items is generic, its decomposed elements may affect various items differently. Before one can investigate how performance can be affected, it is necessary to understand first the three particular measures which are appropriate for describing an item's performance:

- capability
- failure rate (or more broadly, in success space, this can be called reliability)
- time-to-restore following a failure

We recognize failure rate and mean-time-to-restore in combination as availability, so that for all practical purposes availability is the ultimate measure for an item's performance.

Item capability is generally a design issue, but for an operating plant, it can be influenced by: (1) the ability of the item's operators to understand its capability; (2) the effects from the outside environment (that is, the capability of the item under various environmental conditions). Figure 3a shows the various aspects of the item performance.

Item reliability which explains factors that influence its successful operation can be expressed by failure preventive factors and failure protective factors (See Fig. 3b). Failure preventive factors are root cause analysis and preventive maintenance. On the other hand, protective factors are explained through the concept of strength and stress. Here, in order to protect the item from failure, one can either influence the stresses applied to the item (reduce them) or the strength of the item (increase it). Clearly, the strength of the item is a design feature that cannot be significantly influenced in an operating nuclear plant. However, its stresses can be influenced by the plant support staff by controlling the mechanisms of failure that cause such stresses. These mechanisms are either electrical, mechanical, chemical or radiation related. In turn, each of these mechanisms can be broken down into more specific mechanisms of failures. Plant operators can minimize these mechanisms and protect the plant items from failing.

For example, ensuring good working conditions, proper operation procedures, and routine preventive maintenance would minimize challenges to the item and ultimately enhance its reliability.

Effective item time to restore can be divided into item's effective testing, effective maintenance or repair (See Fig. 3c). Effective maintenance, or repair, is of major importance to an item's performance since most plant equipment unavailabilities are the result of some kind of maintenance problem. Maintenance has three distinct phases. The first phase is time spent prior to maintenance (i.e., documents are gathered, faults are isolated, and diagrams and logistics for maintenance are prepared). The second phase is the time of the maintenance itself (factors such as safety, spare parts, tools, and access to failed parts are important to this phase). Finally, the third phase includes factors which are important for proper maintenance after the actual maintenance is performed (for example, checking out the maintained item, reporting and realigning, maintenance testing, and restarting).

The next level of the diamond tree involves the plant programs and their associated activities. There are a number of 'generic programs' that are used by plant owners to support the plant. Each of these programs can be divided into their corresponding activities. For example, some typical programs and activities are shown in Fig. 4. For example, 'Preventative Maintenance' can be divided into two types of activities:

Activity A.1—Reporting of a Preventative Maintenance job.

Activity A.2—Checking of the plant items for leaks, readiness, noise, etc.

It can be seen from Fig. 4 that both activities A.1 and A.2 influence the box 'Preventive and Routine Maintenance'. It would be easy to trace the influence of these activities on safety by following this influence upward through the diamond tree into its top objective of safety. This would reveal the ways in which a preventative maintenance program and associated activities can influence safety. It is possible, and very common, to see that an activity or program can influence more than one box in the diamond tree. This is natural since programs in nuclear plants often have multi-objectives and their influence is therefore spread over a large spectrum of plant items and equipment. Therefore, plant programs and activities are common cures for the unavailability of a large portion of plant equipment. However, the degree of influence may be different from equipment to

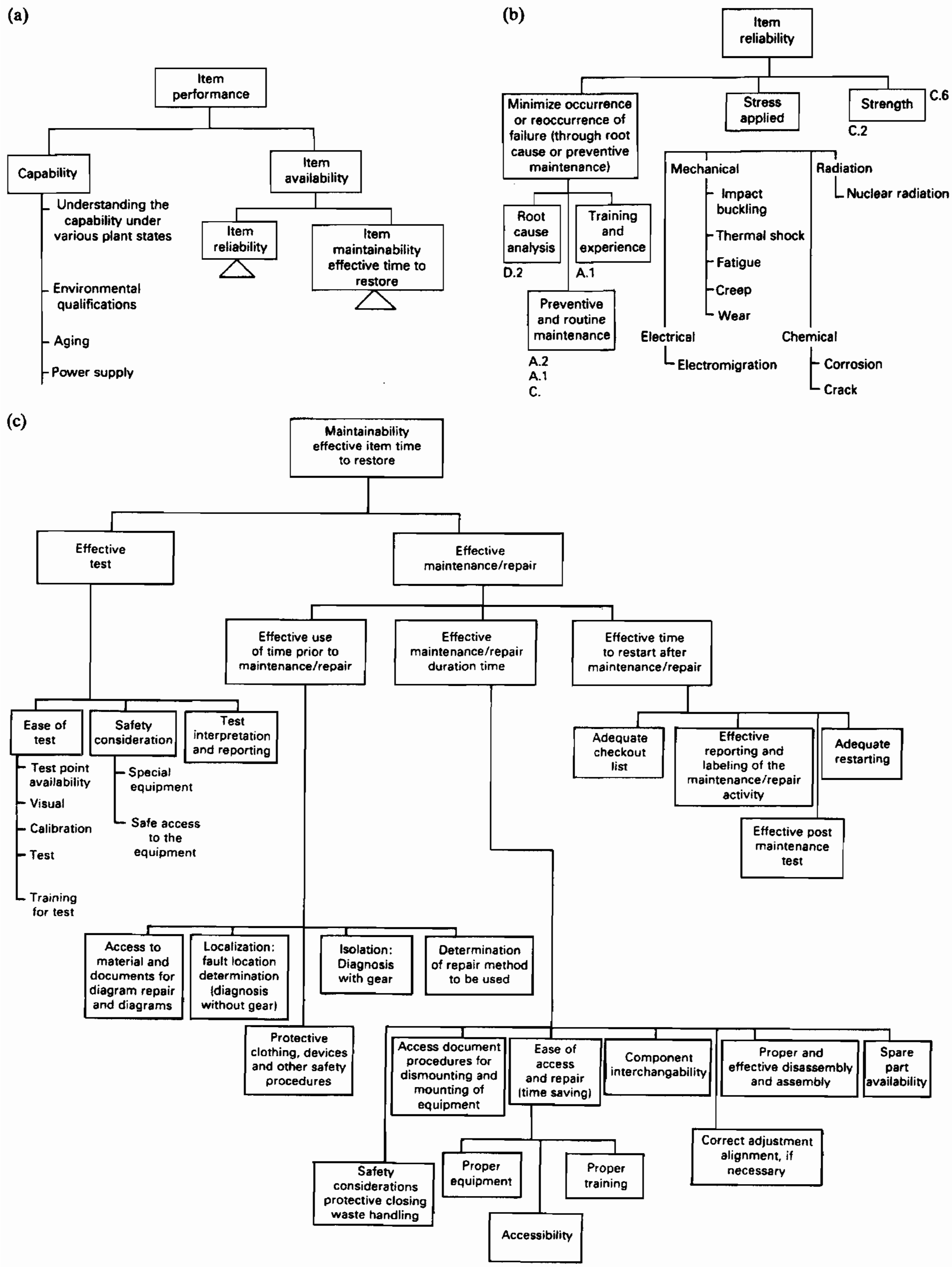

Fig. 3. (a) Item performance tree; (b) item reliability tree; (c) item maintainability tree.

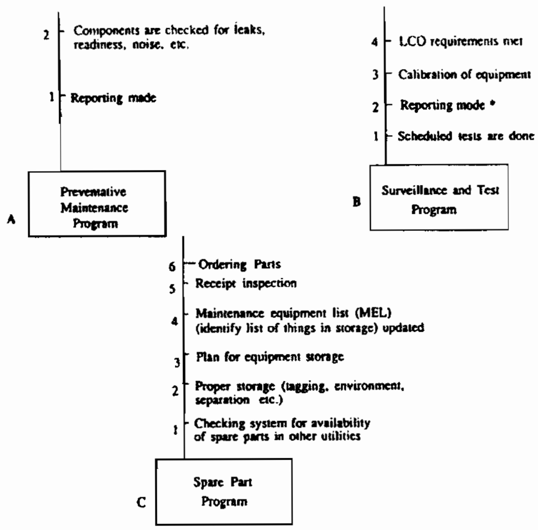

Fig. 4. Examples of plant programs.

equipment, depending on the sensitivity of this equipment to the activity or program.

Plant owners vary in the ways they manage plant programs, and so the connection of these programs to the bottom part of the diamond tree (i.e. down to the CEO) is highly plant specific. However, this part of the diamond tree can be easily developed by using the structure of the management of the plant and their relationship to the programs described, for example, by showing those departments which are responsible for the programs and showing their relationship to the top management of the company.

It is clear from the above discussion that the diamond tree depicts the formal elements of safety in a hierarchic form, but does not consider the psychological behavioral side of the organization. The diamond tree description clearly depicts the role of plant equipment and human activities and shows in what ways they support an objective (e.g. plant safety). Generally, relationships between plant equipment are more formal; however, where human operators get involved, the relationships become more informal and less structured. Therefore, it would be necessary to consider such informal factors as morals, attitudes, and knowledge of plant personnel. For example, the diamond tree can show the need for a spare part department, or a spare part exchange program. However, it does not show to what extent a quality job is performed by its personnel. Since this is an important part of the analysis of plant safety, we need to consider these factors in greater detail. For this reason, we have proposed the use of the organization field model. In this model, a general, but not precise, hierarchy is used to show the relationship between different levels of organization. Each level, in turn, affects the degree to which each of the 'activities' and 'programs' described in the diamond tree are achieved. The relationship of the organization field model and the diamond model in forming the proposed framework is conceptually depicted in Fig. 5. The cones attached to various parts of the diamond tree represent the influence of the organizational factors modeled through the organization field model as described in the following.

The organization field model

The factors of the organization field model were developed through examination of the research in management, organization, and human factors over the last two decades. The structure attempts to depict generic factors that influence a worker's productivity and reliability.

The organization field framework model was conceptually developed from Lewinian field theory, which was developed for personality factors by Foa in the 1960s[12] and elaborated upon in the 1982 Interpersonal Circle by Kiesler.[13] In Lewin's field theory, personality factors were envisioned as charged particles that mutually interacted. The field framework was conceived as a series of concentric fields, much like magnetic fields, that mutually interact but preserve a general identity at each level (as shown in Fig. 6). The levels, or fields, begin with the external environment of the corporation and proceed inward to the single worker, whose acts are the man–machine interaction of interest. Within the worker there are also factors which are influenced by external factors that determine behavior.

The organization field framework begins with Layer 0, which is actually the general environment within which most corporate organizations exist. Since this is not a true 'layer', it is designated with the label of '0'. This layer depicts the regulatory environment, the economic environment (e.g. return on assets, debt/equity ratio) and some of the relationships of the organization to its environment (e.g. public and vendor relations, which are more important to commercial nuclear power plants). The first layer belonging to the organization proper (Layer 1) is made up of such factors as the Management Structure of upper management in the organization, its goal structures (where it plans to go and how those plans are structured), the corporate culture, as well as corporate size, age, and general efficiency. The next layer, Layer 2, depicts the factors that are found at the plant, or site, under investigation. This layer includes such factors as 'Milieu', the plant/site-specific culture (distinguished from the overall corporate culture); the management style specific to the plant or site manager; Leadership Ability, Personnel Control

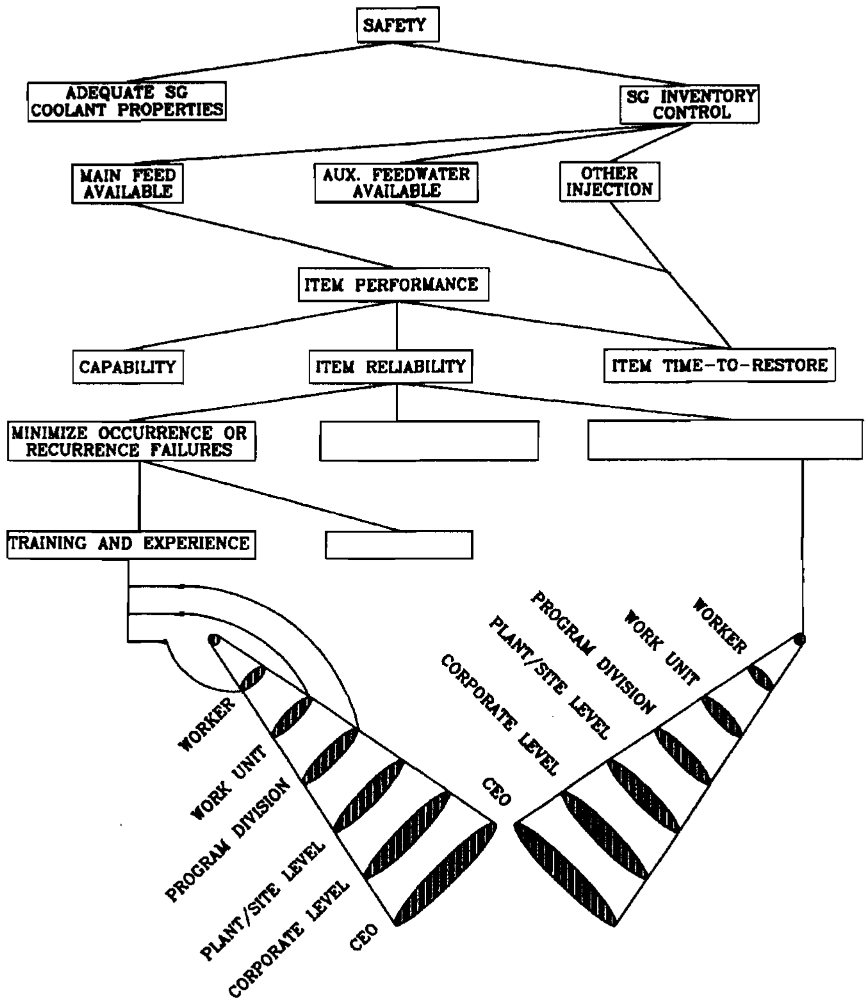

Fig. 5. Schematic representation of the integrated framework.

Methods used by that manager; Management/Labor Relations and Technology Level at this particular plant or site; and several factors that denote the clarity and explicitness of job descriptions, work procedures, and the rules and standards to which the workers are expected to adhere.

Layer 3 depicts the program, division, or other organizational subdivisions. In this layer, such factors as the program/division management style, reward/punishment structures, intercommunication among work units and intercooperation among work units, consistency of work and personnel policies, and availability of career paths are important influences on worker productivity and reliability. At Layer 4 is the work unit (however it may be termed). The work unit is the team/crew/unit that is the worker's immediate physical, social, and technical environment during his/her work day. This environment may be relatively impoverished, such as that of a security guard standing at an isolated post, or relatively rich, such as that of a secretarial pool. Nonetheless, Layer 4 includes strong influences on the worker that directly affect productivity and reliability. These influences include the ergonomic (or human factors engineering) effects of the physical environment, the more general work environment (including the social and technical environment), training quality and availability, how work teams are structured, how well the corporation and line managers support and maintain work teams, the nature and degree of inter- and intra-dependency among teams, and the overall professionalism of the workers, management and work teams.

At the heart of the analysis, Layer 5, is the worker. This layer also has influencing factors. These factors are internal to the worker and include the worker's knowledge, skills, and abilities, the worker's motiva-

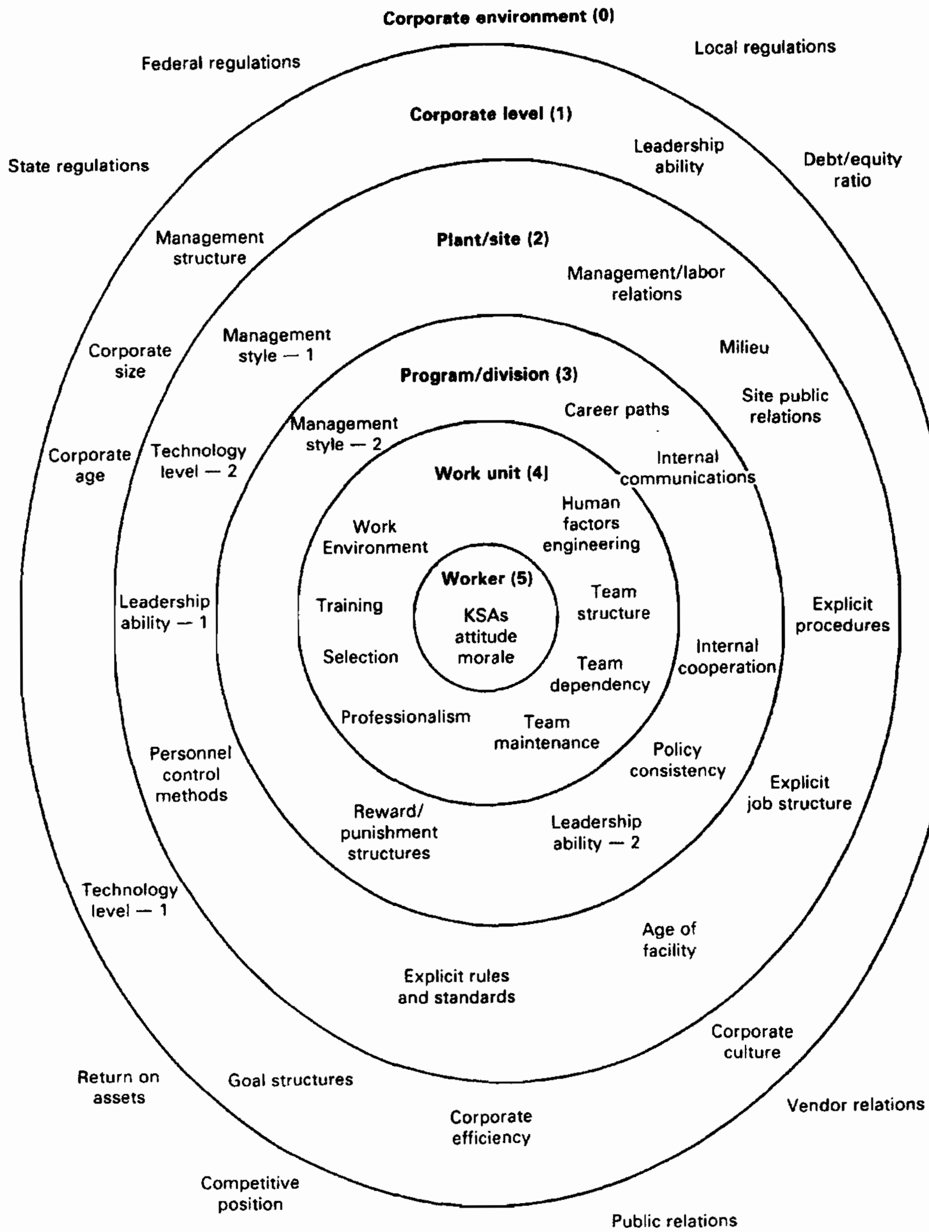

Fig. 6. Organization field model.

tion, the worker's attitudes—i.e. the state of the worker's emotive relationship to the corporation, plant, site, work unit and self on a given day (a 'state' variable) and the worker's more general emotive relationship to all of these, the worker's morale. Morale is, of course, a 'trait' variable. It is useful to distinguish between attitude and morale (state and trait variables) for the purpose of increased accuracy in predicting productivity and reliability. For example, it is meaningful to predict the effects of labor unrest or other temporary situations upon productivity and reliaib!ity as well as the longer term effects of general morale degradation or improvement.

Since in the one-dimensional representation, the model is static and has no provision for dealing with the very dynamic nature of the organization influences, it is only used to show the relationships. A three-dimensional version of the tree should be developed to depict dynamic aspects of the organization and show the hierarchy of major influences.

The next step of development, then, is to develop a framework that would keep the useful concepts of the field model while correcting the deficiencies. This effort led to the development of a 'telescoping field structure' (Fig. 7). The concept assumes different spheres of influence at different levels of the corporation. Although these spheres of influence are drawn in order, it is important to understand that they are not hierarchical—that is, each sphere of influence exerts its influence directly upon the personnel at that corporate level.

The influences from each sphere are assumed to be manifested in the behavior of the personnel at that level, so that the factors that contribute to these influences in turn shape or influence the knowledge, skill and abilities (KSAs), morale, etc., of these persons. Both the outside influences and the personal attributes of these personnel combine to influence the choice of behaviors and/or to restrict the variety in the behavioral repertoire that is available for choice. For example, the behavior of the CEO conditions the environment (spheres of influence) of the corporate level (Level 2), and the behavior of the upper management conditions the environment, and thus influences, the middle managers, and so on down the chain.

The telescoping field framework shown in Fig. 7 can be shown in an alternative representation from the graph theory. Since the layers of each sphere are not hierarchical, the representation shown in Fig. 8 is also

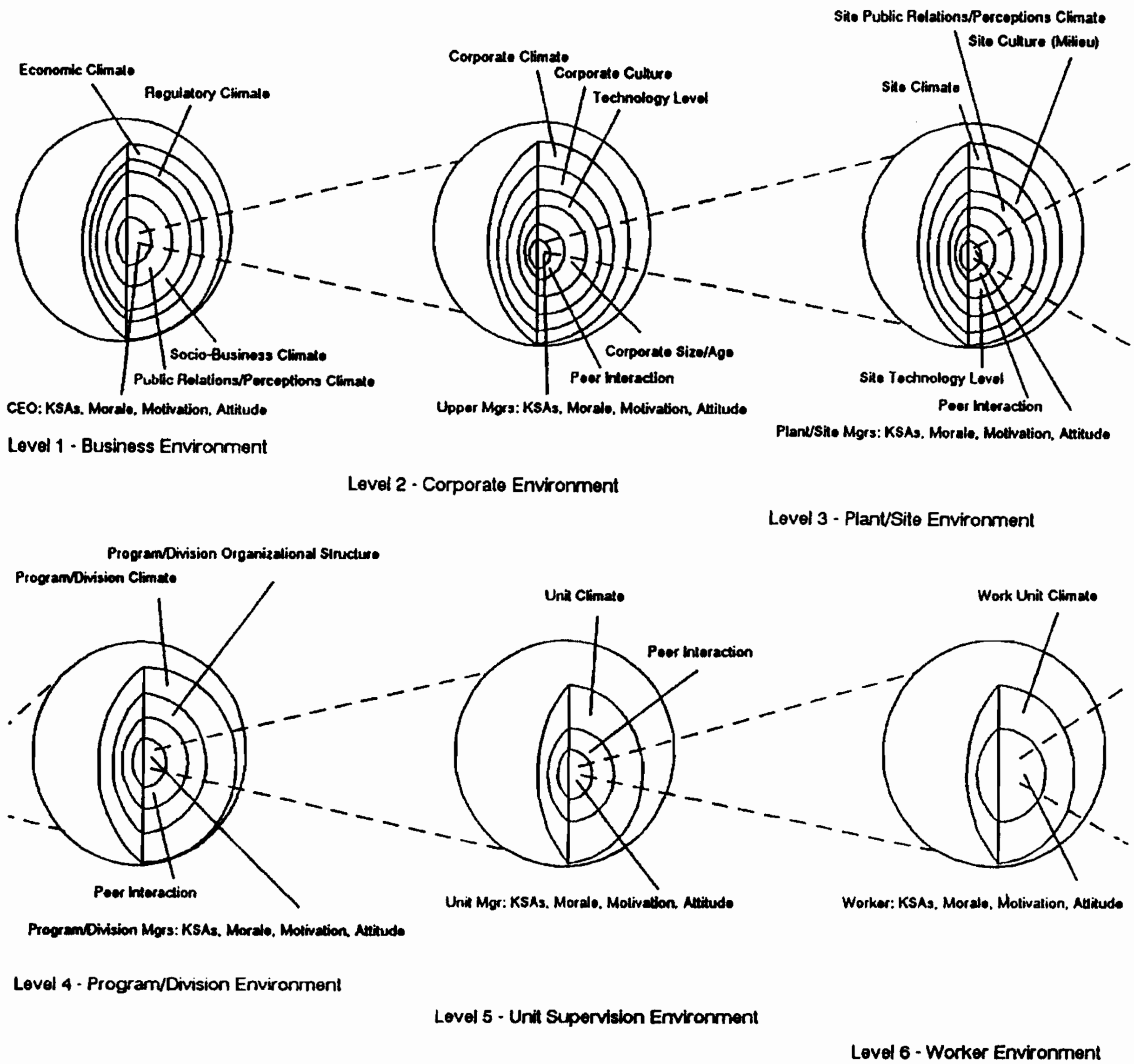

Fig. 7. Telescoping organization field model.

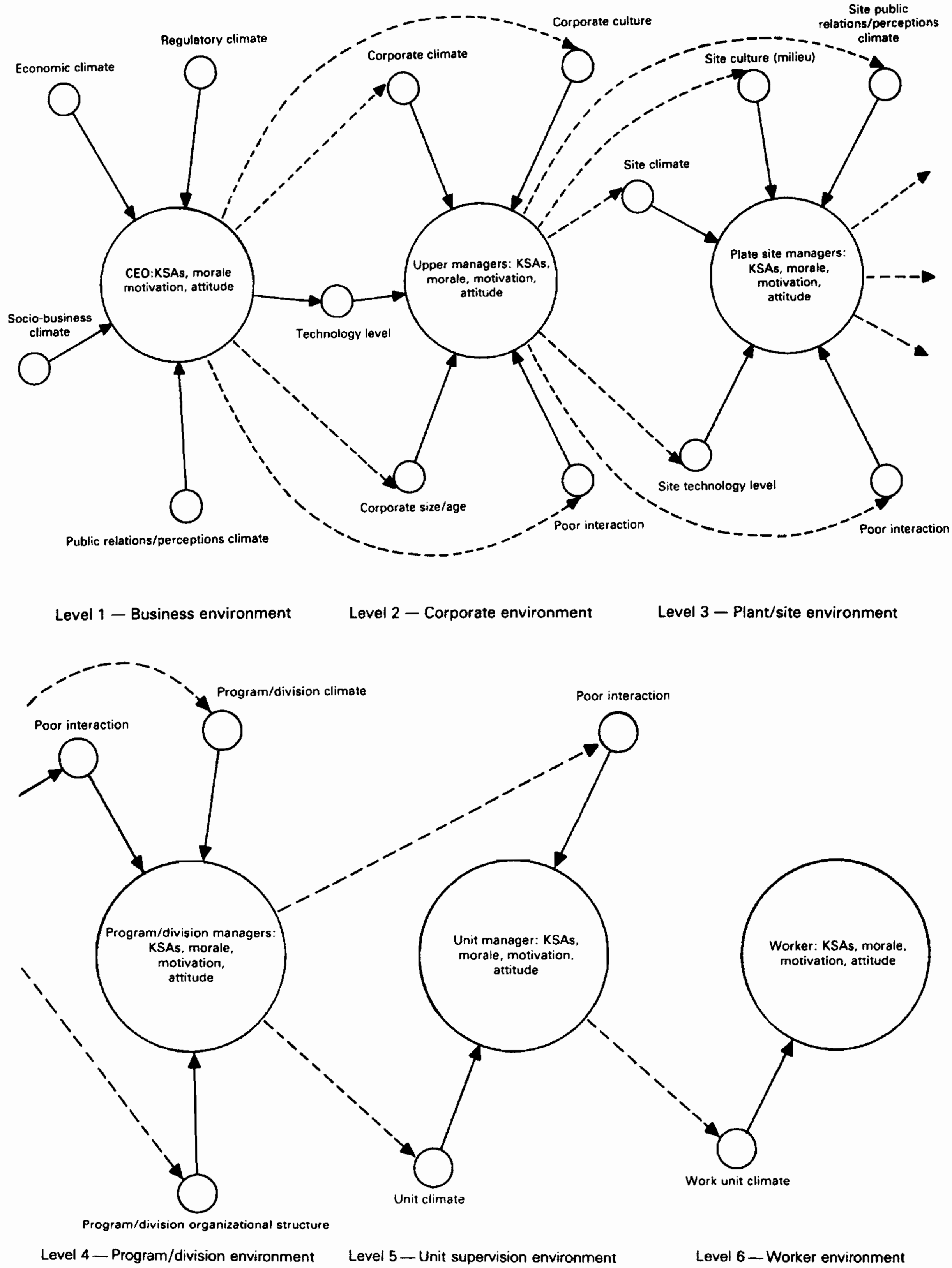

Fig. 8. Graph representation of the organization field model (Part I).

accurate, although it loses some of the flavor of 'spheres of influence' and the concept of managers setting the environment for the level below them. Some advantage of this representation are that graph theory techniques can be used to examine the effects of differential time delays of several spheres of influence or to manipulate differences in intensity and salience.

Thus, graph-style representation allows manipulation of influence variables in the *time* dimension, either in terms of feedthrough delay or in terms of feedback loop delays. Graph representation will also allow examination of the effects of defining influence vectors as complex functions—so that feedback loops can be defined into the vectors. Lastly, graph representation provides a method of varying the *strength* of influences, based on recency and amount of change in the influencing factors and on their saliency characteristics.

USE OF THE FRAMEWORK

In the previous sections, we have presented a framework for identification and representation of the influence of organizational factors on plant safety. The proposed framework can be used in qualitative evaluation of various factors and their interrelationships. It can also be used as the underlying model for quantitative assessment of the influence of organizational factors. For instance, using quantitative measures for safety, such as those used in PRAs, one can, in principle, quantify the effect of various organizational factors and characteristics on the numerical safety measure (e.g. core damage frequency). Of course, this depends on one's ability to develop and quantify appropriate measures that characterize organizations in relation to safety.

Qualitatively, the proposed framework shows how different factors influence plant and personnel performance. The interactions among various elements are easily identifiable. The paths from a given factor to safety, as defined by the hierarchy of elements, provides a qualitative explanation of the influence of that factor. What is not shown in the model is the dynamics of influence. In other words, the time dependence of the influences are not explicitly acknowledged. We note that the form and degree of time-dependent interactions vary depending on the factors involved and the nature of their interactions and influences.

For example, consider the influence of one factor in the outermost layer of the organization model. The initiating event for the pathway in Fig. 9 is assumed to be a degradation in the return on assets (ROA) for the utility as a whole. There are a number of behaviors available to a CEO in these circumstances.

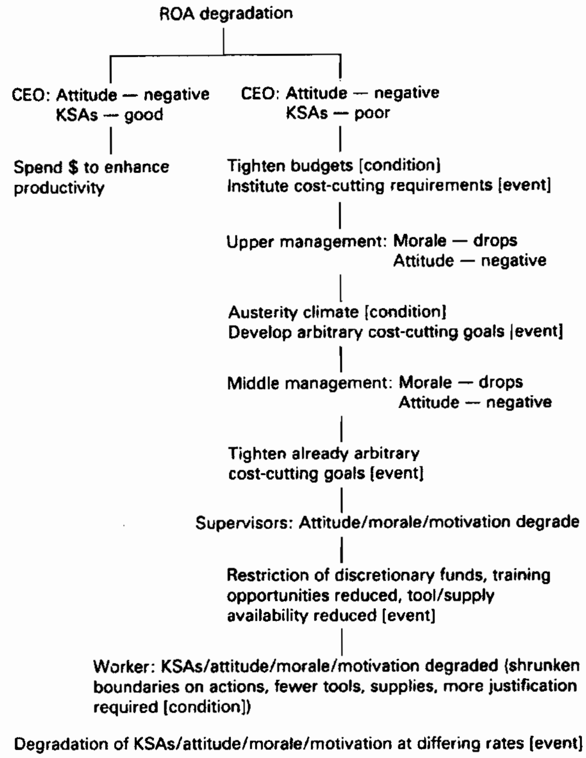

Fig. 9. Influence pathway for degradation of return on assets.

Two of the most extreme are shown here, with the pathway that leads to safety degradation developed completely.

Notice that a CEO who has good management knowledge, skills, and abilities is assumed to have an enlightened management style and could be expected to reallocate resources to enhance productivity in the power plant, for example, through job simplification, tool improvement, training and/or procedure enhancement.

An authoritarian CEO who is suspicious of people and regards workers as expenses can be expected to reflexively tighten budgets and demand cost-cutting measures be taken by his managers. Upper management, almost as reflexively, can be expected to arbitrarily dictate that a certain percentage reduction of costs will be attained, regardless of the actual cost/benefit situations of the departments under them. Mid-level managers can be expected to panic and to add their own percentage reductions to the mandated ones in order to show their cooperative and innovative attitudes. The work unit supervisors will consider these reductions to be impossible goals and start restricting or requiring additional justification for almost all expenditures.

These actions will restrict the scope of action available to the workers, reduce the opportunities for training, professional involvement, and generally degrade the quality of work life. These factors will, in turn, severely degrade morale and attitude quickly and the pool of knowledge, skills, and abilities more slowly. Morale and attitude will slowly rebound to a level below the original level while the knowledge, skill and ability pool will continue to slowly degrade. Austerity measures will persist after the event (ROA degradation) is well past and slowly erode, producing a slow rebound of knowledge, skill and ability in the labor pool.

The effect on safety can be traced through such activities as less thorough and frequent checking of instruments and components, less record-keeping, consistency and timeliness, poorer quality control as knowledge, skill, and motivation degrade, less adequate logistical preparation for training and less adequate and timely training, poorer availability of spare parts, less adequate and timely inspection of received components, and less timely ordering of needed supplies and parts.

One application of the model presented in this paper is in evaluating indicators of safety which have been considered by both the U.S. NRC and the nuclear industry. The so-called Safety Performance indicators are quantifiable measures of different aspects of plant performance in relation to a vaguely defined safety measure. At least two kinds of performance indicators have been defined. The first category includes those that directly measure equipment, systems, or overall plant performance from a hardware point of view. These are called Direct Performance Indicators (DPI). Examples are the number of scrams, number of safety system failures, and equipment-forced outage rate. Another category includes performance indicators that measure certain programmatic or organizational characteristics of the plant. These are known as Indirect Performance Indicators (IPI). Examples are maintenance overtime, debt-to-equity ratio of the utility, and distribution of causes of equipment failures according to a certain classification.

The framework described in this paper can be used to investigate in what way these indicators relate to safety as defined by the top goal of the diamond tree and the underlying hierarchical structure. For this purpose, the performance indicators are redefined (decomposed) in terms of their contributing factors so that at the lowest level they can be related to the elements of the diamond tree. This mapping process will show the aspects of plant functions and organization that are represented by each PI. Figure 10 is a schematic representation of the use of the diamond tree for PI evaluation. Since PIs typically relate to events and since events reflect different challenges to the plant and reveal different roles of systems and equipment, the safety hierarchy of diamond tree is rearranged according to the impact of event on safety. This grouping follows a probabilistic risk assessment (PRA) type philosophy which looks at plant risk as a function of challenge (initiating events) and plant protection given challenge (safeguard systems function). The relations of various performance indicators to safety are shown by identifying the most relevant points of contact with this hierarchical representation of safety. These mapping points are identified by determining possible abnormal behaviors of the elements of the diamond tree that lead to an 'event' whose progression will be counted as a performance indicator. Evaluation involves identification of safety aspects covered by each PI individually and all PIs collectively. This also provides a picture of those aspects not addressed by the indicators, thus providing a context for defining new indicators or refining the existing ones. Also, one can identify PIs that overlap due to the fact that they may be mapped into the same points in the tree.

To perform quantitative assessment of the degree of influence of various organization factors, first one needs to define measures of influence and develop methods for estimation. This clearly is a much more difficult task than the qualitative assessment since for the majority of factors involved even the form of the relationships and exact mechanism of influence are not understood. Nevertheless, the framework can be used as a reference structure in developing, refining and testing quantitative measures of organizational factors.

One approach is to use PRA-type measures of performance for equipment, systems, and operators and estimate the influence of *changes* in organizational factors and characteristics on such performance measures. The vehicle for this is already provided in the form of the expansion of 'item performance tree' of Fig. 3. The contribution of each of the factors identified directly under the 'item reliability' element of the diamond tree can be estimated from existing data bases. The most challenging part, however, is the estimation of the influence of the *change* in organizational factors as determined by the lower part of the diamond tree and the corresponding organization field model. Nevertheless, preliminary results indicate that by identifying, reviewing and analyzing the available information on the relation between groups of organizational factors (profiles) and other more tangible measures of equipment performance (e.g. safety system failure frequency), a semi-quantitative assessment can be achieved.

Given numerical measures of influence for the various elements of the proposed framework, the quantitative assessment of the effect of change in any given element on the quantitative measure of safety can be calculated by first converting the entire model to a digraph representation and then propagating the

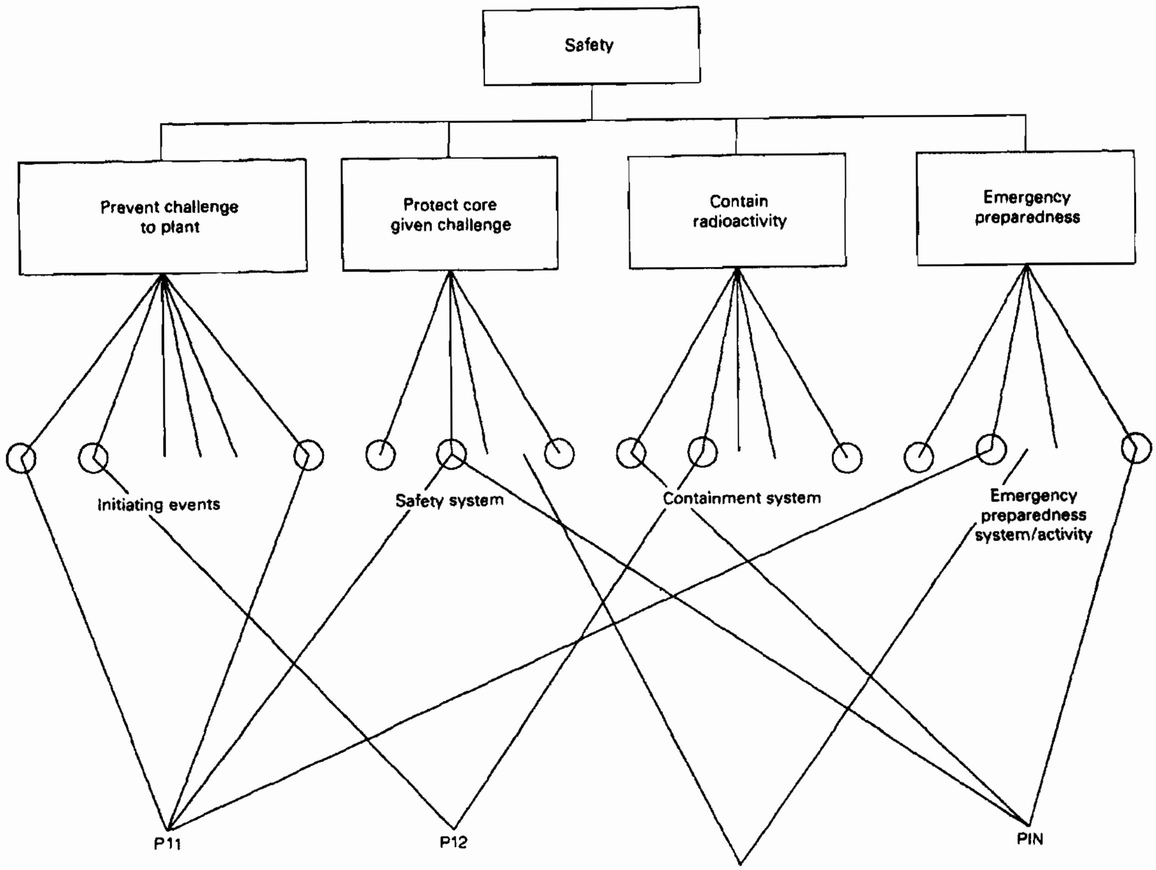

Fig. 10. Overview of the use of the framework for assessment of safety performance indicators.

degrees of influence through the model using special mathematical rules.

A schematic representation of a digraph model is given in Fig. 11. As can be seen, a digraph is a set of nodes (representing various elements of the diamond tree and the organization field model) and links between nodes (indicating existence of a relationship between various elements). The direction of the arrow represents the direction of influence. The influence could be positive or negative, with high or low intensity. For a quantitative evaluation, the intensity or degree of influence, ω_{ij}, of node i on node j is a number which is often chosen in the interval $|\omega_{ij}| \leq 1$. Given ω_{ij}s for various links, the influence of any given node on another node of the graph can be obtained using Mason's rule from Signal Graph Theory:[14]

$$I_{kl} = \frac{\sum T^{(j)} D^{(j)}}{D}$$

where I_{kl} is the degree of influence of the kth element on the lth element and

$$T^{(j)} = \prod \omega_n^{(j)}$$

where $\omega_n^{(j)}$ is the strength (weight) of the nth link in path j from element k to element l. The quantity D is the determinant of the entire digraph and $D^{(j)}$ is the determinant of the subgraph which is obtained by excluding portions of the graph containing loops that overlap with path j. If there are no feedback loops in the digraph, then,

$$I_{kl} = \sum_j T^{(j)}$$

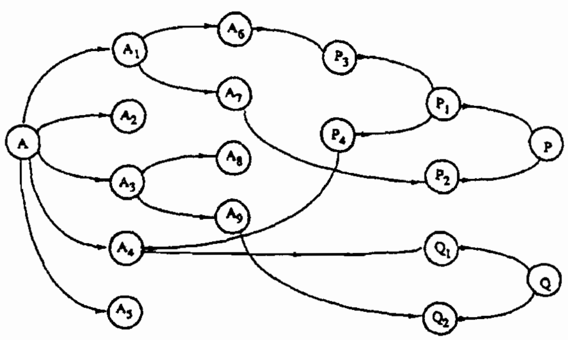

Fig. 11. Schematic representation of a digraph model.

which is a simple multiplicative rule involving measures of influence between various links. Different parts of the graph representation of the diamond tree and field model require different approaches to quantification of measure of influence. For instance, the relation between a system/component element to the top element (safety) can be quantified using risk importance measures developed for PRA application. One such measure is Fussel–Vesely[15] importance. At a lower level of detail the influence of organizational factors on item (system or component) performance can be quantified using information on root causes of failure and duration of equipment down-time (both for repair and maintenance). Also, if the model is used for PI evaluation, the strength of links relating each PI to its contributing events can be calculated from historical records as the relative frequency of each contributing event to the PI in question. In this particular application, the degree of influence (or weight) of each PI relative to safety will be calculated by combining these frequencies and weights according to Mason's rule described earlier.

CONCLUDING REMARKS

This paper has provided a framework for the study of influence of organizations on the safety of a nuclear power plant. The framework introduces concepts that relate the organizational factors to plant hardware through human/hardware interface. Clearly, many issues regarding the exact nature of the interactions among various aspects of plant organization are still open questions. Even the identification of factors involved requires much work. However, the proposed framework can be viewed as a step toward an integrated methodology for evaluation of organizational issues. An application of the proposed framework has already been demonstrated through its use for assessment and integration of safety performance indicators for nuclear power plants. It has been shown that by decomposing the question of impact of organization on safety into the role of programs and activities, and factors influencing these programs and activities, clear and unambiguous relationships can be identified between organizational factors and plant systems and functions. Some of these relationships are also quantifiable in terms of degrees of influence. Others require more investigation and data collection and analysis. The framework nevertheless provides a vehicle for determining questions to be answered and data to be collected.

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