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An Empirical Analysis of Selected Nuclear Power Plant Maintenance Factors and Plant Safety

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ABSTRACT

This report contains a statistical analysis of the relationship between selected aspects of nuclear power plant maintenance programs and safety related performance. The report identifies a large number of maintenance resources which can be expected to influence maintenance performance and subsequent plant safety performance. The resources for which data were readily available were related statistically to two sets of performance indicators: maintenance intermediate safety indicators and final safety performance indicators. The results show that the administrative structure of the plant maintenance program is a significant predictor of performance on both sets of indicators.

EXECUTIVE SUMMARY

This report discusses the role and importance of the maintenance function in plant safety and shows the statistical relationships among selected characteristics of plant maintenance programs and indicators of plant safety. For the purposes of this report, maintenance is defined as the function with the objectives of preserving the inherent reliability and safety of plant structures, systems, and components and of restoring that reliability when it is degraded.

This report has two objectives. The first objective is to develop a model of the relationship of plant maintenance program characteristics to plant safety. The second objective is to take existing measures of maintenance program characteristics, maintenance safety performance, and plant safety performance and to relate these measures to each other statistically.

MAINTENANCE MODEL

The model developed to relate maintenance to plant safety contains three sets of variables: maintenance resources, maintenance intermediate safety indicators, and final indicators of plant safety. These are defined below and a graphic representation of the model is presented.

Maintenance Resources

Plant maintenance resources are those characteristics of a plant maintenance program that are expected to alter how and how well the maintenance function is performed. Maintenance resources include both the physical and the organizational contexts in which maintenance is performed and the tools and skills available to the maintainers for performing maintenance. Maintenance resources can be further broken down into three categories: technical, human, and administrative resources. Technical maintenance resources include such items as the equipment, tools, technical procedures, and parts available to the maintainers. Also included is the basic design of the plant, since it provides the physical context for doing maintenance. Human maintenance resources include the experience and qualifications of maintainers as well as the maintenance recruitment, selection, and training systems. Administrative maintenance resources include the formal structure of the maintenance organization, maintenance administrative policies and procedures, formal controls placed on maintenance units and individuals, and the coordinative mechanisms used to integrate work within maintenance and to link maintenance with related areas.

Final Indicators of Plant Safety

The NRC wants to avoid threats to public health and safety arising from the operation of nuclear power plants. Assessing the safety performance of nuclear power plants (NPPs) is not a simple process, however. "Ultimate" indicators of unsafeness (e.g., core melt with massive radiological releases outside containment) have not occurred in commercial

operating plants. Thus, they cannot be used in a statistical analysis to compare the safety performance of plants. Consequently, safety performance is typically monitored by assessing performance on other indicators of plant safety. Final safety indicators are measures of actual physical harm or direct threats to workers and the public. The term "indicators" is used because safety and ultimate unsafeness cannot be directly observed. Further, safety has a somewhat different meaning for different individuals. The final safety indicators employed in this report measure aspects of (1) physical harm or significant levels of radiation exposure to employees or the public (e.g., Man/REM exposures); and (2) release of significant levels of radioactive material outside containment (e.g., airborne effluents).

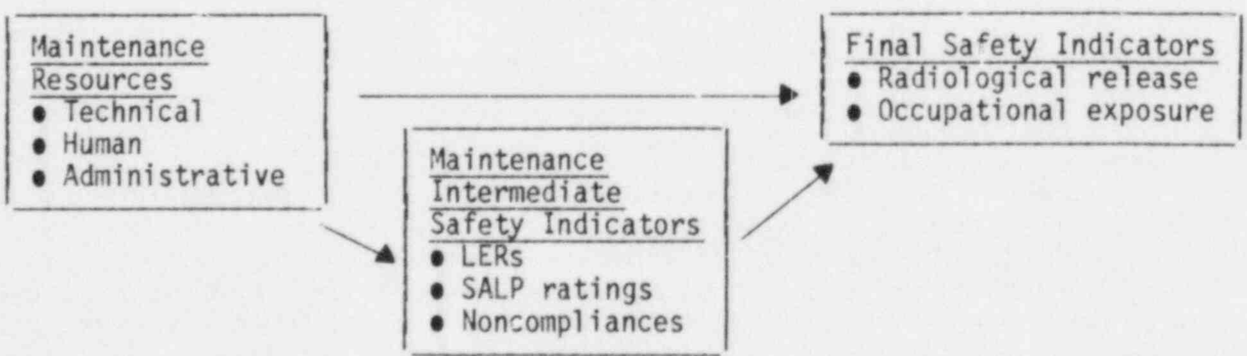
Maintenance Intermediate Safety Indicators

Intermediate indicators are measures of conditions that are not in themselves harmful, but that may be expected to give rise to subsequent harmful conditions. Intermediate indicators relevant to the maintenance function would be measures of maintenance performance that are causative of subsequent performance on the final indicators. The maintenance intermediate safety indicators used in this report include Licensee Event Reports (LERs), noncompliances, and Systematic Assessment of Licensee Performance (SALP) ratings associated with maintenance.

Relationships Among the Variables in the Model

The report investigates the relationships between (a) maintenance intermediate safety indicators and the final safety indicators, (b) the maintenance resources and the maintenance intermediate safety indicators, and (c) the maintenance resources and the final safety indicators.

This model can be graphically presented, as follows:



THE EMPIRICAL STUDY

The analysis contained in this report is an extension of the approach to assessing and explaining plant safety performance employed in previous reports (NUREG/CR-3215; NUREG/CR-3737). The analysis has been limited to data already available from this previous work and to that which could be accessed and coded with a minimum of additional effort. Thus, the maintenance resource measures and maintenance intermediate safety

indicators used constitute subsets of the relevant measures (e.g., maintenance-caused forced outages and trips have not been included).

The available maintenance resource data were collected, coded, and used to predict five maintenance intermediate safety indicators and five final safety indicators for as many operating reactors as possible. The statistical relationships between the maintenance intermediate safety indicators and the final safety indicators were also explored. Statistical controls for plant age, size, region, vendor, and reactor type were used in the analysis.

Maintenance Resources

From an extensive list of potentially important maintenance resources, data for a few key resources were available. The available resources centered on the administrative and human aspects of maintenance. It was not possible within the scope of the project to collect and code data on the technical resources available for maintenance. The administrative and human aspects of maintenance included such resources as the following:

- the size of the maintenance staff
- the way maintenance is organized into departments
- the organizational rank of the top maintenance manager
- the number of administrative levels within maintenance
- qualifications and experience of the maintenance superintendent (e.g., years experience, years nuclear experience).

Maintenance Intermediate Safety Indicators

The five maintenance intermediate safety indicators used were:

- the number of maintenance-related LERs
- the maintenance-area SALP rating
- the surveillance-area SALP rating
- the number of serious maintenance-related noncompliances
- the number of less serious maintenance-related noncompliances

Final Safety Indicators

Five final safety indicators were available:

- the total man/REM exposures for each plant
- the curies of airborne effluents
- the curies of I-131 and particulates

* the curies of liquid effluents

* the curies of Tritium effluents

A number of other factors may influence plant safety performance including reactor size, region, age, vendor, and reactor type. Consequently, in all the analyses, statistical controls for these factors were employed.

Results/Discussion

The relationships between the maintenance intermediate safety indicators and the final safety indicators did not emerge as strongly and as consistently as was hypothesized. Only half of the relationships tested were statistically significant and a third of these were in the direction opposite to that expected. One possible explanation for these findings is that the intermediate and final indicators were measured concurrently rather than in a time sequence, which would be more consistent with the hypothesized causal relationships between them. An even more important explanation for the findings, however, may be that the maintenance intermediate indicators and the final safety indicators employed were incomplete. Including such measures as maintenance-related trips and outages may strengthen the results in future analyses.

The maintenance resources were found to be related to the maintenance intermediate safety indicators. The administrative resources appeared most important for separating above-average from below-average plants. While no single administrative approach was important across all of the intermediate indicators, above-average maintenance programs tended to be smaller in staff size, have fewer supervisory ranks, to combine maintenance and operations into a single department, and to separate the mechanical, electrical, and I&C functions into distinct organizational units to a greater extent than their below-average counterparts.

The experience and qualifications of the maintenance superintendent were generally not predictive of either the intermediate or the final safety indicators. However, maintenance administrative resources were important predictors of the final safety indicators, although the pattern of results was not always consistent with that found for the maintenance intermediate safety indicators. In three of four cases, separation of maintenance and operations was characteristic of the better performing plants. Better performing plants also often had smaller staffs, combined maintenance and I&C units, and had fewer supervisory levels. In sum, the administrative forms associated with better performance on the intermediate safety indicators were somewhat different than the administrative forms associated with better performance on the final safety indicators.

The observed differences in the results across the intermediate and final safety indicators may be due to the problem of coordination within the plant. In other words, more extensive specialization (e.g., separate mechanical, electrical, I&C units) within maintenance may help performance on the maintenance intermediate safety indicators, but at the same time overburden coordination plant-wide, leading to poorer performance on the

final safety indicators. However, combining operations and maintenance into a single overall department may promote coordination and performance on the intermediate safety indicators while, for one reason or another, not assuring high performance on the final safety indicators.

Conclusions

Only a limited number of the potential maintenance resources could be evaluated in this study because of the limited availability of data. However, even this small sample of resources indicates that concern with maintenance administrative resources is warranted. Several of the administrative resources were consistently related to both intermediate indicators and final indicators of plant safety.

There is some indication that maintenance operations that are less hierarchical, smaller, and contain separate units for mechanical, electrical, and I&C work have better intermediate safety indicator performance. However, for better ratings on final indicators of safety, combined mechanical, electrical, and I&C units within maintenance operations seemed desirable. A single pattern does not appear to characterize maintenance operations rated above average on both maintenance intermediate safety indicators and final safety indicators.

Maintenance manager experience/qualifications were not highly correlated with either the intermediate or final safety indicators. It is possible that the qualifications of individual managers may not be as important as other maintenance resources. However, further analysis is needed to draw such a firm conclusion.

Although the conclusions offered by this report are tentative, due to limitations on the scope of the available data and to some inconsistencies in the observed relationships, several of the maintenance resources (e.g., staff size and number of supervisory levels) appear to warrant NRC and utility attention.

ACKNOWLEDGMENTS

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1.0 INTRODUCTION

1.1 Purpose and Approach

Past events at the Salem and Ginna nuclear power plants (NPPs) reconfirmed a lesson of Three Mile Island: plant maintenance plays an important role in contributing to and recovering from potentially dangerous events in NPPs. The quality of maintenance performance, in turn, is determined to a significant extent by the quantity and quality of resources (e.g., staff size, tools, engineering support, etc.) available through the plant's maintenance program. Using existing, published Nuclear Regulatory Commission (NRC) data, this report identifies important resources within plant maintenance programs and statistically relates those resources to indicators of plant safety performance.

1.2 Outline of the Report

This report contains five additional sections. Section 2 defines maintenance, outlines some general reasons why maintenance may be related to plant safety performance, and discusses the hypothesized relationship between specific maintenance resources and plant safety performance. Section 3 outlines a conceptual approach to assessing plant safety. The section identifies potential indicators for estimating the relative safety performance of operating plants for both the maintenance function and the plant as a whole. Section 4 discusses the analytical strategy used in this report to examine the relationships between maintenance resources and safety performance. Further, it provides the definition and operationalization of the variables used in the analysis. Section 5 presents the results of the analyses linking maintenance resources to maintenance and plant safety performance. Section 6 provides a summary and some conclusions.

2.0 MAINTENANCE AND NUCLEAR POWER PLANT SAFETY

2.1 Relation of Maintenance to Plant Safety

Maintenance is defined as the function with the objectives of preserving the inherent design characteristics, reliability, and safety of plant structures, systems, and components and restoring those characteristics and reliability when they are degraded. Maintenance can influence plant safety performance in several ways:

- By maintaining the reliability of multiple or redundant safety systems, the defense-in-depth approach to protecting public health and safety is strengthened.
- By maintaining the reliability of the plant, transient-induced challenges to safety systems and undesired shocks to systems and components are minimized.
- By helping to detect and solve safety issues, and by developing systems and approaches for improving human performance within maintenance, the safety performance of the plant is raised above minimum standards.

Despite these logical, intuitive linkages between maintenance and NPP safety, little empirical analysis has been conducted to examine this relationship. One way to determine which maintenance programs are most effective is to evaluate the statistical relationships that may exist between plant safety performance records and various current approaches to NPP maintenance programs. By observing which approaches to maintenance are associated with above-average and below-average safety performance, a profile of the characteristics of effective maintenance programs can be established. The maintenance characteristics may then be used to predict subsequent plant safety performance. First, however, it is necessary to describe the dimensions along which maintenance programs can be evaluated and to outline the important characteristics within these dimensions.

2.2 Dimensions for Analyzing Maintenance Programs

The ability of the utility and plant maintenance staff to maintain or improve plant safety performance is determined to a significant extent by the quality and quantity of resources available. For this report, maintenance resources are defined as those characteristics of the plant maintenance program that are expected to alter how and how well the maintenance function is performed. As described in more detail below, maintenance resources include the technical (e.g., tools and equipment), human (e.g., personnel and training), and administrative (e.g., organizational structure) characteristics of the maintenance function.

A list of maintenance resources was derived from expert opinion[1] and a review of several recent systematic treatments of maintenance issues, including the following:

(1) Institute of Nuclear Power Operations (INPO) Maintenance Performance Criteria from Performance Objectives and Criteria for Plant Evaluations (INPO, 83-014)

(2) Front-End Analysis for the Nuclear Power Plant Maintenance Personnel Reliability Model (NUREG/CR-2669)

(3) Human Factors Review of Power Plant Maintainability (EPRI-NP-1567)

(4) Recommended Program for the Development of Maintenance Guidelines for Nuclear Power Plants (PNL-4475).

The maintenance resources have been grouped into three broad categories: technical, human, and administrative. A brief discussion of why each type of resource is expected to influence maintenance performance and, therefore, plant safety performance follows.

2.2.1 Technical Resources for Maintenance

NPP maintenance is influenced by the basic nature of plant's systems and components and by the facilities, equipment, tools, parts and technical procedures available to the maintainers. These technical resources influence such things as the inherent reliability of the plant's systems and components, the work setting (e.g., accessibility of components) within which maintenance takes place, and the physical resources (e.g., parts and tools) available to solve and avoid specific maintenance problems. Specific indicators of the technical resources can be grouped into the following categories: (1) systems and components, (2) material and facilities, and (3) technical procedures. Where these resources are inadequate or work conditions too limiting, maintenance performance may not be sufficient to retain an adequate margin of safety. A list of potential technical resources is given in Table A-1 in Appendix A.

2.2.2 Human Resources for Maintenance

Human resources are also important to maintenance performance. An adequate number of experienced, well-trained, qualified, and motivated individuals will enhance the utility's ability to assure coverage of important work activities and to avoid human error. The number and qualifications of maintenance personnel, the character of the maintenance

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[1]An initial list of maintenance resources was developed by a Pacific Northwest Laboratories staff member with an engineering background and considerable experience in supervising and evaluating maintenance programs. The list was reviewed and augmented by additional Battelle staff with knowledge of NPP maintenance issues.

personnel selection system, and the nature of the maintenance training system are all important resources. Specific indicators of the human resources for maintenance can be grouped into the following categories: (1) staffing, (2) qualifications, (3) recruitment and selection, and (4) training. A list of potential human resources is given in Table A-2 in Appendix A.

2.2.3 Administrative Resources for Maintenance

Maintenance management is responsible for developing and monitoring the maintenance organization, appropriate policies and procedures, formal controls, strategies for the allocation of resources, specific coordinative mechanisms, and information and communications systems for maintenance. When nuclear power plant maintenance is examined as a function, it is seen as but one part of the overall operations of the plant. Thus, the efforts of maintenance must be integrated with those of other functional areas. The role of integration is typically assigned to management. These administrative characteristics can also be considered resources since they provide the context within which maintenance takes place. Thus, administrative resources include: (1) formal structure, (2) administrative policies and procedures for the conduct of maintenance work, (3) the formal controls placed on maintenance subunits and individuals, (4) formal coordinative mechanisms within maintenance subunits and between maintenance and related areas, and (5) information and communications systems. A detailed list of potential administrative maintenance resources is given in Table A-3 in Appendix A.

The resources listed in Tables A-1, A-2, and A-3, represent some of the resources that should be included in a complete assessment of maintenance programs. However, the list is not exhaustive and data for many of the resources identified are not readily available from existing sources. Consequently, the analysis contained in this report will be based on a small subset of the identified maintenance resources.

3.0 MEASURING NUCLEAR POWER PLANT MAINTENANCE AND SAFETY PERFORMANCE

Previous discussions of the measurement of NPP safety (see NUREG/CR-3215 and NUREG/CR-3737) have pointed to several difficulties in defining and measuring the concept. The main difficulty is that "ultimate" safety events (e.g., total core melt followed by massive radiological release with injury to the public and workers) happen with such low frequency, or not at all, that the presence or absence of such events cannot be used within the regulatory framework to evaluate the relative performance of the plants. Another set of events (e.g., occupational injuries, radiological releases, and radiological exposures) are less serious than the ultimate events, but are still serious enough that they should be avoided. These events do happen with sufficient frequency so that the variation in its occurrence can be determined and any effect on overall plant safety performance can be assessed. These less serious events are referred to as final safety indicators in this report.[2]

However, to regulate solely on the basis of final indicators is to, in effect, regulate after the harm has been done. Consequently, the NRC has established several mechanisms (e.g., Licensee Event Reports (LERs) and Systematic Assessments of Licensee Performance (SALP ratings) to monitor ongoing NPP safety performance. These measures are assumed by many to be predictors of the ultimate and final events and are called intermediate safety indicators in this report. The purpose of this section is to identify measures that can be used as final indicators of plant safety performance and measures that can be used as maintenance intermediate safety indicators. While beyond the scope of this analysis, the eventual goal of these efforts is the development of valid and reliable indicators of potential or developing safety problems at plants.

3.1 Differentiating Final and Intermediate Indicators

In this report, final indicators of plant safety are defined as measures of actual physical harm or direct threats to workers or the public due to radiation. Examples include radiological releases and radiological exposures. An argument could be made, however, that some level of radiological exposure is unavoidable due to the need to conduct adequate maintenance of equipment. Plants that minimize such maintenance, and thus exposure, may contribute to more severe long-term safety problems. Determining how much exposure signifies adequate maintenance versus how much signifies unnecessary exposure is a major empirical task in its own right and is beyond the scope of this report. Intermediate indicators are

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[2]It is important to note that the relationships between what are being defined here as final and ultimate events is hypothetical. It is not necessarily the case that final events cause or even predict the ultimate events.

measures of conditions in the plant that are expected to affect the scale or frequency of the final indicators. These conditions reflect the nature of the technical, human, and administrative aspects of plant operations, and, as such, are indicators of maintenance performance related to safety.

The final indicators represent conditions that are important to avoid. These conditions are believed to be preceded and caused by another set of conditions, which are measured by the intermediate indicators. If a statistically stable set of usable intermediate indicators of subsequent final indicators can be developed, utility and regulatory resources can be applied to plants that appear to pose a greater risk to public health and safety. Such early intervention, it is hoped, would help avoid or limit the potential negative effects of the intermediate conditions. The first step in this process is to make the conceptual distinction between intermediate and final indicators.

3.1.1 Final Safety Indicators

The choice of criteria for categorizing indicators as final or intermediate varies according to the interests of the evaluator. For example, the utility may be interested in plant reliability and profitability as final performance indicators. The NRC, however, is first and foremost interested in the health and safety of the public and workers. Consequently, there are two general criteria for determining whether a measure should be included as a final indicator:

(1) Physical harm due to radiation or significant levels of radiation exposure to NPP employees; or

(2) Release of significant levels of radioactive material outside containment, thereby increasing the probability of negative health effects to the public.

Not all experts agree on the levels at which radiological exposure and radiological releases begin to constitute actual health risks. One set of definitions for radiological exposure and releases is contained in 10CFR20. Using this definition, almost all plants conform to acceptable levels. However the ALARA (as low as reasonably achievable) concept sees all exposures as events to be avoided. In this report, a compromise position is taken. In the analysis to follow, those plants above the median on yearly exposures and radiological releases will be compared to those plants below the median. This approach, in effect, treats all exposures and releases below the median as trivial, and all those above as significant. To control for the fact that plant age and reactor type are partial determinants of the plant's exposure and release rates, in this analysis, each plant's score will be statistically adjusted for age and type.

Indicators of physical harm include occupational injury and death (due to radiation) and measures of radiological exposure. Indicators also include

the curies of various airborne and liquid radioactive releases.[3] While it is difficult to observe actual harm from radiation exposure, this category is included because such exposure does increase the probability of cancer incidence in the plant workforce or the surrounding populace.

3.1.2 Intermediate Safety Indicators

Intermediate indicators are not so easily defined. The major problem is that intermediate indicators are hypothetical causes of the final indicators and, thus, their identification requires empirical analysis. Initially, however, other indicators can be judged to be intermediate if:

(1) they do not represent physical harm or radiation exposure to workers or the public (i.e., they are not final indicators), and

(2) they are logically linked to the increased future probability of such physical harm or radiation exposure.

Underlying the notion of the intermediate indicator is the idea that it reflects actions or an evaluation of actions that affect the plant's performance as measured by the final indicators. Intermediate indicators, then, are evaluations of behavior relative to safety. There are numerous dimensions on which behavior can be evaluated. For example, behavior can be evaluated as to its efficiency, quality, innovation, compliance to formal standards, and the like. An earlier report (NUREG/CR-3215) outlines how each of these dimensions are logically related to plant safety. However, almost all of the <u>available</u> safety data are concerned with evaluating the level of compliance to NRC standards. Examples include SALP ratings, numbers of LERs, and numbers of Office of Inspection and Enforcement (I&E) noncompliances. In this report, then, intermediate indicators will be defined as deviations from performance standards established by the NRC and contained in the LER, SALP, and noncompliance data systems. Since maintenance performance is the topic of concern, deviations attributable to maintenance will constitute the intermediate indicators and will be referred to as maintenance intermediate safety indicators.

3.1.3 Summary

In summary, the model that has been proposed can be presented graphically as follows.

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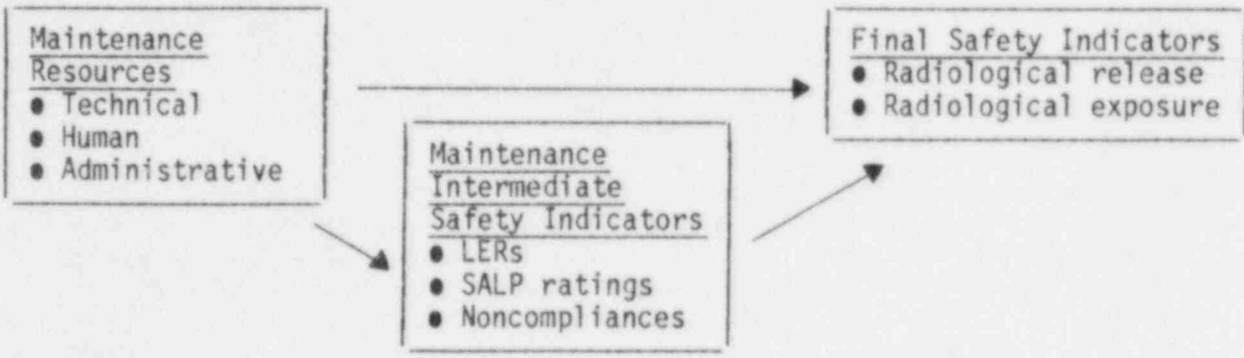
[3]Because the safety of transportation and storage of radioactive waste is still a matter of considerable debate, the total curies shipped and number of shipments of such waste are additional measures of potential harm to workers and the public. However, available waste data have not been included as final indicators due to a) an inability to distinguish between high and low level waste and b) an inability to determine actual radiological release to the environment from this waste.



Maintenance resources are seen as affecting final safety indicators primarily through their effects on the maintenance intermediate safety indicators. Thus, the analysis to follow will examine both (a) the relationship between maintenance resources and the maintenance intermediate safety indicators, and (b) the relationship between the maintenance intermediate safety indicators and the final safety indicators.

However, a case can easily be made that maintenance resources influence the final indicators through the performance of other functional areas (e.g., operations). For example, the way the maintenance department is organized could affect the interchange of information with other functions, thus affecting the knowledge of plant status. Relevant safety indicator data were not readily available for functions other than maintenance. The approach taken here, therefore, will also be to examine the relationship between maintenance resources and the final safety indicators, since this relationship subsumes the effects of the maintenance resources working through other plant functions.

4.0 ANALYTIC STRATEGY AND MEASUREMENT OF THE VARIABLES

This section describes the sources and coding schemes used for the variables in the analysis to follow. There are four broad categories of variables: maintenance resources, maintenance intermediate safety indicators, final safety indicators, and a set of control variables (e.g., plant vendor and size). The scope of this project was restricted to data that were readily available from published sources. The intermediate and final afety indicator data are from the 1981-1982 time frame. Data for the maintenance resources come from either a 1980 survey of technical resources, a 1981 survey of staffing, or the NRC's Final Safety Analysis Reports (FSARs). The NRC requires utilities to amend the FSARs as changes become necessary. So, while the FSARs were originally filed at widely different dates, they likely reflect utility practice at the time (1982) that the FSARs were received from the NRC for this analysis. Of course, utilities may have instituted significant changes in their plant organizations since 1982. Despite some possible variation, the data come from approximately equivalent times for each of the variables in the analysis. Because of the limited data available, it was not possible to include measures of many of the resources listed in Appendix A.

4.1 Maintenance Resources

The available maintenance resource data are limited to a small but important set of human and administrative resources. Within the scope of this effort, it was not possible to collect and analyze data on technical resources. Some of the technical resources could be derived from existing sources that were not immediately available for this analysis; others would require primary data collection.

4.1.1 Measurement of Human Resources for Maintenance

Measurement of the human resources was sought for the subdimensions of (a) staffing, (b) qualifications, (c) recruitment and selection, and (d) training (see Table A-2). In terms of staffing, the Edison Electric Institute survey (reported in PNL-5119) identifies the size of the maintenance staff. This includes the mechanical, electrical, and instrumentation and calibration (I&C) functions, as well as staff functions (e.g., planners and engineers) attached to the maintenance units. Information is not currently available on such potentially important staffing measures as the size of the contractor work force, actual (as opposed to minimum) shift staffing levels, or staffing levels for each occupational specialty within maintenance. Thus (see Table A-2, item 1.3), the staffing level variable used is:

$$\text{MAINT STAFF SIZE} = \frac{\text{Number of maintenance staff at the site}}{\text{Number of units at the site}}$$

It is important to note that plants vary in the use of utility and contracted maintenance staff. MAINT STAFF SIZE is the size of the permanent, on-site staff. The total number of maintenance workers available would also include utility and contractor personnel. In the

analysis in Section 5, MAINT STAFF SIZE will be included with the analysis of administrative resources for maintenance. This is necessary because MAINT STAFF SIZE and the other human resources variables have missing data for different plants. To analyze them together would mean a substantial decrease in the cases available for analysis.

Detailed qualifications data for the maintenance staff are not generally available. All plants purport to conform to the minimum qualifications outlined by the NRC. However, there is little standardization (except for welders) of qualifications in the maintenance area for the average worker. For example, the skills and experience necessary to achieve journeyman's status in a given craft vary widely by state. Qualifications issues, however, are potentially very important for the safety performance of maintenance. The only systematic qualifications data available for this analysis were derived from the Teknekron Survey of Plant Technical Resources (NUREG/CR-1656). This data source provides information on the qualifications of plant maintenance superintendents. Data on other maintenance personnel are not included in the Teknekron report. Thus, for the maintenance superintendent, four qualifications variables, corresponding to items 2.4, 2.5, 2.6, and 2.10 in Table A-2, have been coded.

EXPERIENCE = Number of years of maintenance experience of the maintenance superintendent

NUCLEAR EXPERIENCE = Number of years of maintenance experience in the nuclear power industry for the maintenance superintendent

NAVY EXPERIENCE = 1, if maintenance superintendent has had nuclear navy experience
0, otherwise

RO/SRO LICENSE = 1, if maintenance superintendent has held or maintains a reactor operator (RO) or senior reactor operator (SRO) license
0, otherwise

There were no available data for recruitment and selection or training.

4.1.2 Measurement of Administrative Resources for Maintenance

A number of measures of formal structure were available for administrative resources. The major source for the formal structure data is the organizational chart provided by most utilities in their FSAR submissions. Charts for approximately 45 plants were available in sufficient detail to be included in this analysis.

All plants support the three basic maintenance job functions of electrical, mechanical, and I&C. However, they differ on how these jobs are organizationally linked. Linkage across these functions is potentially important to safety performance since the work activities of

each group affects the work activities of the others. It thus becomes important to coordinate activities and share vital information on plant status and performance. One way to do this is to provide close linkages through the formal structure, usually by having the various groups report to a common supervisor. Variation in the organizational linkages, therefore, is a subject for concern (see Table A-3, item 1.2). Thus, two variables were created from the organizational charts by assigning values based on the following rules:

COMBINED MAINT/I&C = 1, if maintenance and I&C report to a common maintenance superintendent
0, otherwise

COMBINED ELECT/MECH = 1, if both electrical and mechanical functions report to a common maintenance superintendent
0, otherwise

Effective maintenance may also depend on the available linkages to other plant functions. One such linkage of potential importance is between maintenance and operations. For example, operations originates many of the requests for maintenance activities. Operations also depends on maintenance to provide accurate information on the status of equipment out of service. Close coordination, therefore, is needed. The following variable was derived from the organization charts to measure the nature of the formal structural linkage between maintenance and operations (see Table A-3, item 1.8).

COMBINED MAINT/OPS = 1, if maintenance and operations report to a common operations/maintenance superintendent
0, otherwise

Engineering support to the mechanical, electrical, and I&C functions of maintenance may also be important (see Table A-3, item 1.8). There are a number of ways to make engineering support available. One way is to assign engineers in a staff capacity to the various maintenance functions. Thus, the following variable was created from the organization charts:

ENGINEERING SUPPORT = 3, if mechanical, electrical, and I&C functions each have an assigned staff engineer
2, if only two of the three functions have an assigned staff engineer
1, if only one of the three functions has an assigned staff engineer
0, otherwise

Also of interest are the vertical patterns in the maintenance organization. Vertical patterns are potentially important for several reasons. For example, they reflect the distribution of authority and establish limiting conditions on communication, coordination, and control. Two variables were coded from the organizational charts.

OF RANKS = Average number (across mechanical, electrical, and I&C) of managerial ranks from foreman to the maintenance superintendent

MAINT MANAGER RANK = 1, if maintenance department manager reports directly to the plant manager
0, otherwise

The number of ranks in the maintenance organization (see Table A-3, item 1.5) affects the flow of communications and indicates the extent to which the organization emphasizes hierarchy and control. The rank of the maintenance superintendent may be an important factor in determining such things as access to plant management and utility resources.

4.1.3 Summary of Maintenance Resources

Table 1 provides means, standard deviations, and ranges for all the variables in the analysis. These statistics show considerable variation in the way maintenance programs are organized and staffed within the industry. For example, MAINT STAFF SIZE ranges from 15 to 226 maintenance personnel per unit. It is important to note, however, that these figures refer to on-site personnel only. Not included are utility personnel from centralized maintenance staff and contractor personnel. Since it can be anticipated that utilities vary in reliance on these alternative sources, the current measure should be understood as an indicator of on-site resources rather than total human resources available.

About half of the plants combine the maintenance and I&C functions into a single department, about half have separate electrical and mechanical units, and about a third combine operations and maintenance under an operations-maintenance superintendent. The plants also vary in their vertical patterns with the average number of supervisory ranks averaging from fewer than 2 to as many as 4.

Maintenance superintendent qualifications also vary. Approximately 40% of the plants have maintenance superintendents with RO or SRO licenses, and 20% of the plants have maintenance superintendents with nuclear navy experience. The ranges for experience and nuclear experience are substantial. In short, the industry does not appear to have a unitary approach to organizing and staffing for maintenance. The analyses presented in section 4.5 will help to determine whether this variation has implications for safety.

4.2 Maintenance Intermediate Safety Indicators

Five maintenance intermediate safety indicators were included in the current analysis. The analysis contained in this report is an extension of the approach to assessing and explaining plant safety performance employed in previous reports (NUREG/CR-3215; NUREG/CR-3737). The analysis has been limited to data already available from this previous work and to that which could be accessed and coded with a minimum of additional effort. Thus, maintenance intermediate safety indicators used constitute

TABLE 1

MEANS, STANDARD DEVIATIONS, AND RANGES OF VARIABLES IN THE ANALYSIS[a]

VARIABLES	NUMBER OF CASES	MEANS	STANDARD DEVIATIONS	RANGES
A. MAINTENANCE RESOURCES				
1. STAFF SIZE	70	61.12	42.78	15-226
2. COMBINED MAINT/I&C	63	.49	.50	0-1
3. COMBINED MAINT/Ops	63	.32	.50	0-1
4. COMBINED MECH/ELEC	62	.52	.50	0-1
5. # OF RANKS	60	2.78	.58	1.7-4
6. MAINT MANAGER RANK	63	1.29	.46	1-2
7. ENGINEERING SUPPORT	62	1.37	1.36	0-3
8. EXPERIENCE	56	17.16	8.31	7-41
9. NAVY EXPERIENCE	57	.19	.40	0-1
10. NUCLEAR EXPERIENCE	56	11.13	7.30	2-32
11. RO/SRO LICENSE	55	.42	.50	0-1
B. MAINTENANCE INTERMEDIATE SAFETY INDICATORS				
1. MAINT LERS	67	80.32	54.02	13-241
2. MAINT SALP RATING	69	1.98	.73	1-3
3. SURVEILLANCE SALP RATING	68	1.74	.68	1-3
4. SERIOUS MAINT NONCOMPLIANCES	70	.70	1.16	0-5
5. LESS SERIOUS MAINT NONCOMPLIANCES	70	4.2	2.3	0-9
C. FINAL SAFETY INDICATORS				
1. MAN/REM EXPOSURES-1982	69	714.01	509.87	.4-1855.6
2. AIRBORNE EFFLUENTS-1981 (CURIES)	66	18,830.97	51,085.7	0-260,895
3. I-131 AND PARTICULATES-1981 (CURIES)	66	.905	4.45	0-25.84
4. LIQUID EFFLUENTS-1981 (CURIES)	66	1.30	1.73	0-9.2
5. TRITIUM EFFLUENTS-1981 (CURIES)	66	269.16	653.63	0-5289
D. CONTROL VARIABLES				
1. NORTHEAST REGION	70	.30	.46	0-1
2. WEST REGION	70	.07	.26	0-1
3. MIDWEST REGION	70	.31	.47	0-1
4. SOUTH REGION	70	.32	.47	0-1
5. BWR	70	.37	.49	0-1
6. WESTINGHOUSE PWR	70	.37	.49	0-1
7. OTHER PWR	70	.26	.51	0-1
8. SIZE (MWe)	70	745.07	255.28	50-1130
9. MOSCRIT[b]	70	34.53	5.59	3-36
10. MOSPOST[c]	70	49.65	39.30	0-199

[a]The number of plants represented ranges from 55 to 70 plants depending on the availability of data.

[b]Months operational up to 36 months.

[c]Months operational past 36 months.

subsets of the relevant measures. Other measures, most notably maintenance caused forced outages and trips, would be logical and important additions in a future analysis. The first indicator is:

MAINT LERs = Total number of maintenance-related LERs in 1981 and 1982

This indicator was derived from sequence coding of all LERs for 1981 and 1982. These LERs constitute all LERs where maintenance performance was judged to be a contributing cause of the event.

The second and third indicators are:

SERIOUS MAINT NONCOMPLIANCES = total number of maintenance noncompliances rated 1, 2, or 3 for the I&E maintenance inspection module in 1981

LESS SERIOUS MAINT NONCOMPLIANCES = total number of maintenance noncompliances rated 4, 5, or 6 for the I&E maintenance inspection module in 1981

Data for both noncompliance indicators came from a listing of maintenance module noncompliances contained in the 766 file as provided by the NRC. One option when using noncompliance data is to standardize the frequency of noncompliances by the number of inspection hours expended at a given plant. The result would be the number of noncompliances per inspection hour. While this approach is intuitively appealing it contains certain risks. A major concern is that the allocation of inspection hours to a plant is not simply a random event. Central to the determination of level of inspection effort is the NRC's perception of the level of potential problems at the plant. Thus, plants receiving more inspection hours are perceived as needing closer scrutiny. To standardize the number of noncompliances found by the number of inspection hours, however, does not recognize this fact. For example, if the NRC perceives one plant to be performing well and allocates 100 inspection hours resulting in two noncompliances, and another plant to be performing less well and allocates 300 inspection hours resulting in five noncompliances, the second plant would end up with a better score on the normed measure than would the first. Consequently, we have adopted the strategy of using the raw frequency of noncompliances rather than standardizing by inspection hours.

The fourth and fifth indicators were derived from the most recent SALP reports prior to 1983.

MAINT SALP = 3, if SALP report stated that more inspection effort was needed regarding maintenance
2, if SALP report stated that the current amount of inspection effort should be maintained regarding maintenance
1, if SALP report stated that less inspection effort was needed regarding maintenance

SURVEILLANCE SALP = 3, if SALP report stated that more inspection effort was needed regarding surveillance
2, if SALP report stated that the current amount of inspection effort should be maintained regarding surveillance
1, if SALP report stated that less inspection effort was needed regarding surveillance

4.3 Final Plant Safety Indicators

Five indicators were available that fit the definition of final indicators presented in section 3.1.1. The indicators are:

MAN/REM EXPOSURE-1982 = The average 1982 employee exposure per plant in Man/REMs.

AIRBORNE EFFLUENTS-1981 = Curies of airborne effluents for 1981.

I-131 AND PARTICULATES-1981 = Curies of I-131 and particulates for 1981.

LIQUID EFFLUENTS-1981 = Curies of liquid effluents, mixed fission and activation products for 1981.

TRITIUM EFFLUENTS-1981 = Curies of tritium in liquid effluents for 1981.

Descriptive statistics for these variables can be found in Table 1. It should be noted that the large standard deviations (in comparison to the means), which characterize these indicators, suggest a highly skewed distribution. That is, most plants are concentrated at the low end of the distribution while a few plants have extremely high scores. As discussed below, the statistical approach used in compatible with analysis of variables with skewed distributions.

4.4 Control Variables

A number of reviews of existing NPP performance data have argued that certain statistical controls need to be implemented in order to make safety indicator scores comparable across plants. (See NUREG/CR-3215 for a review of this literature.) Specifically, it has been suggested that controls be applied for plant age, reactor size, region, vendor, and reactor type. These controls are necessary since a plant's safety indicator score will be determined, in part, by these factors, which are basically beyond the utility's ability to change. Consequently, both the final safety performance indicators and maintenance intermediate safety indicators have been adjusted to remove the influence of these factors. Reactor size is measured as the plant's design electrical rating (MWe). Region is measured with a set of variables denoting whether a plant is in the Northeast, Midwest, South, or West region. Age is measured with two variables: the first indicating the number of operational months up to 36, since initial criticality (MOSCRIT), and the second indicating the number of operational months in excess of 36 (MOSPOST). The combination

of these two variables is necessary in order to control for the often observed non-linear effect of plant age on performance (NUREG/CR-3215). Another set of variables is used to measure reactor and vendor type. One variable measures whether or not the plant is a Boiling Water Reactor (BWR). A second measures whether or not the plant has a Westinghouse Pressurized Water Reactor (PWR), while a third measures whether or not the plant has a PWR reactor manufactured by Combustion Engineering or Babcock and Wilcox.[4]

4.5 Analytical Strategy

The first analytical task is to adjust the indicator data for the appropriate control variables. The statistical procedure used for adjustment is called residualization. The procedure starts by performing a series of multiple regressions where the control variables are used in combination to predict each of the safety indicators. The resulting equation is then used to calculate a predicted performance score for each plant on each safety indicator. The predicted score is then subtracted from the plant's actual score to derive the adjusted score. The adjusted scores constitute the expected ordering of the plants on the safety indicators if they were identical on age, size, type, region, and vendor. The detailed results of this analysis can be found in Appendix B.

The control variables were significantly related to most of the safety indicators. However, different control variables were related to different safety indicators. BWRs performed less well in terms of Man/REM exposures and airbourne releases than did PWRs. Larger plants tended to have worse SALP ratings and more Man/Rem exposures. Age was not consistently related to performance.[5]

Multiple discriminant analysis was the statistical technique chosen to test the relationships between (a) maintenance safety indicators and the final safety indicators, (b) maintenance resources and the maintenance intermediate safety indicators, and (c) maintenance resources and the final safety indicators. Most of the safety indicators are highly skewed (e.g., most plants are good performers but a few plants are extreme outliers in the poor performance direction). This condition makes the regression approaches less desirable. The statistical technique of multiple discriminant analysis is especially suited for these types of analyses because the skewed distributions can be collapsed into equal-sized categories.

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[4]The combination of all other PWRs into a single category was necessary given the small numbers of each PWR vendor type.

[5]It is interesting to note that increasing age, as measured here, was not associated in most cases with more safety problems. In fact, older plants performed somewhat better in terms of LERs, SALP, and noncompliances. However, the approach taken here did not concentrate on comparing the performance of the very oldest plants with newer ones. Thus, these results should not be taken to mean that there is not a significant aging effect in the industry.

The general strategy was first to adjust the indicators by the control variables. After adjustment, all plants were put into either the above-average or the below-average group on each of the maintenance and plant safety indicators. The plants were placed in either the above-average or below-average category for each safety indicator by splitting the distribution at the median. Except for the SALP ratings, this resulted in relatively equal numbers of high and low performers on the indicators. In a few cases for each safety indicator, data were missing. Consequently, there is some variation in the number of cases used across the various analyses.

The multiple discriminant analysis technique was then used to find (a) which maintenance intermediate safety indicators could successfully predict whether plants were above or below the median on each of the final safety indicators, and (b) which maintenance resources could successfully predict whether plants were above or below the median on each of the maintenance intermediate safety indicators and the final safety indicators.[6]

A number of summary statistics result from a discriminant analysis. Discriminant analysis provides an overall rate of percentage of accurately classified cases. Because the distributions are split at the median, resulting in half the cases in each category, one could expect to accurately classify 50% of the NPPs by chance alone. The stronger the relationships between the predictors and the safety indicator in question, the greater the improvement will be over the 50% rate. In this analysis, accurate classification rates of 60% and beyond generally conform to improvements in classification that are statistically significant. Discriminant analysis also provides coefficients that are very similar to regression weights in multiple linear regression analysis. These coefficients are called canonical discriminant function coefficients. Essentially, these coefficients provide both the direction (positive or negative) and the relative size of the relationship between the predictor and the variable being predicted.[7] Wilks' Lambda was the statistical test used to determine the significance (the likelihood that the observed relationship is not due to chance) of each predictor in discriminating between the high and low performing groups. (Wilks' Lambda is equivalent to the more common F test, but is more consistent with the assumptions

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[6]It is important to note that the term "prediction" is used in a tentative way. Without validation and without a more complete representation of the maintenance resources, this caution is warranted. However, it is judged to be preferable to terms which imply causality (e.g., effect) since no experimental control was possible.

[7]In a few of the analyses, coefficients in excess of 1.0 were noted. This was due to the high intercorrelation of COMBINED MAINT/OPS and MAINT MANAGER RANK. Since removing each one of these variables did not substantially alter the effects of the other variables, they were both retained and the coefficients reported as estimated.

underlying discriminant analysis.) Where the significance is equal to or less than .10, the observed relationship will be considered important and the effect reported. (See Kerlinger and Pedhazur, 1973 pp. 336-360 for a discussion of discriminant analysis and its associated statistics.)

5.0 RESULTS OF THE ANALYSES

5.1 Presentation of the Results

This section presents the results of using the maintenance intermediate safety indicators to predict high/low performance on the final safety indicators and of using maintenance resources to predict (a) high/low performance on the maintenance intermediate safety indicators and (b) high/low performance on the final safety indicators. When the resource variables and the intermediate and final indicators are combined into an analysis, approximately 45 plants have complete data. With only 45 plants in the analysis it is not advisable to combine all of the maintenance resource variables in a single prediction equation. To do so would violate the statistical assumptions underlying discriminant analysis. Therefore, the analyses have been conducted separately using maintenance administrative resources (plus maintenance staff size) and maintenance human resources as separate sets of predictors. Though by definition a maintenance human resource, for the reasons mentioned in Section 4.1, staff size has been included in the analysis with the maintenance administrative resources.

5.1.1 Explanation of the Tables

Tables 2, 3, 4, 5 and 6 provide the detailed presentation of the results. Table 2 gives the results of the discriminant analyses where the maintenance intermediate safety indicators are used to predict the final safety performance indicators. Tables 3, 4, 5, and 6 give the results of the discriminant analyses where the maintenance resources are used to predict the maintenance intermediate safety indicators and the final safety performance indicators. Contained in each table is a list of the variables that are significant predictors for each intermediate and final safety indicator, the associated coefficients indicating the direction and relative size of the relationships, and the percent of the cases accurately classified by the discriminant analyses. Also provided in the tables is the suggested pattern for better performance implied by the results. The number of NPPs in each analysis varies slightly from an average of 45, because of missing data. Table 7 summarizes the significant results.

5.1.2 Predicting Final Safety Indicators Using Maintenance Intermediate Safety Indicators

Table 2 summarizes the findings from the discriminant analyses that use the maintenance intermediate safety indicators to predict the final safety indicators. In this analysis, plant age, reactor type, vendor, region, and size have been controlled using the residualization process outlined above. In general, the maintenance intermediate safety indicators do

TABLE 2

PREDICTION OF ADJUSTED FINAL SAFETY PERFORMANCE INDICATORS USING MAINTENANCE INTERMEDIATE SAFETY INDICATORS FOR APPROXIMATELY[a] 45 NUCLEAR POWER PLANTS OPERATING IN 1981-1982

ADJUSTED FINAL SAFETY PERFORMANCE INDICATORS[b]	SIGNIFICANT PREDICTORS	CANONICAL DISCRIMINANT COEFFICIENT	OVERALL % CORRECTLY CLASSIFIED	BETTER PERFORMANCE ASSOCIATED WITH
1. MAN/REM EXPOSURES (1982)	MAINT SALP RATING	-1.00*	61.7	Worse SALP Rating
	SERIOUS MAINT NONCOMPLIANCES	.68*		Fewer Noncompliances
2. AIRBORNE EFFLUENTS-1981 (CURIES)	SURVEILLANCE SALP RATING	-.92*	67.8	Worse SALP Rating
	SERIOUS MAINT NONCOMPLIANCES	.76**		Fewer Noncompliances
	MAINT LERS	.41**		Fewer LERs
3. I-131 AND PARTICULATES-1981 (CURIES)	LESS SERIOUS MAINT NONCOMPLIANCES	-.44**	70.8	More Noncompliances
	SURVEILLANCE SALP RATING	1.03**		Better SALP Rating
4. LIQUID EFFLUENTS-1981 (CURIES)	MAINT SALP RATING	1.00**	61.5	Better SALP Rating
5. TRITIUM EFFLUENTS-1981 (CURIES)	MAINT LERS	.61*	50.8	Fewer LERs
	SURVEILLANCE SALP RATING	.48*		Better SALP Rating
	LESS SERIOUS MAINT NONCOMPLIANCES	-.63*		More Noncompliances

[a]Number of plants varies slightly from 45 in some analyses due to missing data.
[b]Adjusted for plant age, size, type, vendor, and region.
*Significant at .10 level.
**Significant at .05 level.

not strongly and consistently predict the final indicators. The following findings illustrate this conclusion.[8]

- As expected, low Man/REM exposure plants are also the plants with fewer serious maintenance-related noncompliances. However, low exposure plants tend to have worse maintenance-area SALP ratings.

- Plants with lower levels of airborne effluents tend to have fewer serious maintenance-related noncompliances and fewer maintenance-related LERs. However, low exposure plants also tend to have worse surveillance-area SALP ratings.

- Lower levels of I-131 and particulate releases characterized plants with better surveillance-area SALP ratings but with more of the less serious noncompliances.

- Liquid effluent releases were predicted by only one variable--the maintenance-area SALP rating. A better SALP rating was found in NPPs with lower release levels.

- Finally, tritium effluents are lower in NPPs with fewer maintenance-related LERs and better surveillance-area SALP ratings. However, the frequency of the less serious maintenance-related noncompliances is higher in the low effluent than the high effluent plants.

5.1.3 Predicting Maintenance Intermediate Safety Indicators Using Administrative Maintenance Resources

Table 3 summarizes the findings from a series of discriminant analyses which show the ability of selected maintenance administrative resources to discriminate between above-average and below-average NPPs regarding maintenance intermediate safety indicators. The following paragraphs provide additional explanation of the results presented in Table 3.

- Fewer maintenance-related LERs (MAINT LERs) were associated with a smaller maintenance staff size, combined maintenance and operations departments, and with a higher maintenance manager rank. These variables together accurately classified 68.7% of the NPPs in the analysis.

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[8]While the percent accurately classified by each analysis is given in Table 2, the percentages should be interpreted carefully. The percentages refer to the ability of the maintenance intermediate safety indicators to discriminate between high and low performers, but the discrimination is based both on positive and negative relationships between the intermediate and final indicators.

TABLE 3

PREDICTION OF MAINTENANCE INTERMEDIATE SAFETY INDICATORS USING SELECTED ADMINISTRATIVE MAINTENANCE RESOURCES FOR 45 NUCLEAR POWER PLANTS OPERATING IN 1981-1982[a]

ADJUSTED MAINTENANCE INTERMEDIATE SAFETY INDICATORS[b]	SIGNIFICANT PREDICTORS	CANONICAL DISCRIMINANT COEFFICIENT	OVERALL % CORRECTLY CLASSIFIED	BETTER PERFORMANCE ASSOCIATED WITH
1. MAINT LERS (1981-1982)	MAINT STAFF SIZE	.61**	68.7	Smaller size
	COMBINED MAINT/OPS	-.87**		Combined units
	MAINT MANAGER RANK	.92**		Higher rank
2. MAINT SALP RATING	# OF RANKS	.71*	66.2	Fewer ranks
	MAINT STAFF SIZE	.48*		Smaller size
	MAINT MANAGER RANK	-.49**		Lower rank
3. SURVEILLANCE SALP RATING	COMBINED MAINT/I&C	.57**		Separate units
	COMBINED MECH/ELEC	.66**		Separate units
	MAINT MANAGER RANK	-.38**		Lower rank
4. SERIOUS MAINT NONCOMPLIANCES (1981)	COMBINED MECH/ELEC	.89*	66.2	Separate units
5. LESS SERIOUS MAINT NONCOMPLIANCES (1981)	# OF RANKS	.78**	76.5	Fewer ranks
	COMBINED MAINT/I&C	.72**		Separate units
	COMBINED MECH/ELEC	-.61**		Combined units
	MAINT MANAGER RANK	.78**		Higher rank
	ENGINEERING SUPPORT	-.39**		More support
	COMBINED MAINT/OPS	-.46**		Combined units

[a]Number of plants varies slightly from 45 in some analyses due to missing data.

[b]Adjusted for plant age, size, type, vendor, and region.

*Significant at .10 level.

**Significant at .05 level.

- Better performance on the maintenance SALP rating was associated with fewer ranks within the maintenance department, a smaller staff, and a lower ranking maintenance manager. These associations are somewhat different from those for maintenance-related LERs. The NPPs in the analysis were accurately classified 66.2% of the time.

- Better performance on the surveillance-area SALP rating (SURVEILLANCE SALP RATING) was predicted by the following three conditions: separate maintenance and I&C units, separate mechanical and electrical units, and a lower maintenance manager rank. The NPPs in the analysis were accurately classified 67.2% of the time.

- For serious maintenance noncompliances (SERIOUS MAINT NONCOMPLIANCES), the predictive power of the maintenance administrative resources was marginal. Only one variable (COMBINED MECH/ELEC) was a significant predictor. Plants where the mechanical and electrical functions are in separate units have fewer noncompliances. The NPPs in the analysis were accurately classified 66.2% of the time.

- For less serious maintenance noncompliances (LESS SERIOUS MAINT NONCOMPLIANCES), the percent of the NPPs in the analysis accurately classified was 76.5%. Fewer noncompliances were associated with fewer ranks in the maintenance hierarchy, separate maintenance and I&C functions, combined mechanical and electrical functions, a higher rank on the part of the maintenance manager, and a combined operations and maintenance department.

5.1.4 Predicting Maintenance Intermediate Safety Indicators Using Maintenance Human Resources

Table 4 shows the results from using human resource information to discriminate between plants with higher and lower maintenance intermediate safety indicator performance. Measured qualifications data centered on the experience of the maintenance superintendent.

- In general, the qualifications of the maintenance superintendent were not consistently and significantly predictive of maintenance intermediate safety indicator performance.

- Where the experience of the maintenance superintendent was an important predictor, <u>less</u>, not more, experience was associated with the better performing plants.

- For maintenance human resources, no measures significantly predicted the maintenance-related LERs, the maintenance-area SALP rating, the surveillance-area SALP rating, or the more serious maintenance noncompliances.

TABLE 4

PREDICTION OF MAINTENANCE INTERMEDIATE SAFETY INDICATORS USING SELECTED HUMAN MAINTENANCE RESOURCES FOR 45 NUCLEAR POWER PLANTS OPERATING IN 1981-1982[a]

ADJUSTED MAINTENANCE INTERMEDIATE SAFETY INDICATORS[b]	SIGNIFICANT PREDICTORS	CANONICAL DISCRIMINANT COEFFICIENT	OVERALL % CORRECTLY CLASSIFIED	BETTER PERFORMANCE ASSOCIATED WITH
1. MAINT LERS (1981-1982)	No Significant Predictors	--	--	--
2. MAINT SALP RATING	No Significant Predictors	--	--	--
3. SURVEILLANCE SALP RATING	No Significant Predictors	--	--	--
4. SERIOUS MAINT NONCOMPLIANCES (1981)	No Significant Predictors	--	--	--
5. LESS SERIOUS MAINT NONCOMPLIANCES (1981)	RO/SRO LICENSE	.62*	64.7	No License
	NAVY EXPERIENCE	.63*		No Experience
	EXPERIENCE	.62*		Less Experience

[a]Number of plants varies from 45 in some analyses due to missing data.
[b]Adjusted for plant age, size, type, vendor, and region.
*Significant at .10 level with Wilks' Lambda.

- For less serious maintenance noncompliances, better performance was associated with not having an RO/SRO license, with not having nuclear navy experience, and with having fewer years of maintenance experience. However, these findings should not be taken as definitive. In the first place, the same pattern was not observed for the other maintenance intermediate safety indicators. Second, the less serious maintenance noncompliances probably constitute the least significant and reliable of the maintenance intermediate safety indicators. Thus, these findings cannot be taken to suggest that navy, maintenance, or operations experiences lead to poorer performance. Approximately 65% of the NPPs in this analysis were accurately classified.

5.1.5 Predicting Final Safety Indicators Using Maintenance Administrative Resources

Table 5 shows the results from the discriminant analyses involving administrative maintenance resources and the final safety indicators. In all five cases, at least some of the maintenance administrative resources were significant predictors.

- For the Man/REM exposures in 1982, a higher maintenance manager rank, fewer ranks within the maintenance department, combined maintenance and I&C functions, a combined maintenance and operations department, and a smaller maintenance staff size are predictive of better performance. The percent correctly classified by these discriminating variables is 66.2%.

- Performance on the airborne effluents indicator is better in plants where there is a smaller maintenance staff size, a combined maintenance and electrical department, but separate maintenance and operations departments. Approximately 65% of the cases are correctly classified.

- Performance on the I-131 and particulates indicator is better in plants that are lower in maintenance staff size, have a combined maintenance and I&C department, and fewer ranks in the hierarchy. However, only 58.5% of the cases are correctly classified by the discriminant function.

- The single predictor (COMBINED MAINT/OPS) suggests that separate maintenance and operations departments are preferred. Similarly, only 55.4% of the cases are correctly classified for the liquid effluents indicator.

- Performance on the tritium effluents indicator is better in plants where there are separate maintenance and operations departments, a combined maintenance and I&C department, but less staff engineering support (as measured in this analysis). Sixty percent of the cases are correctly classified.

TABLE 5

PREDICTION OF FINAL SAFETY INDICATORS USING SELECTED ADMINISTRATIVE MAINTENANCE RESOURCES FOR 45 NUCLEAR POWER PLANTS OPERATING IN 1981-1982[a]

ADJUSTED FINAL SAFETY PERFORMANCE INDICATORS[b]	SIGNIFICANT PREDICTORS	CANONICAL DISCRIMINANT COEFFICIENT	OVERALL % CORRECTLY CLASSIFIED	BETTER PERFORMANCE ASSOCIATED WITH
1. MAN/REM EXPOSURES (1982)	MAINT MANAGER RANK	1.18**	66.2	Higher rank
	# OF RANKS	.73**		Fewer ranks
	COMBINED MAINT/I&C	-.48**		Combined units
	COMBINED MAINT/OPS	-.63**		Combined units
	MAINT STAFF SIZE	.39**		Smaller size
2. AIRBORNE EFFLUENTS-1981 (CURIES)	MAINT STAFF SIZE	.43**	64.6	Smaller size
	COMBINED MAINT/I&C	-.62**		Combined units
	COMBINED MECH/ELEC	-.69**		Combined units
	COMBINED MAINT/OPS	.39**		Separate units
3. I-131 AND PARTICULATES-1981 (CURIES)	MAINT STAFF SIZE	.82**	58.5	Smaller size
	COMBINED MAINT/I&C	-.49**		Combined units
	# OF RANKS	.39**		Fewer ranks
4. LIQUID EFFLUENTS-1981 (CURIES)	COMBINED MAINT/OPS	1.00**	55.4	Separate units
5. TRITIUM EFFLUENTS-1981 (CURIES)	COMBINED MAINT/OPS	.80**	60.0	Separate units
	COMBINED MAINT/I&C	-.55**		Combined units
	ENGINEERING SUPPORT	.53*		Less support

[a]Number of plants varies from 45 in some analyses due to missing data.
[b]Adjusted for plant age, size, type, vendor, and region.
*Significant at .10 level.
**Significant at .05 level.

5.1.6 Predicting Final Safety Indicators Using Maintenance Human Resources

The qualifications variables for the maintenance superintendent were weak and inconsistent predictors of the final safety indicators. Table 6 presents the results of these analyses.

- There were a few significant relationships.
- In two cases, Man/REM exposures and tritium effluents, less overall experience was associated with better performance of the NPPs.
- Greater nuclear experience and navy experience were associated with lower Man/REM exposures.
- Having an RO or SRO license was associated with lower tritium effluents.
- Approximately 65% of the cases were correctly classified for Man/REM exposures, and 55% for tritium effluents.

5.2 Discussion and Explanation of Results

This section provides a discussion and possible explanation of the observed results. A summary of all of the significant relationships shown in Tables 3, 4, 5, and 6 can be found in Table 7. This table shows the nature of the administrative and human resources that would be associated with better safety performance on both the intermediate and final indicators.

5.2.1 Maintenance Intermediate Safety Indicators and Final Safety Indicators

It is important to note that the maintenance intermediate safety indicators were not generally predictive of the final safety indicators. Eleven out of a possible twenty-five relationships were statistically significant. Four of the eleven, however, were in the direction opposite to that predicted. One conclusion that can be drawn from this analysis is that the types of compliance data available to the NRC (e.g., LERs, SALP, noncompliances) are not capable of predicting such events as are reflected in the final indicators employed here. Before rejecting the possible usefulness of these data, however, certain alternative explanations should be considered.

First, it may be important to include other types of final safety indicators in the analysis. For example, a more restrictive definition of what constitutes a significant exposure or release may lead to final indicators that are more reliable and more clearly measures of plant safety. In a related sense, the maintenance intermediate safety indicators may be related to particularly significant events (e.g., TMI-type accidents), which others may want to define as final indicators.

TABLE 6

PREDICTION OF FINAL SAFETY INDICATORS USING HUMAN MAINTENANCE RESOURCES FOR 45 NUCLEAR POWER PLANTS OPERATING IN 1981-1982[a]

ADJUSTED FINAL SAFETY PERFORMANCE INDICATORS[b]	SIGNIFICANT PREDICTORS	CANONICAL DISCRIMINANT COEFFICIENT	OVERALL % CORRECTLY CLASSIFIED	BETTER PERFORMANCE ASSOCIATED WITH
1. MAN/REM EXPOSURES (1982)	TOTAL EXPERIENCE	1.00**	64.7	Less experience
	NAVY EXPERIENCE	-.33**		More experience
	NUCLEAR EXPERIENCE	-.58**		More experience
2. AIRBORNE EFFLUENTS-1981 (CURIES)	No Significant Predictors	--	--	--
3. I-131 AND PARTICULATES-1981 (CURIES)	No Significant Predictors	--	--	--
4. LIQUID EFFLUENTS-1981 (CURIES)	No Significant Predictors	--	--	--
5. TRITIUM EFFLUENTS-1981 (CURIES)	TOTAL EXPERIENCE	.70**	55.4%	Less experience
	RO/SRO LICENSE	-.58**		Having license

[a]Number of plants varies from 45 in some analyses due to missing data.
[b]Adjusted for plant age, size, type, vendor, and region.
**Significant at .05 level.

TABLE 7

SUMMARY OF SIGNIFICANT FINDINGS: MAINTENANCE RESOURCE APPROACH ASSOCIATED WITH SAFER PERFORMANCE

	MAINT. INTERMEDIATE SAFETY INDICATORS					FINAL SAFETY INDICATORS				
MAINT. RESOURCES	MAINT LERS	MAINT SALP	SURVEIL-LANCE SALP	SERIOUS MAINT NONCOMP	LESS SERIOUS MAINT NONCOMP	MAN/REM EXPOSURES	AIRBORNE EFFLUENTS	I-131 AND PARTICULATES	LIQUID EFFLUENTS	TRITIUM EFFLUENTS
1. STAFF SIZE	Smaller Size	Smaller Size	--	--	--	Smaller Size	Smaller Size	Smaller Size	--	--
2. COMBINED MAINT/I&C	--	--	Separate Units	--	Separate Units	Combined Units	Combined Units	Combined Units	--	Combined Units
3. COMBINED MAINT/OPS	Combined Units	--	--	--	Combined Units	Combined Units	Separate Units	--	Separate Units	Separate Units
4. COMBINED MECH/ELEC	--	--	Separate Units	Separate Units	Combined Units	--	Combined Units	--	--	--
5. # OF RANKS	--	Fewer Ranks	--	--	Fewer Ranks	Fewer Ranks	--	Fewer Ranks	--	--
6. MAINT MANAGER RANK	Higher Rank	Lower Rank	Lower Rank	--	Higher Rank	Higher Rank	--	--	--	--
7. ENGINEERING SUPPORT	--	--	--	--	More Support	--	--	--	--	Less Support
8. EXPERIENCE	--	--	--	--	Less Experience	Less Experience	--	--	--	Less Experience
9. NAVY EXPERIENCE	--	--	--	--	No Experience	More Experience	--	--	--	--
10. NUCLEAR EXPERIENCE	--	--	--	--	--	More Experience	--	--	--	--
11. RO/SRO LICENSE	--	--	--	--	No License	--	--	--	--	Has License

Second, the maintenance intermediate and the final safety indicators are measured concurrently. This approach does not allow for the effects of the intermediate indicators to emerge over time. It could be that stronger effects would be noted if the maintenance intermediate safety indicators in 1981 were used to predict the final indicators in 1982. A more detailed, time-series analysis should be able to uncover such lag effects, if they exist. The problem of potential lag effects is particularly important for the intermediate indicators that are evaluations of maintenance safety performance (e.g., SALP and noncompliances). Potentially, these indicators are both caused by and are causes of the conditions measured by the final safety indicators. For example, a negative SALP rating may induce a utility to make improvements. A time-series analysis would be necessary to model such causal relationships.

Finally, no attempt has been made in the current analysis to combine the various maintenance intermediate indicators into an overall scale. By creating such a composite index, the strengths of each of the indicators can be combined and a stronger set of relationships with the final indicators is a likely result.

5.2.2 Maintenance Resources and Maintenance Intermediate Safety Indicators

The discriminant analyses show that a number of maintenance resources are significantly related to the maintenance intermediate safety indicators. Some, such as the maintenance staff size, the number of ranks in the hierarchy, and whether maintenance and operations are combined have consistent effects. Others, such as the maintenance manager rank and whether the mechanical and electrical functions are combined have positive effects on some indicators and negative effects on others. While the results do not support a single, clear administrative model for the maintenance programs, there is a tendency for programs that are (1) smaller, (2) have maintenance and operations combined, and (3) are less hierarchical (e.g., fewer ranks) to perform better on the maintenance intermediate safety indicators. For the intermediate safety indicators, then, a somewhat less bureaucratic model may be contributing to better performance. One explanation for this general pattern is that coordination and communication may be enhanced in the smaller, flatter maintenance programs which are closely linked to operations.

Many additional maintenance resources would also have to be entered into the model to increase confidence in causal inferences. However, it is appropriate to speculate about what causal mechanisms could account for the observed relationships. For example, the finding that a smaller maintenance staff size is associated with better performance on two indicators supports several different interpretations. It could be that plants with problems have responded by adding maintenance staff. It could also be that plants that depend more on utility or contractor added maintenance staff perform better. A third alternative is that a smaller maintenance staff size promotes internal coordination and control. The fact that all of these explanations are plausible does not diminish the importance of the finding.

There are few significant relationships when maintenance superintendent qualifications are used to classify above and below average plants on the maintenance intermediate safety indicators. Further, they are often inconsistent. Three significant effects are opposite to those predicted with higher qualifications associated with lower safety performance. Clearly, there is a need for more data and analysis on the role of the qualifications of maintenance superintendents and NPP safety.

5.2.3 Maintenance Resources and Final Indicator Performance

There is evidence linking maintenance resources to final indicators of plant safety. In several instances there are significant results supporting this linkage: separation of maintenance and operations is characteristic of better performing plants on the final safety indicators, and small maintenance staffs, fewer ranks, and combined maintenance/I&C are consistently associated with better performance. While the results for smaller staff and the number of ranks are consistent with those for the maintenance intermediate safety indicators, the finding for combining maintenance and I&C is inconsistent. Another inconsistency across the intermediate and final indicators concerns combining maintenance and operations. For the final indicators, separate rather than combined maintenance and operations is associated with better performance.

Although an explanation of these inconsistencies may not be readily obvious, if these results are combined with those for more general plant-wide organizational factors (NUREG/CR-3737), an explanation does begin to emerge. Plant-wide questions of coordination and integration across functional areas appear important. More specialized units generally create more demands for coordination. It may be that separation of maintenance and operations does not overburden the plant's coordination capacity but further specialization (e.g., separation of maintenance and I&C) may. Reliance upon more managers (more ranks) for coordination does not seem to help and, if anything, is associated with lower safety indicators ratings.

To obtain above average ratings on the measured maintenance intermediate indicators, specialized units appear helpful but the addition of the units may overburden the coordinative capacity of the plant and thus be associated with below average ratings on the final indicators. It is not unusual to find that the resources and organizational design needed for a particular functional area may not be totally compatible with that needed for the operation as a whole. However, it is important not to make premature conclusions. The data are suggestive. Maintenance administrative resources appear to be important, much as are plant-wide organization factors (NUREG/CR-3737). The exact type of organization and the amount of resources needed cannot be established solely from the present analysis.

6.0 SUMMARY AND CONCLUSIONS

The purpose of this report was to examine the statistical relationship between measures of available maintenance resources and two types of performance measures: intermediate maintenance safety indicators and final safety indicators of NPPs. It began by identifying and defining potentially important resources within maintenance programs. Existing data were easily available for only a few resources. Since various maintenance resources can be expected to influence each other's effects on safety, the lack of complete data is a serious impediment to a comprehensive assessment of maintenance.

This report differentiated between final and intermediate indicators of safety. Final indicators of safety were defined as actual measures of physical harm and radiological release. Intermediate indicators were defined as evaluations of behaviors that are expected to cause variation in the final indicators. Two conclusions are suggested by this analysis. First, since the intermediate indicators are hypothetical causes of the final indicators, their ultimate validity must be determined by empirical analysis. That is, a detailed analysis is needed of the relationship between the proposed intermediate indicators and the final indicators. The analysis conducted here did not result in systematic support of the hypothesis that the maintenance intermediate safety indicators are predictive of the final safety indicators. Second, available assessments of behavior are dominated by assessments of compliance to minimum standards. More reliable intermediate indicators may be developed, however, if additional assessment dimensions (e.g., quality, efficiency, innovation) and a time-series approach to data analysis are included.

The empirical analysis contained in this report constitutes only a preliminary attempt to isolate preferred approaches to maintenance for plant safety. The results suggest propositions for future analysis more than firm conclusions for regulatory action. However, the analysis does offer some immediately useful information.

First, the descriptive analysis shows wide variation in the administrative and qualifications variables for which there were data. This variation is informative and suggests the potential for a resulting variation in safety performance. It also suggests that no one maintenance program is shown statistically to be a model for the industry.

Second, the administrative maintenance resources were significantly associated with both maintenance intermediate safety indicators and final safety indicators. While there is some indication that less hierarchical units, smaller units, and units with separate mechanical, electrical and I&C departments perform better, the available data are not sufficiently complete to draw firm conclusions. In key instances, desired characteristics for good performance on maintenance intermediate safety indicators were not desired for good performance on the final safety indicators. It is apparent that designing and operating a successful maintenance program is quite complex. No one preferred pattern can be derived from this analysis.

Third, maintenance superintendent qualifications were not highly predictive of either type of safety criteria. While these results are tentative, they raise the possibility that qualifications of key managers may not be as important in predicting performance as other maintenance resources. Since key manager qualifications is an area that has received NRC attention, additional analysis seems appropriate in order to determine the role and importance of managerial qualifications.

Although the conclusions offered in this report are tentative, due to limitations on the scope of the available data and to some inconsistencies in the observed relationships, several of the maintenance resources appear to warrant NRC and utility attention. Specifically, maintenance staff size consistently predicts both the intermediate and the final indicators, though in an unexpected way. The resource measures concerned with the way units within maintenance are linked and how maintenance is linked to other plant functions are frequently predictive of the intermediate and final indicators. Finally, the lack of relationships between maintenance superintendent qualifications and the intermediate and final indicators suggests that factors other than the qualifications of a single manager may be more important in determining intermediate and final safety performance. While all of the observed relationships are probably due to complex causal forces, their significance provides evidence in support of the conclusion that such maintenance resources should be monitored more closely.

In sum, the analysis is supportive of the proposition that both maintenance intermediate safety indicators and final safety indicators are associated with the resources available to the maintenance program. A number of the maintenance administrative resources were consistently associated with the safety indicators. These associations, in turn, suggest a range of possible causal explanations that should be evaluated in order to more fully understand the determinants of safety performance. Thus, concern with maintenance program characteristics is warranted.

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APPENDIX A

MAINTENANCE RESOURCES

APPENDIX A

MAINTENANCE RESOURCES

TABLE A-1

POTENTIAL MEASURES OF TECHNICAL RESOURCES FOR MAINTENANCE OF NPPS

Resource Type	Specific Resources
1. Systems and Components	1. Component reliability estimates 2. Plant design characteristics 3. Accessibility of components to maintenance workers
2. Material (equipment, tools, parts) and Facilities	1. Total number of maintenance workshops 2. Aggregate square feet of workshop space 3. Total number of tool cribs 4. Total number of "hot" tool cribs 5. Square feet of contaminated items storage 6. Total number of "heavy" "intermediate" and "light" cranes 7. Total number of cargo elevators 8. Total number of personnel elevators 9. Total capital equipment budget for maintenance per year 10. Total number of decontamination work stations in plant 11. Square feet of "hot shop" work space available 12. Average inventory remaining shelf life 13. Average inventory turnover rate 14. Square feet of warehouse space 15. Repair parts availability 16. Total line items of inventory stocked 17. Average illumination level of work areas 18. Average temperature of maintenance work areas 19. Average noise level of maintenance work areas
3. Technical Procedures	1. Proportion of components clearly labeled 2. Proportion of maintenance tasks for which written procedures exist which detail the steps in the maintenance task (safety and non-safety grade) 3. Proportion of written technical procedures with accurate, useful narratives and graphics 4. Proportion of written technical procedures provided by the vendors 5. Number of pages of technical procedures relative to similar plants.

TABLE A-2

POTENTIAL MEASURES OF HUMAN RESOURCES FOR MAINTENANCE OF NPPS

Resource Type	Specific Resources
1. Staffing	1. Names (job title) of each maintenance-related occupational or job specialty and subspecialty
	2. Names (job title) of each maintenance-related organizational rank
	3. Number of full-time workers in each specialty/subspecialty and rank
	4. Number of part-time workers in each specialty/subspecialty and rank
	5. Number of contractor workers used during major outages
	6. Number of contractor workers used for other than refueling outages
	7. Number and types (e.g., mechanical, electrical) of maintenance workers on shift
	8. Number and types of maintenance workers on call
	9. Number of utility-added maintenance workers
	10. Number of maintenance workers covered by union contracts
	11. Shift work schedule
	12. Yearly turnover rates for each category of maintenance personnel
	13. Number and percent of unfilled maintenance positions
	14. Average time positions remain unfilled
	15. Average amounts of overtime worked each year by maintenance personnel
	16. Turnover rates among contractor personnel
	17. Average number of maintenance workers promoted each year.
2. Qualifications (for entry level and each level of job responsibility)	1. Minimum educational qualifications required of each specialty/subspecialty and rank
	2. Average educational attainment of each specialty/subspecialty and rank
	3. Minimum total maintenance experience required of each specialty/subspecialty and rank
	4. Average total experience of each specialty/subspecialty and rank

TABLE A-2 (continued)

Resource Type	Specific Resources
	5. Minimum nuclear power plant experience of each specialty/subspecialty and rank
	6. Average years nuclear experience of each specialty/subspecialty and rank (including Navy and research reactor experience)
	7. Years of "journeyman" experience required
	8. Other qualifications required, (e.g., entry level skills tests)
	9. Average years of plant specific experience
	10. Number of workers holding special credentials (RO, SRO, engineering)
	11. Average qualifications on each shift
3. Recruitment and Selection	1. Proportion of maintenance workers recruited locally
	2. Proportion of maintenance workers recruited from other jobs or units within the utility
	3. Proportion of maintenance workers recruited from other utilities or vendors
	4. Proportion of maintenance workers recruited through union hiring halls
	5. Use of special recruitment incentives (bonuses, relocation costs)
	6. Use of systems for checking credentials of prospective employees
	7. Use of a recruitment plan (schedule, strategy) for maintenance
	8. Use of other types of screening devices (security check, personality tests)
	9. Use of screening devices used for temporary workers
4. Training	1. Minimum days of on-the-job training required by the utility
	2. Minimum days of vendor-sponsored training required by the utility
	3. Minimum days of utility-sponsored classroom training required by the utility
	4. Minimum days of other training required by the utility
	5. Number of hours devoted to each ANSI/ANS 3.1 training area

TABLE A-2 (continued)

Resource Type	Specific Resources
	6. Number of maintenance training personnel
	7. Qualifications of maintenance training personnel
	8. Number of maintenance training instructional aids used
	9. Presence or absence of incentives for worker-initiated education or training
	10. Average number of job specialties in which each worker is trained
	11. Whether or not INPO maintenance training standards are met
	12. Number of hours in minimum union training programs
	13. Proportion of regular training standards applied to temporary workers

TABLE A-3

POTENTIAL MEASURES OF ADMINISTRATIVE RESOURCES FOR MAINTENANCE

Resource Type	Specific Resources
1. Formal Structure	1. The number and type of major maintenance work units (e.g., I&C, mechanical, electrical) 2. Supervisory level at which the maintenance units (e.g., mechanical, electrical, I & C) are linked 3. Rank of the maintenance manager 4. The number and type of formal or ad hoc committees or task forces involve maintenance issues 5. Number of supervisory ranks within each maintenance unit 6. Average supervisory span of control at each level within maintenance 7. Whether or not the maintenance manager reports offsite 8. Level at which maintenance is linked to operations, QC, Health Physics, Radwaste, and plant engineering
2. Policies and Procedures	1. Whether or not written procedures exist for identifying responsibility for writing, reviewing, and controlling maintenance procedures 2. Whether or not written procedures exist which identify the flow of maintenance activities on each safety and non-safety grade component (tag-out, inspection, etc.) 3. The presence of a system for acquiring and updating vendor technical information 4. Planned ratio of preventive-to-corrective maintenance 5. Number of pages in the preventive maintenance plan 6. Proportion of all components covered by the preventive maintenance plan 7. Whether or not there is a maintenance priority system 8. Whether or not work order packages include procedures, tool and manpower requirements 9. Proportion of all maintenance tasks with written post-maintenance testing requirements

TABLE A-3 (continued)

Resource Type	Specific Resources
3. Controls	1. Mean number of maintenance QC inspections performed per year 2. Position authorized to hire, fire, and promote workers 3. Systems present for monitoring worker performance 4. Systems present for rewarding or punishing maintenance performance
4. Coordination	1. Presence of committees to integrate issues with other functional areas 2. What matrix arrangements exist across functional areas 3. What staffing practices (e.g., job rotation, dual training) exist to promote coordination across maintenance areas 4. Whether or not there is a written procedure for integrating work across shifts
5. Information and Communications	1. Presence of plant status monitoring systems for maintenance activities 2. Data storage capabilities exist for maintenance activities 3. Presence of on-line maintenance data bases 4. Policies governing communication across maintenance areas 5. Policies governing communication across maintenance ranks

APPENDIX B

CONTROL VARIABLES AND INDICATORS

APPENDIX B

CONTROL VARIABLES AND INDICATORS

As noted in the text, both the maintenance intermediate safety indicators and the plant safety indicators were adjusted for a number of control variables. Specifically, these control variables were, age of the plant, reactor size, region, reactor vendor, and reactor type. This appendix presents the statistical association between these control variables and the intermediate and final safety indicators. A brief discussion is also included.

Explanation of the Data

Table B-1 presents the results of 10 multiple regression equations where all the control variables are used to predict each indicator. The columns show unadjusted regression coefficients (slopes) for each control variable, the intercept of the equation, the proportion of variance accounted for by all the control variables (R-square), and some interpretive comments regarding the unadjusted regression coefficients which are statistically significant. An explanation of the statistical technique and a detailed discussion of interpretation of such data may be found in Kerlinger and Pedhazur (1973).

As noted in the text, it was necessary to use a series of "dummy variables" to represent region and vendors. The plant was given a score of one if it was in a particular condition (e.g., in the western region), or zero otherwise (e.g., some other region). A series of these "dummy variables" was used to represent all possible regions and vendor/reactor type combinations. In the statistical analysis, dummy variables for one region and one vendor/reactor type combination must be omitted to avoid overspecification of the statistical model. Thus, Table B-1 does not include scores for the Southern region or for non-Westinghouse pressurized water reactors. The effects of the Southern region and the non-Westinghouse PWRs can be inferred from (a) whether the intercept of the equation is statistically significant, and (b) the pattern of findings for the other conditions.

Control Variables and Maintenance Intermediate Safety Indicators

For Maintenance LERs: BWRs, the Southern region, and newer plants (those less than 36 months operational) had more maintenance LERs than others. Plants located in the Midwest and Western regions had significantly fewer maintenance LERs. The proportion of variance explained by all the control variables was .39 and was statistically significant.

For Maintenance SALP: BWRs, larger plants, and those located in the Southern region received worse maintenance SALP ratings than others. The proportion of variance explained by all the control variables was .28 and was statistically significant.

For Surveillance SALP: Larger plants and those located in the South had worse ratings, while those located in the Northeast had significantly better ratings. The proportion of variance explained by all the control variables was .32 and was statistically significant.

For Serious Maintenance Noncompliances: Plants operating in the South had more serious maintenance noncompliances. The proportion of variance explained by all the control variables was .26 and was statistically significant.

For Less Serious Maintenance Noncompliances: Plants located in the West received worse ratings, while those operating in the Northeast and Midwest received fewer, less serious maintenance noncompliances. The proportion of variances explained by all of the control variables was .26 and was statistically significant.

Summary for Intermediate Maintenance Safety Indicators

Across the intermediate maintenance safety indicators, a number of control variables were statistically associated with different indicators. Thus, adjustment of these indicators was considered appropriate. The reader is cautioned not to interpret these results as suggesting that any one type of plant, vendor, region, or age of plant is superior to the others. The analysis only suggests that statistical adjustment is appropriate. It is not known or hypothesized in this report that data represent causal relations, bias, or some underlying relationship not directly measured in this study.

Control Variables and the Final Safety Indicators

Man-REM Exposures: BWRs and larger plants had more exposures. The proportion of variance explained by all the control variables was .32 and was statistically significant.

Airborne Effluents: BWRs had higher airbourne effluents, while those operating in the Midwest and South had lower airbourne effluents. The proportion of variance explained by all the control variables was .25 and was statistically significant.

I-131 and Particulates, Liquid Effluents, and Tritium Effluents: The control variables as a group were not significant predictors of these indicators. However, larger plants did have more reported releases of I-131 and particulates.

Summary for the Final Safety Indicators

Across the five final safety indicators, the control variables were significant predictors in two cases and, for one indicator, one control variable was a significant predictor when taken as the only predictor. This pattern of results was deemed substantial enough to institute the control procedure for all final safety indicators for the purposes of the current project.

TABLE B-1

REGRESSION RESULTS FOR CONTROL VARIABLES PREDICTING INDICATOR SCORES

CONTROL VARIABLES	INDICATORS									
	Maint Lers	Maint SALP	Surveil SALP	Serious Maint Noncomp.	Less Serious Maint Noncomp.	Man/Rem Exposures	Airborne Effluents (Curies)	I-131 & Particulates (Curies)	Liquid Effluents (Curies)	Tritium Effluents (Curies)
Reactor Vendor/Type										
BWR	48.1[a]**	.49*	.22	.35	-.92	516.1**	34945*	2.07	.59	-234.9
Westinghouse PWR	23.7	.23	-.24	.20	-.27	250.6	- 4663	-.77	.59	262.8
Other PWR										
Region										
Northeast	-24.1	-.31	-.49*	-1.42	-.96*	- 12.9	-27519	-.42	.60	208.5
Midwest	-34.7*	.91	-.42	- .98	-.84*	-183.6	-39990*	2.72*	.61	- 29.4
West	- .5*	-.20	.19	-1.51	1.21*	-231.1	-36323	1.73	.98	-134.3
South										
Size										
MWe	.16	.13*	.11*	.28	.62	.9**	-12	.71*	.13	.46
Age										
MOSCRIT[b]	-.9	-.19	-.23	-.91	.90	-1.8	1165	-.76	.45	-8.96
MOSPOST[c]	-.5*	.22	.39	.11	.67	3.7	- 239	.40	.90	1.94
Intercept	118.7*	1.41*	1.76*	5.88**	.28	-295.1	- 5985	-.51	1.73	396.1
R-Square[d]	.39**	.28*	.32**	.26*	.26*	.32**	.25*	.20	.10	.15
P *.05 **.01										
Comments:	BWRs, South, newer plants worse	BWRs, larger plants, South worse	North-east, smaller plants better; South worse	South worse	North-east, Midwest better; West worse	BWRs, larger plants worse	BWRs worse; Midwest, South better	Larger plants worse, but function not significant		

[a]Unstandardized regression coefficients with a sample size ranging from 67-72.
[b]Months operational up to 36.
[c]Months operational past 36.
[d]Proportion of variance explained.

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This report contains a statistical analysis of the relationship between selected aspects of nuclear power plant maintenance programs and safety related performance. The report identifies a large number of maintenance resources which can be expected to influence maintenance performance and subsequent plant safety performance. The resources for which data were readily available were related statistically to two sets of performance indicators: maintenance intermediate safety indicators, and final safety performance indicators. The results show that the administrative structure of the plant maintenance program is a significant predictor of performance on both sets of indicators.

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AN EMPIRICAL ANALYSIS OF SELECTED NUCLEAR POWER PLANT MAINTENANCE FACTORS AND PLANT SAFETY

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